Annual Technology Baseline: The 2023 Electricity Update

Brian Mirletz, Laura Vimmerstedt, Sertaç Akar, Greg Avery, Dana Stright,

Dayo Akindipe, Chad Augustine, Philipp Beiter, Stuart Cohen, Wesley Cole, Patrick Duffy, Annika Eberle, David Feldman, Parthiv Kurup, Daniel Mulas Hernando, Vignesh Ramasamy, Owen Roberts, Evan Rosenlieb, Anna Schleifer, Tyler Stehly, Erik Witter, Jarett Zuboy (National Renewable Energy Laboratory)

Gbadebo Oladosu (Oak Ridge National Laboratory)

Jeffrey Hoffmann (U.S. Department of Energy, Office of Fossil Energy and Carbon Management)

July 24, 2023

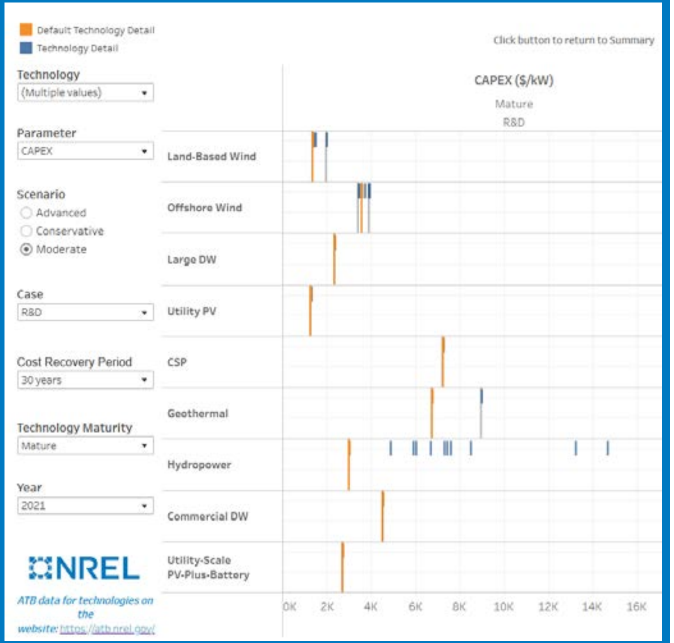
Webinar logistics slides are not included in this published version.

Slide numbering starts on this slide at #5.

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

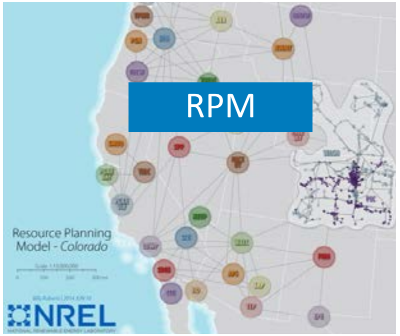
NREL Transforming ENERGY

About Technologies Data Contact

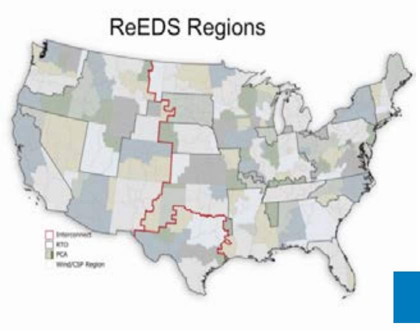
- Ever-changing technologies result in *conflicting reports of technology progress* based on inconsistent—and often opaque—assumptions.
- A *single data set is needed* to credibly and transparently assess the evolving state of energy technologies in the United States.
- The ATB enables *understanding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

ATB Project Overview

The ATB anchors key DOE and national lab analyses.

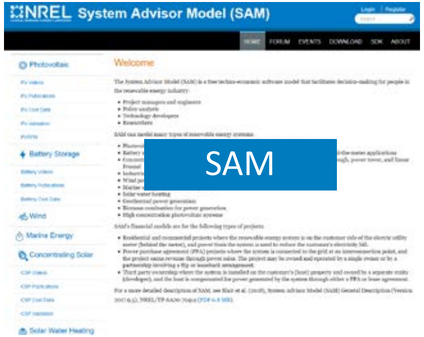


Resource Planning Model

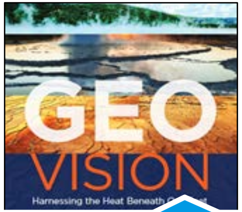


ReEDS

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 ninth 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, 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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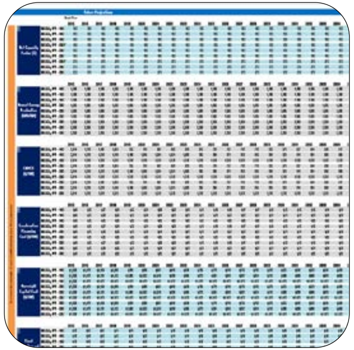
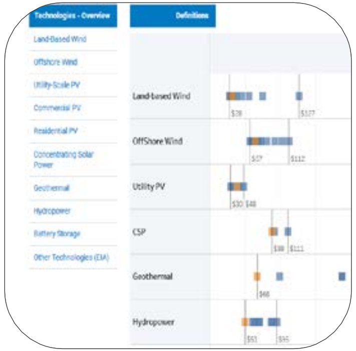
Standard Scenarios

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

The ATB includes a suite of products.



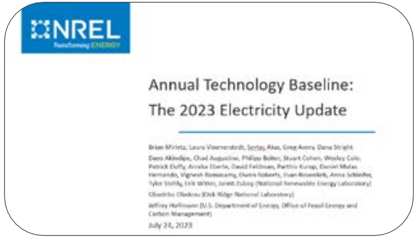


Coming soon! Open-source Python code for LCOE and debt fraction calculations. Register at https://atb.nrel.gov/register for the launch announcement

Interactive Charts

Tableau Workbook

Formatted Data



Spreadsheet

- Calculations
- Cost and performance projections, 2021–2050
- Capacity factor
- Operation 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)

- Summary of selected data (no calculations)
- Interactive charts
- Visual exploration
- Cost and performance projections, 2021–2050
  - Capacity factor
  - O&M costs
  - CAPEX
  - Financing assumptions
  - LCOE
- Structured format

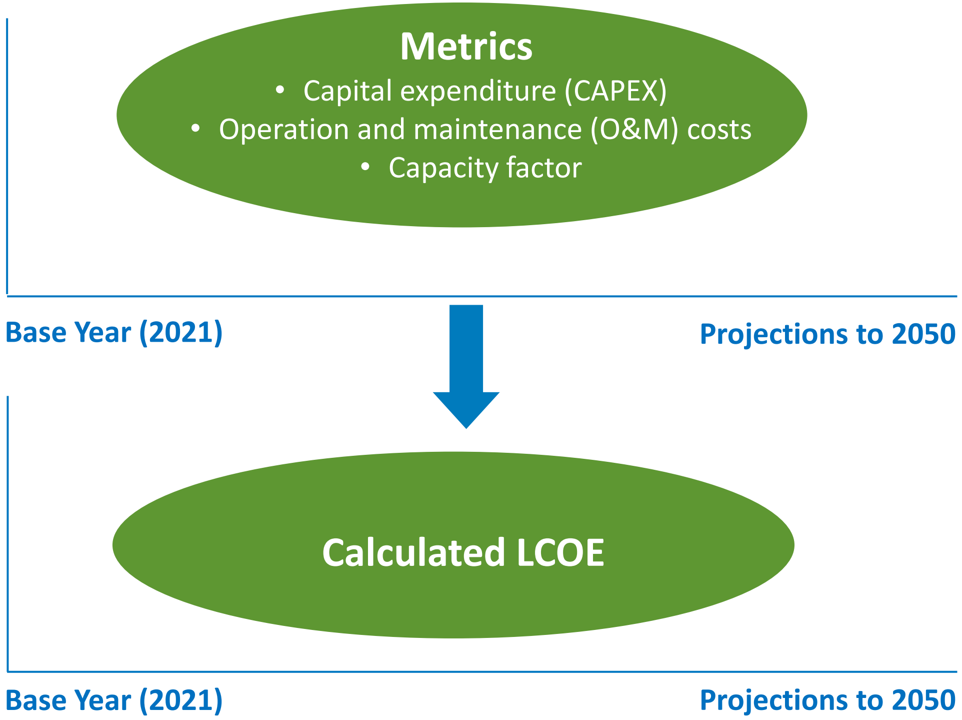
PowerPoint

- Webinar presentation
- Summary presentation

API

- Data published in Open Energy Data Initiative
- Programmatic access through AWS-S3
- Jupyter notebook

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.

LCOE is provided as a summary metric, but it is *not* used as an input to NREL models such as ReEDS, RPM, or SAM. 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 2023

Wind
- Land-based
- Offshore
- Distributed

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

Hydropower
- Non-powered dams (NPD)
- New stream-reach development (NSD)
- Pumped storage hydropower

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)
- Combustion turbine (CT)
- **NEW: Natural Gas Fuel Cell (no CCS, 98% CCS)**
- **NEW: Retrofits (90%, 95% CCS)**

Coal
- Integrated gasification combined-cycle (IGCC)
- Pulverized coal
- Pulverized coal w/ 95%, 99% CCS
- **NEW: IGCC w/ 99% CCS**
- **NEW: Retrofits (90%, 95% CCS)**

Other Technologies

(Energy Information Administration, Annual Energy Outlook 2023)

Nuclear
- Pressurized water reactor (AP1000)
- NEW: Small modular reactor (SMR)

Biopower
- Dedicated (woody biomass)

Methodology Overview: Three Steps

1. Define resource bins for each technology

Group range 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 operation and maintenance (O&M).

3. Calculate LCOE

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

Step 1: Define Technologies/Resource Bin Categories

Bins changed in 2023

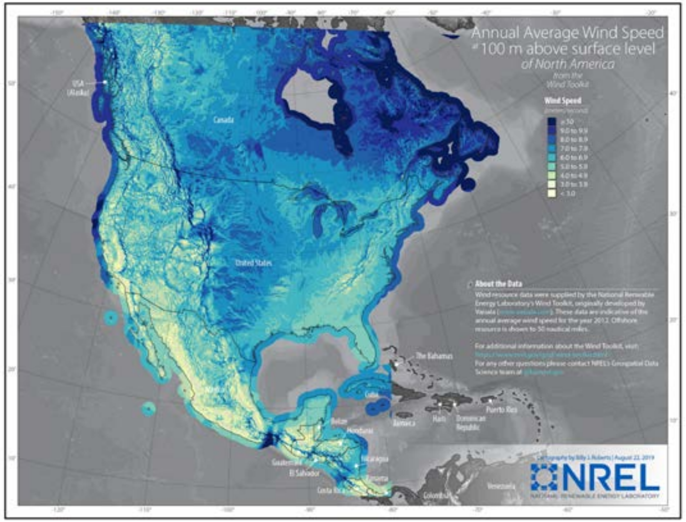
Technology	Bins	Distinguishing Characteristics
Land-based wind	10	Annual average wind speed
Offshore wind	14	Annual average wind speed
Distributed wind	40	Turbine size, annual average wind speed
Utility-scale, commercial, residential PV, and utility-scale PV-plus-battery	10	Horizontal solar irradiance resource level
CSP	3	Direct normal solar irradiance
Geothermal	6[a]	Hydrothermal, EGS, binary or flash systems, reservoir temperature
Hydropower	12[a]	Non-powered dams, new stream-reach development, head, and design capacity
Pumped storage hydropower	15[a]	CAPEX
Utility-scale, commercial, residential battery storage	5	Storage duration
Natural gas	9	Turbine technology, level of CCS
Coal	5	Pulverized coal, IGCC, level of CCS
Nuclear	2	Pressurized Water Reactor (AP1000) or SMR
Biopower	1	Dedicated
Natural gas and coal retrofits	6	Turbine technology, level of CCS

[a] Representative bins for the ATB only: the NREL Regional Energy Deployment System (ReEDS) implements a full site-specific supply curve.

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



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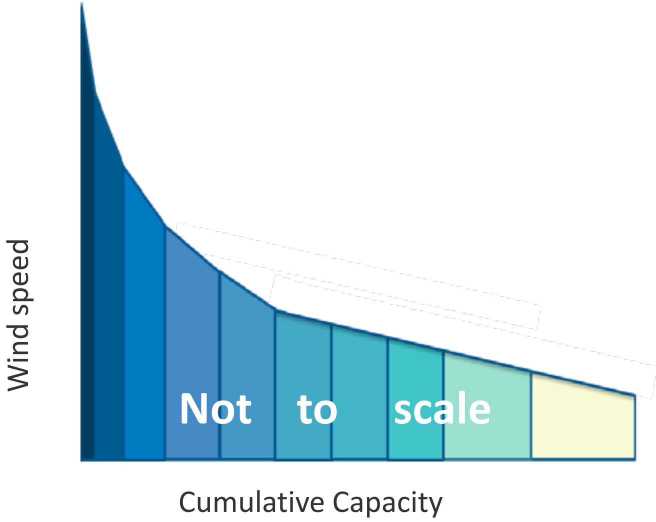


Step 2: Develop Cost and Performance Data

Base Year (2021): 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 R&D	• Widespread adoption of today's cutting edge • 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 (2021)

Technology	Source
Land-based wind power plants	Capital expenditures (CAPEX) associated with the four representative technologies are estimated using bottom-up engineering models for hypothetical wind plants installed in 2021 (Wiser and Bolinger, 2022). The all-in 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	Base year estimates are derived from a combination of bottom-up techno-economic cost modeling (Beiter et al., 2016) and experiential learning effects with economies of size and scale from higher turbine and plant ratings (Beiter et al., 2020), (Shields et al., 2022).
Distributed wind power plants	Base year costs and performance estimates are data obtained from NREL's 2020 Cost of Wind Energy study (Stehly and Duffy 2022).
Utility, residential, and commercial PV plants	CAPEX and O&M for 2021 are based on bottom-up cost modeling and market data from Ramasamy et al. (2021).
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 cost modeling uses Geothermal Electricity Technology Evaluation Model (GETEM) and inputs from the GeoVision BAU scenario (DOE 2019; Augustine et al. 2019).
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. (2022)
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. (2021).
Pumped storage hydropower	Resource characterizations and capital costs 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 PSH resource assessment. 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 ten years (Schmitt et al., 2022), (Buchheit et al., 2023), (Schmitt and Homsy, 2023).
Nuclear and biopower plants	Values from Annual Energy Outlook (EIA 2023) are reported.

Step 3: Calculate Levelized Cost of Energy (LCOE[a])

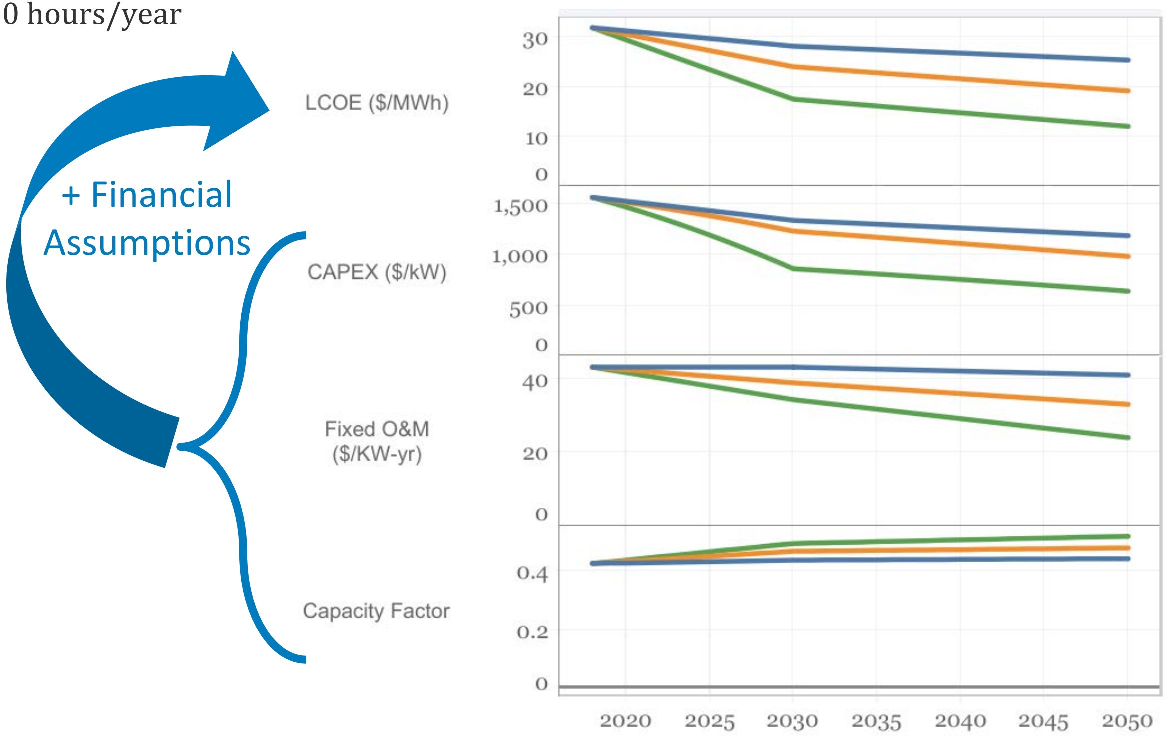
$$\text{Levelized Cost of Energy} = \frac{\text{Fixed Charge Rate} \times \text{Capital Expenditures} + \text{Fixed Operations and Maintenance Cost}}{\text{Capacity Factor} \times 8760 \text{ hours/year}}$$

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

$$+ \text{Fuel Cost}$$

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.



[a]LCOE is for generation technologies only. Levelized cost of storage is not reported.

Changes to All Technologies

https://atb.nrel.gov/electricity/2023/changes_in_2023

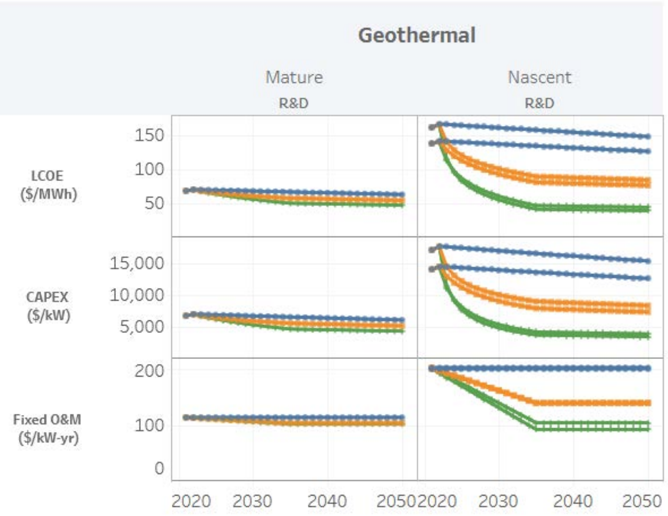
Brian Mirletz

Changes that Affect All Technologies

- Specified costs in 2022
  - Prior ATBs defined base year costs, 2030, and 2050 costs or continuous learning curves from base year
  - We know prices increased in real terms (relative to CPI) from 2021 (base year) to 2022
  - Technologies used technology-specific reports, or technology-neutral average of 3.5% to specify costs for 2022 (in 2021$)
- Additional data on cost reduction assumptions
  - Documentation includes new section “Scenario Assumptions”
  - Covers cost reductions by scenario, including learning rates and deployment assumptions used, if any

Changes that Affect All Technologies

- Maturity Metrics
  - Definition of mature vs nascent:
    - Technology details are defined as mature if a representative plant is operating or under construction in the United States in the base year.
  - Allows for explicit representation of what's in the market in the visualizations:



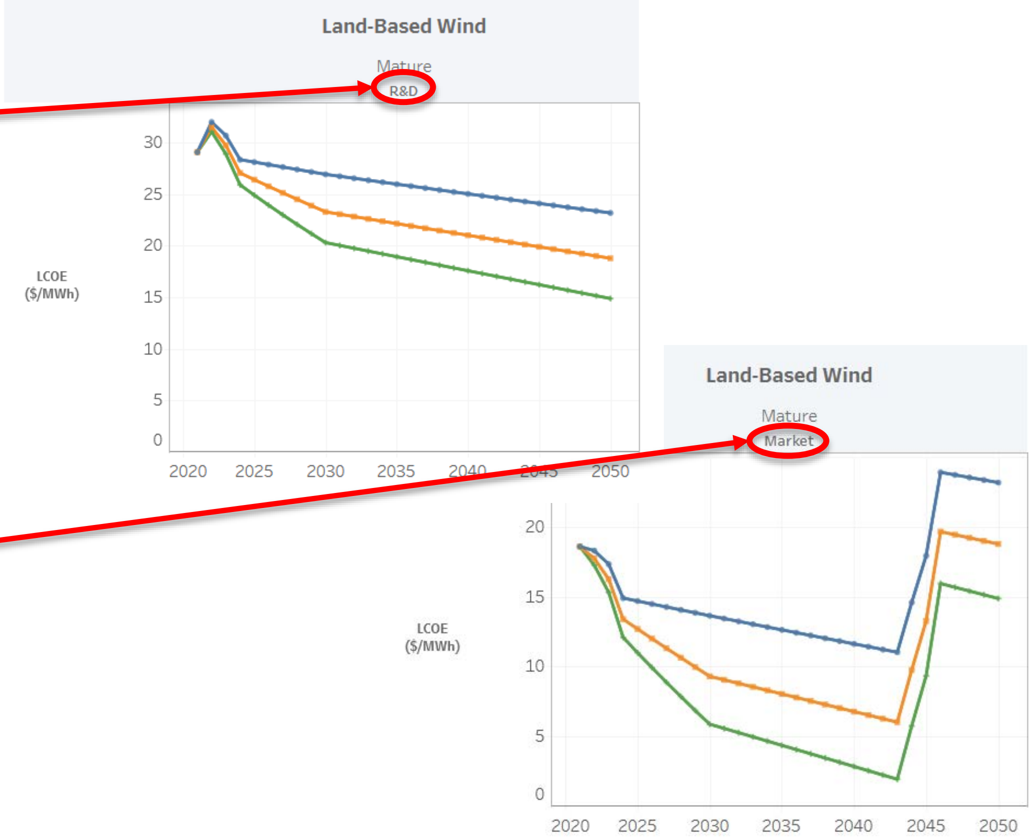
Financial Cases and Methods Updates

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 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 of 2022.



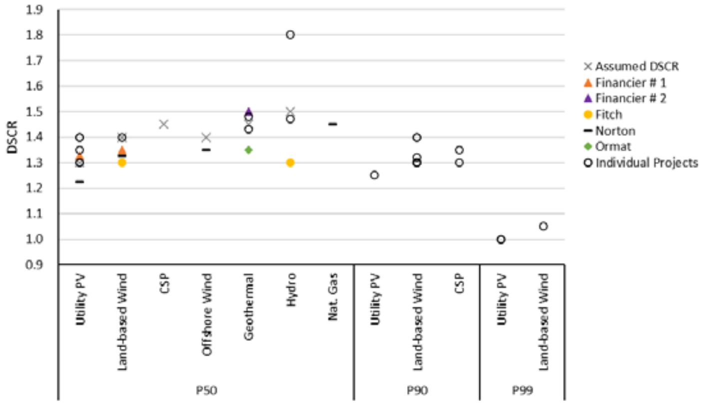
All-Technology Financial Changes in 2023 ATB

- Base year = 2021. Dollar year = 2021. Historical data include data reported in 2021.
- Increased interest rates by 3 percentage points from 2022 ATB base year values for both financial cases
- Increased cost of equity 1 percentage point
- Added Inflation Reduction Act tax credits to Markets + Policies case, with phase out starting in 2038 based on 2022 Standard Scenarios mid-case
  - Assumes labor requirements are met but no bonus credits (30% ITC, $27.50 PTC deflated to 2021$)
- Using System Advisor Model (SAM) to calculate debt fractions, including annual calculations for markets case

Define Financial Scenario, Collect Data, Run Models

- Collected data for renewable energy project financing owned by independent power producers with long-term power purchase agreements, as well as natural gas financial arrangements with quasi-merchant power contracts. (Represents the largest share of new projects in the United States, particularly for renewable energy.)
- Built cash flow model, with ATB and financing inputs, to determine project leverage over time. Methods, analysis, and data fully described by David Feldman, Mark Bolinger, and Paul Schwabe. *Current and Future Costs of Renewable Energy Project Finance Across Technologies*. (Golden, CO: NREL, 2020). NREL/TP-6A20-76881. https://www.nrel.gov/docs/fy20osti/76881.pdf.
    - Interest rate and cost of equity assumptions updated for this ATB (see previous slide). More recent DSCR industry data was assessed and found to be generally consistent with previous assumptions.
- Developed values for two financial cases (R&D and Market + Policies) to reflect current assessments. "R&D" financial case assumes no tax credits and no change in interest rate.
- Financing costs for each technology are developed for (1) construction period and (2) operating period to account for different levels of risk.

DSCR data at different probability of exceedance levels, by technology

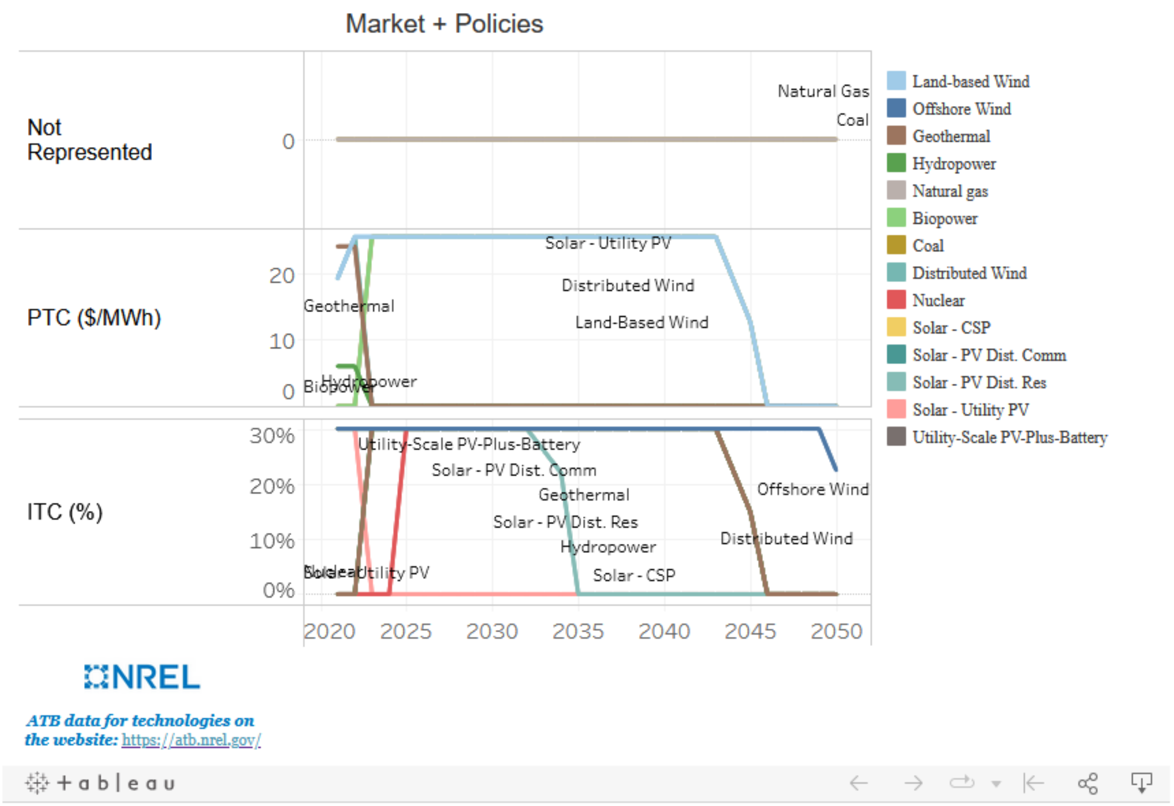


Comparing Financial Assumptions by Technology

The following slides compare financial assumptions that are used in calculating LCOE:

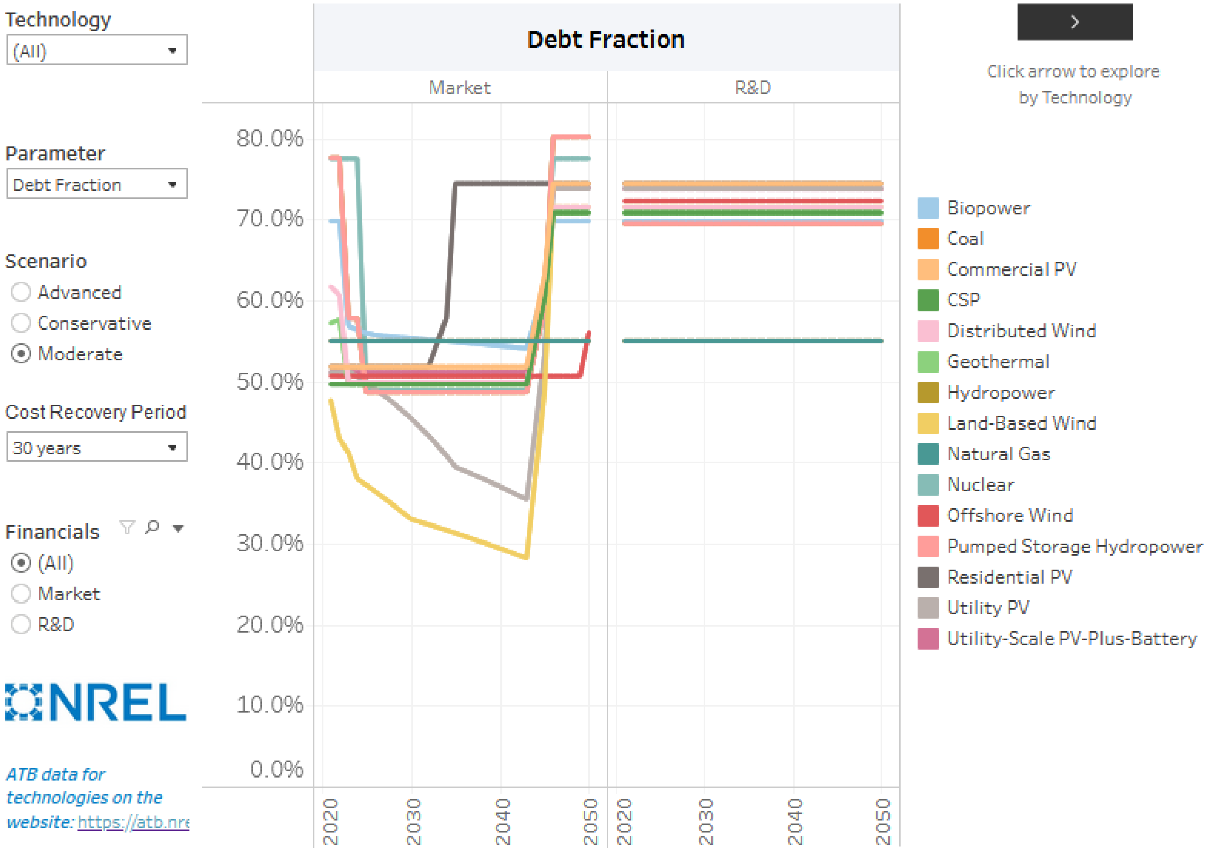
- ITC and PTC
- Term debt fraction
- Term-weighted average cost of capital (real)
- LCOE.

ITC and PTC

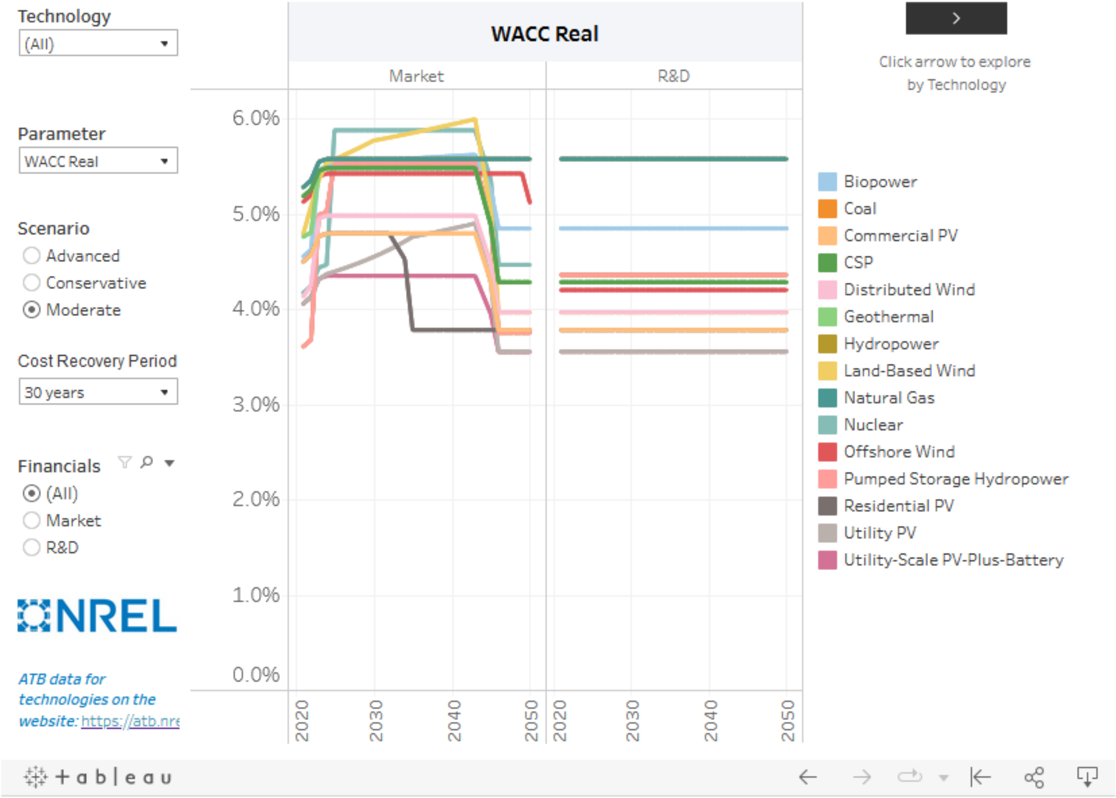


Effects of production tax credits and investment tax credits

Term Debt Fraction by Financial Case

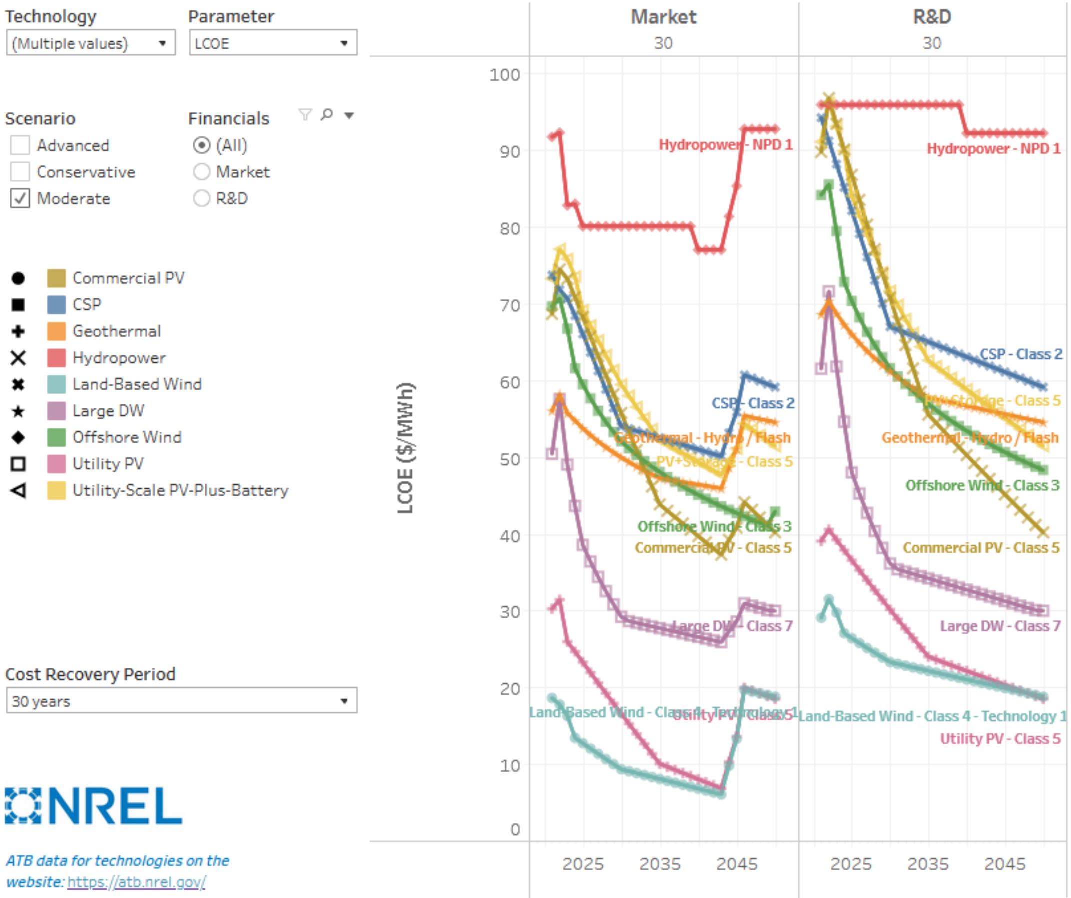


Term WACC (Real) by Financial Case



Financial parameters by technology and financial assumptions case

LCOE by Financial Case



Technology-Specific Updates

https://atb.nrel.gov/electricity/2023/changes_in_2023

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

- **Land-Based Wind: :** Wind turbine **technology configuration is now wind speed class-specific** and is selected by the technology configuration with the lowest LCOE within each wind speed class.
- Offshore Wind: Empirical market data are updated, leading to a lower CAPEX learning rate of 7.2%.
- Distributed Wind: No major updates in the 2023 ATB
- **Photovoltaics (all scales):** Initial cost metrics are informed by **new benchmark results from** (Ramasamy et al., 2021), and projections are based on (Ramasamy et al., 2022). **Utility-scale capacity factor numbers now assume bifacial panels.**
- Concentrating Solar Power: Component and system cost estimates for the Base Year **now include data from recent heliostat bottom-up analysis** (Kurup et al., 2022). There have been updates to the defaults in the System Advisor Model (SAM) power tower molten salt physical model.
- **Geothermal:** Near-field and deep enhanced geothermal system (EGS) **plant costs are fully distinguished**. A single-factor learning curve is applied to future projections in the Moderate and Advanced scenarios.
- Hydropower: No changes from the 2021 ATB.

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

- Hydropower: No changes from the 2021 ATB.
- Utility-Scale PV-Plus-Battery: **Cost savings for colocated systems** have been updated using (Ramasamy et al., 2022). O&M **costs now include the full replacement** of the battery in year 15
- **Battery Storage (all scales):** Base year CAPEX is updated consistent with new benchmark results in (Ramasamy et al., 2022). **Projections are revised** based on a new literature survey (Cole and Karmakar, 2023).
- Pumped Storage Hydropower**: Capital costs and resource characteristics are updated**, with changes relative to (Rosenlieb et al., 2022) described in "Closed-Loop Pumped Storage Hydropower Supply Curves" (NREL).
- **Natural Gas and Coal:** The **2023 ATB adds retrofit cases** for natural gas and coal technologies. **The trajectory for Natural Gas Fuel Cells** has been provided independently of combined cycle plants. Learning rates are updated to reflect (EIA, 2023).
- Nuclear: Costs updated to reflect EIA (2023).

Land-Based Wind

Base Year

Capital expenditures (CAPEX) associated with the four representative technologies are estimated using bottom-up engineering models for hypothetical wind plants installed in 2021. The Base Year value for each wind speed class is dependent on the selected representative technology. The all-in OPEX cost for each representative technology is informed by recent literature (Liu and Garcia da Fonseca, 2021) and varies by the representative wind turbine's rating. 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-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 (Liu and Garcia da Fonseca, 2021) and change for each scenario based on assumed learning rates. Net cash flow projection methods are similar to the base year but 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

data updated: 06/14/2023 v5.73

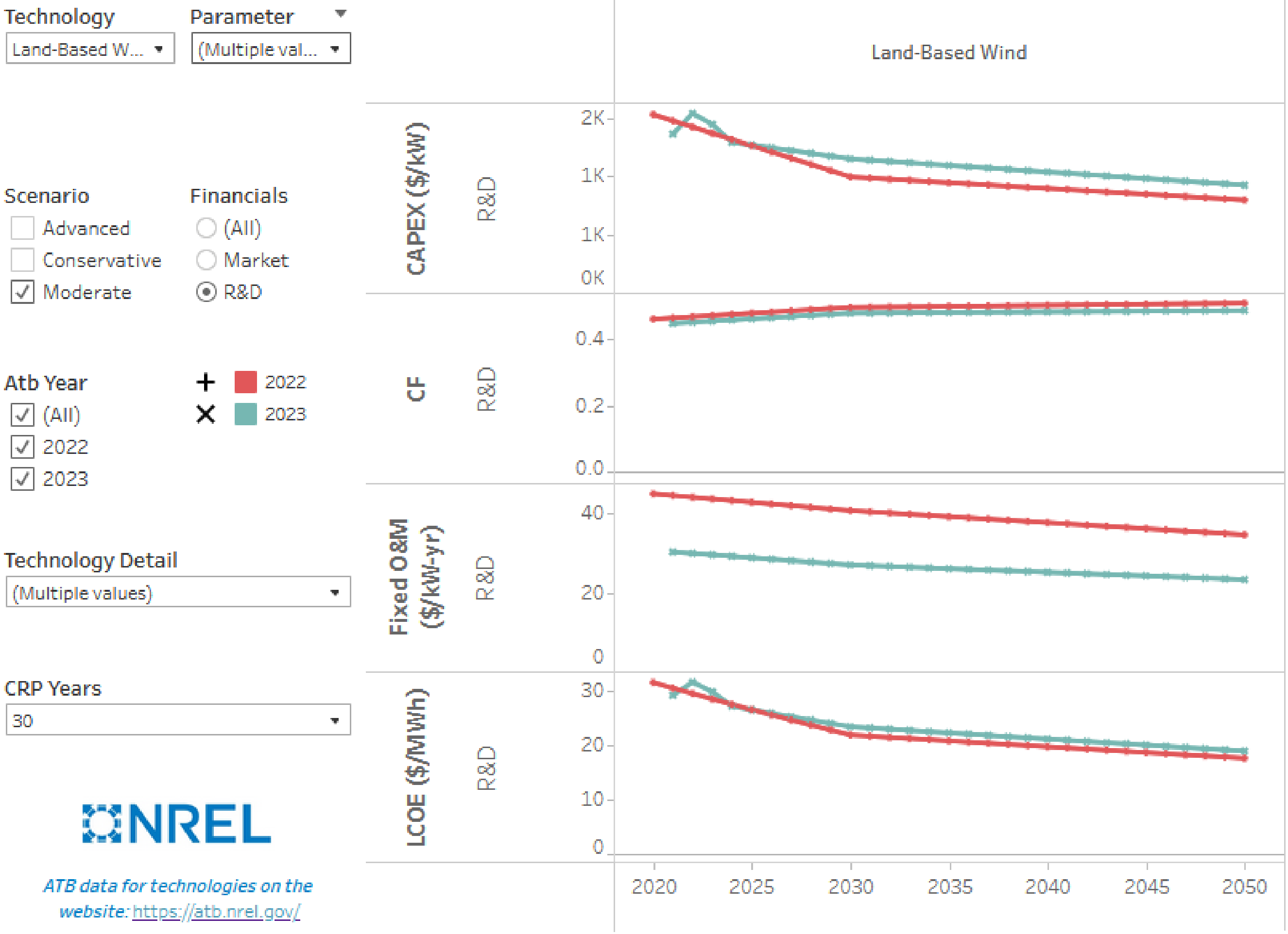
NREL

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

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



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Offshore Wind

Base Year

As in the 2022 ATB, Base Year estimates are derived from a combination of bottom-up techno-economic cost modeling (Beiter et al. 2016) and experiential learning effects with economies of size and scale from higher turbine and plant ratings (Beiter et al. 2020, Shields et al. 2022).

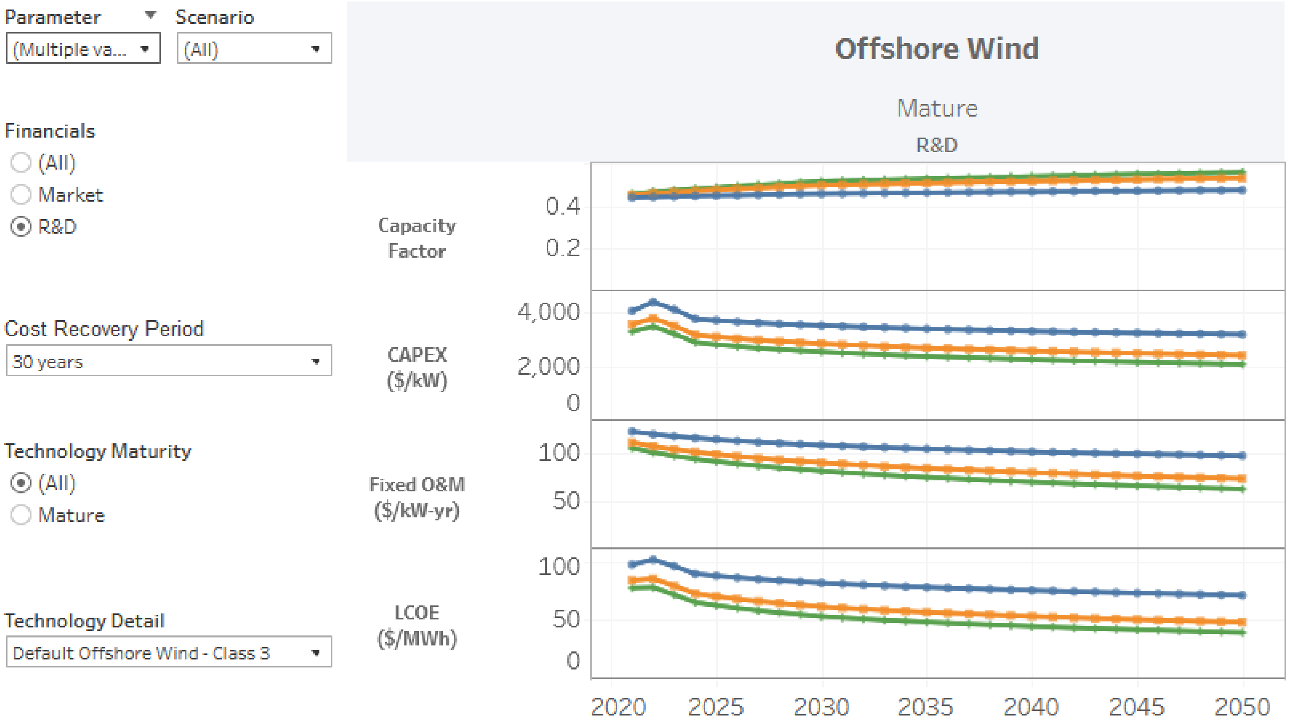
Projections

Future CapEx estimated based on cost reductions from learning. Learning rate (7.2%) derived based on empirical project data. Assumed offshore wind deployment trajectories obtained from literature.

Future OpEx and AEP estimated based on innovations trajectories and expert elicitation

Patrick Duffy, Daniel Mulas Hernando, and Philipp Beiter

Offshore Wind



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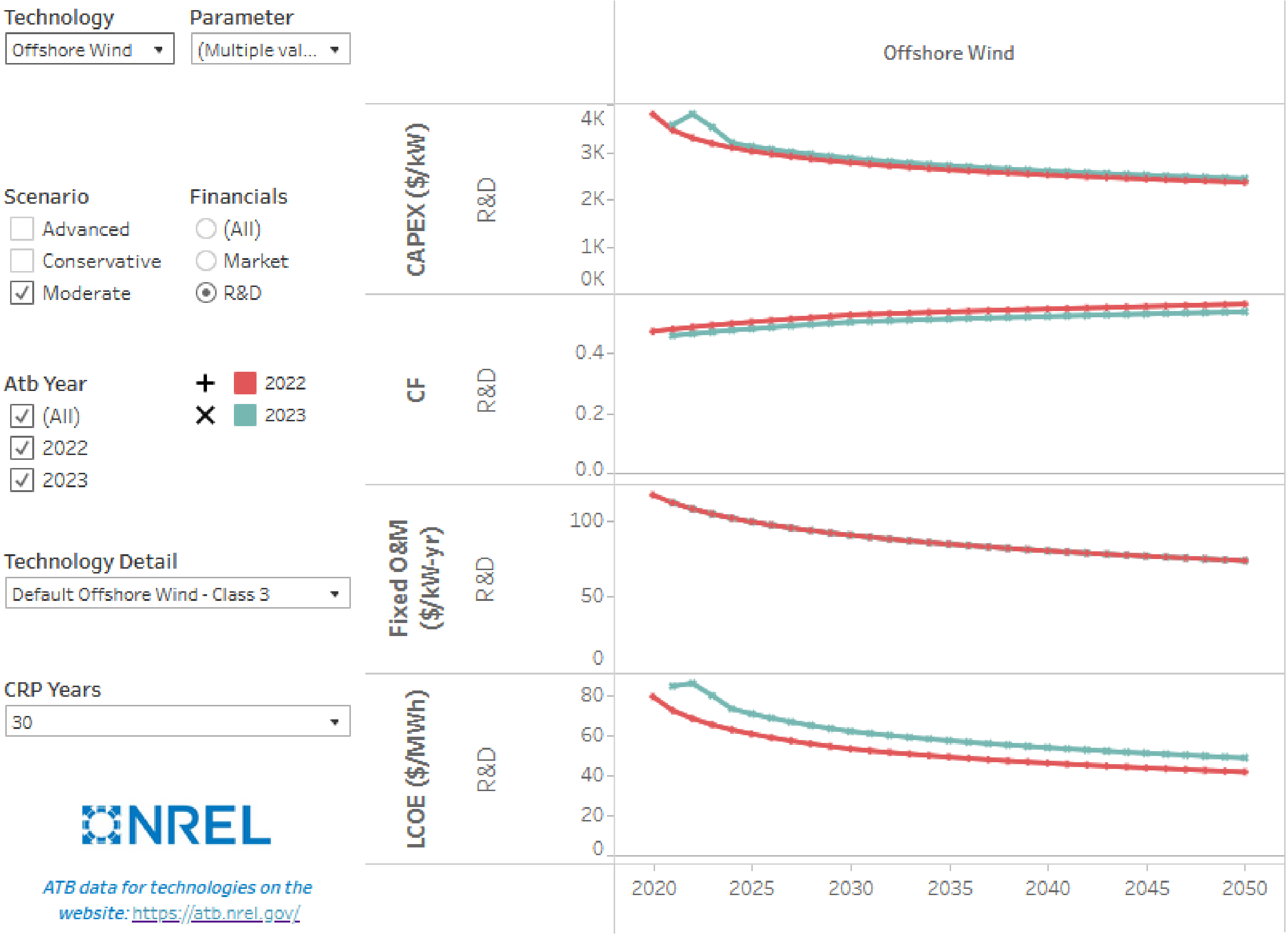
Offshore Wind



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

Distributed Wind

Base Year

CAPEX is based on the Distributed Wind Futures Study and uses 2020 CAPEX and O&M costs from the Cost of Wind Energy study (Stehly and Duffy 2022).

Projections

CAPEX projections for distributed wind projects use methods from Lantz et al. (2016). 2020 costs are from the Cost of Wind Energy study (Stehly and Duffy 2022; DOE and NREL 2015). And updates are from the Distributed Wind Futures Study (McCabe et al. 2022).

Tyler Stehly and Owen Roberts

Distributed Wind

data updated: 06/14/2023 v5.73

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

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

Technology: Large DW

Parameter: (Multiple val...

Scenario
- [ ] Advanced
- [ ] Conservative
- [x] Moderate

Financials
- ( ) (All)
- ( ) Market
- (•) R&D

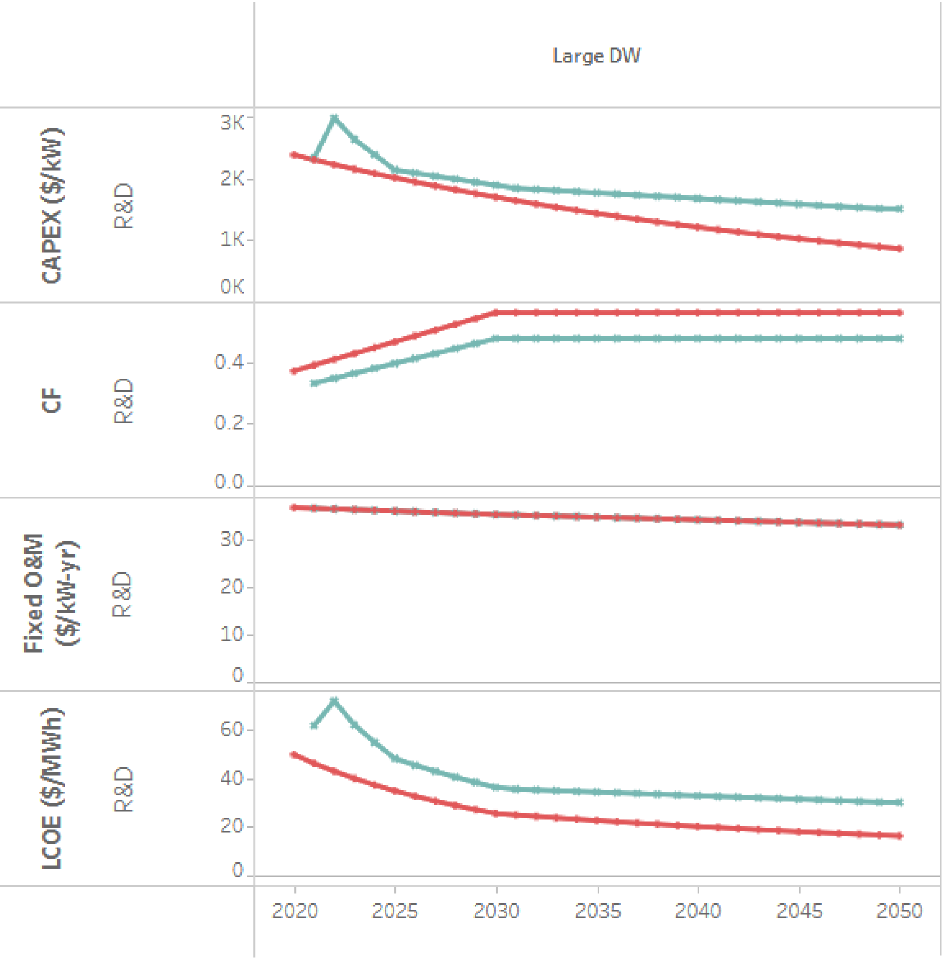
Atb Year
- [x] (All)
- [x] 2022
- [x] 2023

+ 2022
× 2023

Technology Detail: Default Large DW - Class 7

CRP Years: 30

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



Solar PV

Base Year

CAPEX for plants with a commercial operation date of 2021 is based on bottom-up modeling and market data from (Ramasamy et al., 2021), the same source as the 2022 ATB. For the 2022 commercial operation date CAPEX, the new data are from (Ramasamy et al., 2022). The O&M costs are based on modeled pricing for PV systems from those same references.

Projections

The DC-to-AC ratio (or inverter loading ratio) for utility-scale PV is changed from 1.28 in the 2022 ATB to 1.34 in the 2023 ATB for the base year and future years. The straight-line improvements in cost metrics through 2035 are now calculated using the 2022 benchmarks from (Ramasamy et al., 2022) as the initial points.

Jarett Zuboy and David Feldman

Solar PV

The 2030 LCOE is higher in ATB 2023 than in ATB 2022 for all PV sectors for several reasons:

- Higher 2022 cost benchmarks
  - Benchmarked real PV system costs rose between 2021 and 2022.
- Less aggressive projected cost reductions
  - The projection target year is shifted from 2030 to 2035, which stretches the timeframe for improvements and raises costs because of the straight-line interpolation method.
  - Projected module costs are based on a combination of MSP and global spot prices, rather than a combination of U.S. and global spot prices.
  - Significant hardware supply chain costs are maintained for residential and commercial systems.
  - Installer margin and overhead costs are higher.
- ATB 2023 financial assumptions (e.g., higher interest rates, higher WACC) increase LCOE.
  - The difference in financing assumptions between ATB 2023 and ATB 2022 explains 65% of the difference in 2030 LCOE across the two ATB years for utility-scale PV and 34% for residential PV.
  - Higher financing assumptions (and CAPEX assumptions) affect all technologies analyzed in 2023 ATB.

Utility-scale LCOE increases are offset partially by higher capacity factors

- ATB 2023 assumes the use of bifacial modules.

The 2050 LCOE is also higher in ATB 2023 for the same reasons, plus a lower module efficiency (28% vs. 30%) is assumed in the breakthrough case.

Utility-Scale Solar PV

Parameter: (Multiple va...

Scenario: (All)

Financials

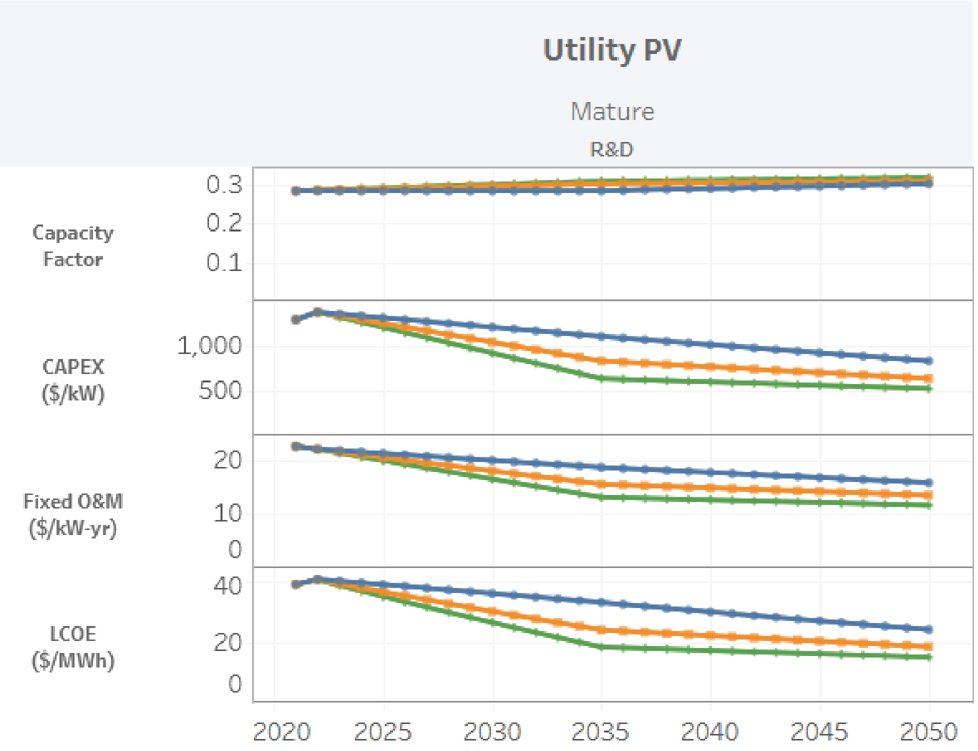
- (All)
- Market
- (•) R&D

Cost Recovery Period: 30 years

Technology Maturity

- (•) (All)
- Mature

Technology Detail: Default Utility PV - Class 5



data updated: 06/14/2023 v5.73

NREL

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

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 Solar PV

Technology: Utility PV

Parameter: (Multiple val...

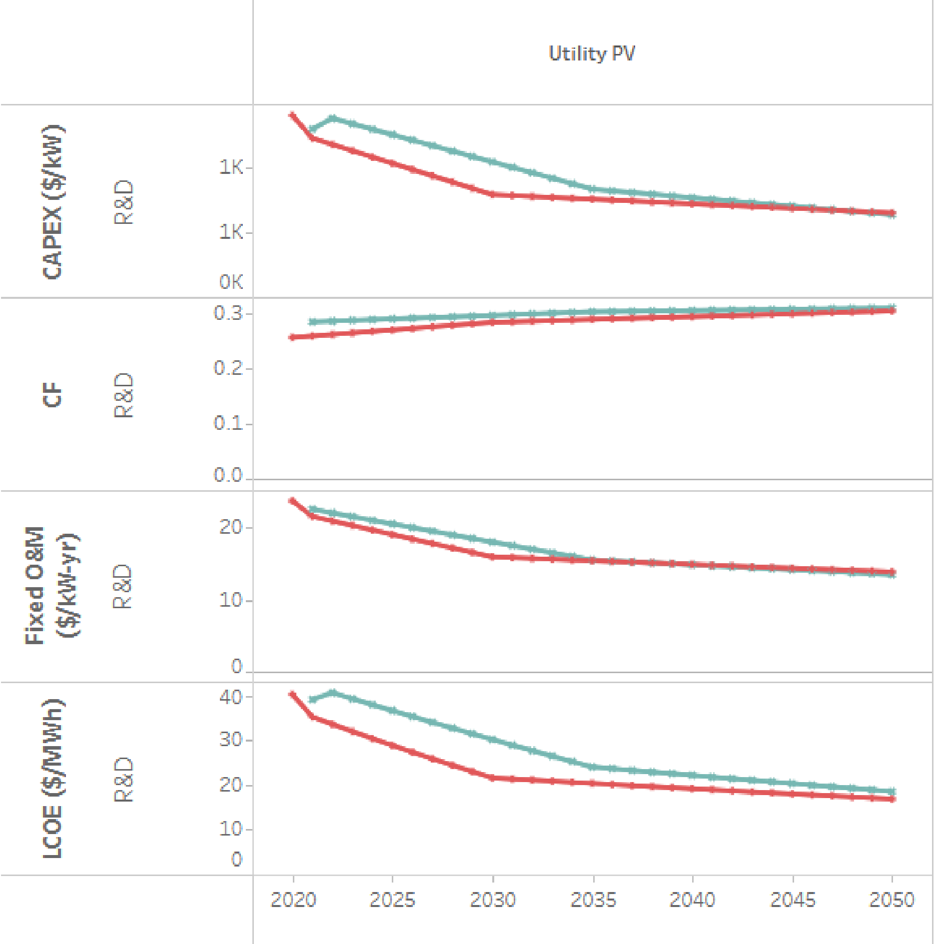
Scenario
- [ ] Advanced
- [ ] Conservative
- [x] Moderate

Financials
- ( ) (All)
- ( ) Market
- (•) R&D

Atb Year
- [x] (All)
- [x] 2022
- [x] 2023

Technology Detail: Default Utility PV - Class 5

CRP Years: 30



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

Concentrating Solar Power

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 2023 ATB are based on cost estimates for CSP components that are available in Version 2021.12.02 of the System Advisor Model (SAM).

Projections

As in the 2022 ATB, the Moderate Scenario assumes a transition to a supercritical CO_2 cycle in the powerblock, advanced coatings on the receiver, improved tanks, pumps, and component configurations for the thermal storage unit, and improved heliostat installation and learning that are due to 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.

Chad Augustine and Parthiv Kurup

Concentrating Solar Power

Parameter
(Multiple va...

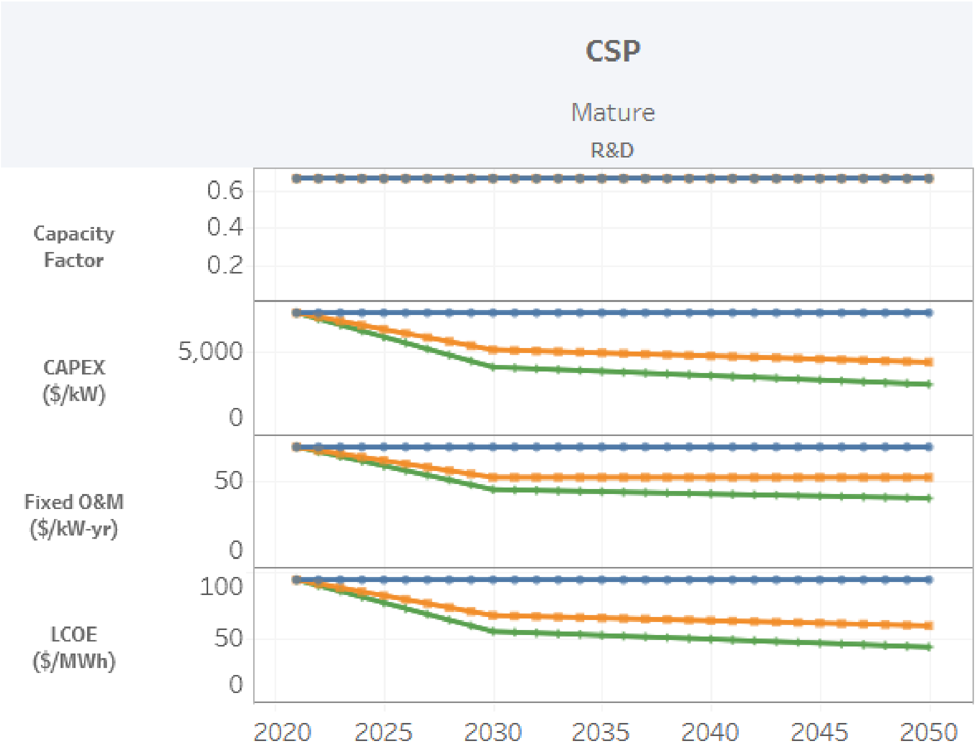
Scenario
(All)

Financials
- (All)
- Market
- (•) R&D

Cost Recovery Period
30 years

Technology Maturity
- (•) (All)
- Mature

Technology Detail
Default CSP - Class 2



data updated: 06/14/2023 v5.73

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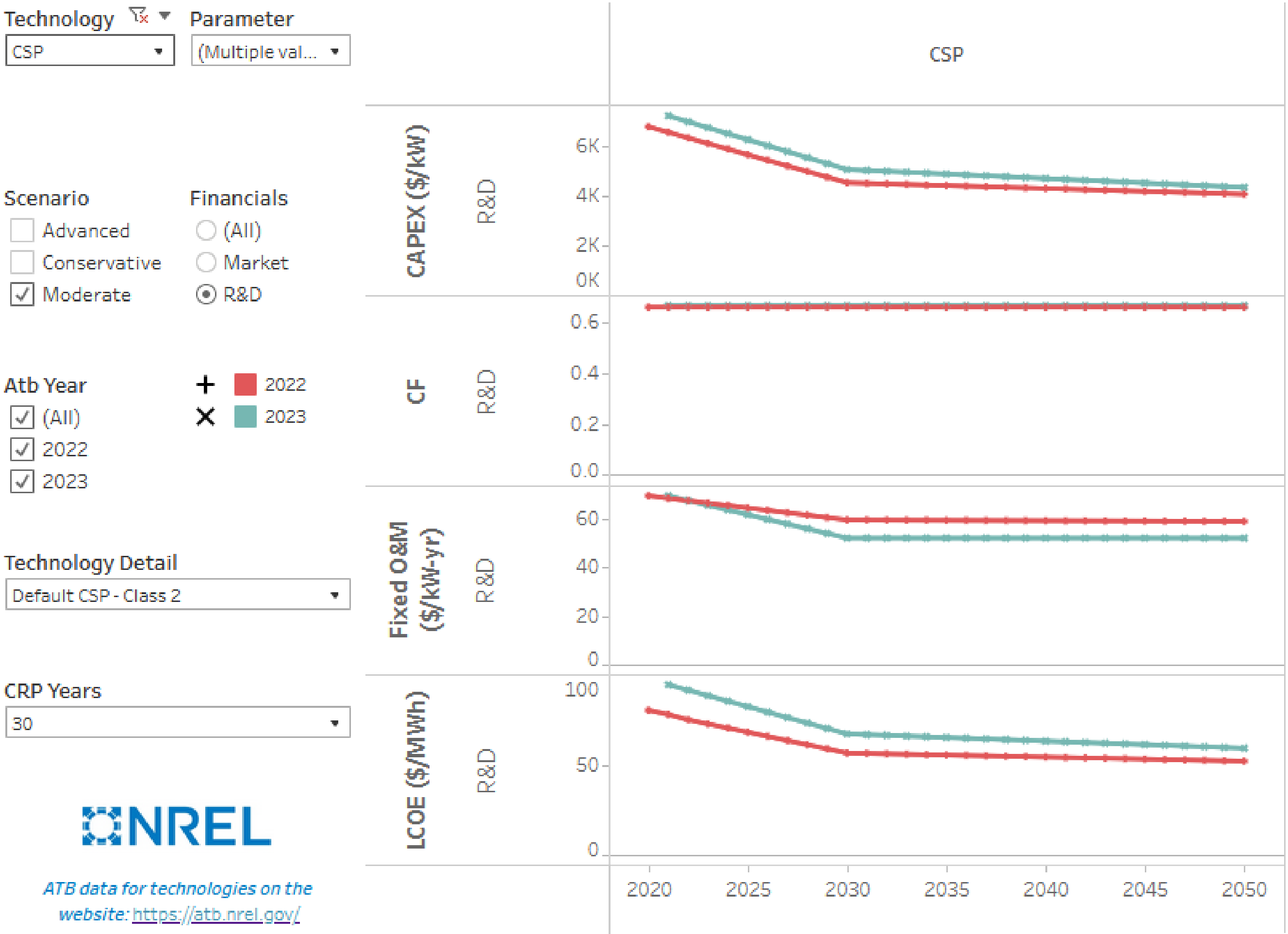
ATB data for technologies on the website: https://atb.nrel.gov/

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.

Concentrating Solar Power



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

Geothermal

Base Year

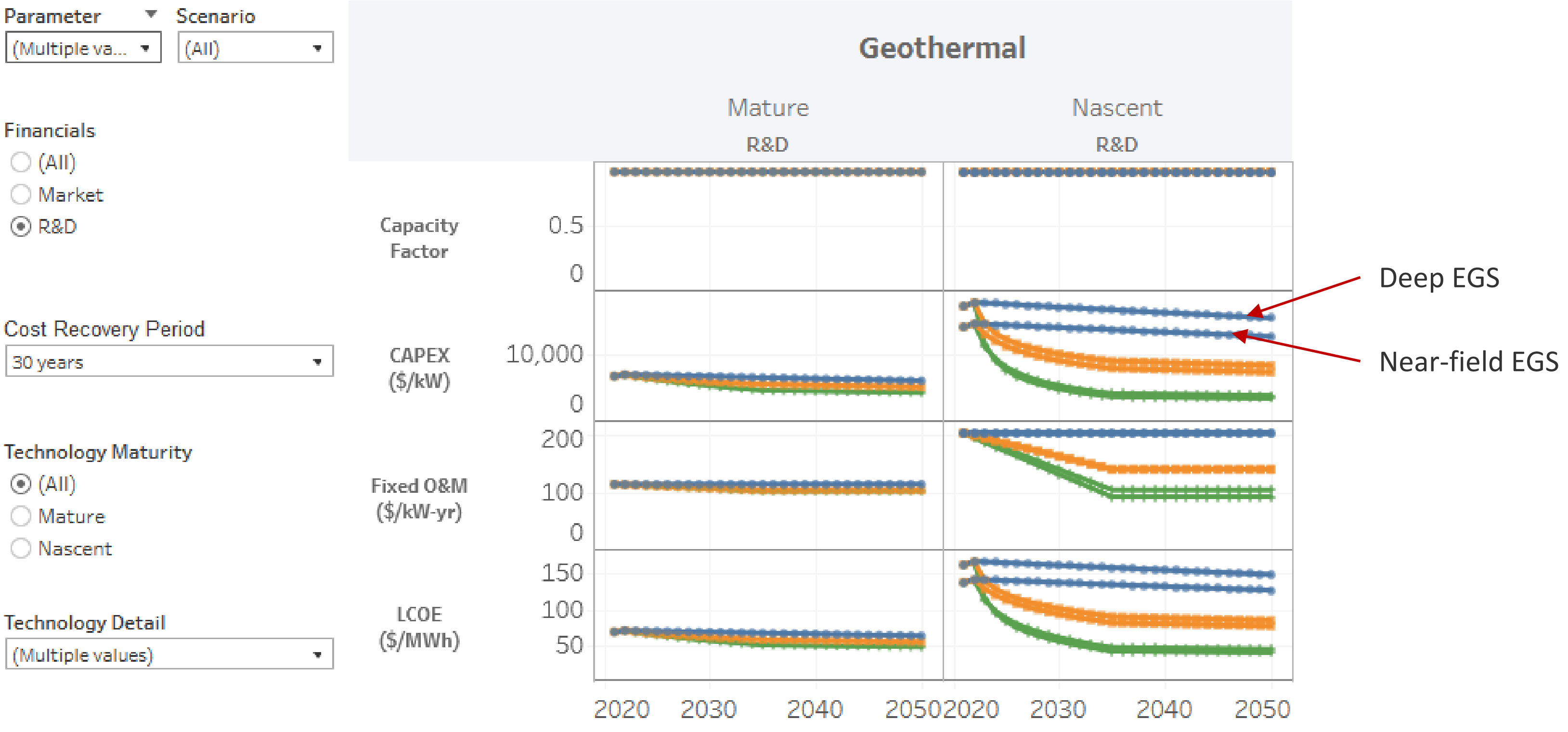
- Base Year estimates are from bottom-up cost modeling in the Geothermal Electricity Technology Evaluation Model (GETEM) using baseline assumptions from the GeoVision study (DOE, 2019).
- A reduction in plant contingency from 15% to 10% results in lower CAPEX for most technologies.
- Revisions in model assumptions for exploration drilling resulted in significantly lower CAPEX for EGS
- As in the 2022 ATB, the O&M derived from GETEM decreased by 23% based on proprietary geothermal industry data.

Projections

- For 2022 estimates, a technology-agnostic CPI factor was applied to account for the 2022 inflationary trends.
- Beyond 2022, projections were made based on scenarios:
  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 afterwards
  Advanced: An 30% learning rate up to 2035, and then a 0.5% decline afterward (Fukui et al., 2017); (Latimer and Meier, 2017).
- Moderate and Advanced estimates were implemented in 2035 when tech maturity is expected.

Dayo Akindipe and Erik Witter

Geothermal



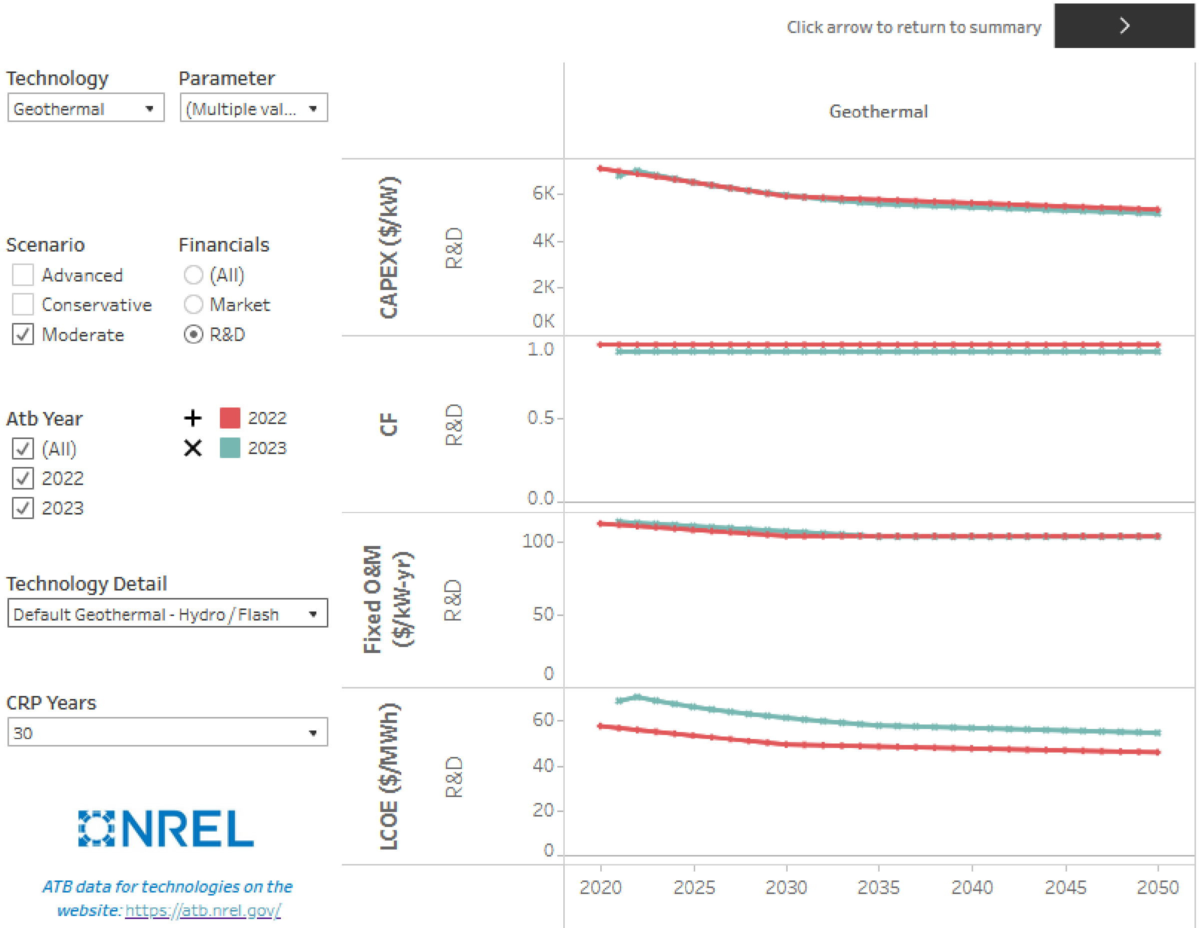
data updated: 06/14/2023 v5.73

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.

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

Geothermal - Default (Hydrothermal Flash)



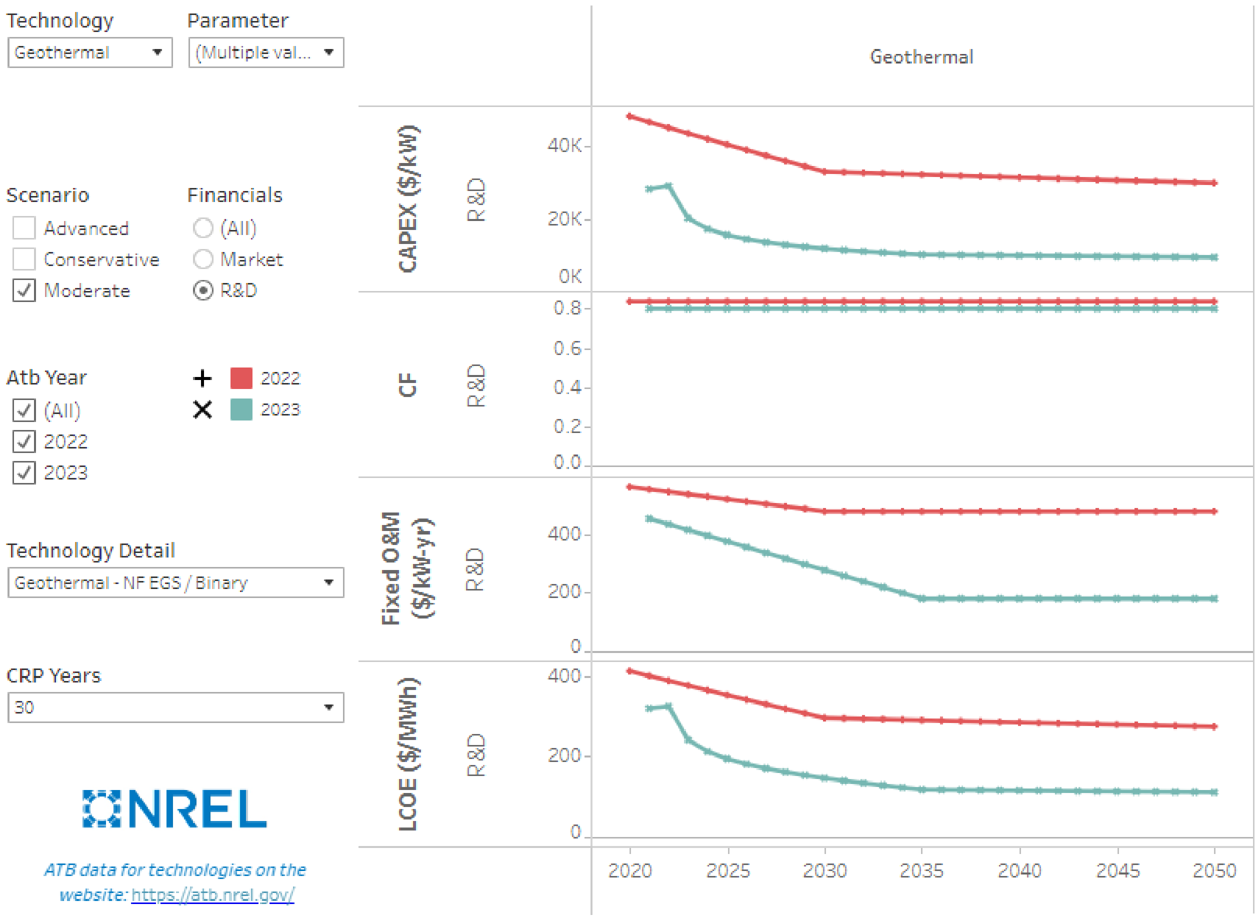
Hydrothermal Flash

2022 ATB: $7,071/kW
2023 ATB: $6,750/kW

2022 ATB: $112/kW-yr
2023 ATB: $114/kW-yr

2022 ATB: $58/MWh
2023 ATB: $69/MWh

Geothermal - Near Field EGS



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

NF-EGS Binary

2022 ATB: $48,395/kW
2023 ATB: $28,237/kW

2022 ATB: $561/kW-yr
2023 ATB: $453/kW-yr

2022 ATB: $413/MWh
2023 ATB: $320/MWh

Hydropower

Base Year

The non-powered dam (NPD) data in the 2023 ATB are estimates of costs from a reduced-form model estimated with bottom-up simulation results for nearly 20 reference sites (Oladosu et al., 2021). Data for New stream-reach development (NSD) in the 2023 ATB are retained from previous years based on projections developed for the Hydropower Vision study (DOE, 2016) using technological learning assumptions and bottom-up analysis of process and/or technology improvements to provide a range of future cost outcomes (O'Connor et al., 2015).

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

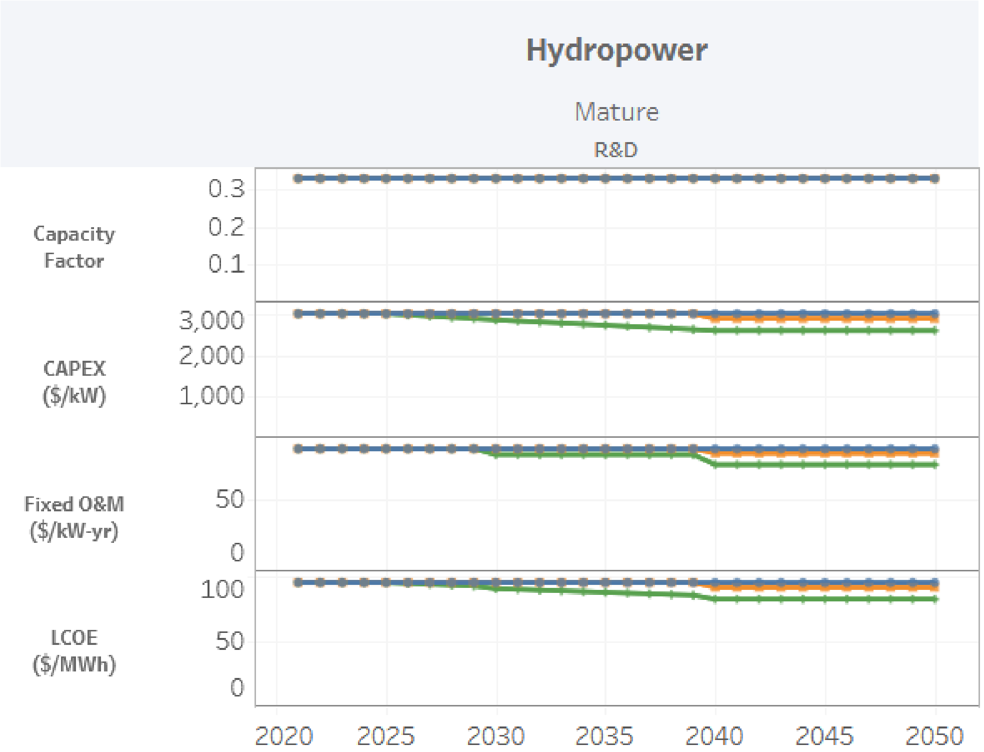
Parameter: (Multiple va...
Scenario: (All)

Financials
- (All)
- Market
- R&D (selected)

Cost Recovery Period: 30 years

Technology Maturity
- (All) (selected)
- Mature

Technology Detail: Default Hydropower - NPD 1



data updated: 06/14/2023 v5.73

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

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.

Hydropower

Technology: Hydropower

Parameter: (Multiple val...

Scenario
- [ ] Advanced
- [ ] Conservative
- [x] Moderate

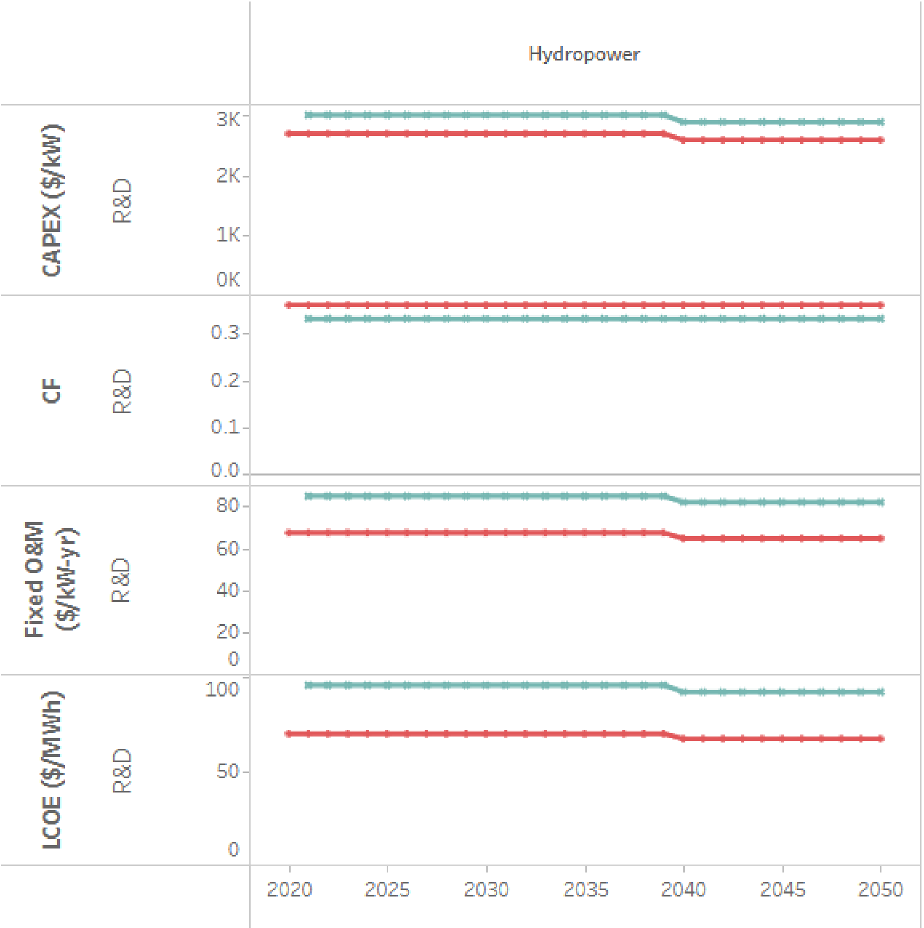
Financials
- ( ) (All)
- ( ) Market
- (•) R&D

Atb Year
- [x] (All)
- [x] 2022
- [x] 2023

+ 2022
× 2023

Technology Detail: Default Hydropower - NPD 1

CRP Years: 30



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

Utility-Scale PV-Plus-Battery

Base Year

CAPEX for plants with a commercial operation date of 2022 is based on new bottom-up modeling and 2022 Q1 market data from (Ramasamy et al., 2022). Cost savings for colocated systems have also been updated using that report. O&M costs now include the full replacement of the battery in year 15, in contrast with the augmentation schedule in the 2022 ATB.

Projections

As in the 2022 ATB, PV-plus-battery projections in the 2023 ATB are driven primarily by CAPEX cost improvements but also by improvements in energy yield, operating cost, and cost of capital (for the Market + Policies case). Projected technology costs are based on a new report (Ramasamy et al., 2022) .

Vignesh Ramasamy and Anna Schleifer

Utility-Scale PV-Plus-Battery

Parameter
(Multiple valu...

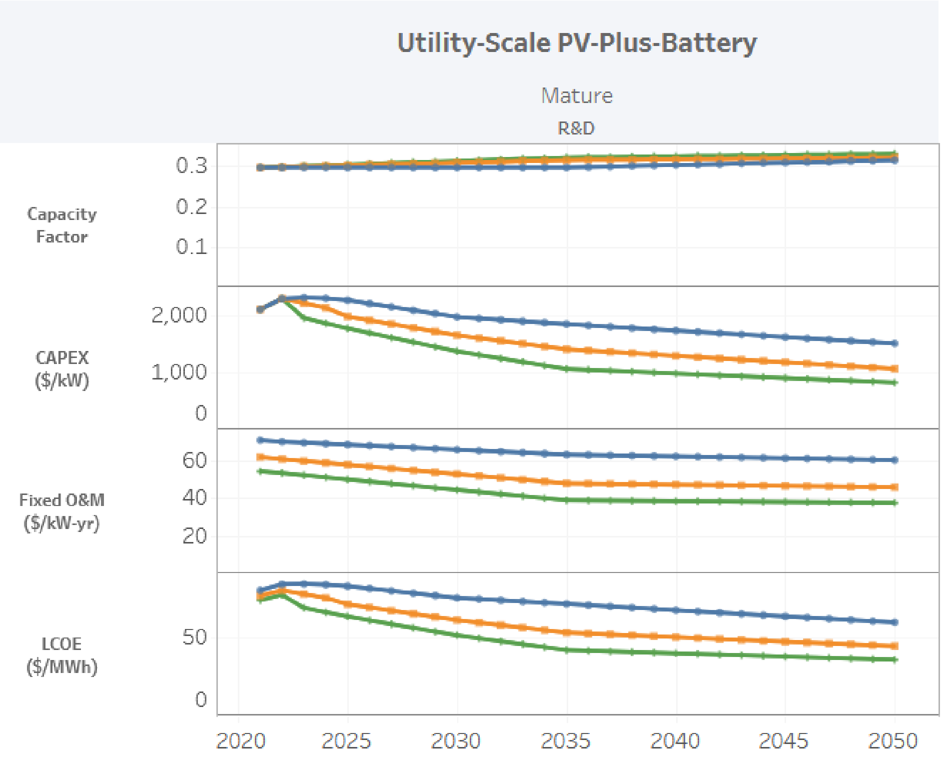
Scenario
(All)

Financials
- (All)
- Market
- R&D (selected)

Cost Recovery Period
30 years

Technology Maturity
- (All) (selected)
- Mature

Technology Detail
Default PV+Storage - Class 5



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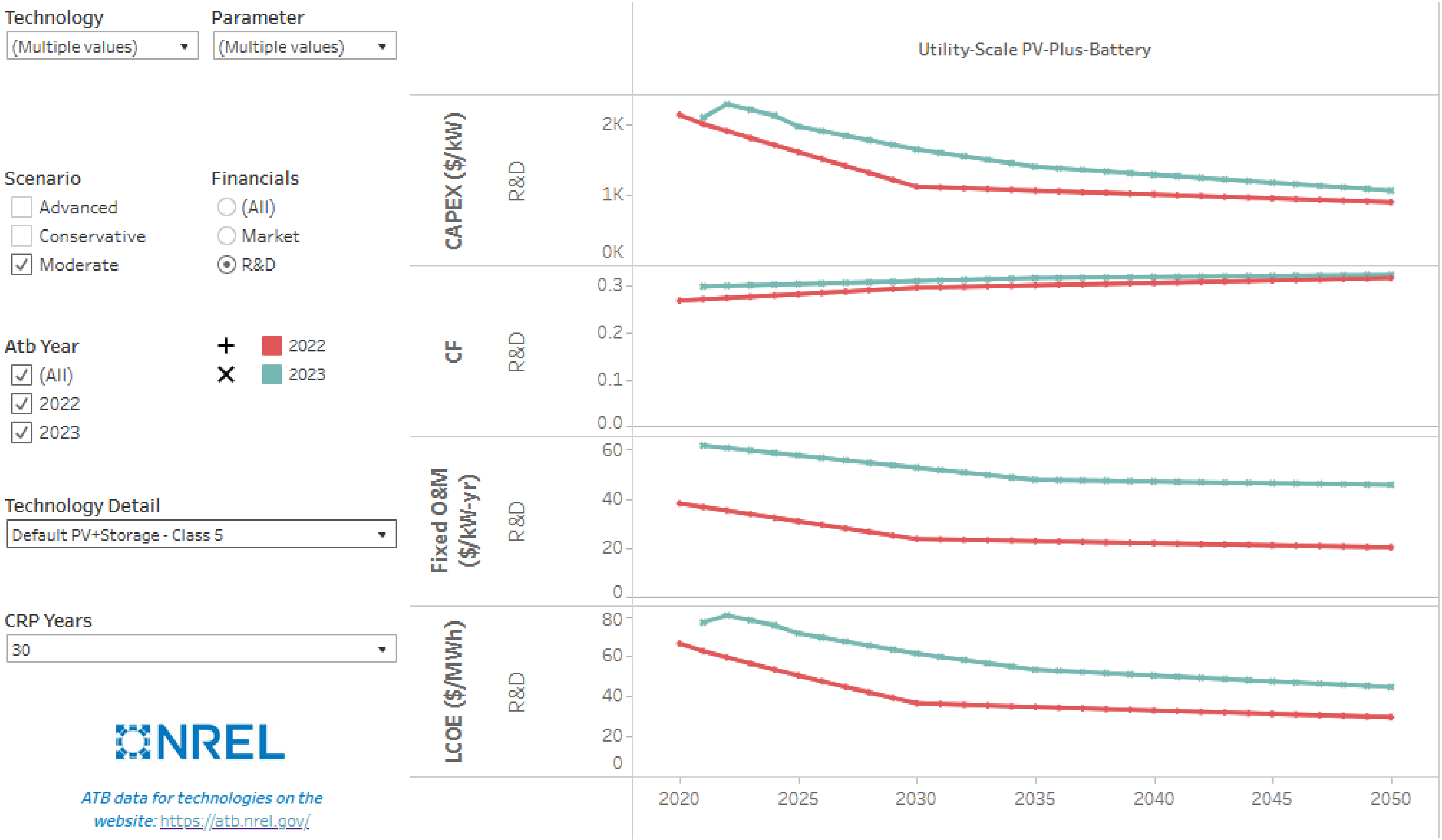
ATB data for technologies on the website: https://atb.nrel.gov/

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



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

Utility-Scale Battery Storage

Base Year

CAPEX is based on new bottom-up modeling and market data from a new report (Ramasamy et al., 2022).

Projections

Updated cost projections are based on a literature survey as described by (Cole and Karmakar, 2023). This literature survey incorporates projections that show near-term increases in price, as well as those that project rapid price declines.

Vignesh Ramasamy and Wesley Cole

Utility-Scale Battery Storage

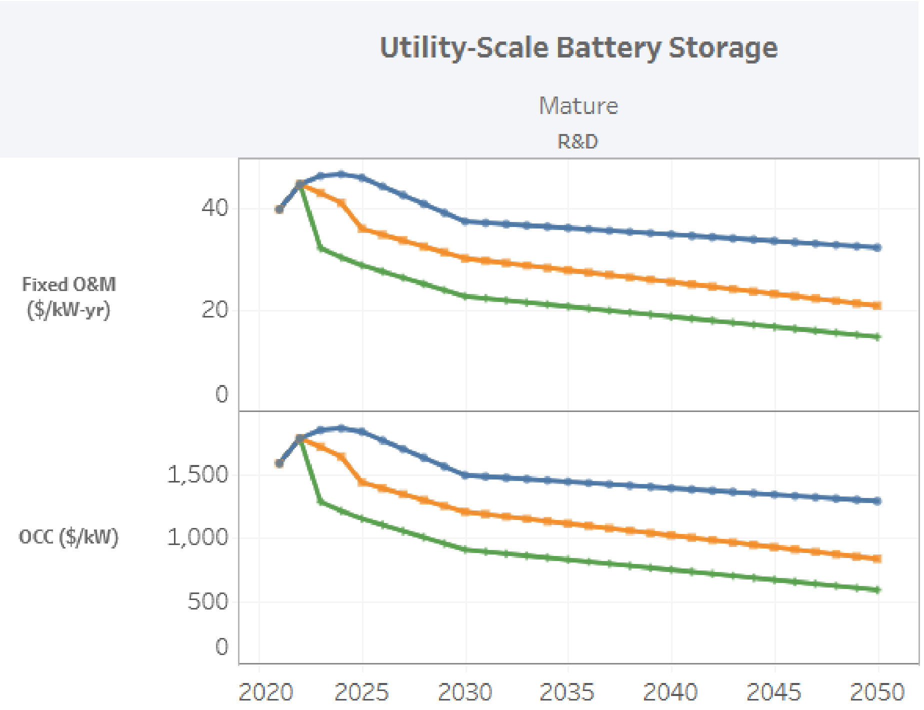
Parameter: (All)
Scenario: (All)

Financials
- (All)
- Market
- R&D (selected)

Cost Recovery Period: 30 years

Technology Maturity
- (All) (selected)
- Mature

Technology Detail: Default Utility-Scale Battery Sto...



data updated: 06/14/2023 v5.73

NREL

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

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

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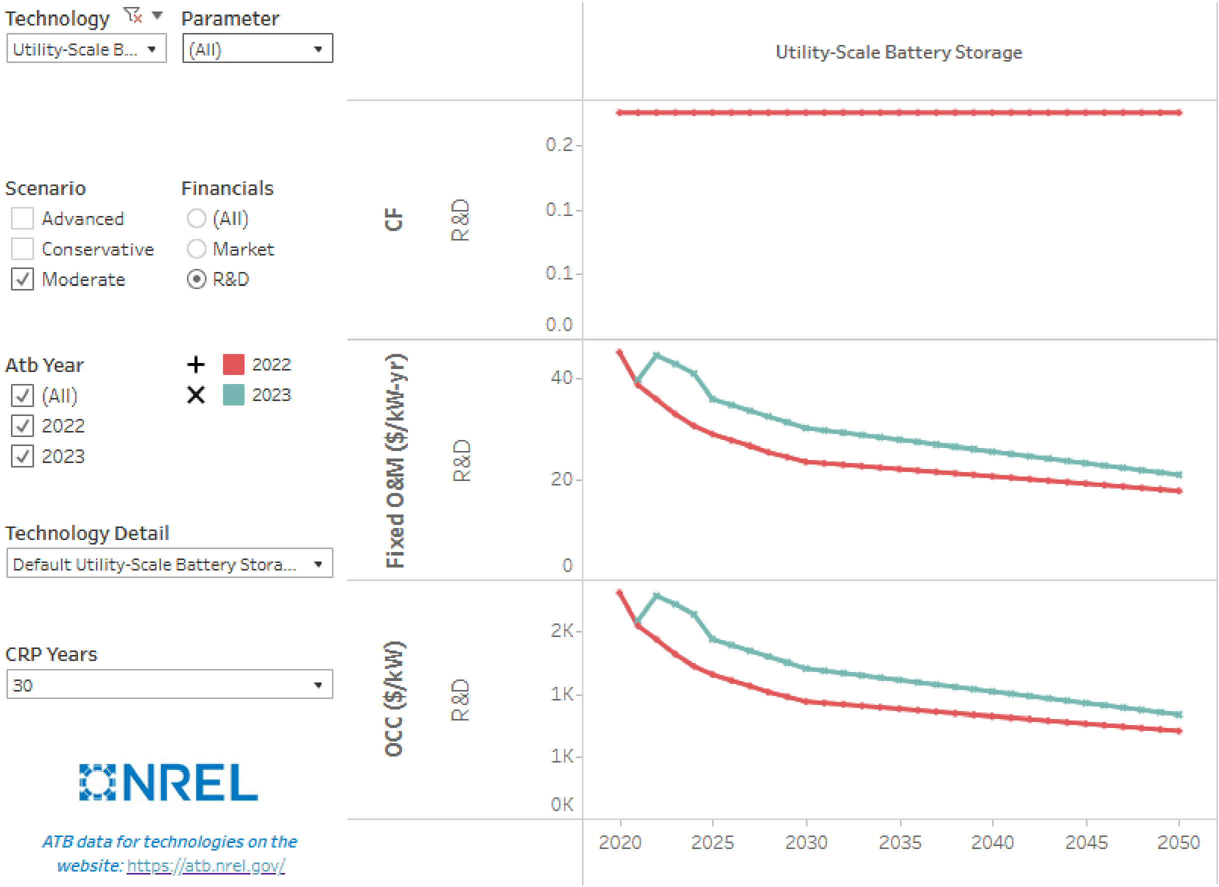
Utility-Scale Battery Storage



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

Pumped Storage Hydropower

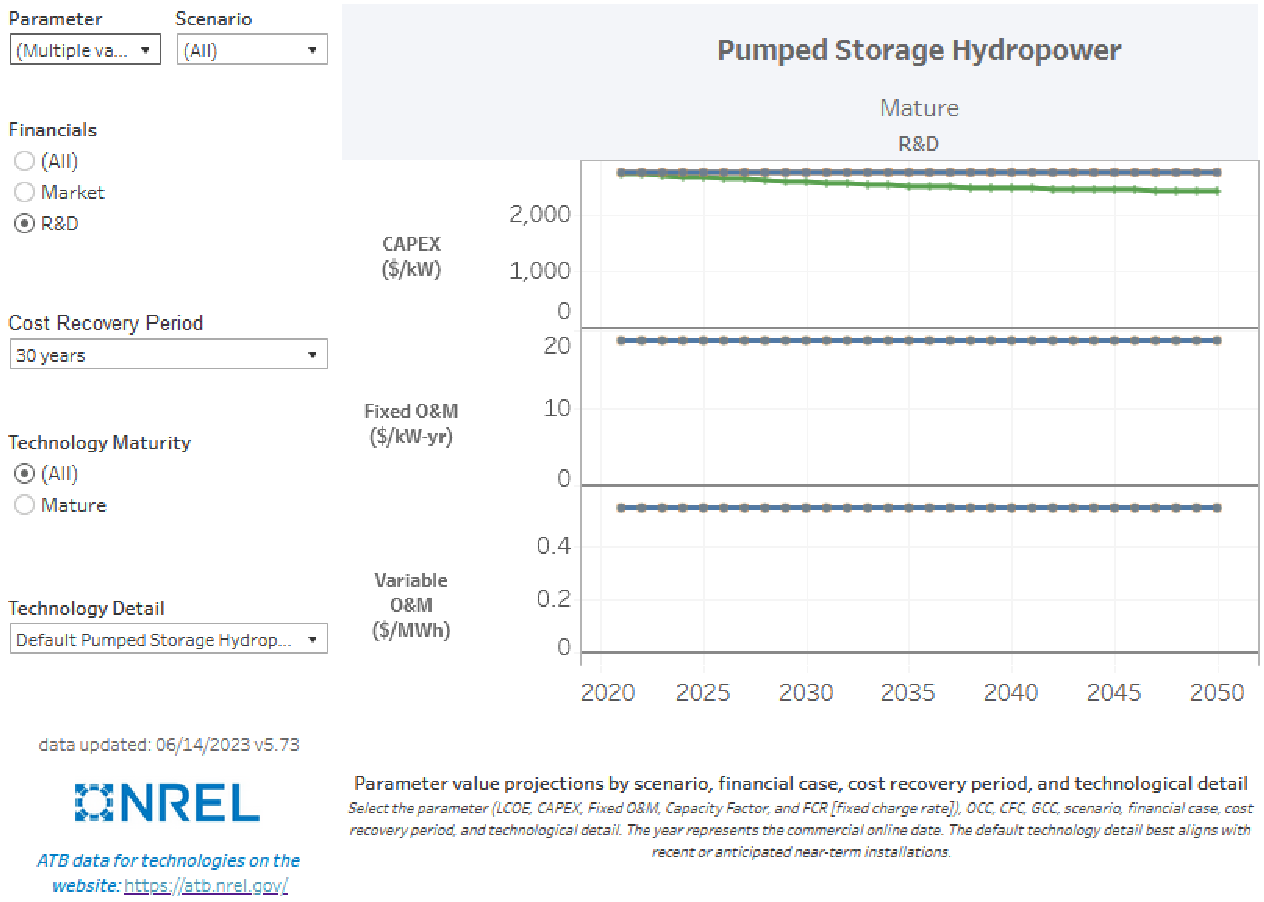
Base Year

- Capital costs and resource characteristics are updated, with changes relative to (Rosenlieb et al., 2022) described in "Closed-Loop Pumped Storage Hydropower Supply Curves" (NREL).

Projections

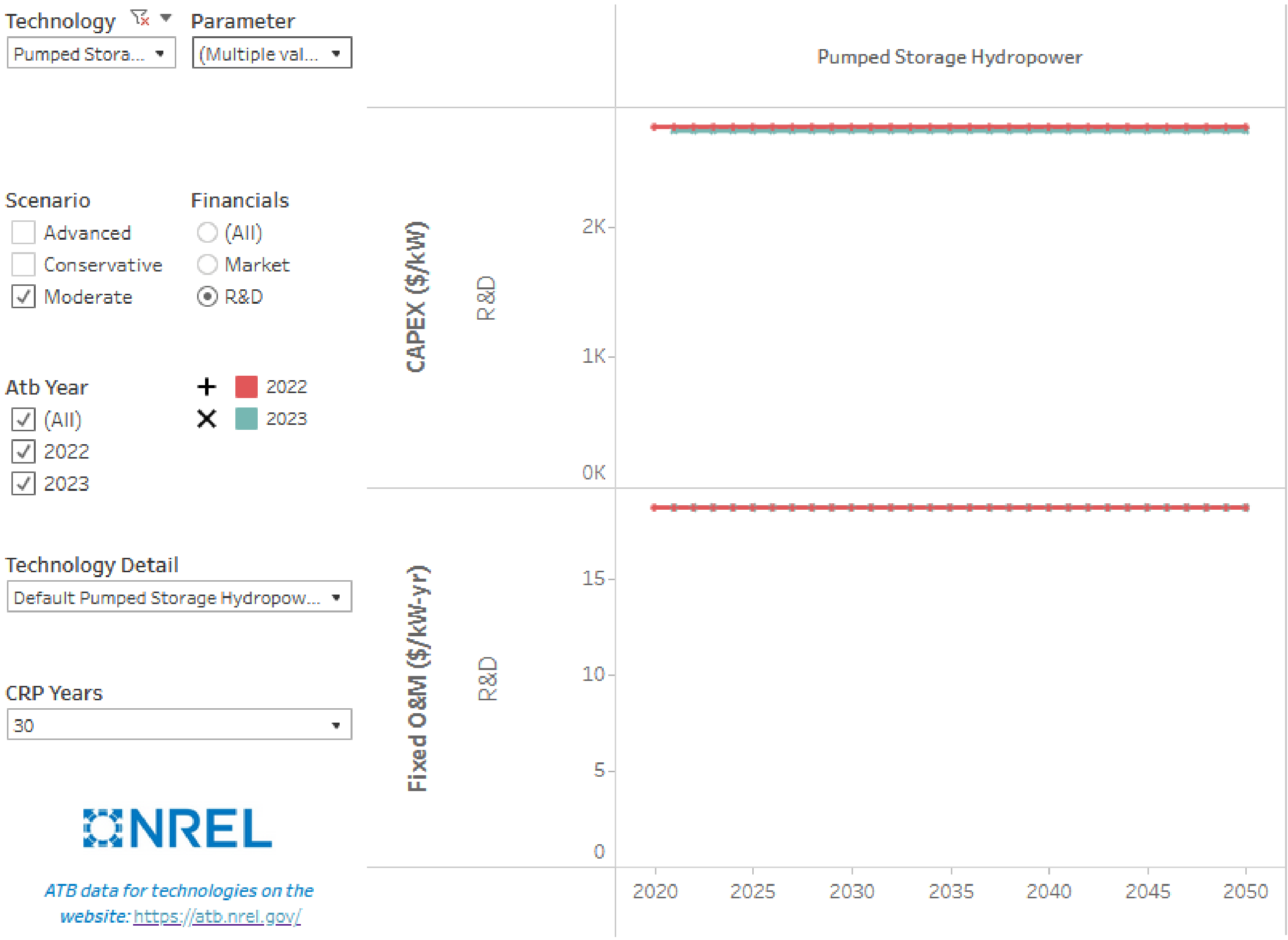
- These have not changed for the 2023 ATB. Projected cost reductions in the Advanced Scenario are based on innovations in modularity, materials, pumps and turbines, and closed-loop concepts, as described in (DOE, 2016).

Pumped Storage Hydropower



CAPEX is shown for class 3 when binned nationally by cost.

Pumped Storage Hydropower



Fossil Energy

Base Year

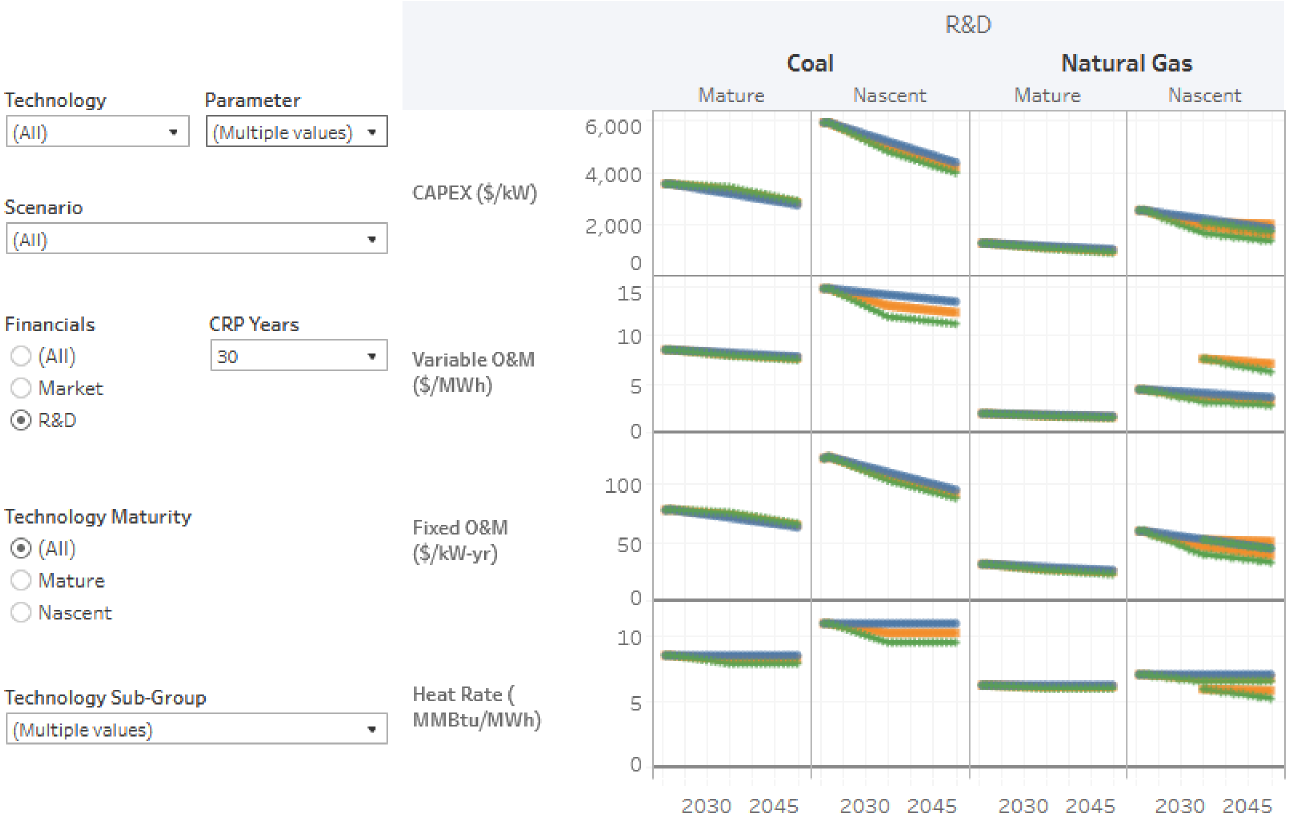
Estimates of performance and costs for currently available fossil-fueled electricity-generating technologies are representative of current commercial offerings and/or projects that began commercial service within the past 10 years for both new plants and retrofits (Schmitt et al., 2022), (Buchheit et al., 2023), (Schmitt and Homsy, 2023).

Projections

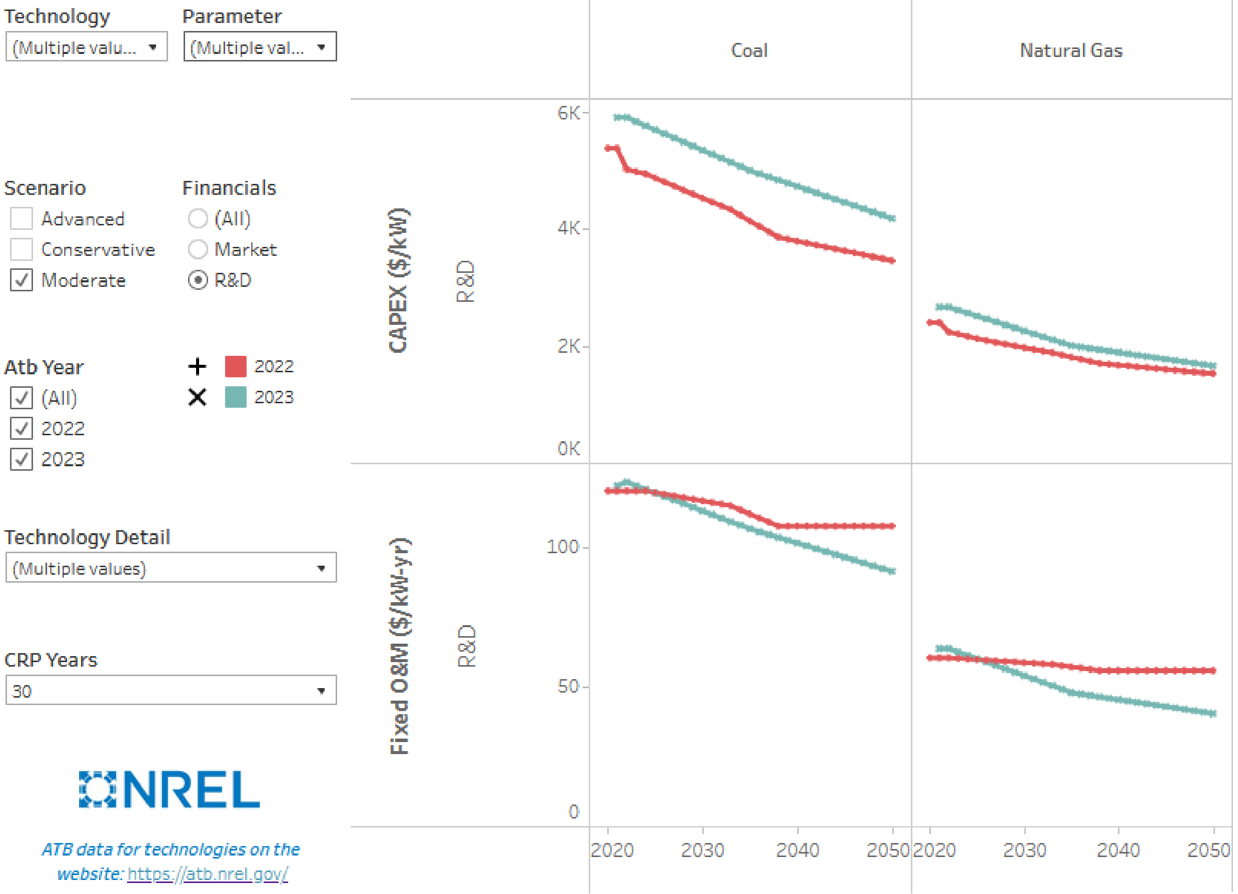
Projections in the 2023 ATB are based on the rate of cost improvement from the AEO2023 (EIA, 2023). Natural Gas Fuel Cell technologies are represented as a discrete technology trajectory.

Jeffrey Hoffmann

Fossil Energy Capital Cost Projections



Fossil Energy Capital Cost Projections



Fossil Energy Capital Cost Projections

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.

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

References

A complete list of references for the 2023 Electricity ATB can be found at https://atb.nrel.gov/electricity/2023/references.

Acronyms and Abbreviations

AEO	Annual Energy Outlook
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)
GETEM	Geothermal Electricity Technology Evaluation Model
IGCC	Integrated gasification combined cycle
ITC	Investment tax credit
LCOE	Levelized cost of energy
MW	Megawatt
MWDC	Megawatt-direct current
NGCC	Natural gas combined cycle
NPD	Non-powered dam
NREL	National Renewable Energy Laboratory
NSD	New stream-reach development
ORNL	Oak Ridge National Laboratory
O&M	Operations and maintenance
PSH	Pumped storage hydropower
PTC	Production tax credit
PV	Photovoltaic
RPM	Resource Planning Model
SAM	System Advisor Model
SMR	Small modular reactor (a nuclear technology)

Acknowledgments

https://atb.nrel.gov/electricity/2023/about

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- **Solar: Concentrating solar power:** Chad Augustine and Parthiv Kurup, NREL
- **Hydropower:** Gbadebo Oladosu, Oak Ridge National Laboratory
- **Geothermal:** Dayo Akindipe and Erik Witter, NREL
- **Battery storage:** Vignesh Ramasamy and Wesley Cole, NREL
- **Utility-scale PV-plus-battery:** Vignesh Ramasamy and Anna Schleifer, NREL
- **Pumped storage hydropower:** Stuart Cohen and Evan Rosenlieb, NREL
- **Nuclear and biopower (Data from U.S. Energy Information Administration):** Wesley Cole, NREL
- **Fossil technologies (Data from DOE Office of Fossil Energy and Carbon Management source):** Jeffrey Hoffmann, DOE Office of Fossil Energy and Carbon Management
- **Finance:** David Feldman and Brian Mirletz, NREL
- **Project coordination:** Laura Vimmerstedt and Brian Mirletz, NREL
- **Data and documentation development:** Sertac Akar, Greg Avery, and Dana Stright, NREL
- **Website production:** Mike Bannister and Jeremy Jenkins, NREL
- **Editing:** Mike Meshek, Ashish Sedai, Sophie-Min Thomson, NREL.
- **U.S. DOE Project Manager:** Paul Spitsen

Thank you.

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Brian.Mirletz@nrel.gov

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Q&A