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

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Abstract

The Washington State Clean Energy Transformation Act (CETA) transitions Washington, U.S.A., to 100% clean energy by 2045. We examine the potential for flexible resources, including small modular reactors (SMRs), to replace existing fossil-fuel generation. We partner with X-energy, developer of a Gen-IV High-Temperature Gas-cooled Reactor (HTGR) – the Xe-100, to gain access to proprietary cost data and develop realistic cost estimates. We design future resource mix scenarios compliant with CETA and include deployments of SMRs and other flexible resources. We use power systems analysis tools (production cost modeling and transient stability analysis) to examine cost and stability of the future resource mix. We investigate the economic feasibility of SMRs using the value of services earned. With our integrated economic and engineering modeling approach, we find that the Xe-100 has a levelized cost of electricity ranging from $48 to $59, depending on incentives. We find that revenues earned are sufficient to cover variable O&M costs, but capacity payments or power purchase agreements will likely be necessary for SMRs to participate in the future resource mix. Other benefits from incorporating SMRs in the future resource mix include reduced carbon dioxide emissions, and in some scenarios, reduced congestion and price volatility.

1. INTRODUCTION

With clean energy policies penalizing or eliminating emissions-intensive fossil fuel generation, flexibility may be at a premium in the future resource mix. Two potential resources for providing needed flexibility are small modular reactors (SMRs) and superhot rock enhanced geothermal systems (SHR EGSs). We examine the contributions of these new resources to electricity cost and stability under hypothetical scenarios designed to be compliant with the Washington State Clean Energy Transformation Act (CETA) which transitions the state to 100% clean energy by 2045 through eliminating coal generation by 2025, enacting a $60/MWh tax on natural gas generation by 2030, and requiring 100% clean energy for all generation serving Washington (WA) load by 2045.

Strict limits on new hydropower production, seasonal variation in existing hydropower production, and imperfect correlation of wind and solar power with net load mean that flexibility may be at a premium, however analysis is needed to understand how SMRs and SHR EGSs will contribute to the future resource mix. Adding to the challenge is that available cost data for SMRs and SHR EGSs varies widely, is location specific, and excludes interconnection costs. For example, [1] found that a SMR at the WA Hanford Site could produce electricity in the $55/MWh range for an nth-of-a-kind facility, but the first of its kind has yet to be built [2]. Cost estimates for SMRs range from $131–$204/MWh (excluding interconnection costs).

To address these challenges, we developed an integrated economic and engineering modelling approach which allows us to analyse the stability and economic feasibility of the future resource mix, including the contributions of new, flexible technologies. To overcome cost data limitations, we partnered with X-energy, the developer of a Gen-IV High-Temperature Gas-cooled Reactor (HTGR) – the Xe-100, and AltaRock Energy, the developer of an SHR EGS, for proprietary cost and operational data that we used to develop realistic cost estimates. We then used power system analysis tools (production cost modelling [PCM] and transient stability analysis [TSA]) to examine the cost and stability of the future resource mix. Using the value of services earned, we determined the economic feasibility of new, flexible technologies in the future resource mix.

2. ECONOMIC AND ENGINEERING MODELLING APPROACH

Our integrated economic and engineering modelling approach had four distinct tasks: 1) Estimate costs of SMRs and SHR EGSs; 2) Design future resource mix scenarios compliant with WA's CETA; 3) Perform power systems analysis to evaluate the costs of the future resource mix (variable operating and maintenance (O&M) and fuel costs) with PCM and the stability future resource mix (in terms of reactive power, voltage, frequency, and inertia) with TSA; and 4) Evaluate of the economic feasibility of SMRs and SHR EGSs within the future resource mix using the value of services provided.

3. ESTIMATING COSTS FOR NEW, FLEXIBLE TECHNOLOGIES

Our methodology for estimating the cost of new, flexible technologies followed an eight-step process where we selected the technology location based on discussions with industry partners and available infrastructure; obtained proprietary design and process flow data from industry partners; determined major equipment requirements and obtained cost data from industry partners; developed required balance of plant components; estimated bill of materials and determined O&M costs; estimated electricity output; estimated interconnection costs (if needed); and determined $/MWh required to meet the rate of return on equity investment.

3.1. Small Modular Reactors

We partnered with X-energy, developer of the Xe100, a Generation IV high-temperature gas-cooled nuclear reactor powered by TRISO fuel, to develop an nth-of-a-kind cost estimate for the SMR.[1] We selected the Xe-100 as it is highly flexible, with a 94% capacity factor due to a pebble bed design, which allows for online refueling, and a modular design that allows for 80 MW reactors to be scaled into a 4-pack 320 MW plant. X-energy is part of the U.S. Department of Energy's Advanced Reactor Demonstration Program and X-energy's existing partnerships support the potential development and commercial demonstration of the SMR in WA.

To obtain needed proprietary cost data, we provided X-energy with a nuclear cost data questionnaire. We then used G4ECONS [3] to develop the levelized cost of energy (LCOE). As G4ECONS did not include a model for a reactor similar to the Xe-100 as one of its six modules, we used proprietary cost data from X-energy, uranium market mining, conversion, and enrichment cost data, literature review, as well as PNNL calculations to determine appropriate parameters in the G4ECONS nuclear-economic model. Based on these data, and assuming the clean electricity production tax credit (PTC) available from the Inflation Reduction Act[2] of 1.5 cents per kW (in 1992 dollars, inflation adjusted) for SMRs applies, the LCOE was $48/MWh for an nth-of-its-kind plant. Without the PTC, the LCOE was $59/MWh. Variable O&M and ramping costs were based on proprietary data provided by X-energy. Other operational parameters were based on Columbia Generating Station (conventional nuclear plant), scaled for the enhanced efficiency of the Xe-100.

3.2. Superhot Rock Enhanced Geothermal Systems

We partnered with AltaRock Energy, a technology leader in SHR EGSs to obtain proprietary design, cost, and operational data. We selected SHR EGS as a potential technology as drilling into superhot rock provides higher steam temperatures and higher turbine efficiency, allowing for economies of scale not available for current geothermal systems. Because the drilling technology for accessing superhot rock at the selected location – Newberry Volcano in Oregon state – is unproven, financing and permitting costs are primary limitations for deploying this technology at scale.

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[1] See https://x-energy.com/reactors/xe-100 for additional design information.

[2] The clean electricity production tax credit of 1.5 cents/kWh (inflation adjusted) per kWh applies for 10 years for facilities placed in service after 12/31/24. The 1.5 cents/kWh assumes prevailing wage and apprenticeship requirements are met. If the ANR is also located in an energy community (brownfield site) the credit increases to 1.65 cents/kWh [4]. We assume the credit does not phase out, i.e., U.S. GHG emissions from electricity are greater than 25% of 2022 emissions.

We obtained a proprietary LCOE model from AltaRock which contained assumptions about wellfield capital expenditure, power plant capital expenditure (based both on the literature and AltaRock proprietary models), and AltaRock's expected costs of financing. We made several adjustments to the LCOE model including adjusting the effective tax rate to be inclusive of federal and Oregon state taxes, which affected the weighted average cost of capital[3]; adding insurance costs based on the U.S. Department of Energy's Geothermal Electricity Technology Evaluation Model (GETEM)[4]; adding a corporate activities tax, applicable to business revenues over $1 million in Oregon [5], adding a depletion allowance of 15% (26 U.S.C. § 613) capped by the value of the property (Oregon Rev. Stat. § 317.374); and adding a Clean Electricity Investment Tax Credit, which is up to 30% of initial capital and added wells with new modifications from the Inflation Reduction Act [4]. The LCOE, inclusive of taxes and incentives, was $45/MWh for an nth-of-its-kind plant. Because the Clean Electricity Investment Tax Credit declines as emissions reduction goals are met, assuming the Clean Electricity Investment Tax Credit would not apply, the LCOE was $56/MWh. Variable O&M costs were based on proprietary data provided by AltaRock.[5] Ramping capabilities and other operational characteristics were based on the Geysers geothermal plants in California.

4. FUTURE RESOURCE MIX SCENARIOS

Future resource mix scenarios are designed to comply with requirements and penalties from WA's CETA. Due to the network structure of the electricity grid, to model the cost and stability of the future resource mix in WA required modelling the entire Western Interconnection. Our future resource mix scenarios modified the Western Electric Coordinating Council (WECC) 2028 planning model[6] [6] to reflect the expected future resource mix in WA in 2030 (GHG Neutral Scenario) and 2045 (100% Clean Energy Scenario). We use the unmodified 2028 planning model results as a baseline for comparison with the 2030 and 2045 cases.

4.3. 2030 Greenhouse Gas Neutral Scenario

The 2030 GHG Neutral Scenario (Fig.1) included the elimination of coal plants in WA, and a carbon tax (to reflect the alternative compliance payment) for any generation serving WA load of $150/MWh for coal-based generation, $84/MWh for natural gas-based peaking power plants, and $60/MWh for natural gas combined cycle generation.[7] We added two new plants to the WECC 2028 planning model, a 100.5 MW SHR EGS at Newberry Volcano in Oregon and a 320 MW SMR in Grant County, WA. Both plants were added at existing nodes that did not require additional transmission investments or network changes.[8]

4.4. 2045 100% Clean Energy Scenario

The 2045 100% Clean Energy Scenario (Fig. 2) added sufficient clean energy supply to meet the 100% clean energy standard for serving WA load without upgrading the existing transmission system. New clean energy

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[3] The assumed federal tax rate is 21%, because it is currently unclear whether the tentative minimum tax of 15% from the Inflation Reduction Act would apply (Inflation Reduction Act of 2022).

[4] The GETEM model is available at https://www.energy.gov/eere/geothermal/geothermal-electricity-technology-evaluation-model (accessed 5/19/2024).

[5] We noted an issue with the calculation of variable O&M costs that was identified too late to be included in this analysis. O&M costs were estimated based on a percentage of capital costs, but because the variable quantity of power produced declines over time, O&M costs are higher per unit of power produced at the end of the project than at the beginning of the project. O&M costs are a discounted average of O&M costs over the life of the project, but they are discounted at the after-tax weighted average cost of capital (WACC) when O&M costs should be discounted at the pre-tax WACC. This error could understate O&M costs; however, it was noted that AltaRock's assumption of O&M costs as a percent of capital expenditure was roughly 1% higher than typical geothermal O&M costs (based on GETEM).

[6] 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.

[7] Penalties were modelled as an addition to variable O&M cost in the PCM. To allow for analysis in 2022 dollars, we did not escalate alternative compliance payments at the rate of inflation.

[8] We selected substations with high voltage (500 kV) and assumed there would be sufficient head room for capacity to be injected into the network.

supply locations were determined from previous analyses of supply locations within WECC that would minimize transmission congestion and variable renewable energy spillage. Changes in the two new flexible energy systems reflected their potential expansion: the SHR EGS expanded to 1 GW at Newberry Volcano in Oregon and in addition to the 320 MW SMR in Grant County, WA, we assumed two additional 320 MW SMRs were operational—one at the Hanford Site and one at the retired Centralia Generating Station, WA.

As transmission constraints occur when moving power west across the Cascade Range to the Interstate 5 (I-5) corridor and north/south along the I-5 corridor, additional SMRs were added at existing sites built to support baseload supply near the existing Columbia Generating Station, the retired Centralia Generating Station, and a failed nuclear development near Aberdeen, WA. New wind power was added in the Lower Snake River region, along the Columbia Gorge, and on the west side of the Cascades in coastal WA. New solar PV was also added along the Lower Snake River region, in the Hanford Site area, and the retired Centralia Generating Station area. Four-hour battery energy storage was distributed with added solar generation. 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 on-shore 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.

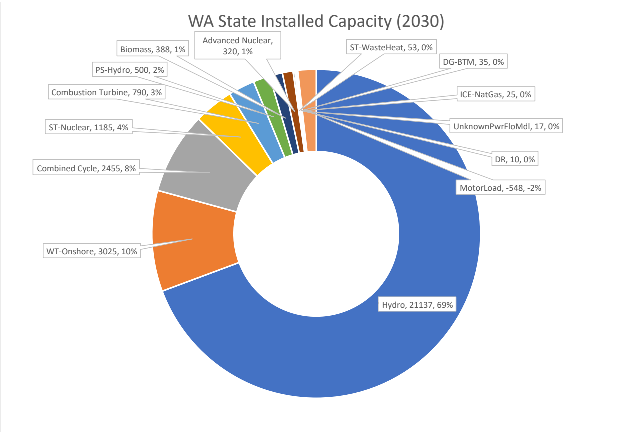


Fig. 1: ***WA State Installed Generation Capacity (2030) (MW, %)***

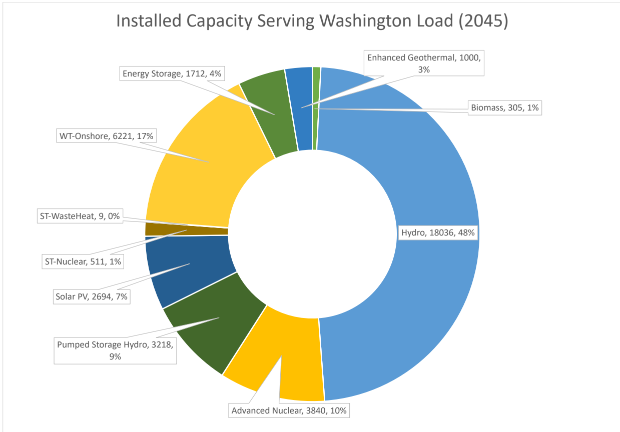


Fig. 2: ***WA State Installed Generation Capacity Serving WA Load (2045) (MW, %)***

5. POWER SYSTEMS ANALYSIS

Power system analysis enables understanding of investment decisions beyond operational costs and is critical for reliable power system operations. Power system tools specialize in modelling specific features of the grid. For example, while production costing is very good at capturing hourly operational decisions and costs over the course of a year, its simplified DC power flow model only captures real power flows on the system. To truly study the impact of variable renewable energy resources on reactive power flows and voltages, AC power flow and stability analyses are necessary. Our methodology leverages both PCM and TSA power flow analyses.

5.5. Production Cost Model

We evaluated the technical potential and system cost impact of new, flexible resources under our future resource mix scenarios using the PCM (GridView), which is intended to represent actual system operations and permit system planners and operators to model the existing system as well as permutations to the system. Inputs to the model include detailed cost and operational data (including those estimated for new, flexible technologies), as well as load and grid service requirements. We adjusted the PCM (DC power flow model) to reflect our future resource mix scenarios and evaluated results for several criteria including unserved load, production costs, carbon emissions and costs, and renewable curtailment relative to the WECC 2028 planning model baseline.

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. The reduction in carbon dioxide (CO_2) emissions were greatest in the 2045 100% Clean Energy Scenario given the enforcement of 100% clean energy policies (remaining emissions were from a small amount of biomass). Results for locational marginal prices (LMP) did not follow the same pattern, with an increase in the average LMP for the 2030 GHG Neutral Scenario, likely due to the increased balancing costs from natural gas generation due to compliance penalties, and a decrease in the average LMP in the 2045 100% Clean Energy Scenario, likely due to reduced price volatility from added SMRs. Finally, we saw reduced renewable curtailment in the 2030 GHG Neutral Scenario, likely due to added flexibility from SMRs and SHR EGS, however we saw increased curtailment in the 2045 100% Clean Energy Scenario due to fossil fuel retirements and added variable renewable energy (VRE) supply.

Table 1: ***PCM System Impacts for Oregon and Washington (2018$)***

Scenario	*Generation Cost (M$)*	*Simple Avg. LMP ($/MWh)[d]*	*Load Weighted LMP ($/MWh)[d]*	*CO2 Emissions (M Short Ton)*	*Renewable Curtailment (GWh)*
Base Case	1,236	27	28	22.9	155
2030 GHG-Neutral Scenario[a]	876	39	40	17.2	129
Deviation from Base	-29%	44%	43%	-25%	-17%
2045 100% Clean Energy Scenario[b]	349	16	16	1.5	2,189
Deviation from Base	-72%	-41%	-43%	-94%[c]	1,311%

[a]The Base Scenario and 2030 GHG Neutral Scenario detail is from the DOPD, GCPD, AVA, PGE, PSEI, SCL, TPWR, BPAT, and CHPD balancing areas in the PCM model, which provide electricity in both Washington and Oregon.
[b]The 2045 100% Clean Energy Scenario detail is from the share of resources attributed to serve Washington load. This distinction is due to a PCM modeling approach ensuring 100% clean energy serves Washington load.
[c]Remaining emissions are from a small amount of biomass in Washington.
[d] Simple average LMP accounts for LMPs at all buses, including both generation and load. Load-weighted LMP is influenced by higher prices during peak load periods, leading to slightly higher values compared to simple-average LMP.

5.6. Transient Stability Analysis (TSA)

Our TSA used a staged approach to answer two main questions 1) how do new, flexible resources contribute to grid stability, and 2) can a stable electric grid be achieved with 100% clean energy resources. To answer the first question, we analyzed how SMRs and SHR EGS contributed to grid stability under an increasing penetration of renewable resources. 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). To answer the second question, we analyzed if the 100% Clean Energy Scenario was stable through analyzing the system after a large addition of VREs.[9] For both scenarios, a step-up interconnection system (buses and transformers) from low voltage to high voltage were added to support supply.

Our TSA analysis involved (1) exposing the system to a large N-2 contingency; (2) observing the response of the system; (3) comparing the response of the system with and without ANRs and SHR EGSs included at previously selected locations within the WECC 2028 planning model to assess how the new, flexible resources contribute to system stability; and (4) comparing the response of the system with and without a large addition of VREs to assess system stability under high renewables penetration. To analyse the modified system for its transient stability, an experiment was conducted by tripping the two largest generator units (each 1,250 MW unit) in the WECC system, also known as the Palo Verde contingency.

When examining the contribution of flexible technologies to grid stability in the 2030 GHG Neutral Scenario, we found that voltage profiles remained stable, even after applying the contingency, and voltage limit violations remained similar to the base scenario. In addition, system inertia was improved from 7158.14 MWsec to 7186.8 MWsec by adding new SMRs and SHR EGS. When examining the contribution of flexible technologies to grid stability under increased renewables penetration and the planned expansion of new, flexible technologies,

[9] In practice, we examine the bus with the large addition of wind generation capacity (1350 MW). This simplifying assumption was made due to time and budget constraints. 57 generators were added for the 100% Clean Energy Scenario.

we found that frequency response characteristics were improved as shown in Fig. 3 (base case, adjusted for increased wind) compared to Fig. 4 (expanded renewables). The frequency nadir was only up to 59.89 Hz in the expanded renewables case compared to 59.835 Hz in the base case with added wind, both scenarios were evaluated for the entire system. System inertia was improved from 7,485.59 MWsec to 7,586.17 MWsec, the voltage profile remained stable, and no new violations due to generation loss contingencies were introduced.[10]

Fig. 3 ***Base Case (with Added Wind)***

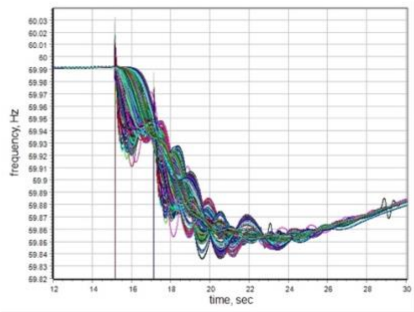
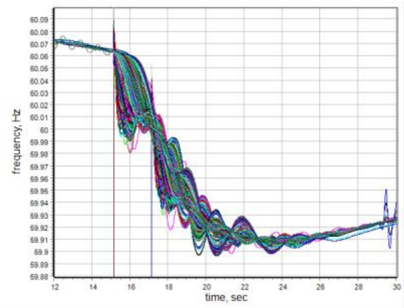


Fig 4. ***Expanded Renewables***



To examine if the system is stable under 100% clean energy, we added a total of nine, 150 MW wind farms to the system. Under Palo Verde contingency conditions, both frequency and voltage were stable over the 50 second simulation. Due to lack of reactive power adjustments, both the original and modified cases had some violations in frequency at certain 0.5kV generation units. Overall, there was no introduction of any new violations due to generation loss contingencies across transmission system due to the added wind generation.

6. ECONOMIC FEASIBILITY AND DISCUSSION

To determine if new, flexible resources were economically feasible we examined the value of services provided by the PCM. Primary inputs included total revenue earned in energy and ancillary service markets, variable O&M costs, variable fuel costs, and total generation (in MWh). Each metric was provided at the generator level and summed to total annual values by technology type. Our primary definition of economic feasibility was if the revenues earned in the future resource mix were sufficient to cover both variable O&M costs and fuel costs. However, because the PCM does not capture total costs (total annualized fixed costs from capital investment are not included), we compared revenue to levelized cost of energy estimates.[11]

In the base scenario most technologies in the resource mix earned sufficient revenue to cover variable O&M costs and fuel costs (not shown) but did not earn enough to cover total costs (LCOE, not shown) even when including subsidies. In the 2030 GHG Neutral Scenario, more wind, nuclear, and hydropower were dispatched, and significantly less natural gas power was dispatched. 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).

We estimated a capacity payment of up to $10 (unsubsidized) would be necessary for SHR EGS in 2030, those payments increased from $27 (subsidized) to $38 (unsubsidized) in 2045. SHR EGSs had increased dispatch but decreased revenues from the 2030 to 2045 scenarios, resulting in the need for an increased capacity payment. We estimated a capacity payment of up to $12 (unsubsidized) would be necessary for SMRs in 2030, those payments increased from $26 (subsidized) to $38 (unsubsidized) in 2045, as shown in Table 2. As ANR dispatch increased but revenues decreased from the 2030 GHG-Neutral Case to the 2045 100% Clean Energy Case, the magnitude of the needed capacity payment increased due to declining revenues per unit of generation (although generation increased substantially). Although important limitations exist in our research design, such as limitations due to current system topology (existing transmission constraints), our research contributes to our

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[10] Overall inertia is comparable due to aggregated renewable plant models being deployed in similar locations.

[11] LCOE estimates by technology type are available from the EIA's Annual Energy Outlook 2023 for new resources entering service in 2028 (in 2022 dollars per megawatt-hour), including applicable subsidies. LCOE estimates for new SMRs and SHR EGSs were developed in this research.

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.

Table 2: Economic Feasibility in the Future Resource Mix

Technology	**Economic Feasibility Metrics – 2030**			
	Revenue ($/MWh)	***LCOE Inc. Tax Credit ($/MWh)***	***Subsidized Profit (Loss) ($)***	***Percentage of Generation Mix***
Hydropower	43	57	(14)	65%
Combined Cycle Natural Gas[a]	56	43	13	8%
Onshore Wind	33	31	2	14%
Nuclear (Columbia Power Plant)	53	28	25	6%
Advanced Nuclear (excluding Columbia Power Plant)[b]	47	48	(0)	2%
Enhanced Geothermal	46	45	1	1%

[a] CCNG includes $60/MWh tax in Washington State resulting in a higher LMP and variable O&M cost in that state (not reported). As discussed in Section 5.5, 2030 GHG Neutral Scenario detail is from the DOPD, GCPD, AVA, PGE, PSEI, SCL, TPWR, BPAT, and CHPD balancing areas in the PCM model, which provide electricity in both Washington and Oregon. Reported LCOE is from EIA.
[b]Numbers for profit (loss) do not sum to revenue minus LCOE in table due to rounding error, subsidized loss is (0.15).

Technology	**Economic Feasibility Metrics – 2045**			
	Revenue ($/MWh)	***LCOE Inc. Tax Credit ($/MWh)***	***Subsidized Profit (Loss) ($)***	***Percentage of Generation Mix***
Hydropower	15	57[a]	(42)	49%
Solar PV	18	23	(5)	4%
Onshore Wind	18	31	(13)	14%
Nuclear (Columbia Power Plant)	40	28	12	3%
Advanced Nuclear (excluding Columbia Power Plant)	22	48	(26)	23%
Enhanced Geothermal	18	45	(27)	6%

[a] LCOE estimates are from EIA Annual Energy Outlook 2023 for new resources entering service in 2028 (in 2022 dollars per megawatt-hour), including applicable subsidies, existing resources with lower capital costs will have lower LCOEs.

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