Annual Technology Baseline: The 2024 Electricity Update

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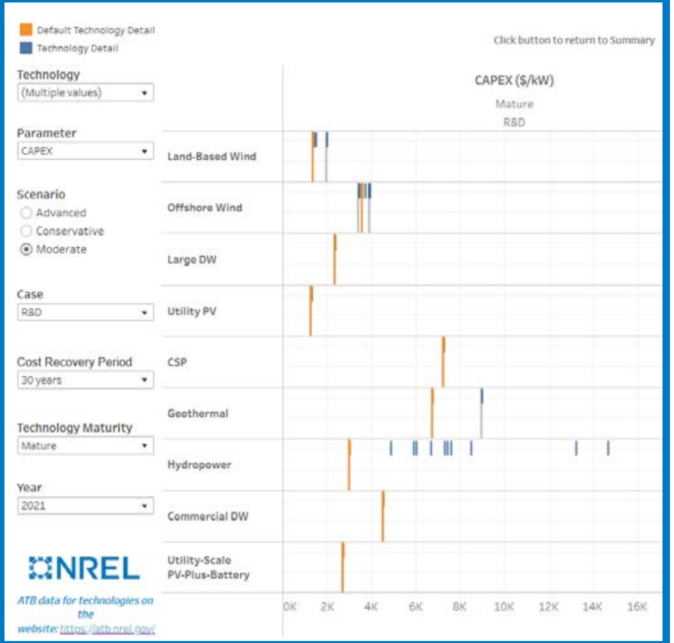
July 23, 2024

Agenda

- Introduction and Overview
  - Why the ATB?
  - ATB Overview
- Updates
  - Changes Affecting All Technologies
  - Financial Cases and Methods
  - Technology-Specific Updates
- Questions and Comments
- Breakout Groups

Why the ATB?



Annual Technology Baseline

About Technologies Data Contact

- Ever-changing technologies result in *conflicting reports of technology progress* based on inconsistent—and often opaque—assumptions.
- A *single dataset is needed* to credibly and transparently assess the evolving state of energy technologies in the United States.
- The ATB enables *understanding of technology cost and performance across energy sectors* and thus informs electric sector analysis nationwide.

National Renewable Energy Laboratory (NREL) ATBs

Annual Technology Baseline

NREL
Transforming ENERGY

Electricity Transportation Contact Archive Login

The NREL Annual Technology Baseline (ATB) provides a consistent set of technology cost and performance data for energy analysis. The ATB electricity and transportation datasets are freely available.

To inform electric and transportation sector analysis in the United States, each year NREL provides a robust set of modeling input assumptions for energy technologies (the Annual Technology Baseline) and a diverse set of potential electricity generation futures or modeling scenarios (Standard Scenarios). In 2020, an Annual Technology Baseline is provided for the transportation sector for the first time.

The ATB is a populated framework to identify technology-specific cost and performance parameters or other investment decision metrics across a range of fuel price conditions as well as site-specific conditions for electric generation technologies at present and with projections through 2050.

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

ATB homepage: https://atb.nrel.gov
Electricity: https://atb.nrel.gov/electricity/
Transportation: https://atb.nrel.gov/transportation/

Transportation ATB: Assumptions for Energy Systems Analysis

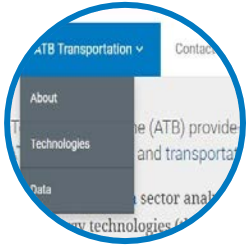
Coming Soon: 2024 Update

Core ATB Data

Base Year and Projected Data for…

- Fuel Economy
- Vehicle Price
- Fuel Cost
- Fuel Emissions
- Financing Assumptions
- Levelized Cost of Driving
- Emissions

ATB Product Suite



atb.nrel.gov

- User guidance
- Additional analyses
- Methodologies
- Comparison to other projections (e.g., EIA)

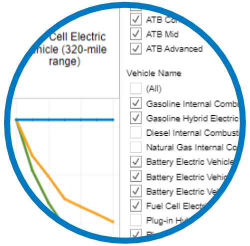
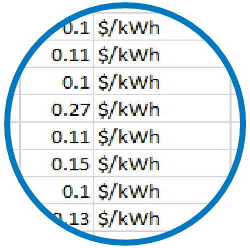


Tableau Workbook

- Summary of selected data (no calculations)
- Cost and performance projections, 2022–2050
- Interactive charts
- Visual exploration



Formatted Data

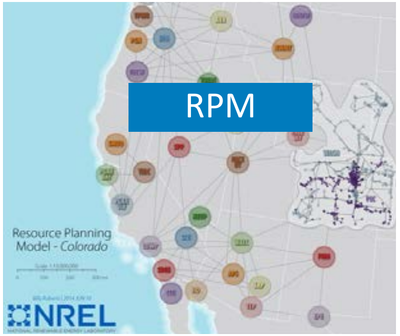
- Database-friendly summaries
- Cost and performance projections, 2022–2050
- Structured format

Presentation Slides

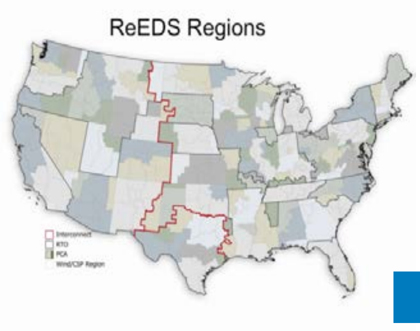
- Webinar presentation
- Summary presentation

ATB Project Overview

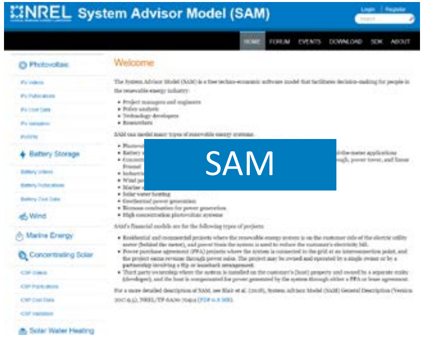
The ATB anchors key U.S. Department of Energy (DOE) and national laboratory analyses.



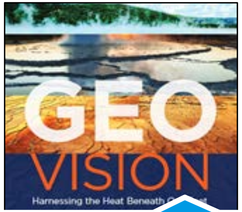
Resource Planning Model



Regional Energy Deployment System



System Advisor Model



Geothermal Vision

Hydropower Vision

Evaluating Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Power System

LA100

Standard Scenarios

Storage Futures

Important Scenario Analyses Used ATB Projections

Now in its 10th year, the ATB is frequently used by planners, academics, analysts, and others.

Federal Agencies
Bureau of Land Management, U.S. Department of Energy and labs, U.S. Environmental Protection Agency

Grid Operators
North American Electric Reliability Corporation, Midcontinent Independent System Operator, Pennsylvania-New Jersey-Maryland Interconnection, New York Independent System Operator

Utilities
Hawaii Electric Company, Dominion Energy, Xcel Energy

Consultants
Rhodium Group, Navigant, M.J. Bradley & Associates, Analysis Group

Nonprofits
Resources for the Future, Environmental Defense Fund, Union of Concerned Scientists

Academia
Stanford University, University of Maryland, University of Texas, Duke University, University of Colorado, Colorado School of Mines

State Officials
Hawaii, Michigan, California

International
Chilean Ministry of Energy, Global Carbon Capture and Storage Institute, Canadian Institute for Integrated Energy Systems

Media
Utility Dive

These are examples of users—*not* a comprehensive list.

The ATB data are inputs for the Standard Scenarios.

Annual Technology Baseline

Cost and performance assumptions for renewable and conventional technologies

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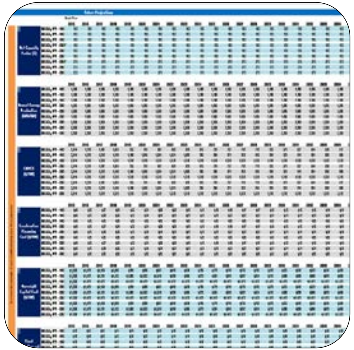
Standard Scenarios

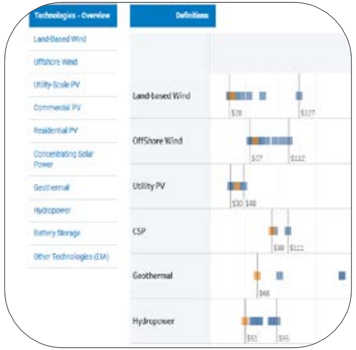
Ensemble of future scenarios for the U.S. electric power sector

The Electricity ATB includes a suite of products.



Spreadsheet

- Calculations
- Cost and performance projections, 2022–2050
- Capacity factor
- Operations and maintenance (O&M) costs
- Capital expenditures (CAPEX)
- Financing assumptions
- Levelized cost of energy (LCOE)



Web App

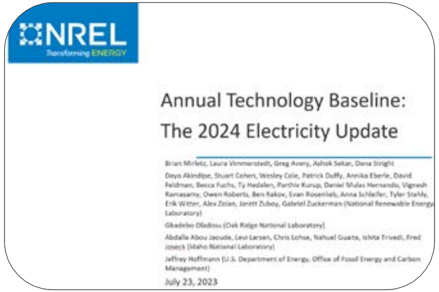
- atb.nrel.gov
- User guidance
- Additional analyses
- Methodologies
- Interactive charts
- Historical trends and comparison to other projections (e.g., EIA)

Interactive Charts

Tableau Workbook

Formatted Data

- Summary of selected data (no calculations)
- Interactive charts
- Visual exploration
- Cost and performance projections, 2022–2050
  - Capacity factor
  - O&M costs
  - CAPEX
  - Financing assumptions
  - LCOE
- Structured format



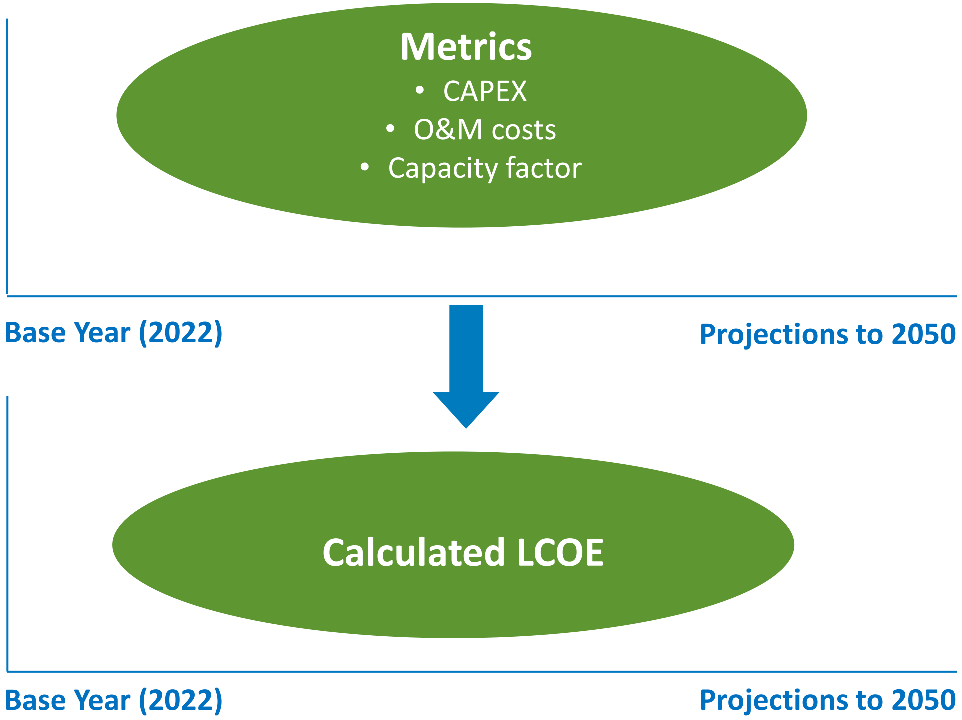
PowerPoint

- Webinar presentation
- Summary presentation

Open Data/Code

- Data published in Open Energy Data Initiative
- Programmatic access through AWS-S3
- Jupyter Notebook
- ATB-calc GitHub Repository

The ATB provides cost and performance data.



Cost and performance data are:

- Provided for each
  - Year
  - Metric
  - Resource
  - Technology
  - Technology cost scenario
- Used to calculate LCOE for each financial assumption scenario

LCOE is provided as a summary metric but is not used as a Regional Energy Deployment System (ReEDS) model input. Its limitations are described in the documentation. The user can select or specify financial assumptions for calculating LCOE.

Technologies Covered

Renewable Energy Technologies

New in 2024

Wind
- Land-based
- Fixed-bottom Offshore
- Floating Offshore
- Distributed

Solar
- Utility photovoltaics (PV)
- Commercial and industrial PV
- Residential PV
- Utility PV-plus-battery
- Concentrating solar power (CSP)

Hydropower
- Nonpowered dams (NPD)
- New stream-reach development (NSD)
- Pumped storage hydropower
- **NEW: Pumped storage hydropower using existing reservoirs**

Geothermal (Flash and Binary)
- Hydrothermal
- Near-field enhanced geothermal systems (EGS)
- Deep EGS

Storage
- Utility-scale
- Commercial-scale
- Residential

Fossil Energy Technologies

Natural Gas
- Natural gas combined cycle (NGCC)
- NGCC-carbon capture and storage (95%, 97% CCS)
- **NEW: NGCC with one steam turbine and one heat recovery generator**
- Combustion turbine (CT)
- Natural gas fuel cell (no CCS, 98% CCS)
- Retrofits (90%, 95% CCS)

Coal
- Integrated gasification combined cycle (IGCC)
- Pulverized coal
- Pulverized coal with 95%, 99% CCS
- IGCC with 99% CCS
- Retrofits (90%, 95% CCS)

Nuclear
- **NEW: Large (1,000 kilowatt [kW])**
- **NEW: Small modular reactor (300 kW)**

Other Technologies

(Energy Information Administration, Annual Energy Outlook [AEO] 2023)

Biopower
- Dedicated (woody biomass)

Methodology Overview: Three Steps

1. Define resource bins for each technology

Group ranges of resources for contiguous United States into bins with common resource quality and characteristics or develop representative plants.

2. Develop cost and performance data

Develop base year and projected values for Conservative, Moderate, and Advanced technology cost scenarios for CAPEX, capacity factor, and O&M.

3. Calculate LCOE

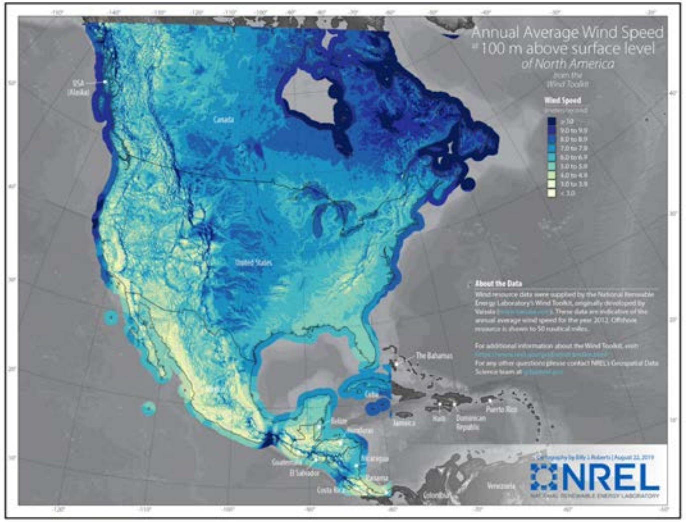
Use selected financial assumptions to calculate LCOE from CAPEX, capacity factor, and O&M.

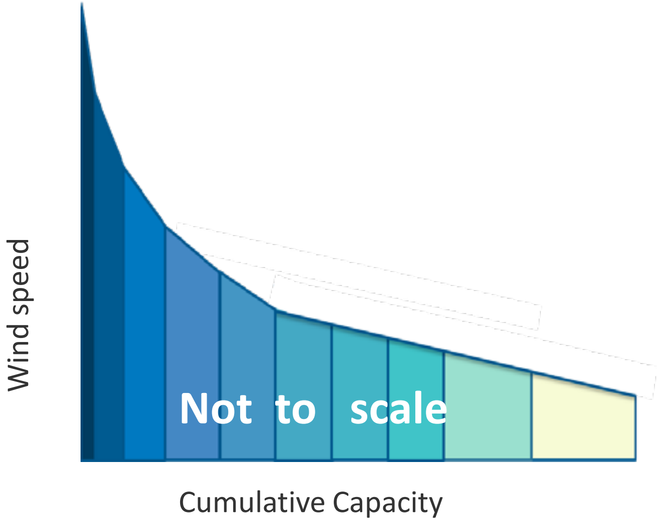
ATB Bins Technologies and Resources Based on Various Characteristics

Example: Wind ATB bins based on annual average wind speed

Annual average wind speed

ATB wind classes





https://www.nrel.gov/gis/assets/images/wtk-100-north-america-50-nm-01.jpg

Step 1: Define Technologies/Resource Bin Categories

Bins changed in 2024

Technology	Bins	Distinguishing Characteristics
Land-based wind	10	Annual average wind speed
Offshore wind	14	LCOE
Distributed wind	40	Turbine size, annual average wind speed
Utility-scale, commercial, residential PV, and utility-scale PV-plus-battery	10	Horizontal solar irradiance resource level
CSP	3	Direct normal solar irradiance
Geothermal	6[a]	Hydrothermal, EGS, binary or flash systems, reservoir temperature
Hydropower	12[a]	Nonpowered dams, new stream-reach development, head, and design capacity
Pumped storage hydropower	20[a]	CAPEX
Utility-scale, commercial, residential battery storage	5	Storage duration
Natural gas	12	Turbine technology, level of CCS
Coal	5	Pulverized coal, IGCC, level of CCS
Nuclear	2	Large reactor or small modular reactor (SMR)
Biopower	1	Dedicated
Natural gas and coal retrofits	6	Turbine technology, level of CCS

[a] Representative bins for the ATB only: ReEDS implements a full site-specific supply curve.

Step 2: Develop Cost and Performance Data

Base Year (2022): Informed by market reports, market data, and bottom-up modeling

Projections: Generally rely on bottom-up modeling and published studies; qualitatively harmonized to three scenarios of future technology innovation:

Conservative Technology Innovation	**Moderate** Technology Innovation	**Advanced** Technology Innovation
• Today's technology with little innovation • Continued industrial learning • Decreased public and private research and development (R&D)	• Widespread adoption of today's cutting-edge technology • Expected level of innovation • Current levels of public and private R&D	• Market success of currently unproven innovation • New technology architectures • Increased public and private R&D

Sources of Base Year (2022)

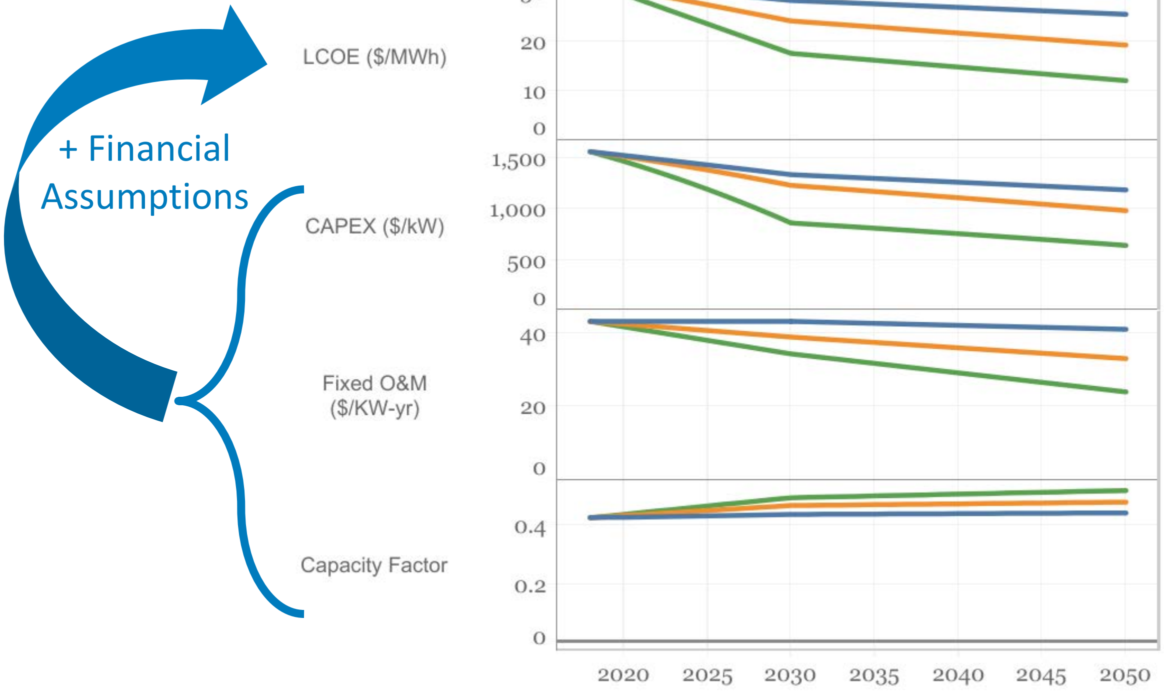
Technology	Source
Land-based wind power plants	CAPEX associated with the four representative technologies are estimated using bottom-up engineering models for hypothetical wind plants installed in 2022 (Wiser and Bolinger 2023) and (Eberle et al. 2024). The all-in operating expenses (OPEX) (O&M) cost for each representative technology is informed by recent literature (Liu and Garcia da Fonseca 2021) and (Wiser et al. 2019).
Offshore wind power plants	The Renewable Energy Potential Model (reV) and NREL Wind Analysis Library (NRWAL) are used to assess offshore wind plant costs across U.S. waters (Maclaurin et al. 2019); (Nunemaker et al. 2023). Estimates are informed by ORBIT for CAPEX, WOMBAT for OPEX, and the FLORIS tool for annual energy production (AEP) (Nunemaker et al. 2020); (Hammond and Cooperman 2022); (National Renewable Energy Laboratory [NREL] 2021)
Distributed wind power plants	CAPEX are estimated using bottom-up engineering models and empirical data for hypothetical wind projects installed in 2022 (Stehly et al. 2023). OPEX estimates are informed by historical data and are reported in (Stehly et al. 2023).
Utility, residential, and commercial PV plants	CAPEX for 2022 are based on bottom-up cost modeling and market data from (Ramasamy et al. 2022). O&M costs are based on modeled pricing for PV systems (Ramasamy et al. 2022).
Concentrating solar power plants	Assumptions are based on recent assessment of the industry in 2022 and bottom-up CSP cost analysis for heliostat components (Kurup et al. 2022).
Geothermal plants	Bottom-up modeling with Geothermal Electricity Technology Evaluation Model (GETEM) using baseline cost assumptions from the GeoVision Business-as-Usual scenario (DOE 2019) adjusted for technology improvements from ongoing demonstration projects and industry stakeholder consultations (Pengju Xing et al. 2024); (Norbeck and Latimer 2023).
Hydropower plants	NPD data are based on bottom-up 2020 cost analysis (Oladosu et al. 2021). NSD data from previous years based on Hydropower Vision study (DOE 2016); bottom-up cost modeling is from O'Connor et al. (2015).
Utility-scale PV-plus-battery	CAPEX assumptions for utility-scale PV-plus-battery are based on new bottom-up cost modeling and market data from (Ramasamy et al. 2023).
Utility, residential, and commercial battery storage	Costs for utility-scale battery energy storage systems (BESS) are based on a bottom-up cost model using the data and methodology for utility-scale BESS in (Ramasamy et al. 2023).
Pumped storage hydropower	Resource characterizations are from Rosenlieb et al. (2022) with updates described at https://www.nrel.gov/gis/psh-supply-curves.html, which describes a national closed-loop pumped storage hydropower (PSH) resource assessment. Capital costs are from Cohen et al. (2024). O&M costs are from Mongird et al. (2020).
Natural gas and coal	Estimates of performance and costs for currently available fossil-fueled electricity generating technologies are representative of current commercial offerings and/or projects that began commercial service within the past 10 years (Schmitt et al. 2022), (Buchheit et al. 2023), (Schmitt and Homsy 2023), (Leptinsky et al. 2024).
Nuclear	CAPEX and O&M values are based on a compilation of historical and recent cost estimates in (Abou-Jaoude et al. 2024).

Step 3: Calculate Levelized Cost of Energy*

$$\text{Levelized Cost of Energy} = \frac{\text{Fixed Charge Rate} \times \text{Capital Expenditures} + \text{Fixed Operation and Maintenance Cost}}{\text{Capacity Factor} \times 8760\ \text{hours/year}}$$

$$+ \text{Variable Operation and Maintenance Cost}$$

$$+ \text{Fuel Cost} - \text{Production Tax Credit}$$



LCOE is a summary metric with important limitations. See documentation at atb.nrel.gov.

Capacity factor refers to utilization for geothermal, hydropower, coal, gas, nuclear, and biopower.

* LCOE is for generation technologies only. Levelized cost of storage is not reported.

Changes to All Technologies

https://atb.nrel.gov/electricity/2024/changes_in_2024

Brian Mirletz

Changes That Affect All Technologies

- Grid connection costs
  - Prior years were inconsistent about costs such as spur lines and interconnection studies.
  - Example: PV included interconnection cost; other technologies did not.
  - All front-of-meter technologies now include nominal grid connection costs (spur line, point of interconnection, some network upgrades).
  - Technologies besides offshore wind do not vary by resource classification. Tools such as reV and ReEDS account for site-specific variation.

Changes That Affect All Technologies

Overnight capital costs (OCC):

- Balance of system
- On-site electrical equipment
- Generation equipment
- Site, owners', and indirect costs

Grid connection costs (GCC):

- Spur line
- Point of interconnection
- *Some* network upgrades

Lopez et al. 2024

Changes That Affect All Technologies

Nascent technology starting years:

Technology	Starting Year	Cost Type
Floating Offshore Wind	2030	Next commercial offering
Enhanced Geothermal	2022	Pilot project
Small Modular Nuclear	2030	Next commercial offering
Carbon Capture and Storage	2022	Next commercial offering
Natural Gas Fuel Cell	2035	Next commercial offering

Financial Cases and Methods Updates

https://atb.nrel.gov/electricity/2023/financial_cases_&_methods

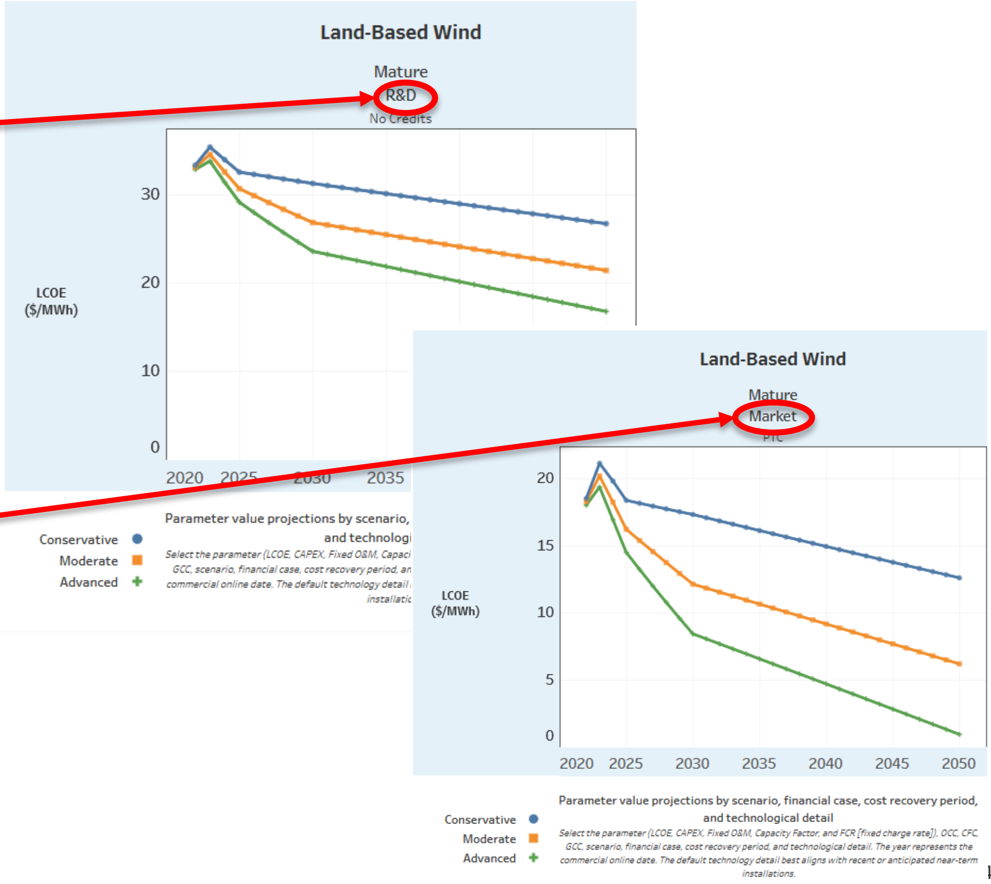
Brian Mirletz and David Feldman

ATB Financial Cases

Two financial cases:

- R&D: This sensitivity case allows technology-specific changes to debt interest rates, return on equity rates, and debt fraction to reflect the effects of R&D on technological risk perception, but it holds background rates constant and excludes effects of tax reform and tax credits.

- Markets + Policies: This sensitivity case retains the technology-specific changes to debt interest and return on equity rates from the R&D Only Case and adds in the effects of the tax credits in the Inflation Reduction Act (IRA) of 2022.



Financial Changes in 2024 ATB

- Base year = 2022. Dollar year = 2022. Historical data include data reported in 2022.
- Updated financial assumptions:
    - Construction financing costs for batteries
    - IRA tax credits remain through 2050 (based on 2023 Standard Scenarios)
    - Updated after-tax equity returns (selected examples below)

Technology	2023 ATB Equity Returns	2024 ATB Equity Returns
Utility PV and Utility PV+Battery	8.75%	8.5%
CSP	11%	10.5%
Land-based Wind	10%	9%
Offshore Wind	11%	10.5%
Geothermal	11%	10.5%
Hydropower	11%	9.75%
Nuclear	11%	10.5%

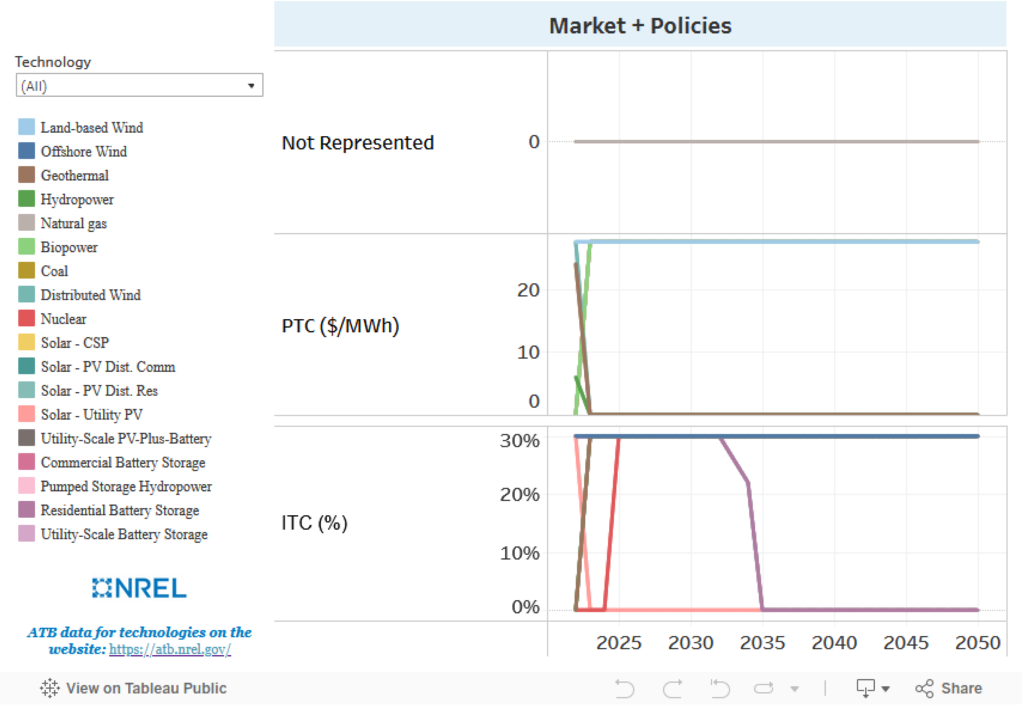
Comparing Financial Assumptions by Technology

The following slides compare financial assumptions used to calculate LCOE:

- Investment tax credits (ITC) and production tax credits (PTC)
- Term debt fraction
- Term-weighted average cost of capital (WACC) (real)
- LCOE

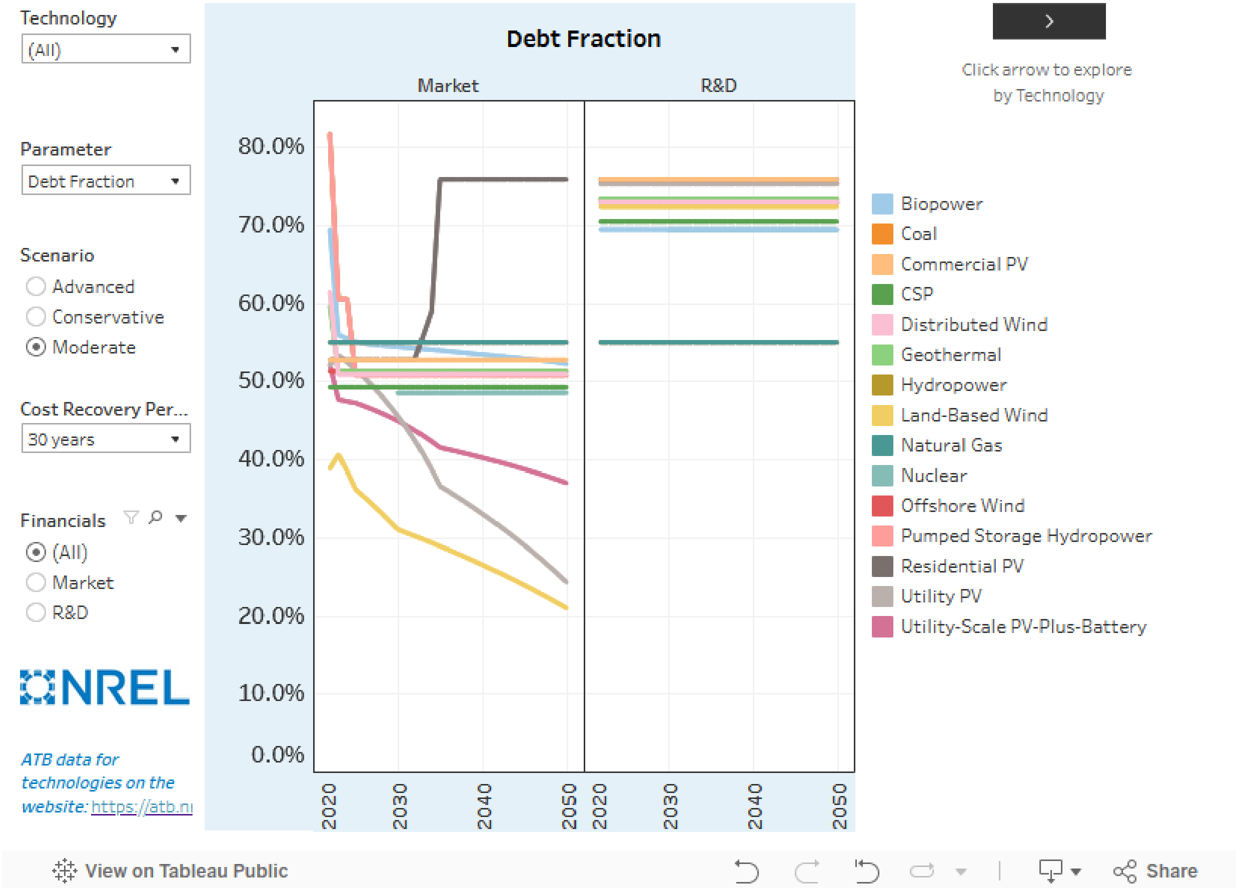
ITC and PTC

Assumptions for production tax credits and investment tax credits

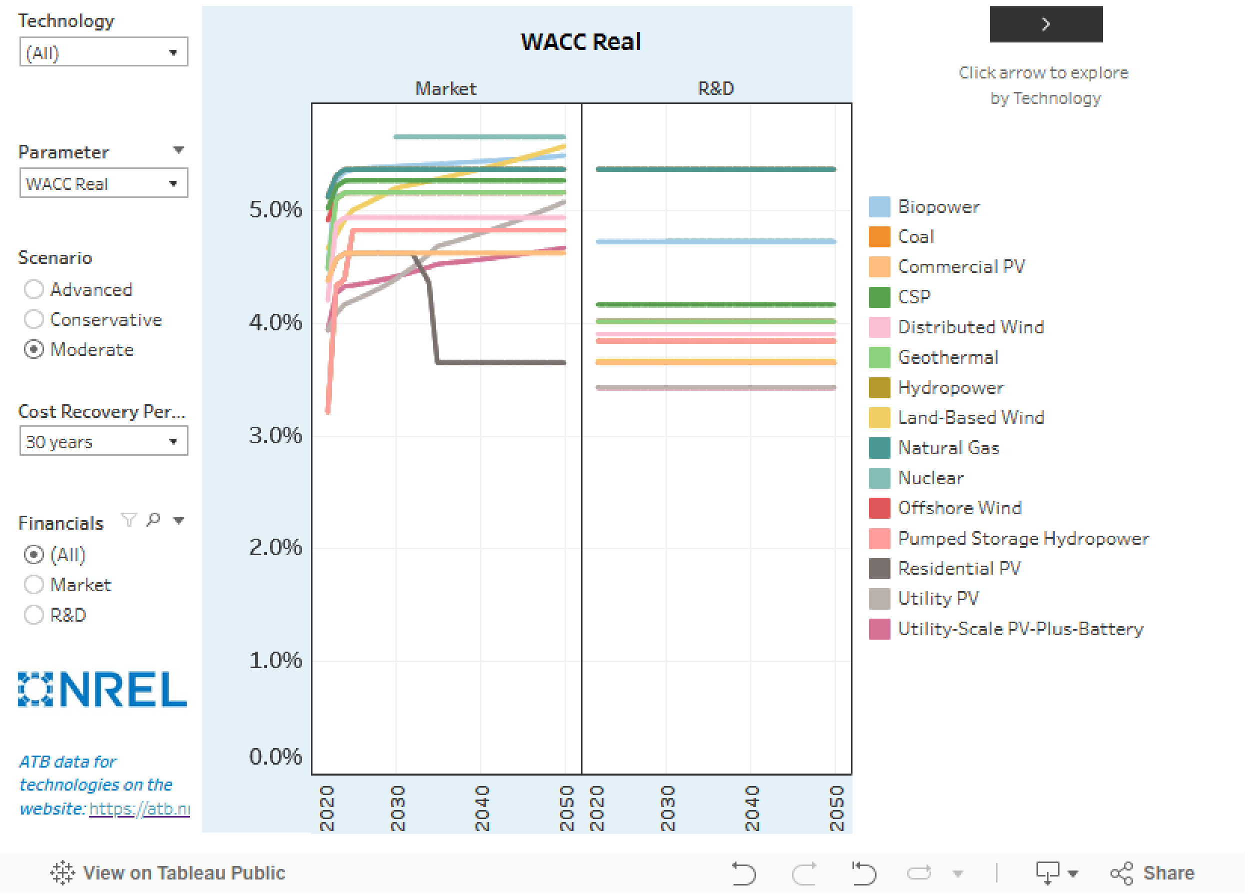


Annual comparison of production tax credits and investment tax credits

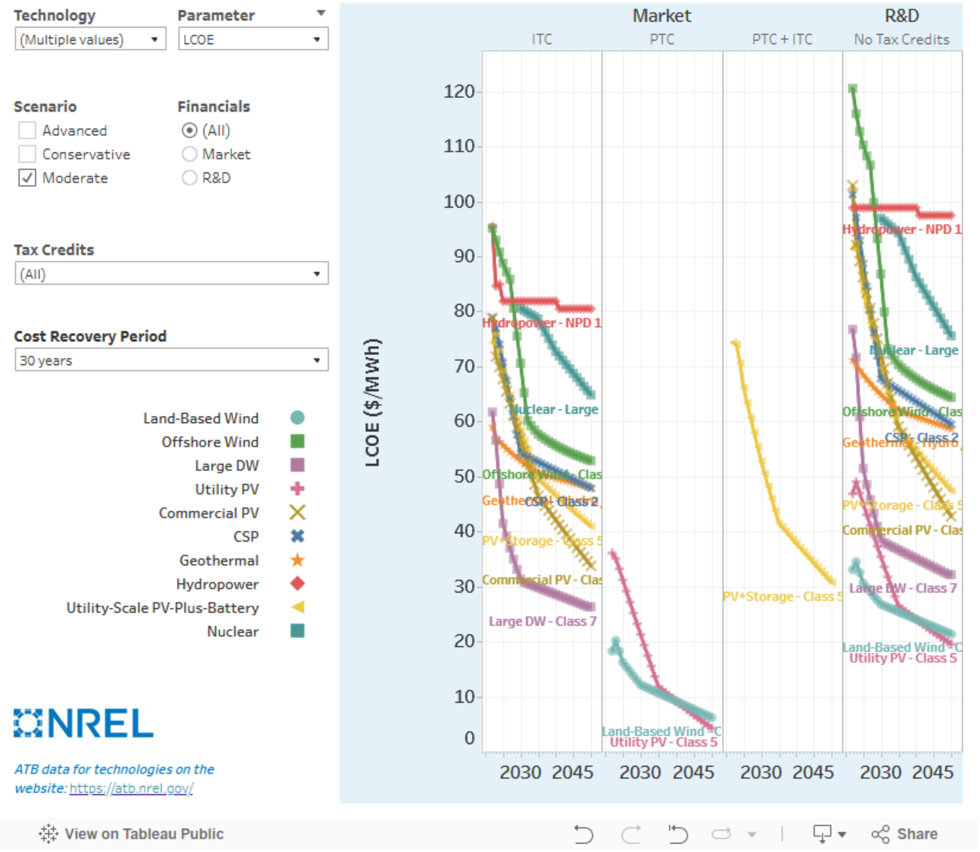
Term Debt Fraction by Financial Case



Term WACC (Real) by Financial Case



LCOE by Financial Case



LCOE by technology and financial assumptions case

Technology-Specific Updates

https://atb.nrel.gov/electricity/2024/changes_in_2024

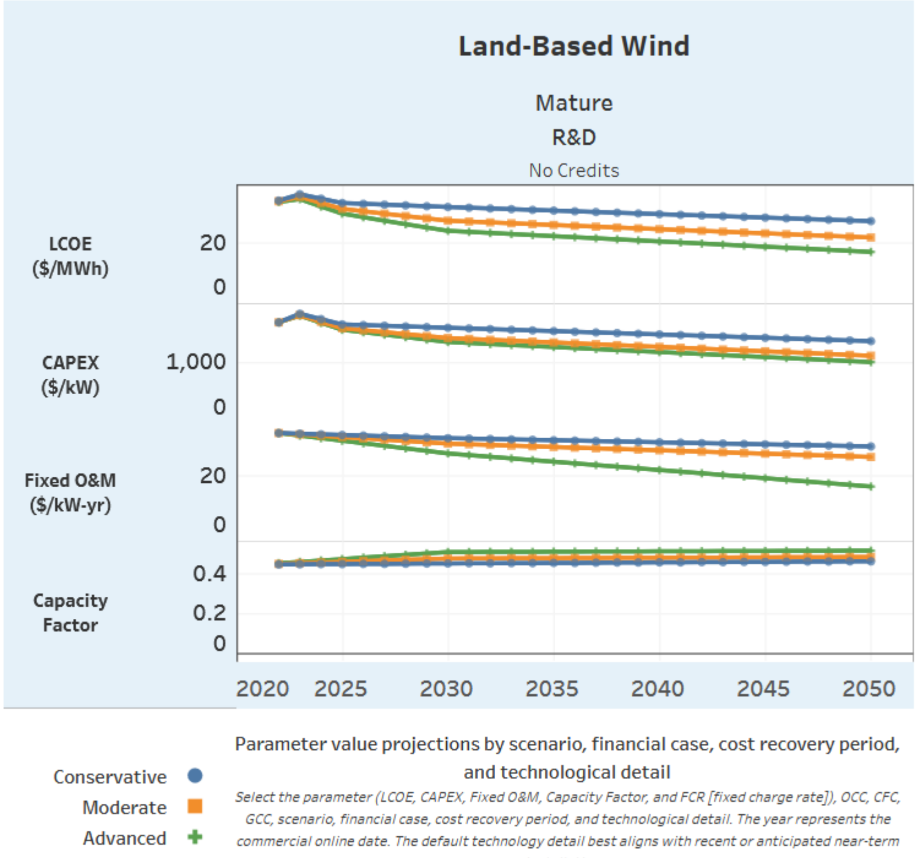
Updates by technology: Changes in **bold**. Main webinar session topics **underlined**.

- Land-based Wind: No major updates in the 2024 ATB.
- **Offshore Wind**:
  - Cost trajectories informed by both long-term industry learning and short-term **adjustments for macroeconomic headwinds facing early U.S. offshore wind projects** (such as rising interest rates, inflation, and supply chain shocks).
  - **Updated methodology for floating offshore wind to capture the cost reduction impacts of maturing from a nascent industry to the first wave of commercial projects.** Prior ATB efforts modeled Nth-of-a-kind commercial-scale floating wind projects assuming mature supply chains in all years. The 2024 ATB **presents floating offshore wind energy costs in 2030 and beyond,** when the first commercial-scale floating wind projects in the United States could feasibly come online.
- Distributed Wind: No major updates in the 2024 ATB.
- Photovoltaics (all scales): Initial cost metrics are informed by (Ramasamy et al. 2022), and straight-line improvements in cost metrics through 2035 are calculated using the 2023 benchmarks from (Ramasamy et al. 2023) as the initial points.
- Concentrating Solar Power: No major updates in the 2024 ATB.
- Hydropower: No major updates in the 2024 ATB.

Updates by technology: Changes in **bold**. Main webinar session topics underlined.

- Geothermal: Near-field and deep EGS **representative plant sizes are aligned for the base case.** The representative plant size for the EGS Binary Moderate scenario is updated to 40 MWe based on planned commercial developments.
- Utility-Scale PV-Plus-Battery: Tax credits have been updated to allow users to **select either the ITC for both components, or the PTC for PV and the ITC for battery.**
- Battery Storage (all scales): Base year CAPEX for utility-scale and commercial storage are **updated consistent with new benchmark results** in (Ramasamy et al. 2023).
- **Pumped Storage Hydropower: Added sites that use existing reservoirs. Capital costs and resource characteristics are updated** to use a new cost model described in (Cohen et al. 2024).
- **Natural Gas and Coal: Expands the set of NGCC power plant options to include an H-class 1x1 configuration** comprising a single combustion turbine with heat recovery providing steam to a Rankine bottoming cycle from (Leptinsky et al. 2024).
- **Nuclear:** Capital costs and plant characteristics in the 2024 ATB are **based on research from Idaho National Laboratory** from (Abou-Jaoude et al. 2024).
- Biopower: No changes in the 2024 ATB beyond dollar year updates.

Land-Based Wind



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

Land-Based Wind

Base Year

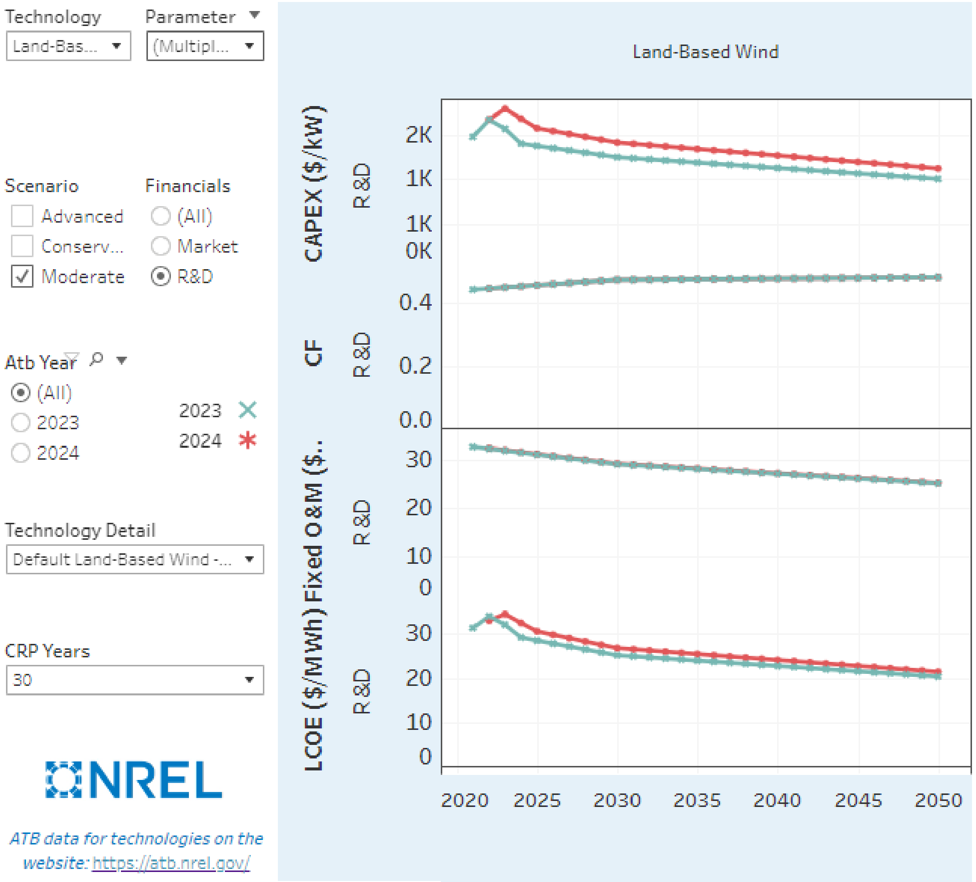
CAPEX associated with the four representative technologies are estimated using bottom-up engineering models for hypothetical wind plants installed in 2022. The Base Year value for each wind speed class depends on the selected representative technology. The all-in OPEX cost for each representative technology (varies by the representative wind turbine's rating) is informed by recent literature and expert elicitation. Capacity factors are calculated by generating a power curve for each representative wind turbine technology using the Weibull distribution and the average annual wind speed in the wind speed class in which the representative wind turbine is placed.

Projections

The technology configurations are used to estimate the total system CAPEX of a theoretical commercial-scale (e.g., 200-megawatt [MW]) project and changes for each of the scenarios (i.e., Conservative, Moderate, and Advanced) from bottom-up engineering models and assumed learning rates. OPEX estimates vary by wind turbine rating and change for each scenario based on calculated and assumed learning rates. Net capacity projection methods assume technology innovations that increase wind plant energy capture through advanced controls and reduce total system losses for each scenario.

Tyler Stehly, Annika Eberle, Owen Roberts, and Daniel Mulas Hernando

Land-Based Wind Changes

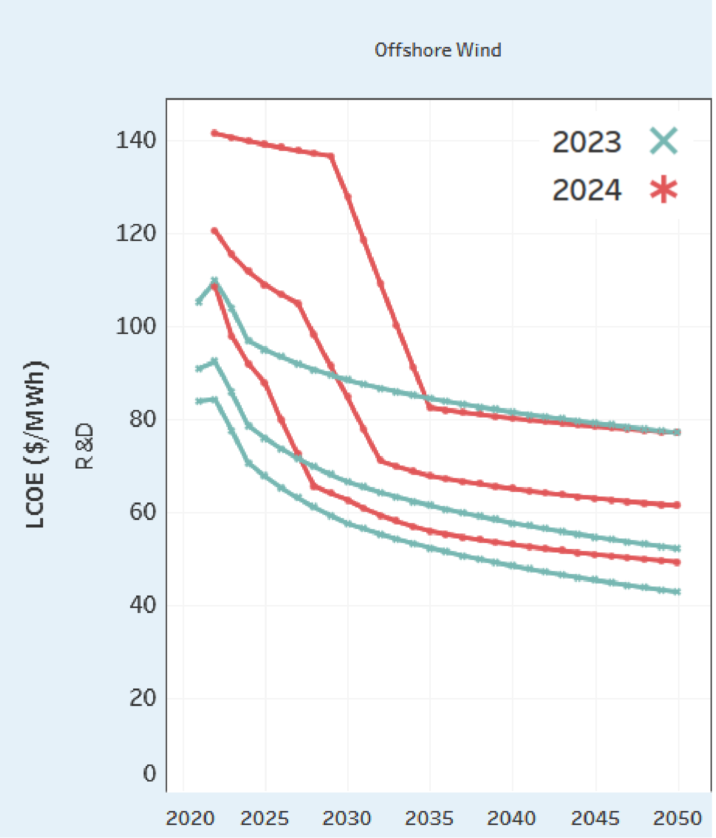


NREL

ATB data for technologies on the website: https://atb.nrel.gov/

Fixed-Bottom Offshore Wind Costs

- Updates to better reflect cost impacts experienced by the industry:
  - Inflation
  - Supply chain disruptions
  - Higher interest rates
- Adjustments applied to both fixed-bottom and floating offshore wind project CAPEX
- Results in higher projected LCOE values through the 2020s compared to the 2023 ATB (LCOE 30% higher in 2022 and 8% higher in 2035 for Moderate Case)

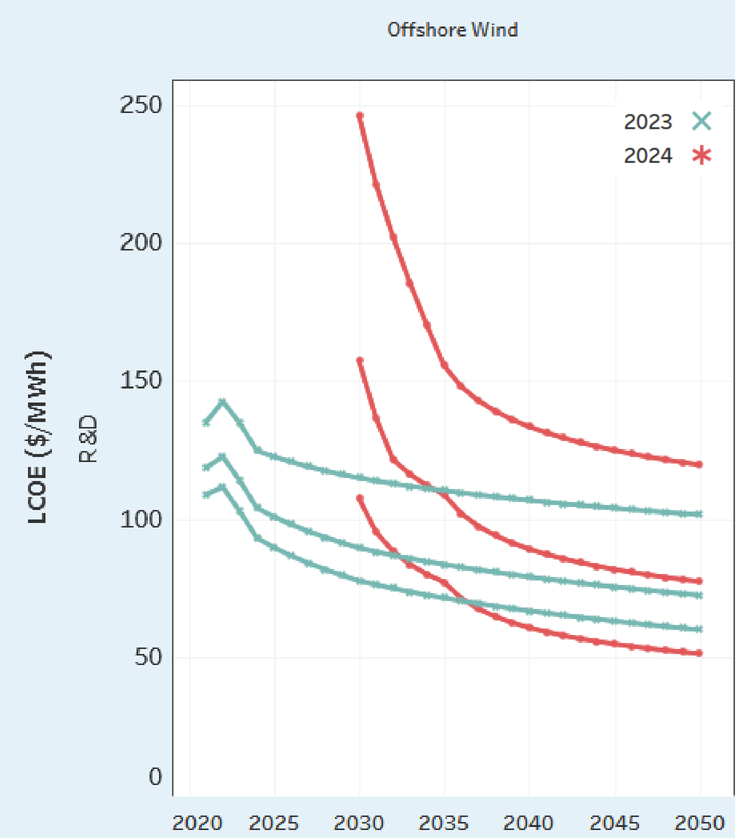


Year-over-year comparison of fixed-bottom offshore wind LCOE estimates.
Note: Conservative, Moderate, and Advanced scenarios shown for R&D financing case.

Patrick Duffy, Becca Fuchs,
Daniel Mulas Hernando, and Gabriel Zuckerman

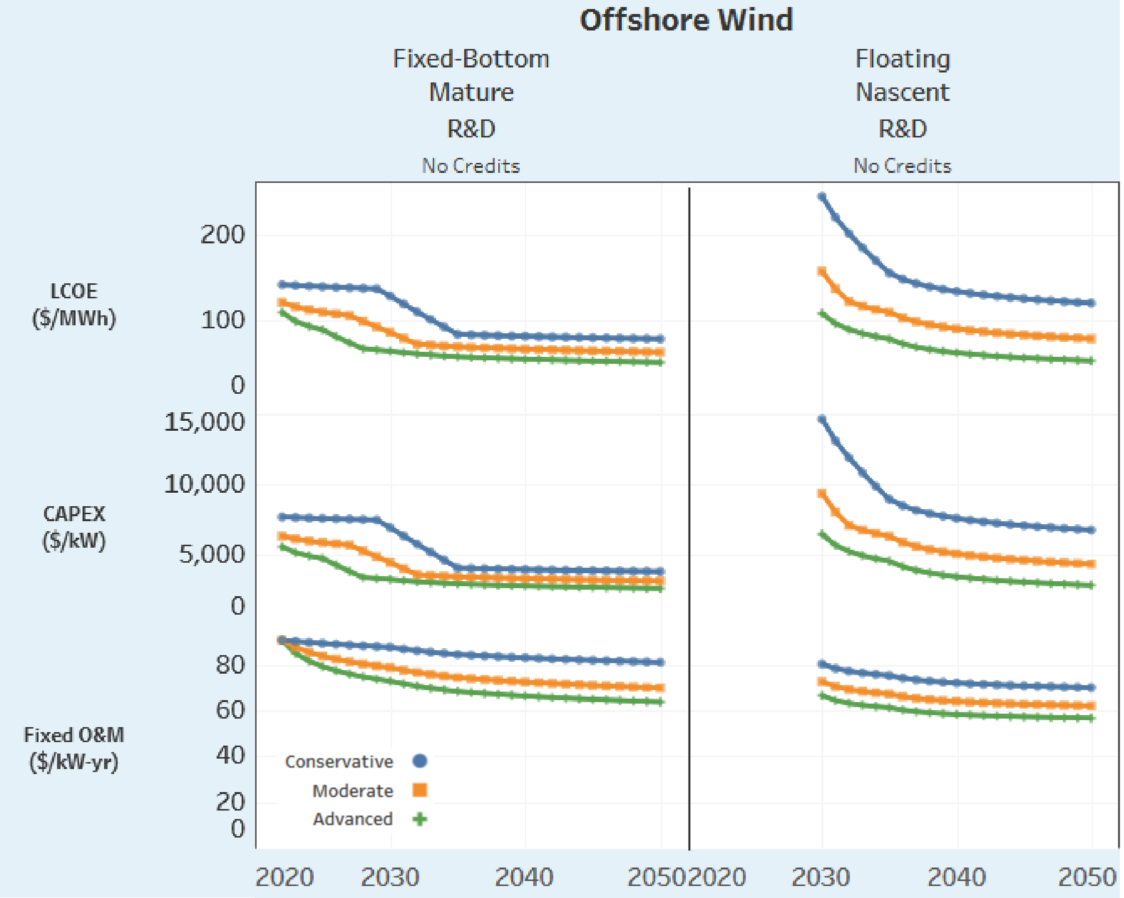
Floating Offshore Wind Costs

- Floating cost methodology change better represents the cost impacts of the technology maturing over time with global deployment.
- 2023 ATB reported floating wind costs for commercial-scale plants assuming fully mature supply chains.
- 2024 ATB presents in 2030 and beyond when the first gigawatt-scale projects could feasibly be constructed in the United States.
- Results in significantly higher LCOE values through the early 2030s but demonstrates the long-term cost reduction potential as industry matures (LCOE 35% higher than 2023 ATB in 2035 for Moderate Case).
- Highlights the importance of investments in infrastructure and the role of early projects and driving costs down through learning and de-risking the technology.
- Early U.S. West Coast floating wind deployment can play a key role in helping mature the technology and bring costs down.



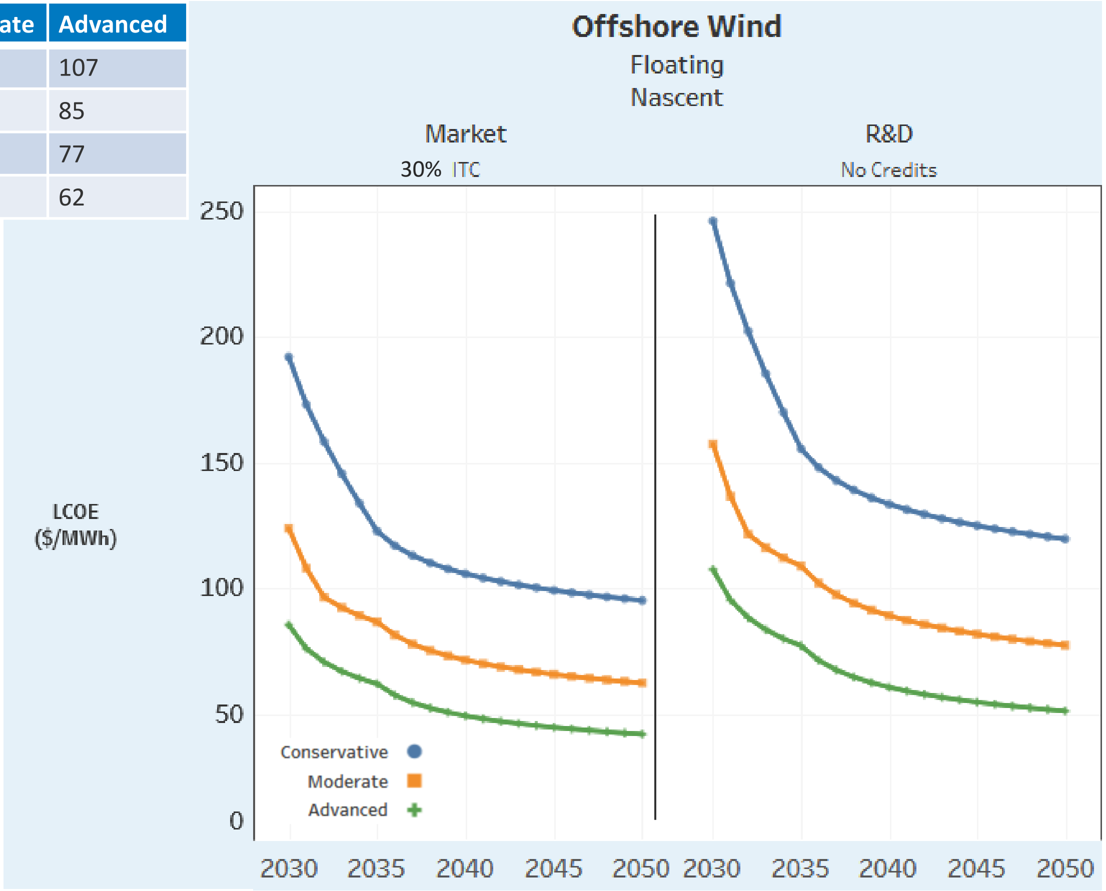
Year-over-year comparison of floating offshore wind LCOE estimates.
Note: Conservative, Moderate, and Advanced scenarios shown for R&D financing case.

2024 ATB Offshore Wind Estimates



Floating Wind Estimates by Financing Scenario

Scenario	Conservative	Moderate	Advanced
2030 R&D	246	157	107
2030 Market	192	124	85
2035 R&D	155	109	77
2035 Market	123	87	62



Note ATB applies 30% ITC in “Market” financial case (does not include IRA bonus credits).

Distributed Wind

Base Year

Modeled NREL's bottom-up cost models for gigawatt-scale fixed-bottom projects and demonstration scale (<100 MW) floating projects:

- reV and NREL Wind Analysis Library (NRWAL) used to assess offshore wind plant costs across U.S. waters as a function of site-specific parameters including wind resource, water depth, and distances to critical infrastructure.
- Those site-specific cost estimates informed ORBIT for CAPEX, Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT) for OPEX, and the FLOw Redirection and Induction in Steady State (FLORIS) tool for annual energy production (AEP).
- ATB cost estimates are spatial averages presented in terms of wind classes.

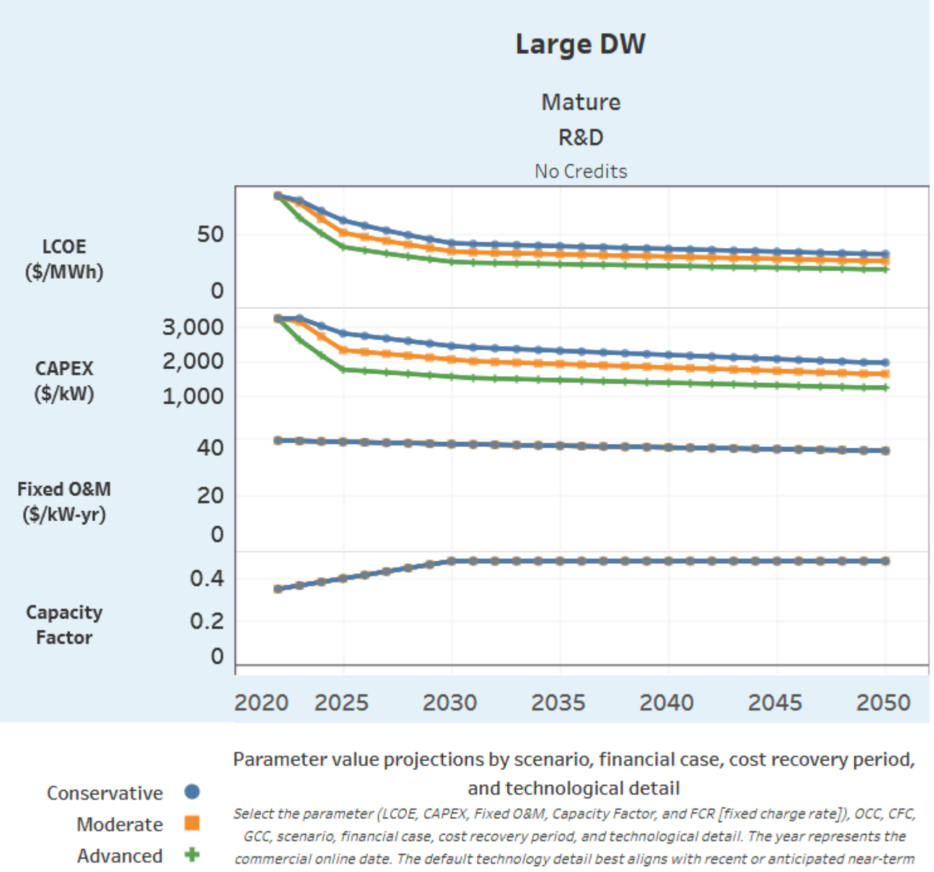
Projections

2024 offshore wind ATB cost trajectories derived for each scenario in two parts:

- A long-term CAPEX projection based on global industry experience.
    - Use the FORCE model (Shields et al. 2022) to derive learning curves for each scenario from historical offshore wind project CAPEX data and projected global offshore wind deployment. Floating CAPEX projections include effects from improving plant economies of scale as the floating offshore wind industry matures, whereas fixed-bottom CAPEX projections reflect gigawatt-scale projects in all years.
    - The long-term projections for OPEX and capacity factor improvements are informed by Wiser et al. (2021).
- A near-term CAPEX adjustment to account for macroeconomic conditions facing early U.S. offshore wind energy projects not captured in the learning curves. A range of short-term CAPEX adjustments corresponding to the three ATB scenarios is derived from literature and industry publications to highlight near-term macroeconomic uncertainty.

Tyler Stehly and Owen Roberts

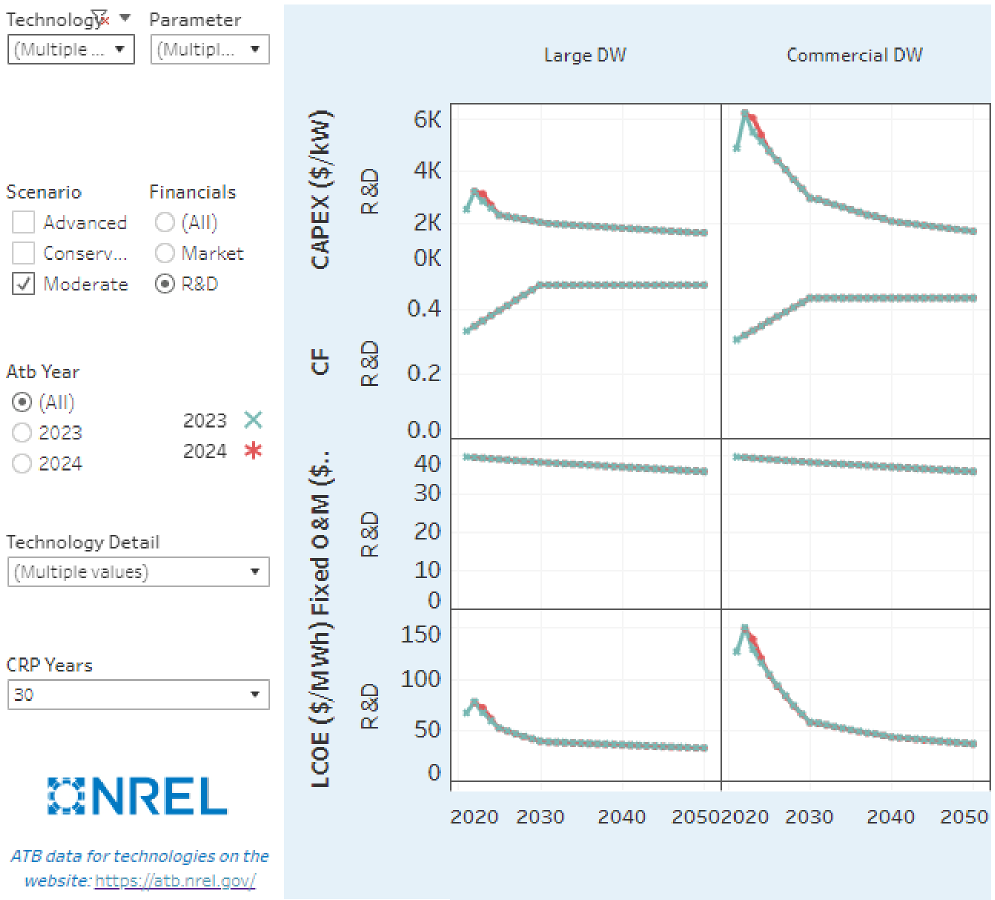
Distributed Wind



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

Distributed Wind Changes



PV

Base Year

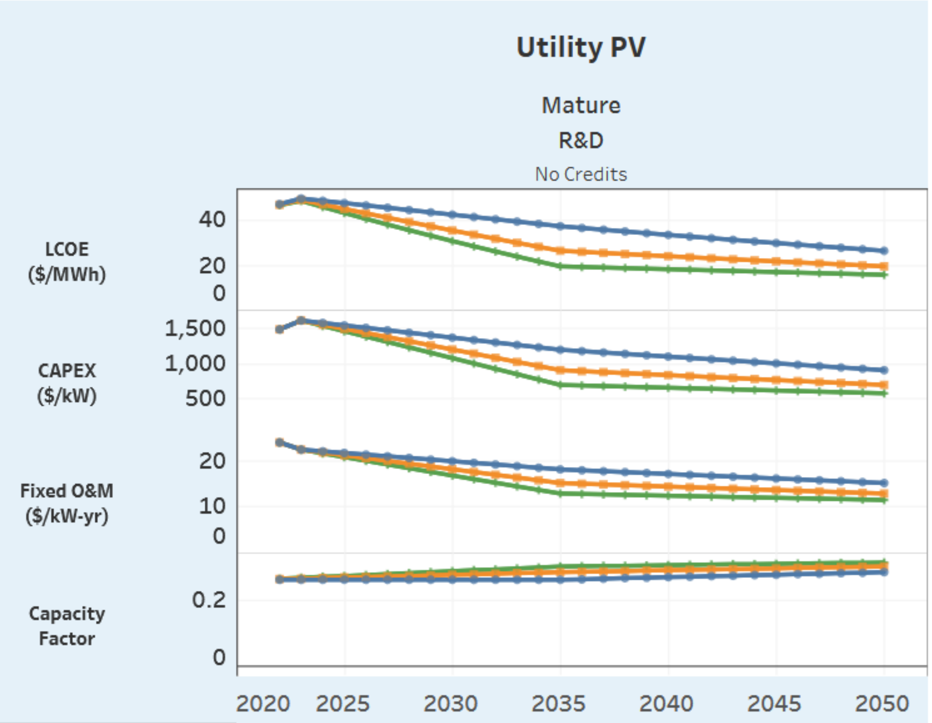
CAPEX for plants with a commercial operation date of 2022 are based on bottom-up modeling and market data from (Ramasamy et al. 2022), the same source as the 2023 ATB. For 2023 commercial operation date CAPEX, the new data are based on (Ramasamy et al. 2023). The O&M costs are based on modeled pricing for PV systems from those same references.

Projections

The straight-line improvements in cost metrics through 2035 are now calculated using the 2023 benchmarks from (Ramasamy et al. 2023) as the initial points.

Jarett Zuboy and David Feldman

Utility PV

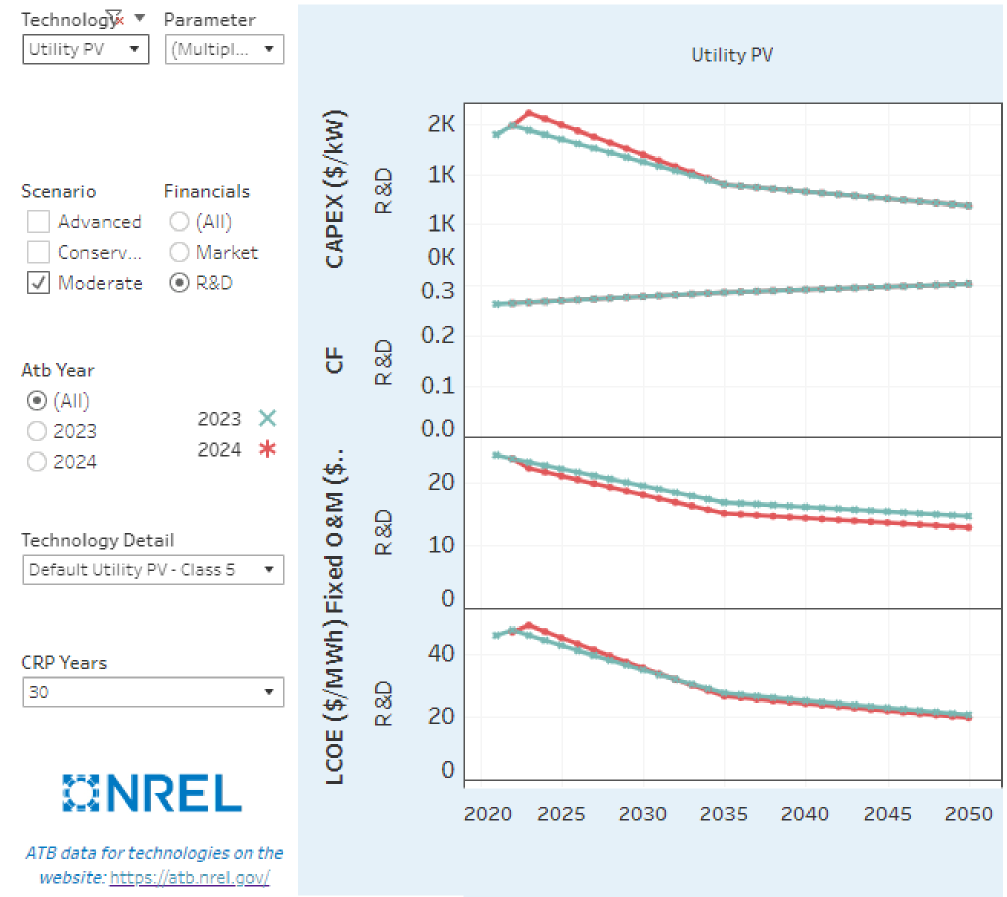


Conservative
Moderate
Advanced

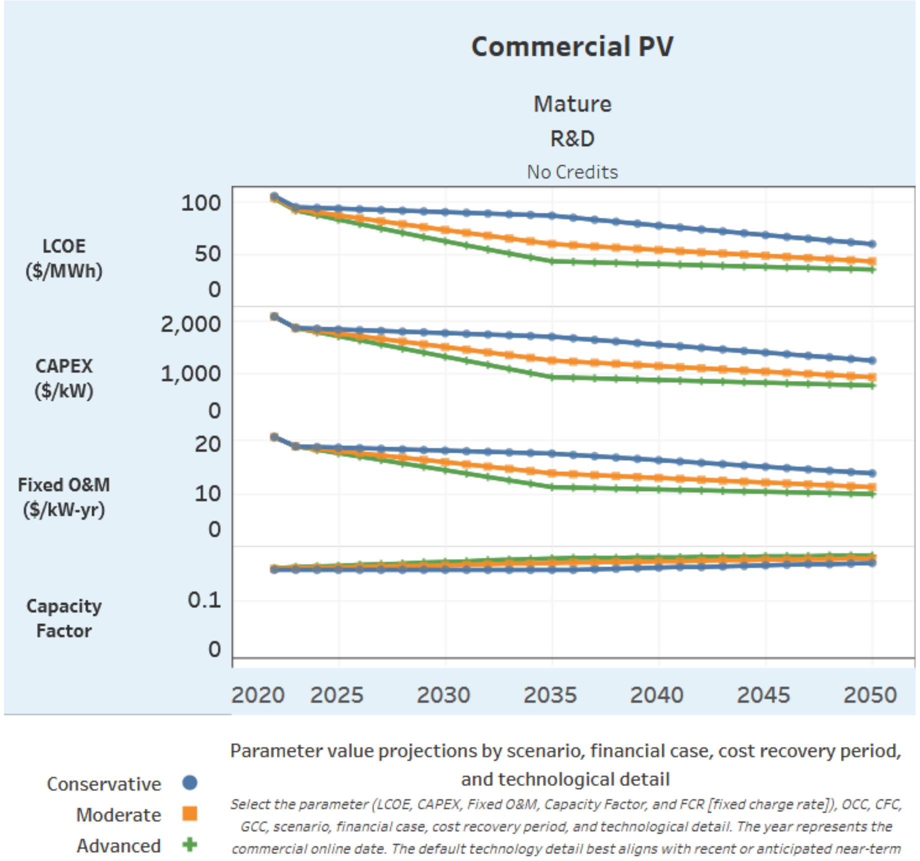
Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

Utility PV Changes



Commercial PV



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

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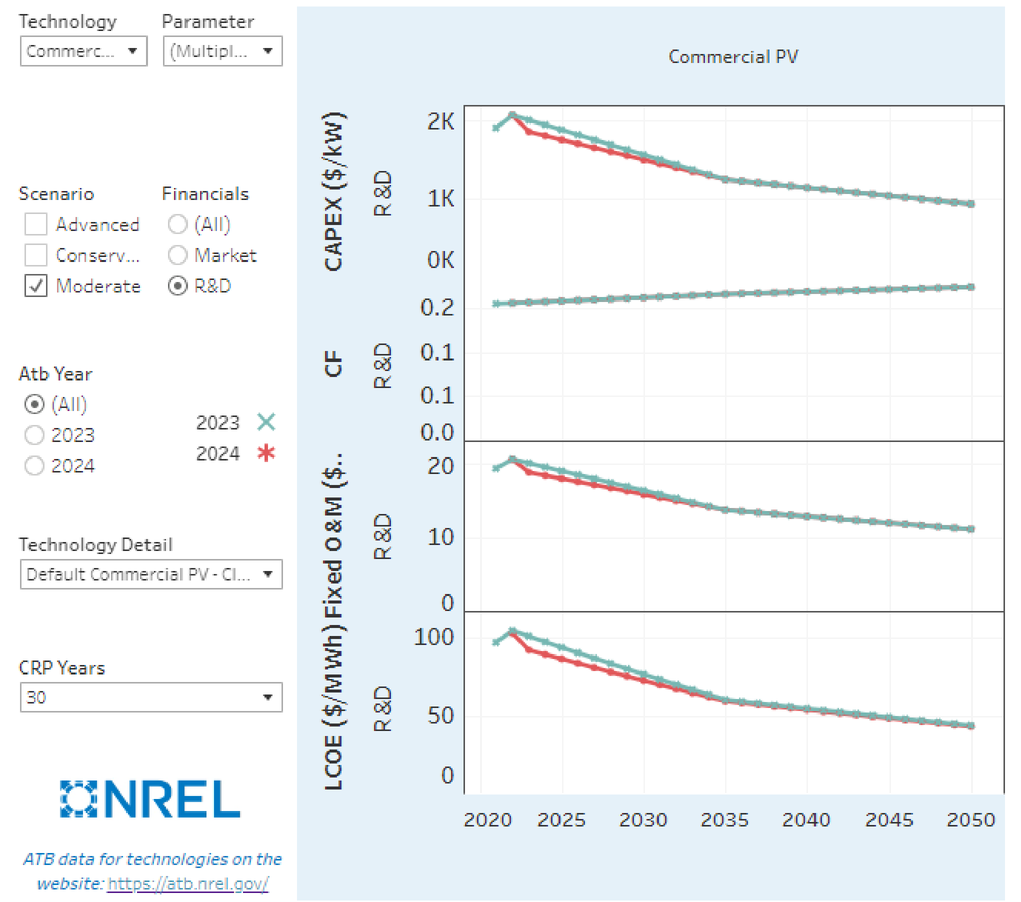
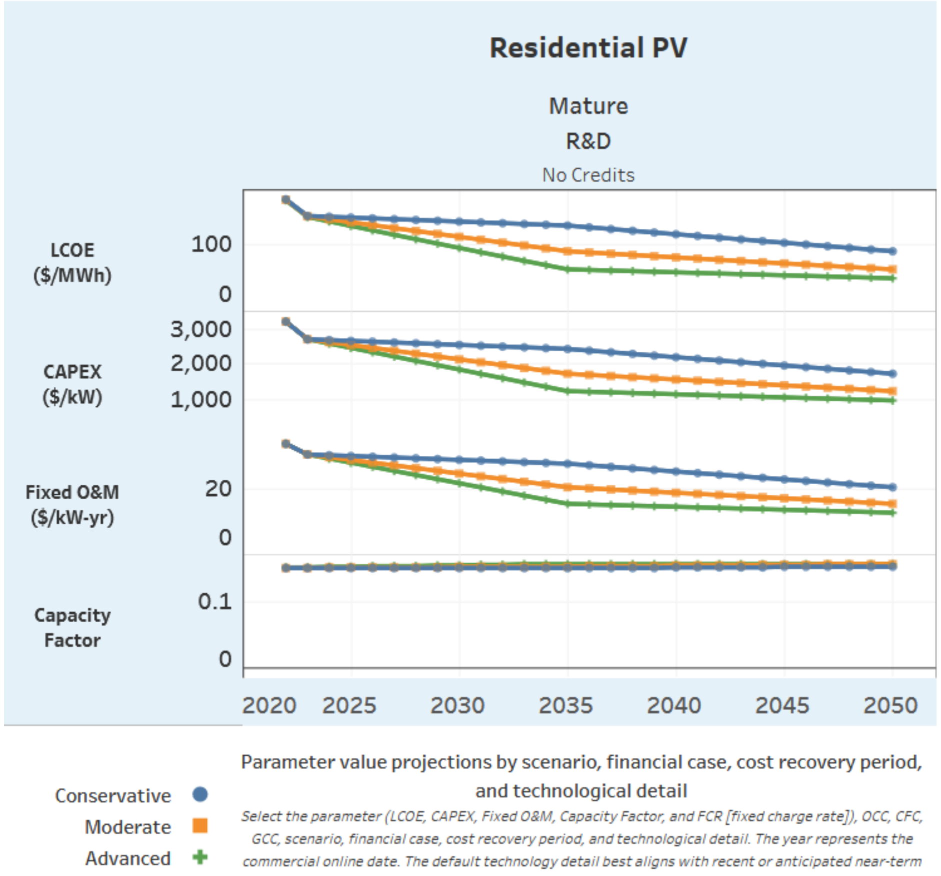
Commercial PV Changes



Residential PV



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

Residential PV Changes

Technology: Residenti...
Parameter: (Multipl...

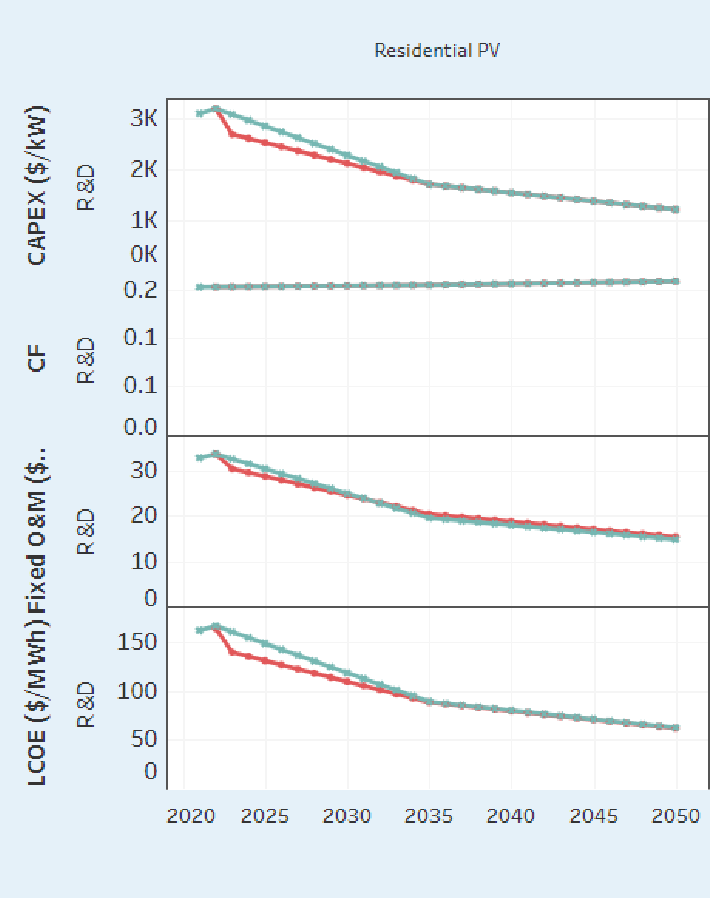
Scenario
- [ ] Advanced
- [ ] Conserv...
- [x] Moderate

Financials
- (All)
- Market
- (•) R&D

Atb Year
- (•) (All)
- 2023
- 2024

Technology Detail: Default Residential PV - Cl...

CRP Years: 30



ATB data for technologies on the website: https://atb.nrel.gov/

CSP

Base Year

Based on a recent assessment of the industry, bottom-up cost model, and initial supply chain analysis (Turchi et al. 2019); (Kurup et al. 2022), CSP costs in the 2024 ATB are based on cost estimates for CSP components that are available in Version 2023.12.17 of the System Advisor Model (SAM). As in the 2023 ATB, future year projections are informed by the literature, NREL expertise, and technology pathway assessments for reductions in CAPEX.

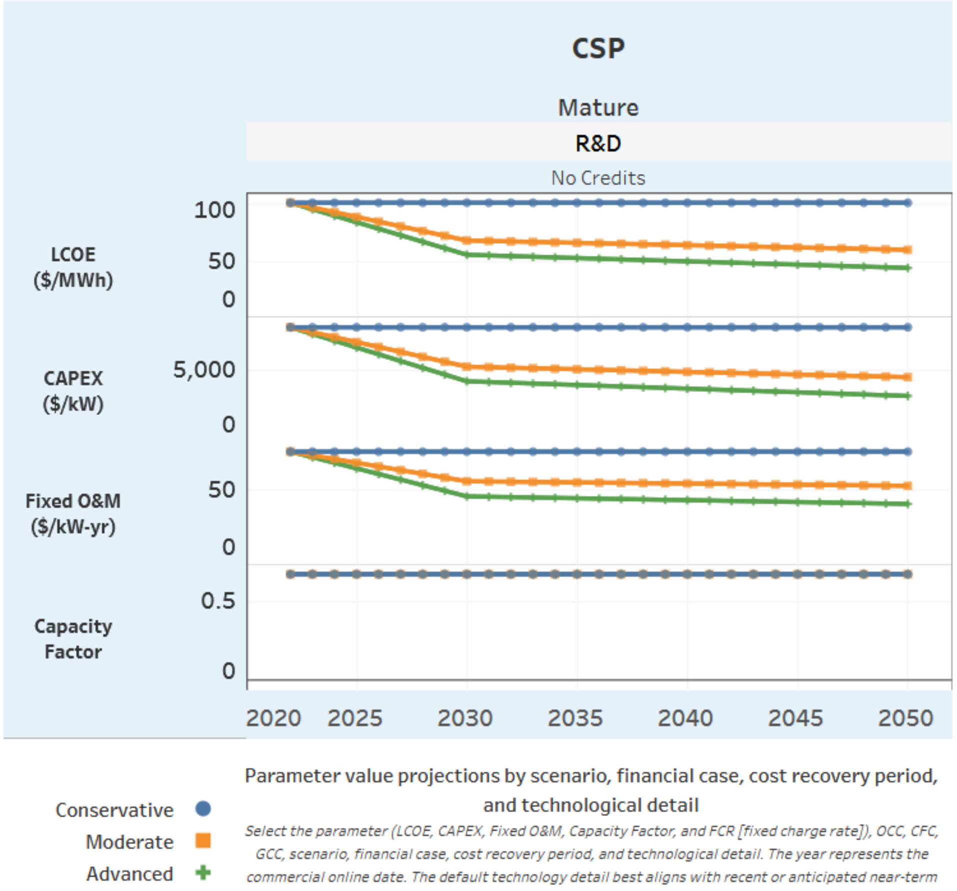
- SAM Version 2023.12.17 has had default updates, including an update in the power cycle calculations to fix an error. The National Solar Radiation Database has been updated with new resource data. The heliostat field design point was changed from 99% to 95% based on findings from the HelioCon Roadmap (Zhu et al. 2022). After these changes were implemented, the SAM optimization routines were run. The SAM CSP molten salt power tower heliostat field size and the power tower height have increased because of the reoptimization.

Projections

As in the 2023 ATB, the Moderate Scenario assumes a transition to a supercritical CO_2 cycle in the power block; advanced coatings on the receiver; improved tanks, pumps, and component configurations for the thermal storage unit; and improved heliostat installation and learning that are the result of deployment in the solar field. The Advanced Scenario assumes higher-temperature supercritical CO_2; a higher-temperature receiver; advanced storage compatible with higher temperatures; and low-cost, modular solar fields with increased efficiency.

Parthiv Kurup and Alex Zolan

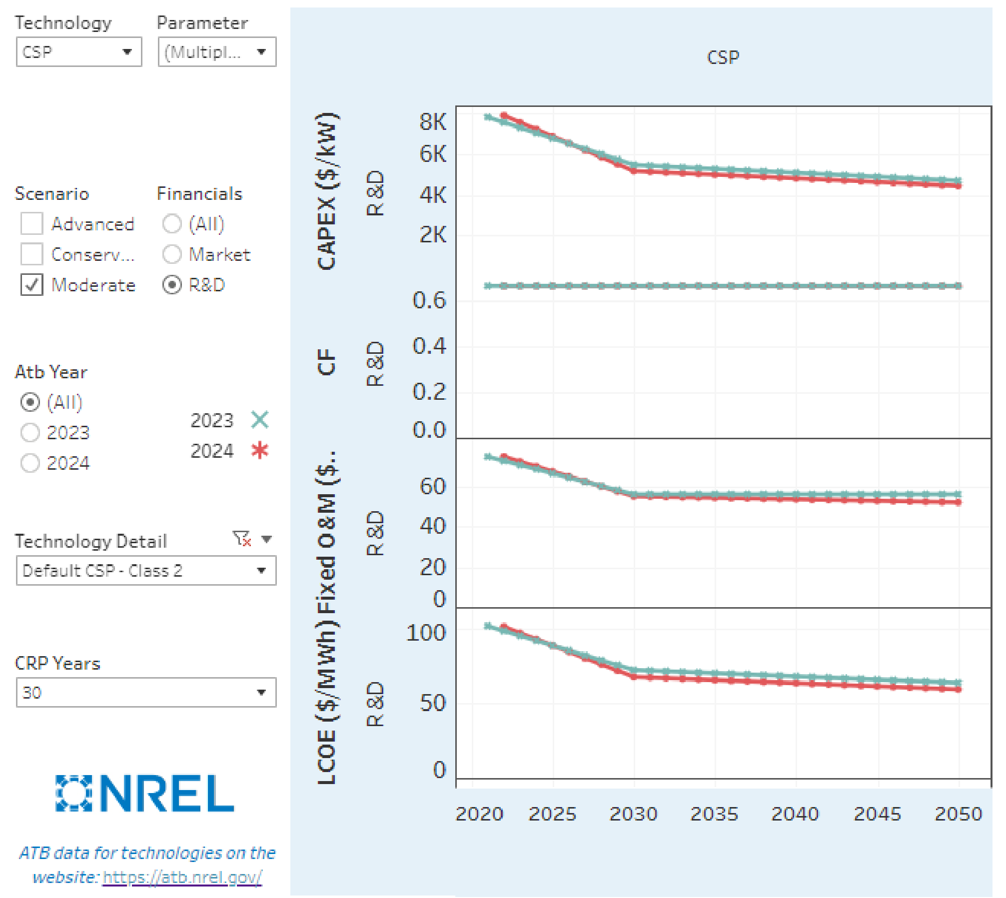
CSP



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

CSP Changes


Technology
CSP
Parameter
(Multipl...
Scenario
Advanced
Conserv...
Moderate
Financials
(All)
Market
R&D
Atb Year
(All)
2023
2024
2023
2024
Technology Detail
Default CSP - Class 2
CRP Years
30
CSP
CAPEX ($/kW)
CF
LCOE ($/MWh) Fixed O&M ($..
R&D
8K
6K
4K
2K
0.6
0.4
0.2
0.0
60
40
20
0
100
50
0
2020
2025
2030
2035
2040
2045
2050
ATB data for technologies on the website: https://atb.nrel.gov/

Geothermal

Base Year

Base Year estimates are derived from bottom-up cost modeling in GETEM primarily using baseline assumptions from the GeoVision study (DOE 2019) and updated assumptions based on recent technology improvements in drilling and stimulation.

Projections

Beyond 2022, projections were made based on scenario:

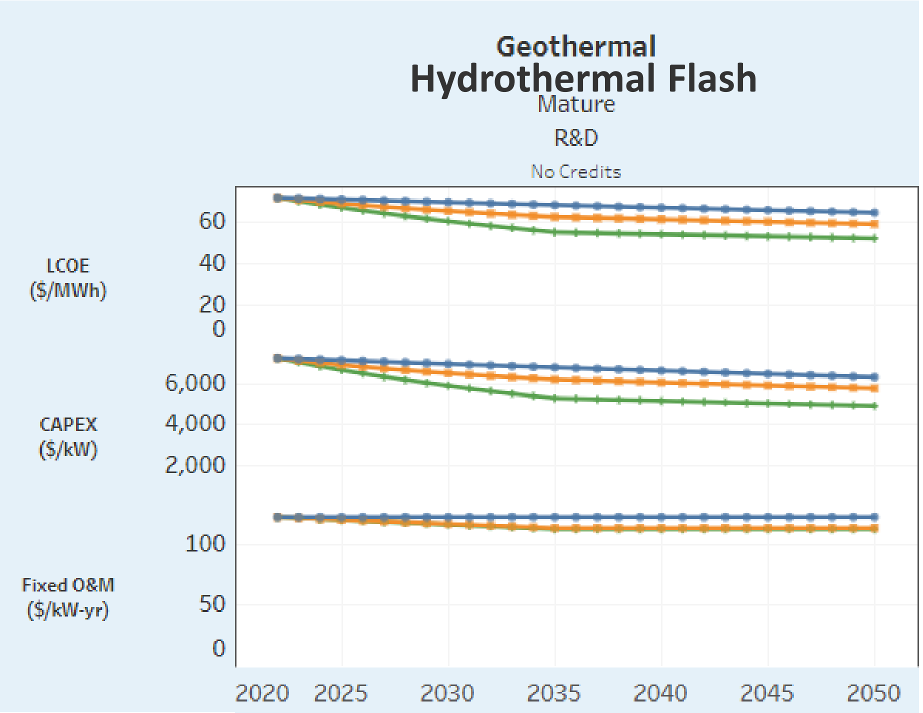
- Conservative: A 0.5% annual decline in cost up to 2050
- Moderate: An 18% learning rate up to 2035 and then a 0.5% decline afterward
- Advanced: 30% (Hydrothermal) and 35% (EGS) learning rate up to 2035 and then a 0.5% decline afterward (Fukui et al. 2017); (Latimer and Meier 2017); (El-Sadi et al. 2024).

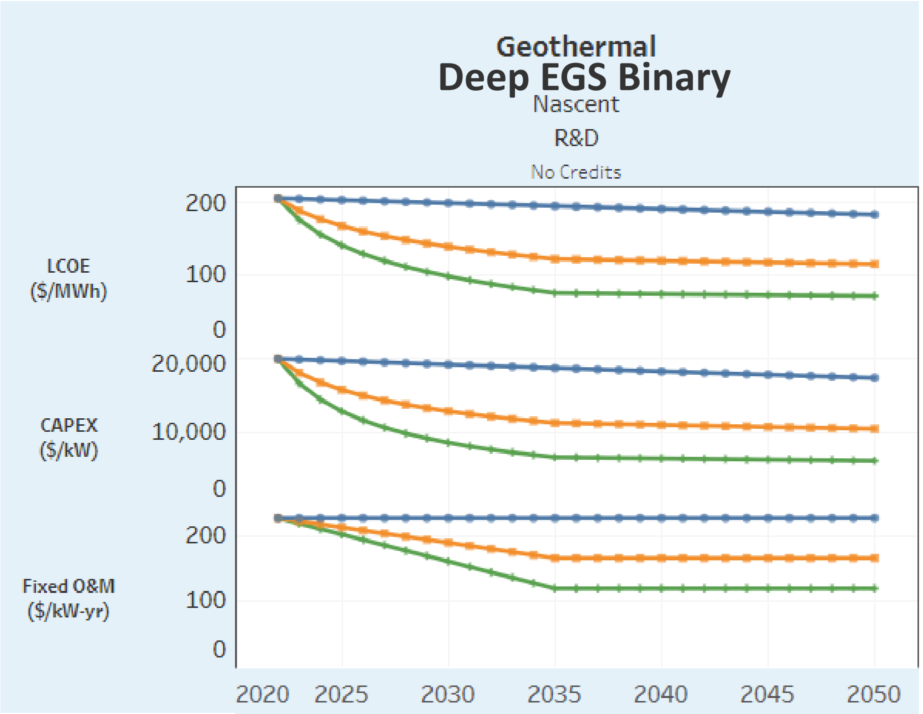
Major Changes in FY24

- Near-field and deep EGS representative plant sizes are now aligned for the Base Case.
- The representative plant size for the EGS Binary Moderate scenario was updated to 40 megawatts electric (MWe) based on planned commercial developments.
- A 7% decline in the baseline drilling cost (in addition to the 3% reduction in the 2021 ATB) is applied to account for an increase in drilling efficiency as reported in ongoing demonstration and commercial-scale projects (El-Sadi et al. 2024); (Dupriest et al. 2024).
- EGS reservoir performance parameters were updated to reflect economical levels reported in (Norbeck and Latimer 2023).
- Other updates are made to assumptions on drilling and stimulation success rates as well as plant sizes.

Dayo Akindipe and Erik Witter

Geothermal: Main Scenario Results



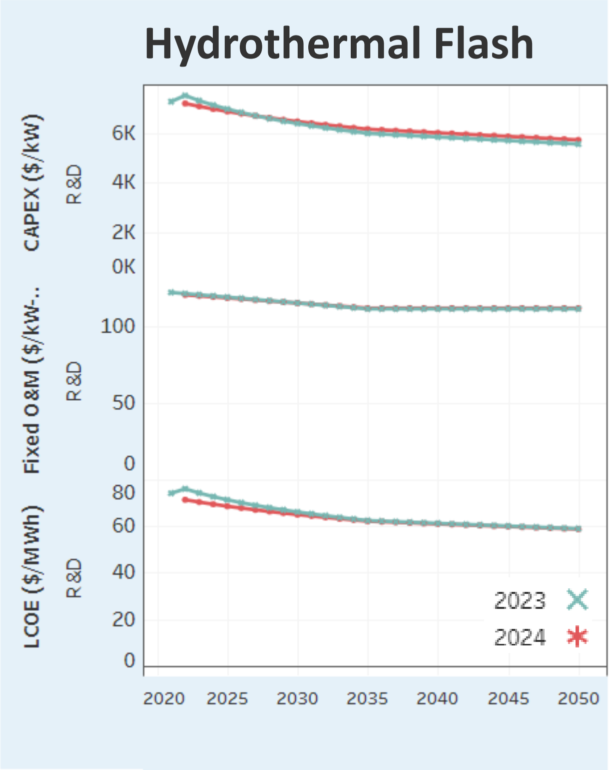


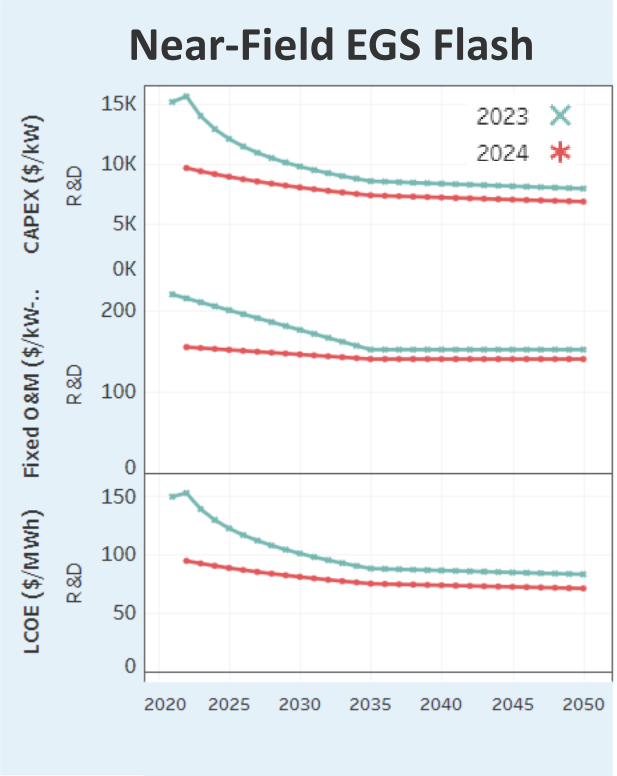
Conservative ●
Moderate ■
Advanced ✚

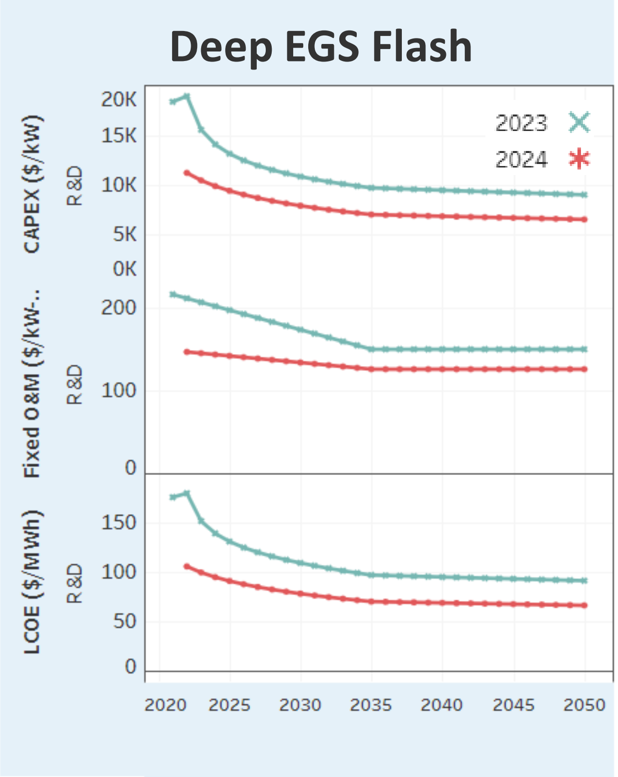
Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

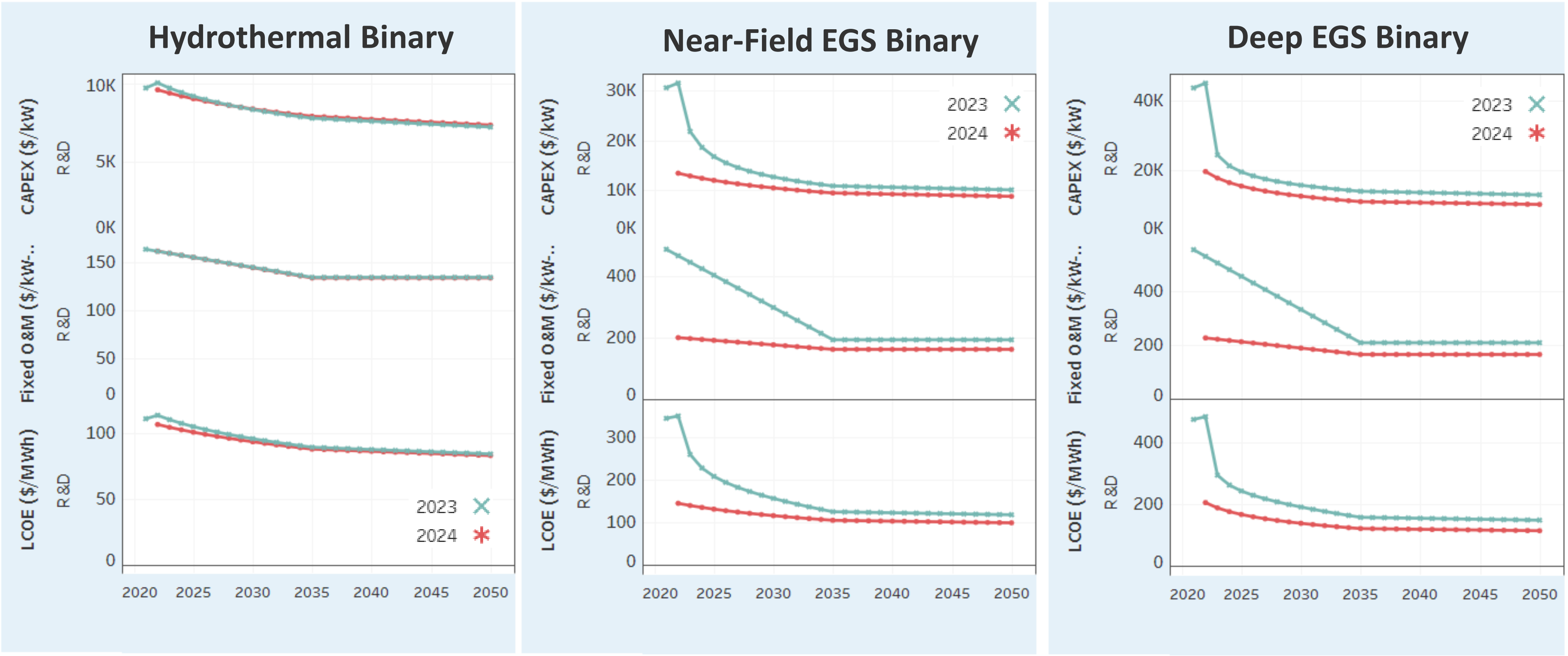
Geothermal Year-on-Year Changes (Moderate)







Geothermal Year-on-Year Changes (Moderate)



Hydropower

Base Year

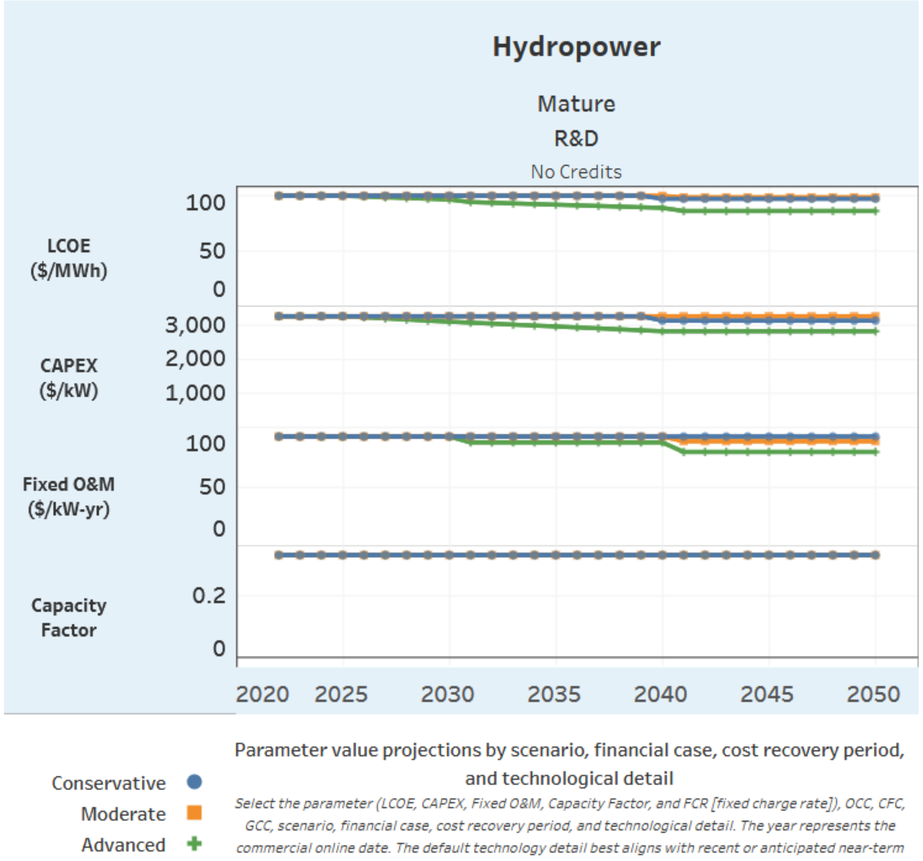
- As in the 2023 ATB, data based on (Oladosu et al. 2021) (NPD) and (DOE 2016) (NSD).
- For NPD, interconnection costs (i.e., electrical infrastructure) were separated from the 2024 ATB capital expenditures. For NSD, $60/kW was subtracted from the 2024 ATB capital costs, and a separate grid connection cost variable with a value of $100/kW was created. The dollar base year was updated to 2022 using the U.S. Consumer Price Index.

Projections

- The near-term innovation case for NPD is judged to be applicable in the next 5–10 years and includes the use of new materials for penstocks and matrix turbines to reduce the cost of civil works (Oladosu et al. 2021).
- The NSD projections use a mix of the U.S. Energy Information Administration's technological learning assumptions, input from a technical team of Oak Ridge National Laboratory researchers, and the experience of expert hydropower consultants.

'Debo Oladosu

Hydropower



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

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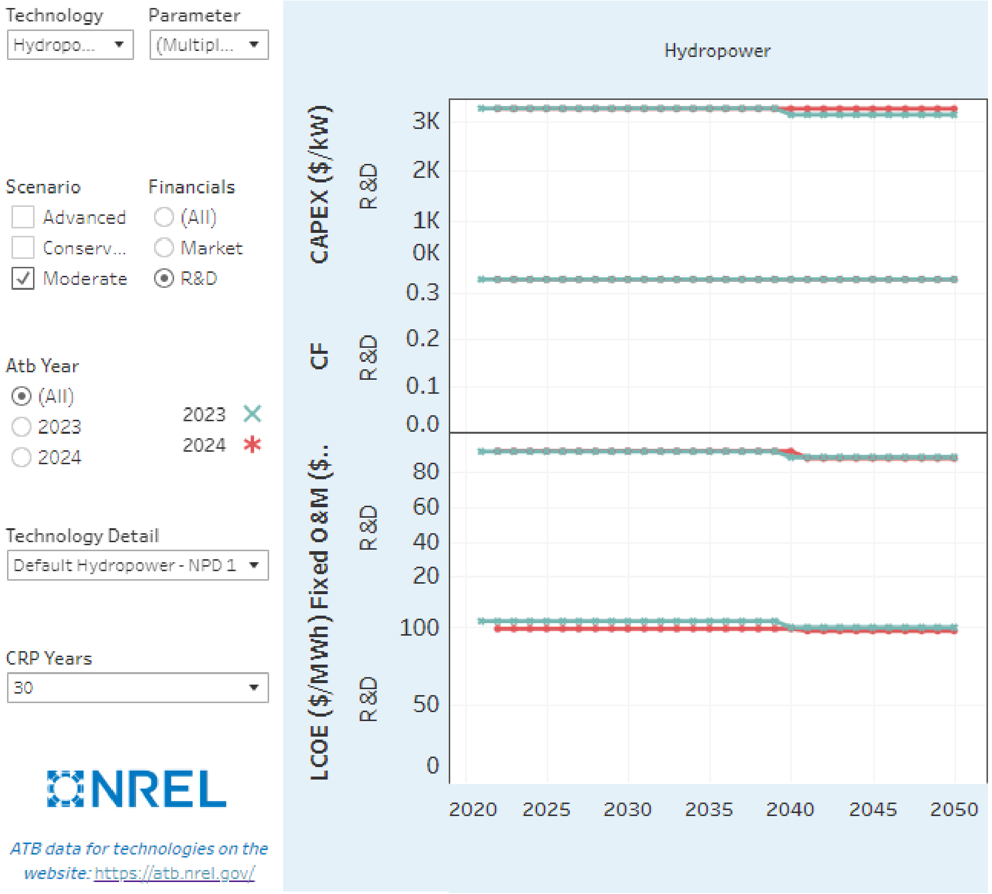
Hydropower Changes



Battery Storage

Base Year

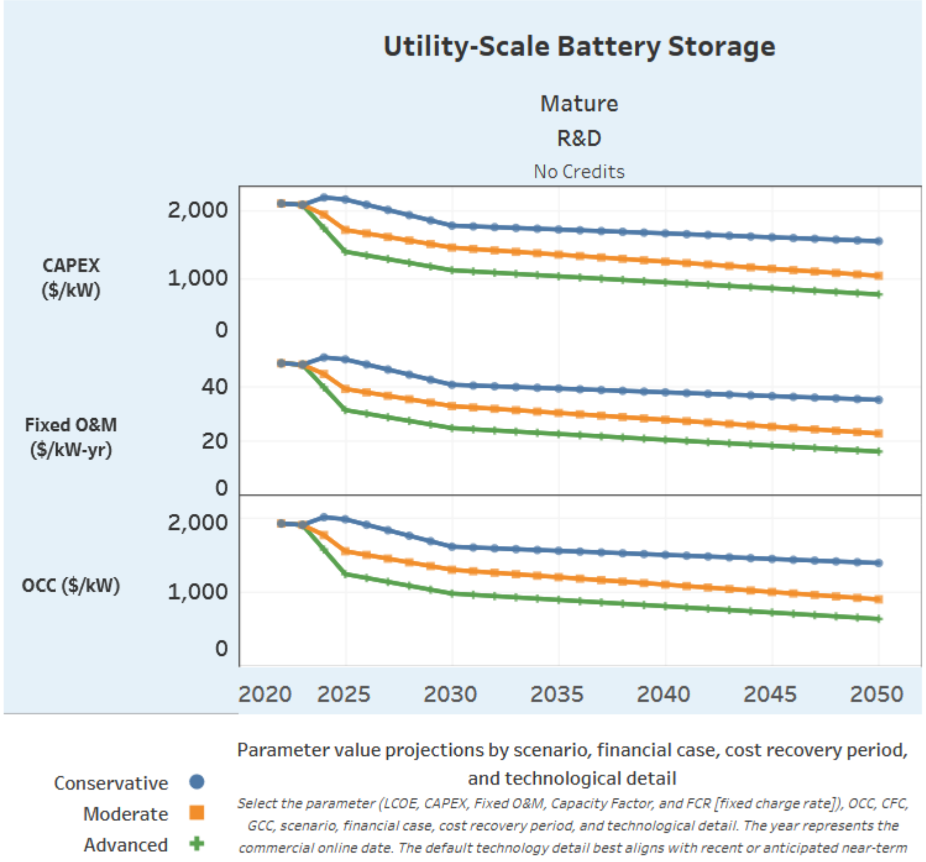
Base year CAPEX for utility-scale solar is updated consistent with new benchmark results in (Ramasamy et al. 2023). Residential and commercial storage are unchanged other than updating the dollar year.

Projections

Cost projections are nearly the same as last year, based on a literature survey as described by (Cole and Karmakar 2023). Pre-2025 values were adjusted to improve interpolation from the new starting point and the previous 2025 values.

Vignesh Ramasamy and Wesley Cole

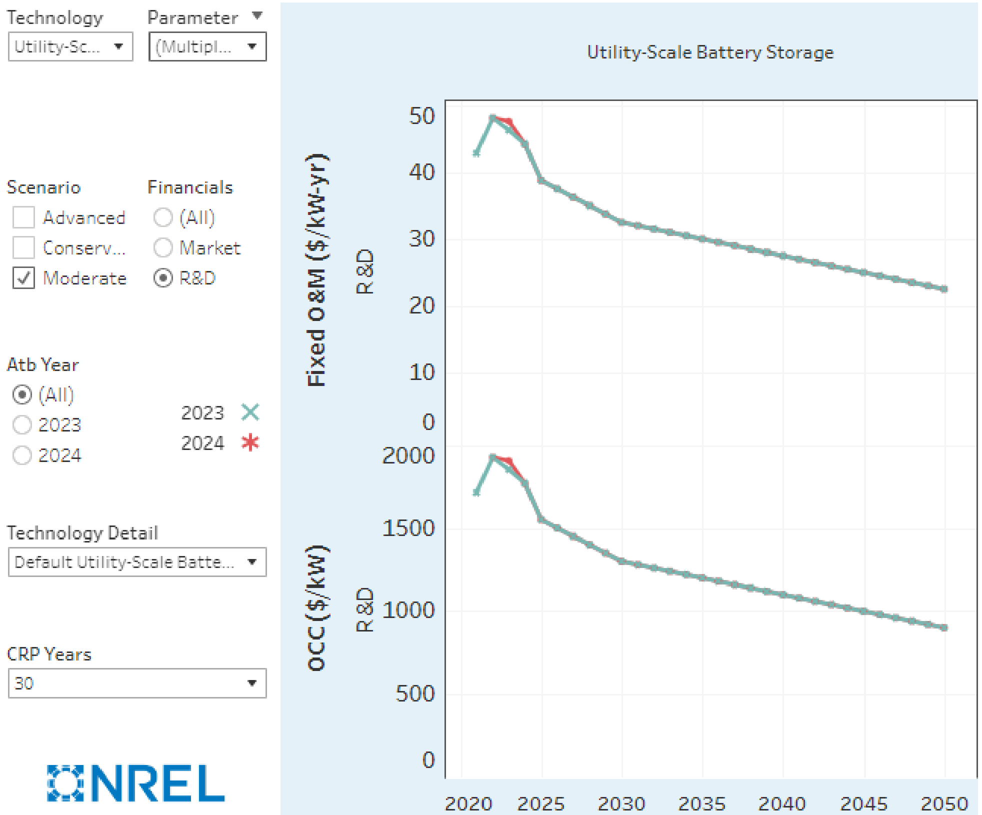
Utility-Scale Battery Storage



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

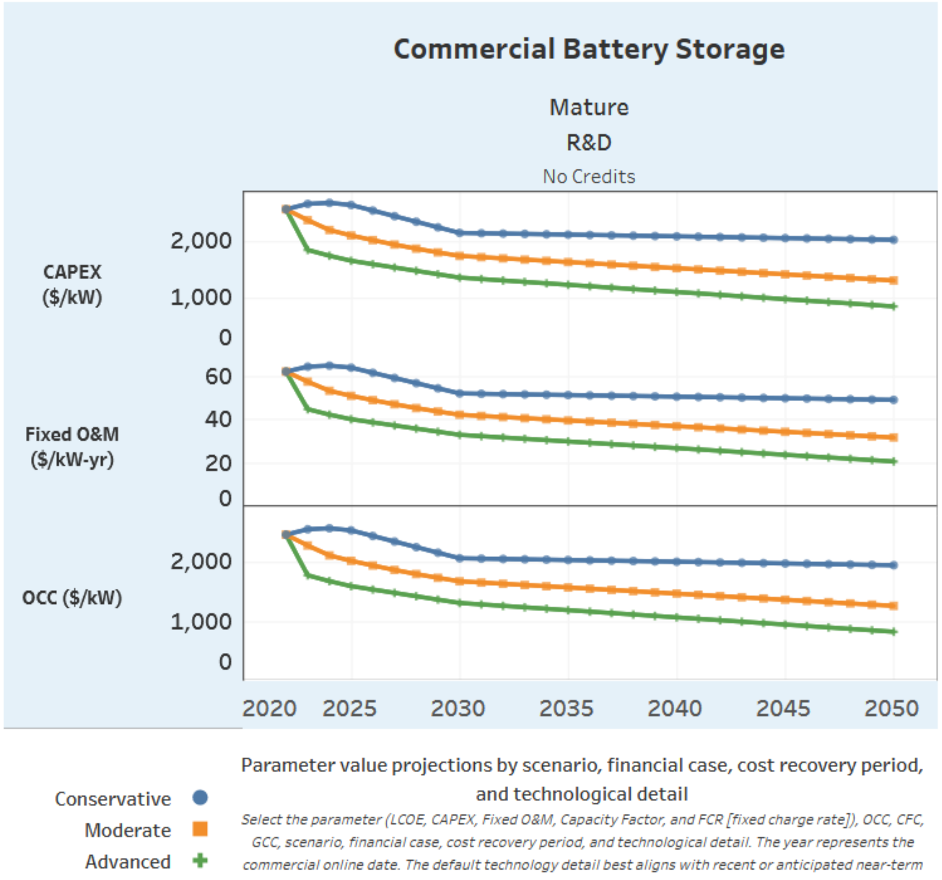
Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

Utility-Scale Battery Storage Changes



ATB data for technologies on the website: https://atb.nrel.gov/

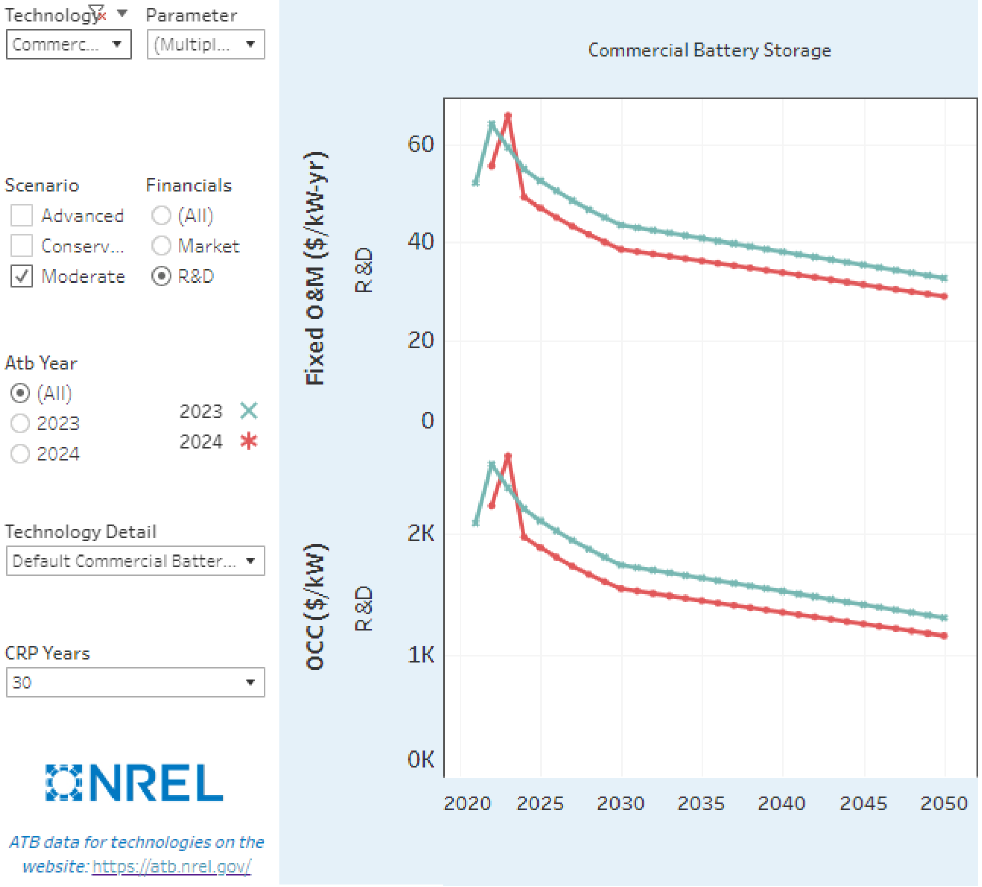
Commercial Battery Storage



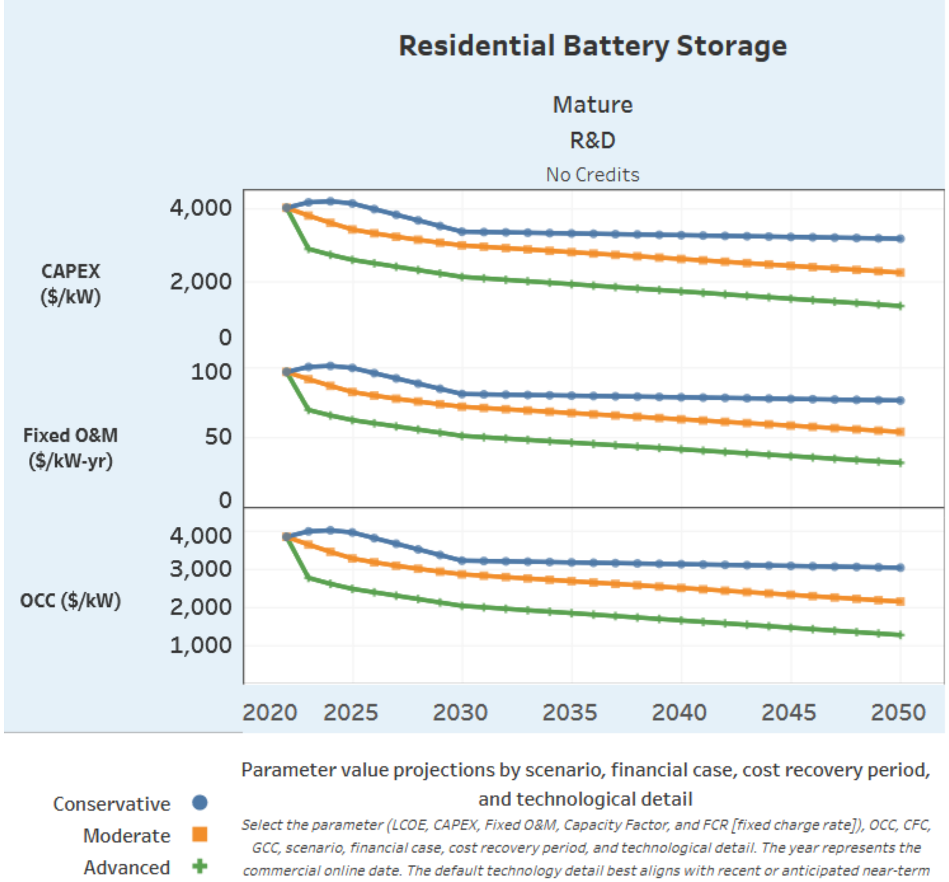
Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

Commercial Battery Storage Changes



Residential Battery Storage



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

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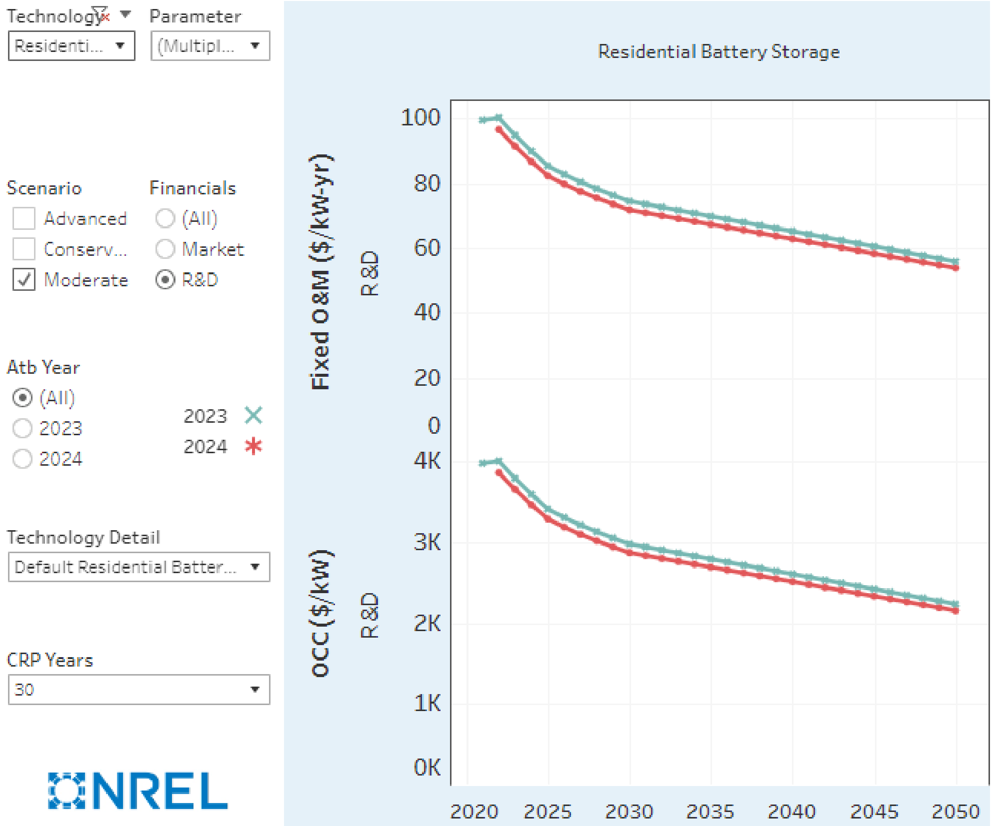
Residential Battery Storage Changes



ATB data for technologies on the website: https://atb.nrel.gov/

Utility Scale PV-Plus-Battery

Base Year

Estimates are derived from the bottom-up system cost modeling of stand-alone PV and stand-alone battery system (Ramasamy et al. 2023).

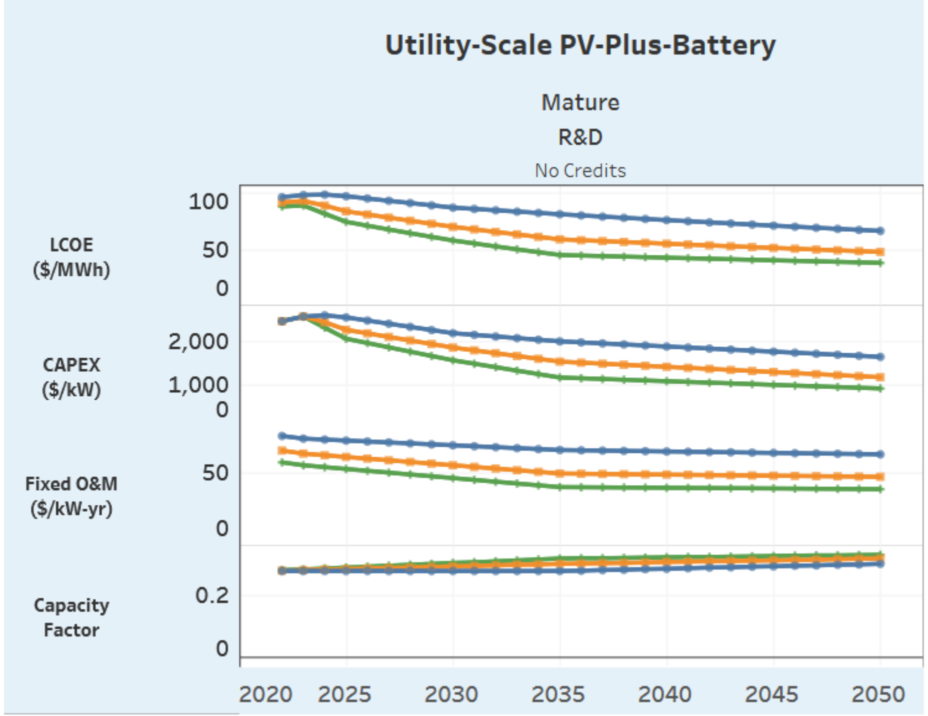
CAPEX Projections

CAPEX projections of PV + Battery = (CAPEX of Stand-alone PV + CAPEX of Stand-alone BESS)*Co-location Savings Rate of DC-Coupled Systems.

- The O&M cost projections assume a $10 adder to stand-alone PV O&M costs and includes a full replacement cost of battery systems at year 15.
- When accounting for state-of-charge and round-trip efficiency constraints, the usable stored energy sizing in recent and proposed utility-scale PV-plus-battery projects (Bolinger et al. 2023).
- Capacity factors assume 75% of the energy used to charge the battery component is derived from the coupled PV (on an annual basis).

Vignesh Ramasamy and Anna Schleifer

Utility-Scale PV-Plus-Battery

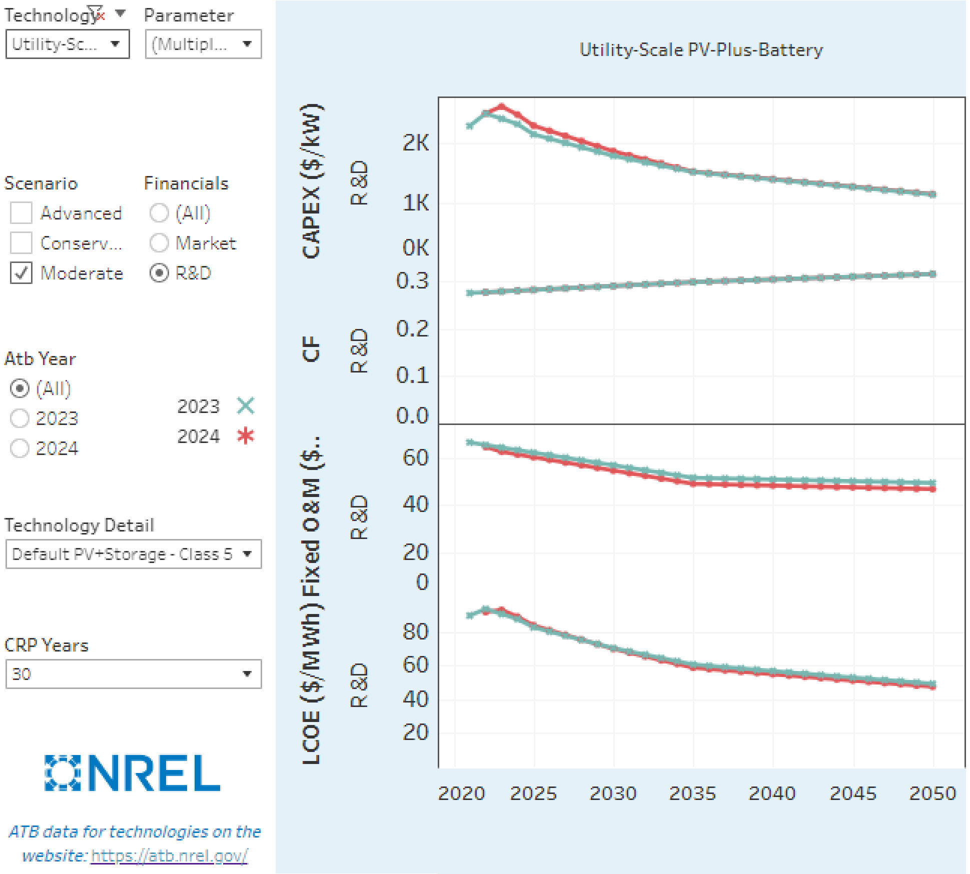


Conservative
Moderate
Advanced

Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

Utility-Scale PV-Plus-Battery Changes



Pumped Storage Hydropower

Base Year

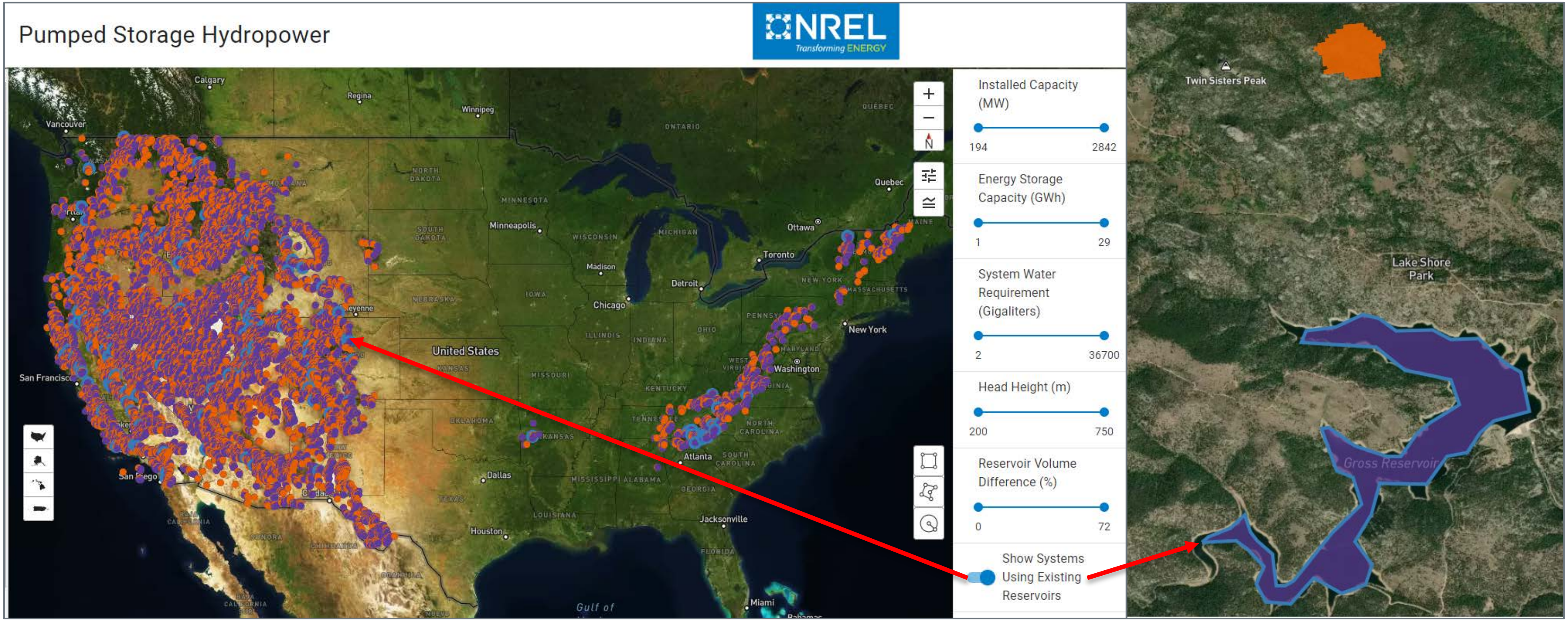
Capital costs are updated to use a new, more detailed cost model described in (Cohen et al. 2024) and "Pumped Storage Hydropower Cost Model." We also added a PSH subtype for sites using existing reservoirs.

Projections

These have not changed for the 2024 ATB. Projected cost reductions in the Advanced Scenario are based on innovations in modularity, materials, pumps and turbines, and closed-loop concepts as described in (DOE 2016).

Stuart Cohen, Evan Rosenlieb

Sites With Existing Reservoirs Are Viewable on the NREL PSH Supply Curve Tool



https://www.nrel.gov/gis/psh-supply-curves.html

The PSH Cost Model Includes a Spreadsheet Tool and Web Page

Inputs & Assumptions

Site Related

Location	United States	#
Avg. Max Upper Reservoir Depth	101	feet
Upper Reservoir Area	191	acres
Avg. Max Lower Reservoir Depth	120	feet
Lower Reservoir Area	163	acres
Nominal (Max) Head	1560	feet
Total Conveyance Length (vert+horiz)	14394	feet
Avg. Upper Dam Height	120	ft
Upper Dam Crest Length	1300	ft
Avg. Lower Dam Height	60	ft
Lower Dam Crest Length	1100	ft
Acreage to be acquired	2185	acres
Generation Time	18.5	hours

Output Specifications

Project Related

Conveyance Length	2.726	miles
Avg. Upper Reservoir Volume =	19291	ac-ft
Avg. Lower Reservoir Volume =	19560	ac-ft
Total Upper Dam Volume =	2385110	CY
Total Lower Dam Volume =	691570	CY
Active Storage =	16397.35	ac-ft
Energy Storage =	18593	MWh
Mean Gen Discharge =	10725	cfs
Min Gross Head =	1092	feet
Mean Gross Head =	1326	feet
Min Gen Discharge =	9733	cfs
Max Gen Discharge =	11633	cfs
Nominal Tunnel Dia =	25.4	feet
No. Tunnels =	1	#
Adjusted Tunnel Dia =	25.4	feet
L/H =	10.9	#

Cost Components	Include in Total? (Yes or No - User Option)	*Unit*	*Qty*	Base Unit Cost ($/unit) (Includes material, equipment rental, installation labor)	Locational Factor	Inflation Factor (2022)	Market Adjustment Factor (MAF)	Adjusted Unit Cost ($)	*Override Qty*	*Override Unit Cost ($)*	*Total Component Cost ($)*
Land and Land Rights	Yes	Acres	2,185	$ 3,093.33	1.00	2.41	1.00	$ 7,444	0	$ -	$ 16,264,166
Powerplant Structure	Yes	kW	1,283,325	$ 39.06	1.00	2.41	1.30	$ 122	0	$ -	$ 156,806,248
Reservoirs, Dams, and Waterways											
Upper Reservoir Dam and Spillway	Yes	CY	2,385,110	$ 7.92	1.00	2.41	1.40	$ 26.67	0	$ -	$ 63,610,836
Upper Reservoir Intake/Outlet	Yes	#	1	$ 1,483,192.61	1.00	2.41	2.00	$ 7,138,076.30	0	$ -	$ 7,138,076
Surge Facilities	Yes	LS	40%	NA				NA	0%	NA	$ 103,340,771
Lower Reservoir Intake/Outlet	Yes	#	1	$ 6,772,919.08	1.00	2.41	1.30	$ 21,187,166.38	0	$ -	$ 21,187,166
Lower Reservoir Dam and Spillway	Yes	CY	691,570	$ 8.35	1.00	2.41	1.40	$ 28.13	0	$ -	$ 19,455,802
Water Conductors											
Upper Low & High Pressure Tunnels	Yes	Ft	6,268	$ 3,667.29	1.00	2.41	1.60	$ 14,119.48		$ -	$ 88,504,416
Vertical Shafts	Yes	Ft	1,326	$ 4,761.61	1.00	2.41	1.80	$ 20,624.35		$ -	$ 27,347,887
Penstock Tunnels	Yes	Ft	1,326	$ 4,825.82	1.00	2.41	1.90	$ 22,063.68		$ -	$ 29,256,438
Draft Tube Tunnels	Yes	Ft	800	$ 6,763.65	1.00	2.41	1.90	$ 30,923.47		$ -	$ 24,738,772
Tailrace Tunnels	Yes	Ft	6,268	$ 3,667.29	1.00	2.41	1.60	$ 14,119.48		$ -	$ 88,504,416
Surface Penstock	Yes	Ft	-	$ -	1.00	2.41	1.30	$ -	0	$ -	$ -

System Cost	
Total Direct and Indirect Cost $	$ 2,361,867,589
$/kW (Max. Power Capacity)	$ 1,840
$/kWh (Max. Energy Capacity)	$ 99

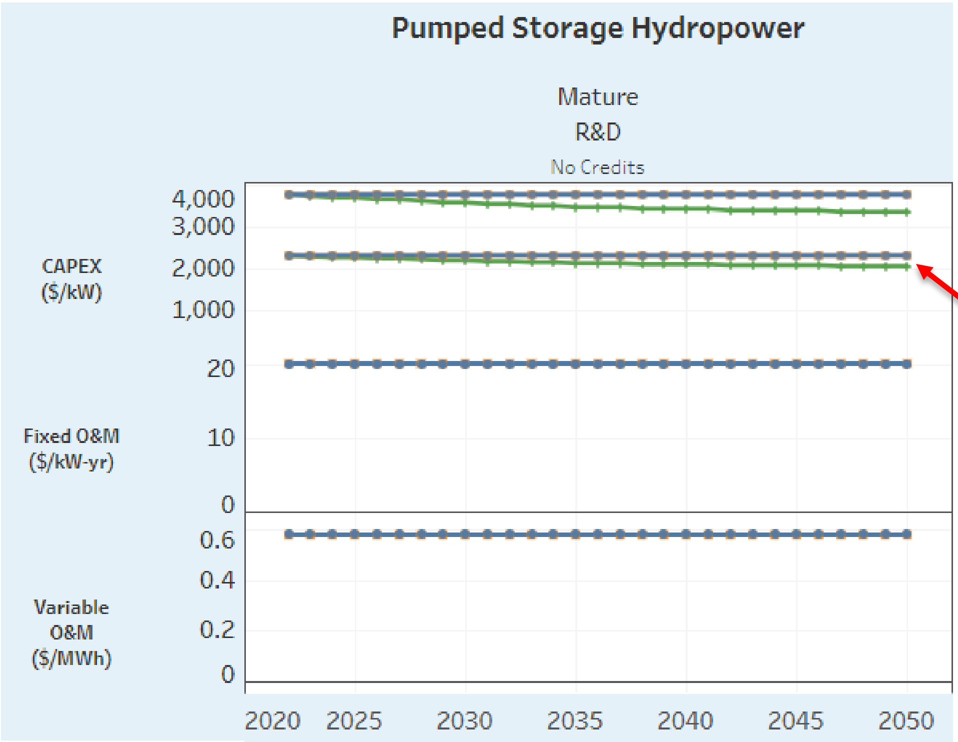
Pumped Storage Hydropower Cost Model

With NREL's cost model for pumped storage hydropower technologies, researchers and developers can calculate cost and performance for specific development sites.

Pumped storage hydropower (PSH) plants can store large quantities of energy equivalent to 8 or more hours of power production. As the country transitions to a 100% clean energy power grid, these plants could play a key role in keeping the grid reliable and resilient. But, without adequate data on PSH development costs or performance, it's difficult to compare PSH to other technologies to identify which could maximize grid performance and reliability.

https://www.nrel.gov/water/pumped-storage-hydropower-cost-model.html

Pumped Storage Hydropower



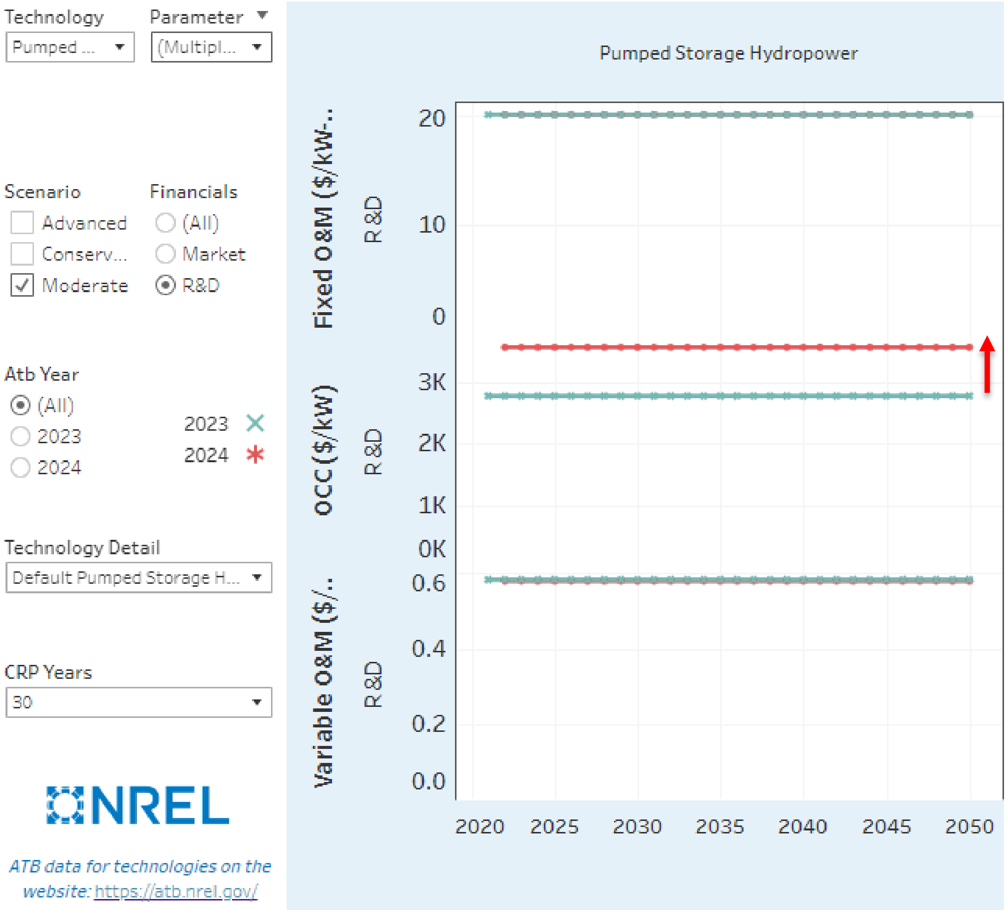
Conservative
Moderate
Advanced

Parameter value projections by scenario, financial case, cost recovery period, and technological detail.

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), OCC, CFC, GCC, scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations.

Sites with existing reservoirs have lower costs but do not include any costs to retrofit the existing reservoir.

Pumped Storage Hydropower Changes



New bottom-up cost model has greater component-level detail and accuracy and uses higher indirect costs.

Cost model was built with industry collaboration and review.

Nuclear

Nuclear

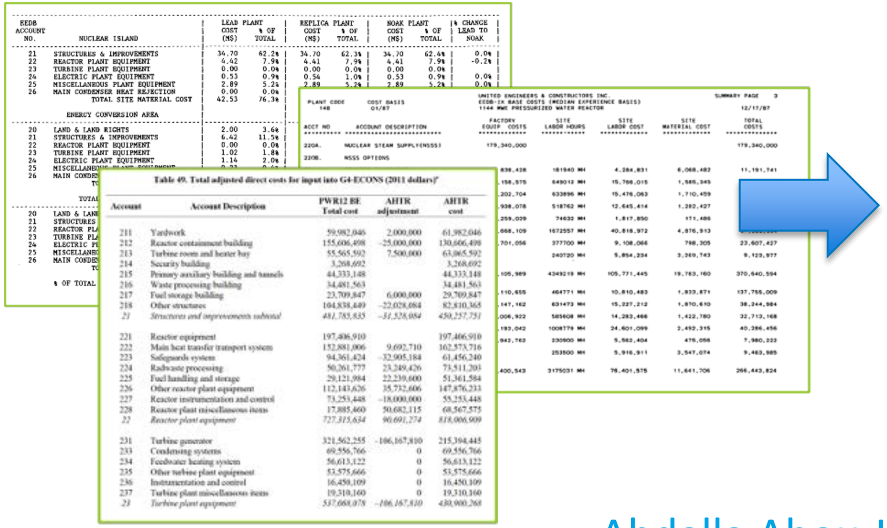
Capital costs and resource characteristics are updated from AEO2022 Reference Scenario (EIA 2022) to costs and characteristics based on (Abou-Jaoude et al. 2024).

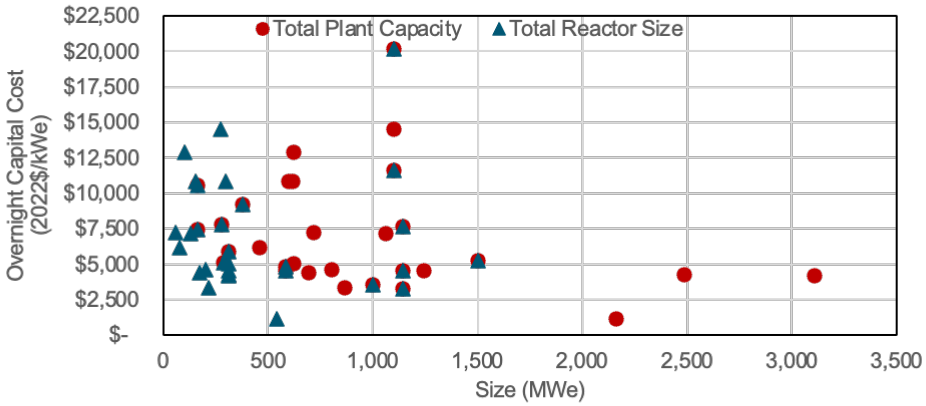
Base Year

Base year costs are taken from (Abou-Jaoude et al. 2024). All values are in 2022 dollars.

Projections

Projections are based on a learning rate for projected deployments across the scenario as described in (Abou-Jaoude et al. 2024).





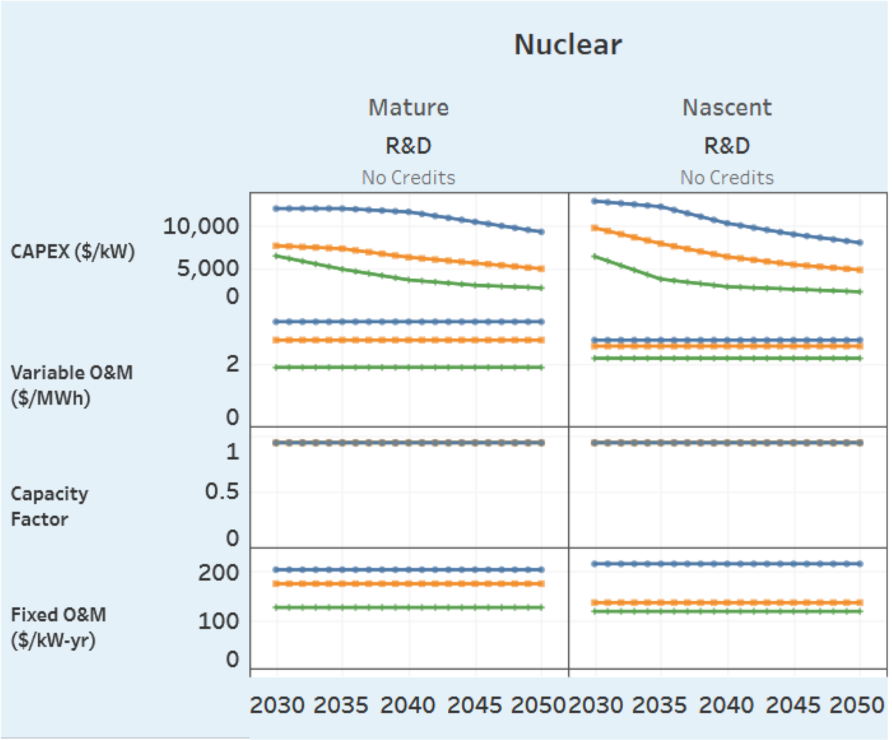
Abdalla Abou Jaoude, Levi Larsen, Chris Lohse

Nuclear

Cost are divided between large reactors (1,000 MWe) and Small Modular Reactors (300 MWe).

Each type has different CAPEX, O&M, construction duration, and so on.

Estimates start from 2030 (based on advanced reactor demonstration project start) and projected to drop based on different scenarios for Conservative/Moderate/Advanced.



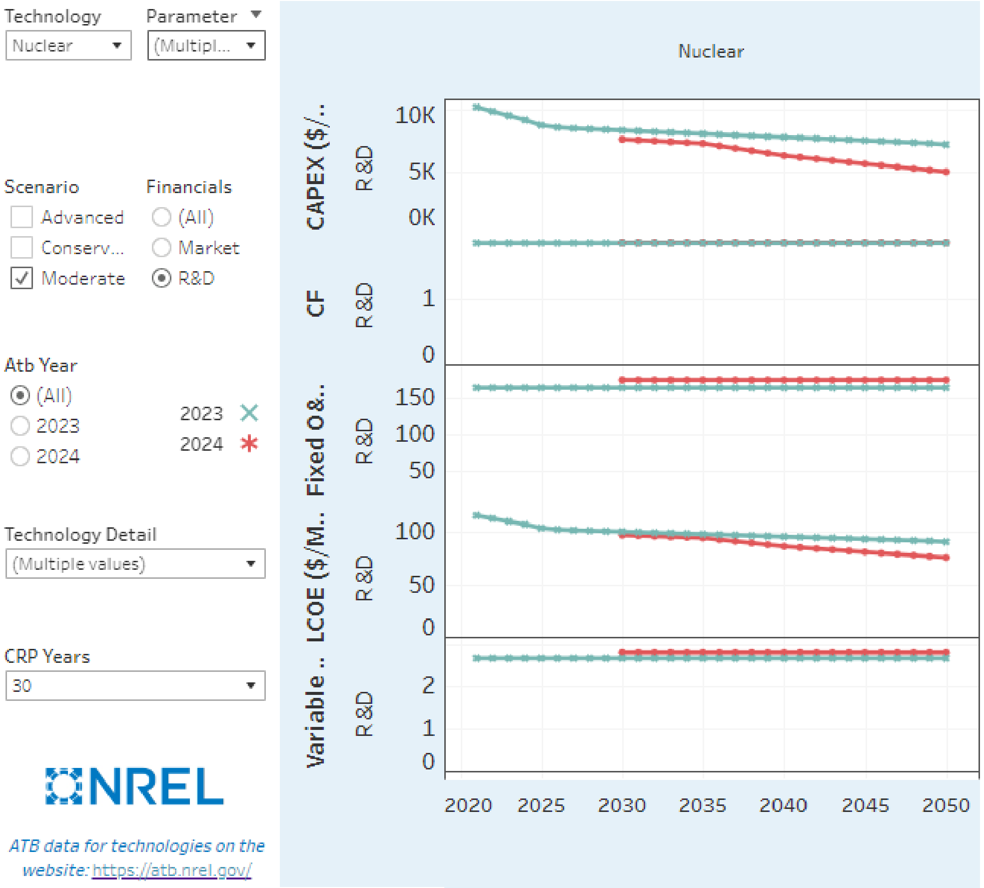
Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations. Scenarios are labeled with ATB names but correspond to AEO scenarios.

Nuclear Changes

Relative to 2023 model (from EIA):

- Cost reductions are more pronounced after 2035
- Advanced scenario provided (in addition to Moderate and Conservative)
- Differences in SMR definition (300 MWe instead of 600 MWe)



Fossil Technologies

Base Year

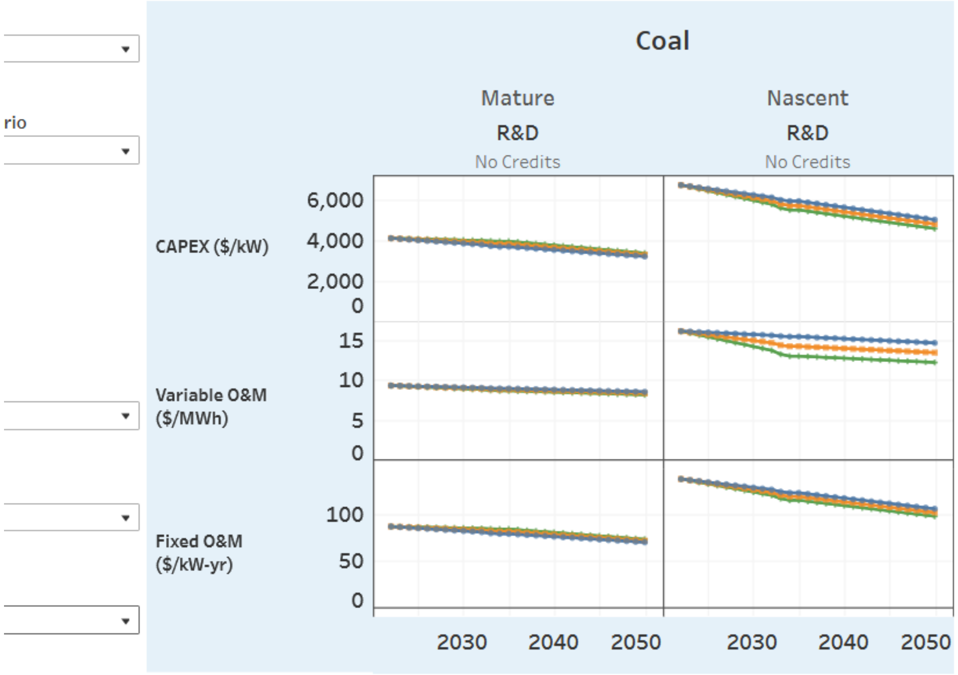
Estimates of performance and costs for currently available fossil-fueled electricity generating technologies are representative of current commercial offerings and/or projects that began commercial service within the past 10 years for both new plants and retrofits (Schmitt et al. 2022); (Buchheit et al. 2023); (Schmitt and Homsy 2023). The 2024 ATB expands the set of NGCC power plant options to include an H-class 1x1 configuration (a single combustion turbine with heat recovery providing steam for a Rankine bottoming cycle) to provide cost and performance for deploying H-class technology for smaller plants (i.e., less than nominal 1 gigawatt [GW] for a new-build conventional new electricity generating unit).

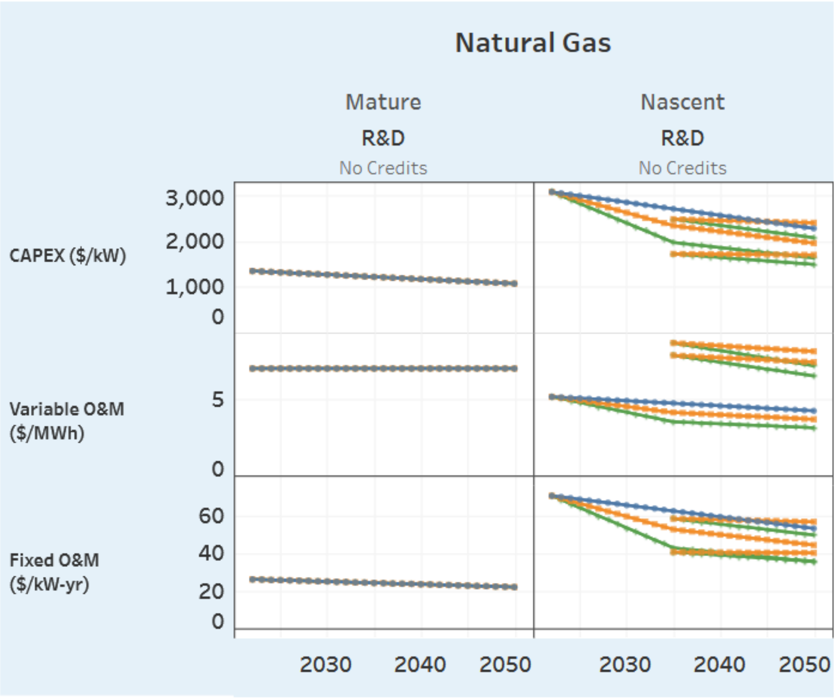
Projections

Projections in the 2024 ATB include rate of cost improvement from the AEO2023 (EIA 2023) as in 2023. Projections for advanced fossil energy technologies (Shultz et al. 2020); (Iyengar et al. 2022); (Leptinsky et al. 2023); (Leptinsky et al. 2024) are informed by outcomes from relevant Fossil Energy and Carbon Management (FECM) -funded R&D, with commercial availability premised on sufficiently aggressive research, development and demonstration necessary to facilitate technology readiness for widescale deployment.

Jeffrey Hoffmann

Fossil Technologies





Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations. Scenarios are labeled with ATB names but correspond to AEO scenarios.

Parameter value projections by scenario, financial case, cost recovery period, and technological detail

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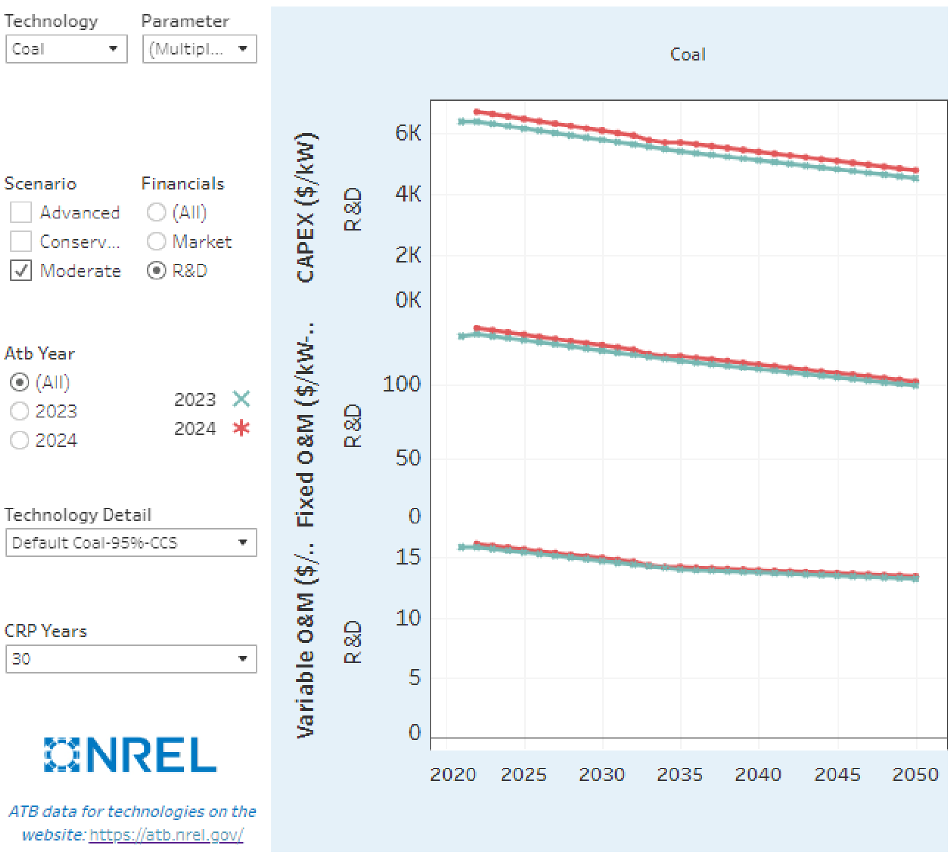
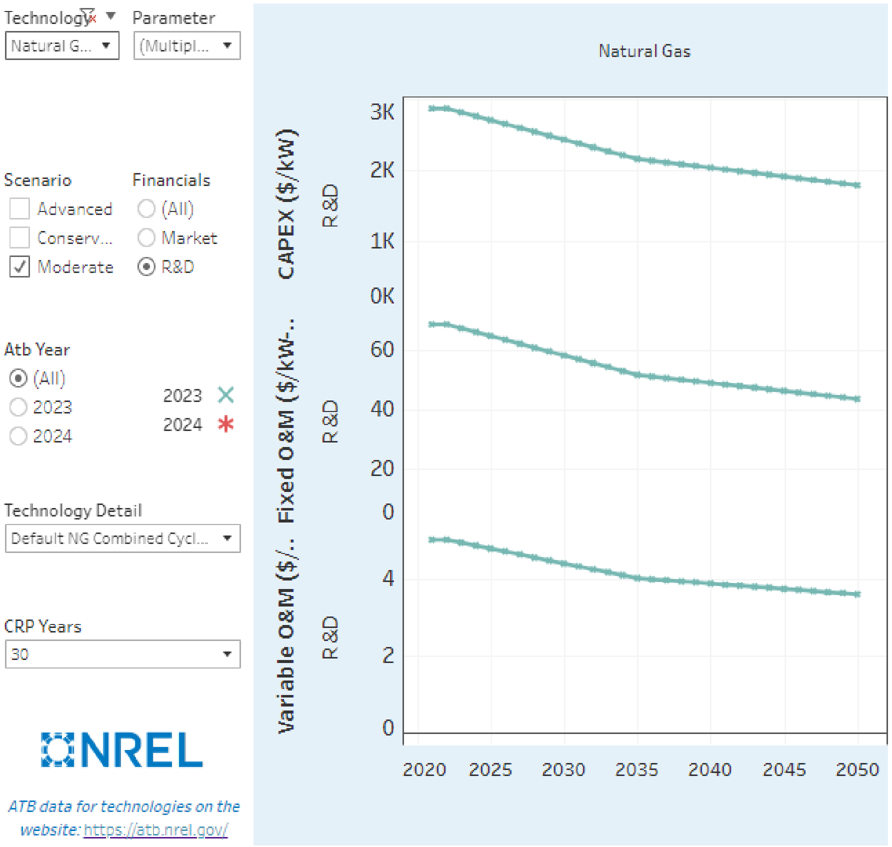
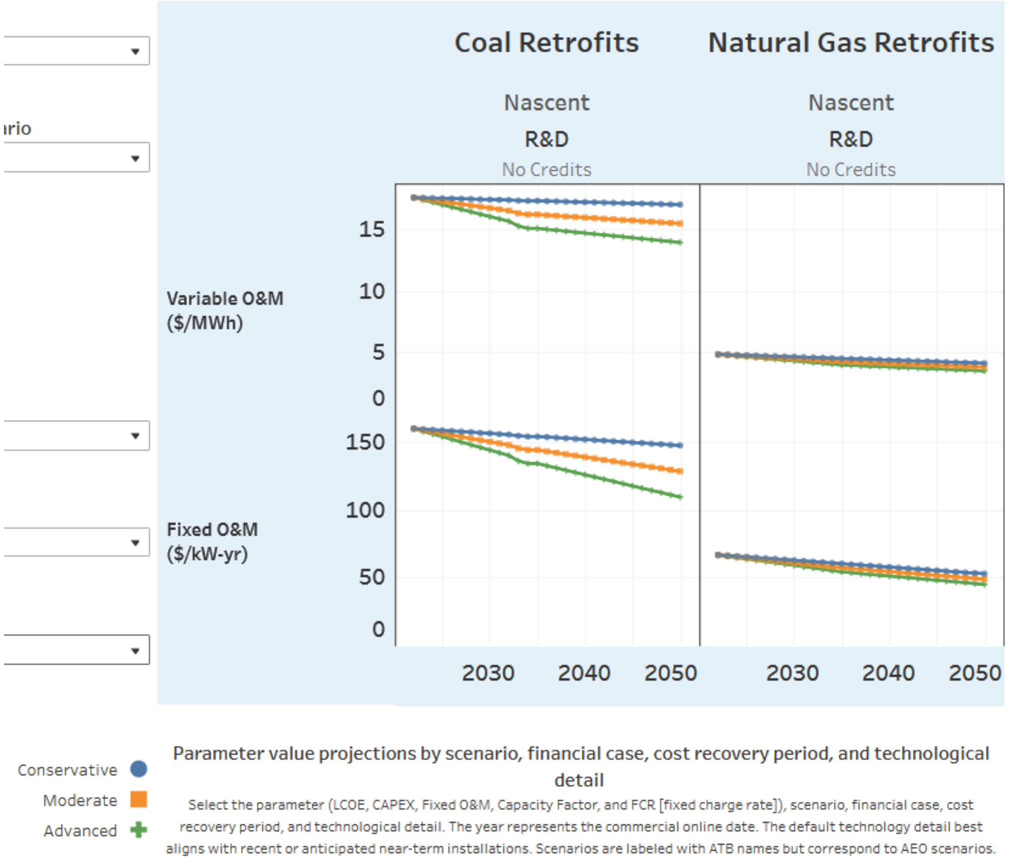
Fossil Technology Changes





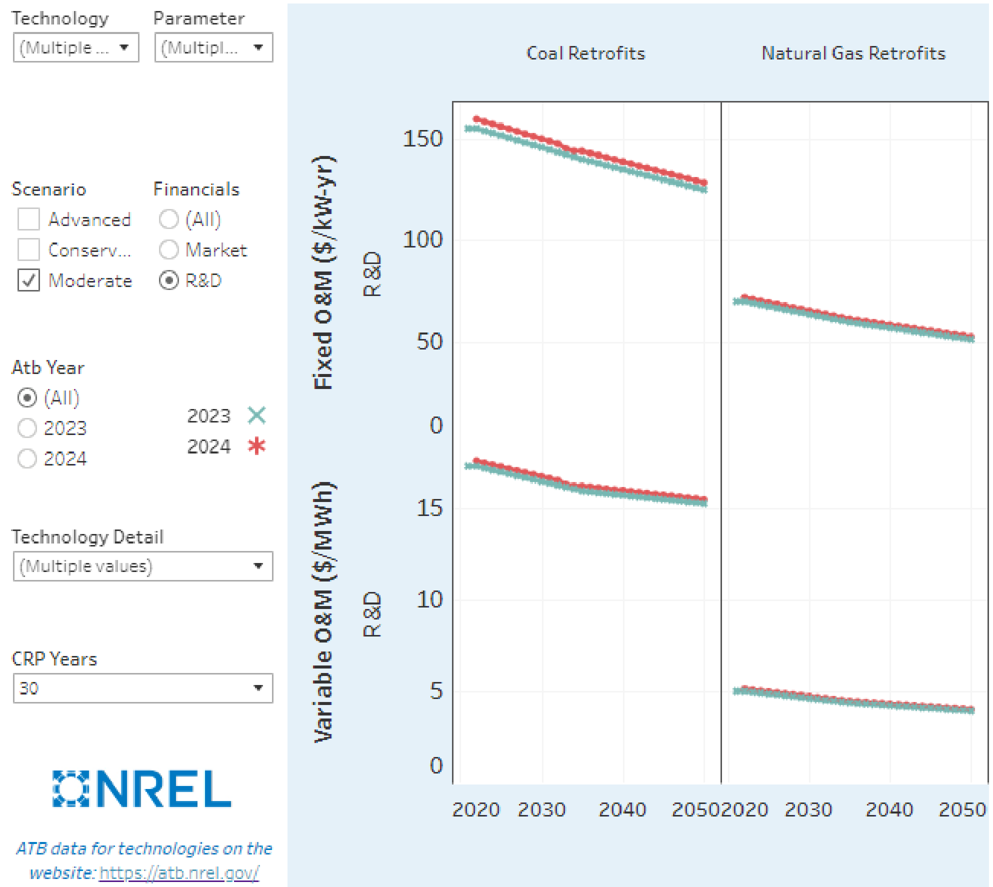
Fossil Retrofits



Parameter value projections by scenario, financial case, cost recovery period, and technological detail

Select the parameter (LCOE, CAPEX, Fixed O&M, Capacity Factor, and FCR [fixed charge rate]), scenario, financial case, cost recovery period, and technological detail. The year represents the commercial online date. The default technology detail best aligns with recent or anticipated near-term installations. Scenarios are labeled with ATB names but correspond to AEO scenarios.

Fossil Retrofit Changes



References

A complete list of references for the 2024 Electricity ATB can be found at https://atb.nrel.gov/electricity/2024/references.

Acronyms and Abbreviations

AEO	Annual Energy Outlook
AEP	annual energy production
API	application programming interface
ATB	Annual Technology Baseline
AWS	Amazon Web Services
BAU	business as usual
BESS	battery energy storage system
CAPEX	capital expenditure
CCS	carbon capture and storage
CSP	concentrating solar power
CT	combustion turbine
DOE	U.S. Department of Energy
DSCR	debt service coverage ratio
EGS	enhanced geothermal system
EIA	U.S. Energy Information Administration
FECM	Fossil Energy and Carbon Management (a U.S. DOE office)
FLORIS	FLOw Redirection and Induction in Steady State
GCC	grid connection costs
GETEM	Geothermal Electricity Technology Evaluation Model
GW	gigawatt
IGCC	integrated gasification combined cycle
IRA	Inflation Reduction Act
ITC	investment tax credit
kW	kilowatt
LCOE	levelized cost of energy
MW	megawatt
MWE	megawatt electric
NGCC	natural gas combined cycle
NPD	nonpowered dam
NREL	National Renewable Energy Laboratory
NRWAL	NREL Wind Analysis Library
NSD	new stream-reach development
OCC	overnight capital costs
ORNL	Oak Ridge National Laboratory
O&M	operations and maintenance
OPEX	operating expenses
PSH	pumped storage hydropower
PTC	production tax credit
PV	photovoltaic
R&D	research and development
ReEDS	Regional Energy Deployment System (model)
reV	Renewable Energy Potential (model)
RPM	Resource Planning Model
SAM	System Advisor Model
SMR	small modular reactor (a nuclear technology)
WACC	weighted average cost of capital
WOMBAT	Windfarm Operations and Maintenance cost-Benefit Analysis Tool

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https://atb.nrel.gov/electricity/2024/about

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- Solar: Concentrating solar power: Parthiv Kurup and Alex Zolan, NREL
- Hydropower: Gbadebo Oladosu, Oak Ridge National Laboratory
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