EVERGREEN 2045: AN ENERGY MIX TO DECARBONIZE WASHINGTON STATE
Assessing Contributions of Small Modular Reactors to the Cost and Stability of the Future Resource Mix

Thank you for providing constructive feedback on our manuscript submission.

Most notably, we have more clearly summarized the assumptions used to develop our analysis as requested by the reviewer, as well as provided additional context to answer the reviewer's questions.

We believe the recommended revisions have improved the paper and are grateful for the review. We are also available to address any remaining concerns.

Sincerely,
Brittany Tarufelli

A. Could you please facilitate where does the data for 2030- and 2045 GHG Neutral Scenario analysis come from? Does data come from The Washington State Clean Energy Transformation Act? Could you also explain how were the results presented in table 1 obtained?

   Future resource mix scenarios were designed by our team to comply with the requirements and penalties of Washington State's Clean Energy Transformation Act. We changed the first sentence of Section 4 to state "Future resource mix scenarios are designed to comply with requirements and penalties from WA's CETA" to make this clearer.

   The results in Table 1 are from the production cost model analysis of the future resource mix scenarios (it is a summary of the production cost model output). We've added an additional detail to the first sentence of the second paragraph of Section 5.5 to make that clear "As shown in Table 1, which shows results from our PCM analysis, we found a reduction in generation cost relative to the baseline, likely due to reduced fossil-fuel use."

B. The modelling is done considering Xe-100 SMR to be a part of hybrid energy system, however there are no reference for the design in the paper. Surely the authors are well familiar with this design. Adding these references would be valuable for readers (e.g. junior experts or experts with non-technical background) willing to learn more on this topic.

   We added a footnote: See https://x-energy.com/reactors/xe-100 for additional design information.

C. C. Fig.1 and Fig.2. It is challenging to read. Could you please fix the font size and colour?

   We increased the size of these figures to help with readability.

D. Fig.4 "Expended renewables", could you please facilitate on which "renewables" are considered in the analysis?

   This scenario considered how the planned expansion of flexible resources in 2045 100% Clean Energy Scenario (3 x 320 MW SMRs and 1 GW SHR EGS) contributed to grid stability when wind penetration was increased by 1,150 GWh. We added clarification in the first paragraph of

Section 5.6: “We evaluated the 2030 GHG Neutral Scenario for stability, and then considered how the planned expansion of flexible resources in 2045 100% Clean Energy Scenario (3 x 320 MW SMRs and 1 GW SHR EGS) contributed to grid stability when wind penetration was increased by 1,150 GWh (Expanded Renewables Scenario).”

Few remarks for the authors:

1. The LCOE of both SMRs and Geothermal systems seems very low. would it be possible to share additional information concerning the main data used, in particular for the cost of capital used (WACC) and overnight cost, if not proprietary information?

   This is proprietary information. For context, we shared our results with our industry partners and these LCOEs are in alignment with their internal calculations.

2. The paper indicates that the cost assumptions refer to NOAK technology but does not address the issue of investing in a FOAK project.

   Proprietary information provided was for NOAK technology.

3. In Table 1, it would be interesting to have not only Simple averages LMPs, (I assume time-averaged) but also quantity-averaged LMPs in the 3 scenarios considered.

   The Simple Average LMP is the time-averaged Locational Marginal Price (LMP) across all load areas in Washington State. In our production cost modeling (PCM) analysis, we also calculated load-weighted average LMP and generation-weighted average LMP. In the revised version of the paper, we have provided both load-weighted and simple-average LMPs.

   The key difference between the two is that the simple average LMP accounts for LMPs at all buses, including both generation and load buses. On the other hand, load-weighted LMP is influenced by higher prices during peak load periods, which leads to slightly higher values compared to simple-average LMP. We added this information as a footnote to Table 1.

4. Especially in the 2040 scenario, revenues for nearly all technologies are insufficient to cover their total cost, and indeed cover only a small part of these cost. Capacity payments are sought for nuclear and geothermal plants, but no indication is given on how to provide the right incentives for investments in wind, solar and hydro plants. The very low electricity prices and revenues for generation plants might be due to a non-optimal generation mix, with excess capacity.

   We will address the reviewer’s last point first. The low electricity prices observed in our study can be attributed to several factors:

   1. Renewable capacity additions: We added renewable generation capacity comparable to the retired capacity of coal and gas plants in Washington State. An objective of our study was to integrate enough renewables to meet Washington’s Clean Energy Transformation Act using the existing transmission infrastructure, meaning we ensured that existing transmission line capacities were respected. This resource mix is optimized based on that available transmission capacity, as stated in our paper, “New clean energy supply locations were determined from previous analyses of supply locations within WECC that would minimize transmission congestion and variable renewable energy spillage.” We

take the point that our approach does mean that renewable capacity can be overbuilt in certain locations, which could potentially be addressed with transmission expansion. To highlight this point we did add (last paragraph of the paper) “Although important limitations exist in our research design, such as limitations due to current system topology (existing transmission constraints), our research contributes to our understanding of the economic feasibility of the future resource mix in WA as well as the role and economic feasibility of two future technologies that could provide valuable flexibility services to the future resource mix.” We would also like to note that this significant increase in renewables is aligned with Washington State's 100% clean electricity target.

2. Dominant Renewable Generation: The lower electricity prices are largely due to the dominance of renewable generation, which has zero marginal costs. The price reducing impacts of zero marginal costs resources on the electricity system as a whole are widely documented in the literature.

3. Interconnection Flows: We did not account for interconnection flows, which could moderate electricity prices. In 2045, this is assumption is specific for WA’s CETA which requires 100% clean energy to serve WA load. In reality, higher marginal cost generators may exist outside of Washington State, affecting the price dynamics of the WECC system as a whole.

4. CO2 Tax Consideration: Our study did allow for CO2 taxes for electricity imported into Washington State in 2030 (alternative compliance payments were allowed) in line with policy requirements. However, we did not model compliance payments in 2045 (this is the policy requirement, 100% of load must be served by clean energy). In practice, this could result in higher marginal cost generators located outside of Washington state that are not allowed to serve Washington load.

These factors combined contribute to the observed lower electricity prices in our analysis.

With respect to the question on capacity payments and determining the right incentives for all technologies, due to page limitations, we provide the subsidized profit or loss for each technology (where loss indicates the need for a capacity payment). We do say: “Revenues were sufficient to cover variable O&M and fuel costs for most technologies but were insufficient to cover total costs without PTCs. In the 2045 100% Clean Energy Scenario, the resource mix serving WA load was primarily composed of hydropower, onshore wind, and advanced nuclear power from SMRs. Revenues were again sufficient to cover variable O&M and fuel costs for most technologies (except SMRs, not shown), but were insufficient to cover total costs (even with PTCs or ITCs).”

Determining the right incentives for investments in all resources in the future resource mix is a great question but beyond the scope of this work.

5. Fonts in Figure 5 are not readable.

There isn’t a figure 5 in the paper. We are not sure to which figure this comment applies but did address comments on Figs. 1&2.

6. It would be useful to have a more detailed description on hydro resource (run-of-the river, dam or pumped hydro. Though I find the results to be fairly reasonable, it is quite difficult to determine whether data used is appropriate for the analysis performed.

   Hydro resources were those that exist in the WECC 2028 planning case which is available online (reference 6). We have information in the 2045 100% Clean Energy Scenario (Section 4.4) which details: "New, closed-loop pumped storage hydropower was added on the east side of the Cascades (where surplus wind and solar exist), as well as along the Columbia Gorge and Mid-Columbia area. In total, we added 57 non-emitting generation units, including 13 onshore wind power units totalling 4,540 MW, six utility-scale PV units totalling 1,924 MW, 12 advanced nuclear reactor units totalling 3,840 MW, eight pumped hydro units totalling 3,000 MW (with 14-hr storage), and 11 battery storage units (with 4-hr storage) totalling 1,980 MW."

   i. Additional information which can be helpful to determine the validity of the paper are follows:
      1. LMP is used in the analysis, but how many nodes were considered and how were demands and variable renewable supply determined for these nodes.
         Pricing nodes are those defined in the WECC 2028 Planning Case (reference 6), which is free and available online. Please also see footnote 6 which says, "This model represents an expected electric system for the 2028 year, developed by WECC and based on inputs from all its member utilities. The model contains a direct current transmission network topology with about 30,000 load and generation buses, including discrete modelling of all major generators across the WECC electric system. This includes the major generation in Washington and Oregon, our states of interest." We do not consider the change in demand from WECC 2028 Case as change load is out of the scope of this study."

      2. When curtailment is happening in the system, are there nodes with negative price? If so, how is that negative price determined?
         We have clarified in Section 5.5 that we used GridView which determines LMPs based on congestion, losses, and energy cost.

         In PCM simulation, we have observed negative LMPs in some areas. This is due to the large supply of renewables during a low demand period at a cheaper price, which then forces the congestion price or LMP to decrease or even go negative.

      3. How are market prices for energy and ancillary services determined? Even variable renewable is able to provide downward ancillary services, but are these characteristics reflected in the model?

         In our PCM simulations, we did not explicitly model ancillary services such as demand response. However, we did incorporate smaller ancillary service requirements for generation and load as mandated by the Western Electricity Coordinating Council (WECC). Specifically, we adhered to the

requirements outlined in the NERC BAL-003-2 standard, which can be found here: [NERC BAL-003-2 Standard] (https://www.nerc.com/pa/Stand/Reliability%20Standards/BAL-003-2.pdf).

This standard requires an additional 1.5% spinning reserve in generation and a 1.5% increase in load for the day-ahead market. We ensured that these requirements were met in our PCM simulations.

4. The description above Figure 1 and 2 are different from figure title, but are WA state capacity and Capacity serving Washington Load the same thing?

They are not. This reflects that in the 100% Clean Energy Case we report the installed capacity serving Washington load as clean energy resources were specifically attributed to serve Washington load in the PCM to verify compliance with the 2045 100% clean energy standard in Washington state.

5. How come I see DR in Figure 1 but not in Figure 2?

There is a very small percent of DR in Washington State in the WECC 2028 Case (10 MW, which is 0% of the resource mix) that is not attributed as part of the supply to serve WA load in the 2045 100% Clean Energy Case. Considering DR additions to optimize the future resource mix was beyond the scope of this work.

6. I think the general direction that the paper going is good, but I think the results are just not supported enough to provide confidence in the analysis. Predetermined inputs usually dictate much of the model results. I think providing more detailed reasoning for default and scenario values would improve the paper greatly.

Our primary limitation here is page constraints, as we are at 7 pages, adding additional detail requires taking away something else. We understand the concern and would like to point out that the base case is the WECC 2028 ADS planning case (reference 6) which is publicly available. (Note that WECC is currently migrating their website and the documents may appear unavailable in the near term, the guidance we received from WECC is as follows: Due to the WECC website transition, ADS data is not currently accessible on the website. Our IT Department is working hard to make the data available as soon as possible. The link Anchor Data Set (ADS) | Western Electricity Coordinating Council (wecc.org) is the correct one, but it won't show any data until IT resolves the issue. You should be okay to use the link in your paper.)

We clearly document all changes implemented to the base case for both the 2030 GHG Neutral scenario in Section 4.3 and the 100% Clean Energy Scenario in Section 4.4. We hope that this clarification in addition with the

other changes made in response to the helpful reviewer comments address this concern.