Generation Technology Options: 2024

Program on Technology Innovation

Technical Update

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Abstract

This report provides an executive-level overview of present (2023) and longer term (2035) cost and performance estimates for electricity generation and hydrogen fuel production technologies. The information in this report is based on recent EPRI research results, drawing from detailed studies performed throughout EPRI's research portfolio to provide cost and performance estimates and brief descriptions for fossil fuel, nuclear, renewable, hydrogen, and storage technologies. The purpose of this document is to provide a public domain reference for industry executives, policymakers, and other stakeholders.

Cost and performance estimates are for representative U.S.-based generating units and are presented in constant third-quarter (Q3) 2023 dollars.

Keywords

Utility-scale power generation technologies

Cost and performance

Levelized cost of electricity

Technology evaluation

Technology trends

Introduction

Introduction

The *Generation Technology Options: 2024* report provides an executive-level overview of present (2023) and longer term (2035) electricity generation and hydrogen fuel production technology costs and performance. The purpose of this document is to provide a public domain reference for industry executives, policymakers, and other stakeholders.

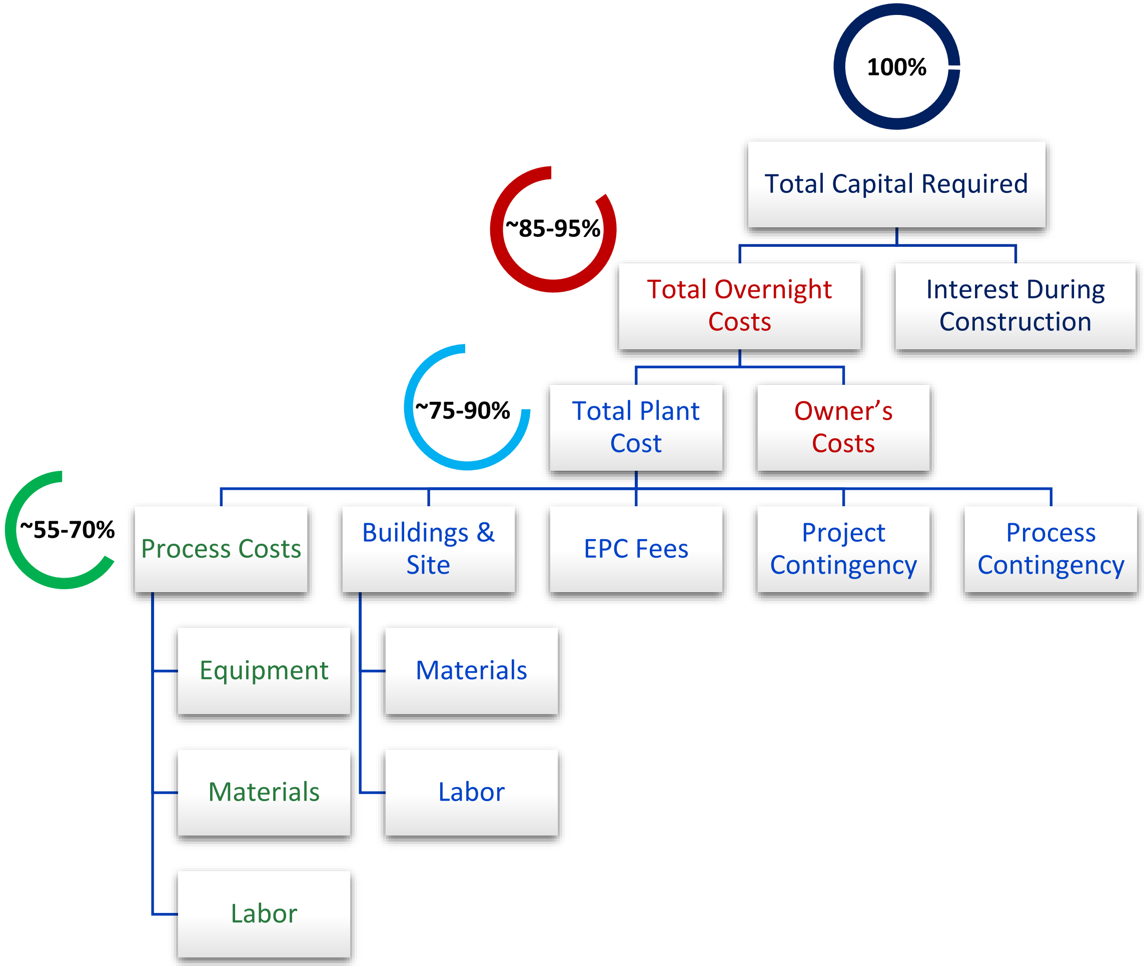
This report is based on recent EPRI research results and draws on information from detailed studies performed throughout EPRI's research portfolio to provide cost and performance estimates and brief descriptions for fossil fuel, nuclear, renewable, hydrogen, and storage technologies.

Cost and performance estimates are for representative U.S.-based generating units and are presented in constant Q3 2023 dollars.

Capital Cost Components

Capital costs are presented in this report as both Total Plant Cost and Total Capital Required. **Care should be taken when comparing costs across different studies or reports to ensure that costs are being presented at the same level.** Key components of Total Plant Cost and Total Capital Required include:

- **Total Plant Cost (TPC)**
  - Includes all process and general facilities capital, engineering and home office overhead, EPC fees, project and process contingencies.
- **Owner's Costs**
  - Includes prepaid royalties, preproduction (startup) costs, inventory capital (working capital), initial catalyst and chemical charges, land cost, and other project development costs incurred by project owners.
- **Interest During Construction**
  - Interest expenses accumulated during plant construction.
  - Also referred to as allowance for funds during construction (AFUDC).
- **Total Capital Required (TCR)**
  - Total Plant Cost + Owner's Cost + Interest During Construction + Escalation During Construction (in current-dollar analyses)

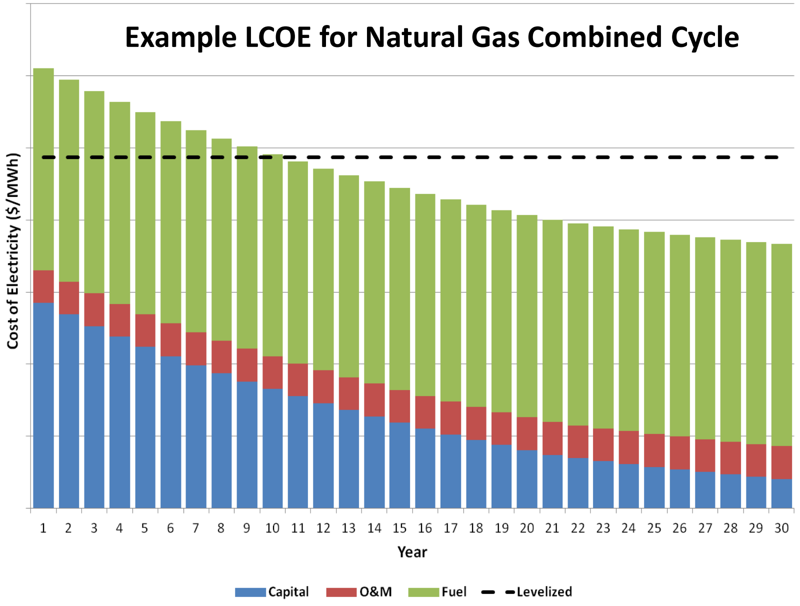


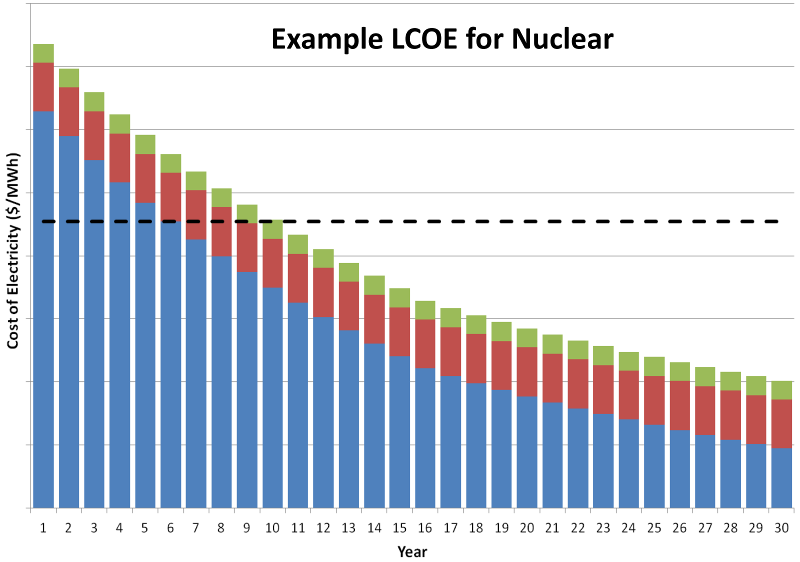
Notes:

- Cost estimating variables vary by location. The breakdown of TCR provided here is approximate and depends on the chosen analysis method (constant-dollar vs. current-dollar), site-specific estimates, and technology-specific assumptions.
- The analysis results are presented in constant-dollar in this report. Therefore, escalation during construction due to inflation is not considered.

Levelized Cost of Electricity Calculations

- The levelized cost of electricity (LCOE) represents an annualized cost of generating electricity over the lifetime of a plant in $/MWh, including:
  - Capital cost
  - O&M
  - Fuel
  - Financing assumptions
  - Annual electricity production (capacity factor)
- LCOE values in the tables and charts throughout this report do not include tax credits or other incentives except for sensitivity charts explicitly showing the impact of Inflation Reduction Act (IRA) tax credits.
- Illustrative figures show a representative LCOE graph for a natural gas combined cycle unit and a nuclear plant to show how the influence of capital cost and fuel cost can vary by technology.
- Although LCOE is a useful metric to compare technologies on a common basis, actual plant investment decisions are influenced by various project-specific factors. **LCOE should not be used as the sole basis for technology comparison.**

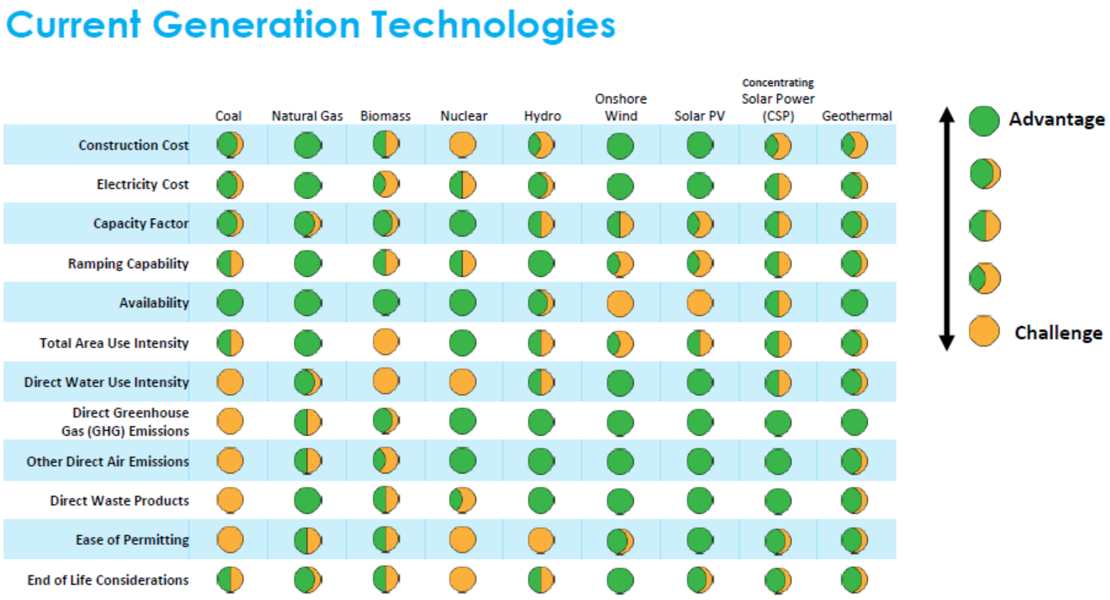


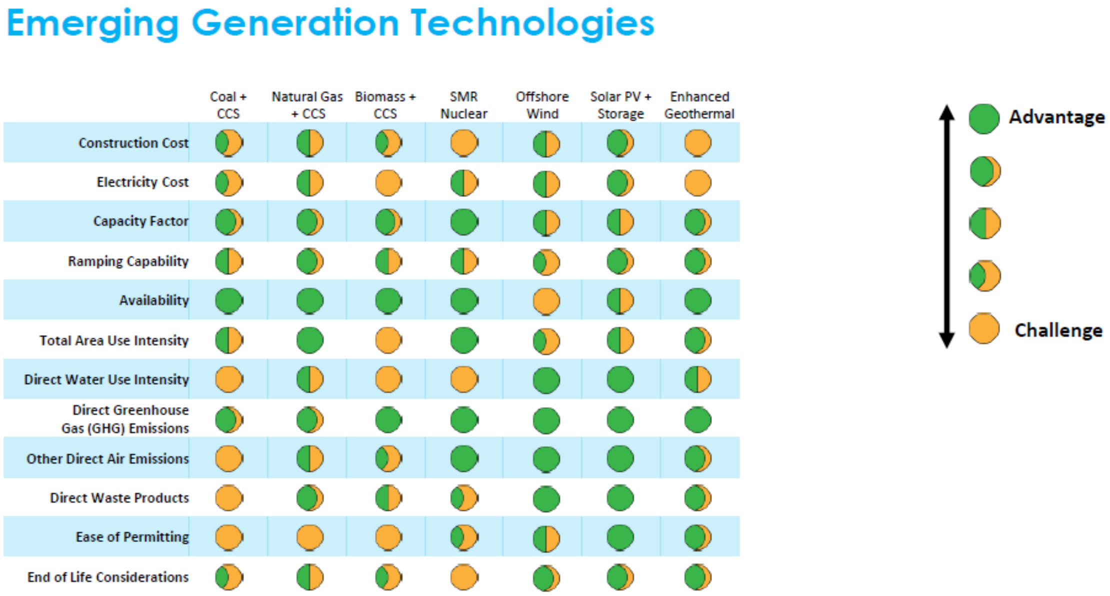


(for illustrative purposes only)

Beyond LCOE Evaluations

- While this report uses LCOE as a way to compare technology costs and annual generation on a common basis, **actual plant investment decisions will include considerations about the plant's ability to meet peak energy demands, the plant's capacity value, environmental benefits, resource mix, desire for portfolio diversification, and costs of integrating intermittent resources**.
- All electricity generation technologies have advantages and disadvantages. Understanding the tradeoffs among generating technologies reinforces the importance of having a diverse generation technology portfolio for reducing greenhouse gas emissions while economically and reliably meeting electricity demand.
- EPRI's *Energy Supply Reference Card* (3002027620) explores some of the Advantages and Challenges of both current and emerging electricity generation technologies by comparing attributes including cost, availability and operational capabilities, and environmental considerations. Refer to this report for more information on advantages and challenges of different power generation technologies.

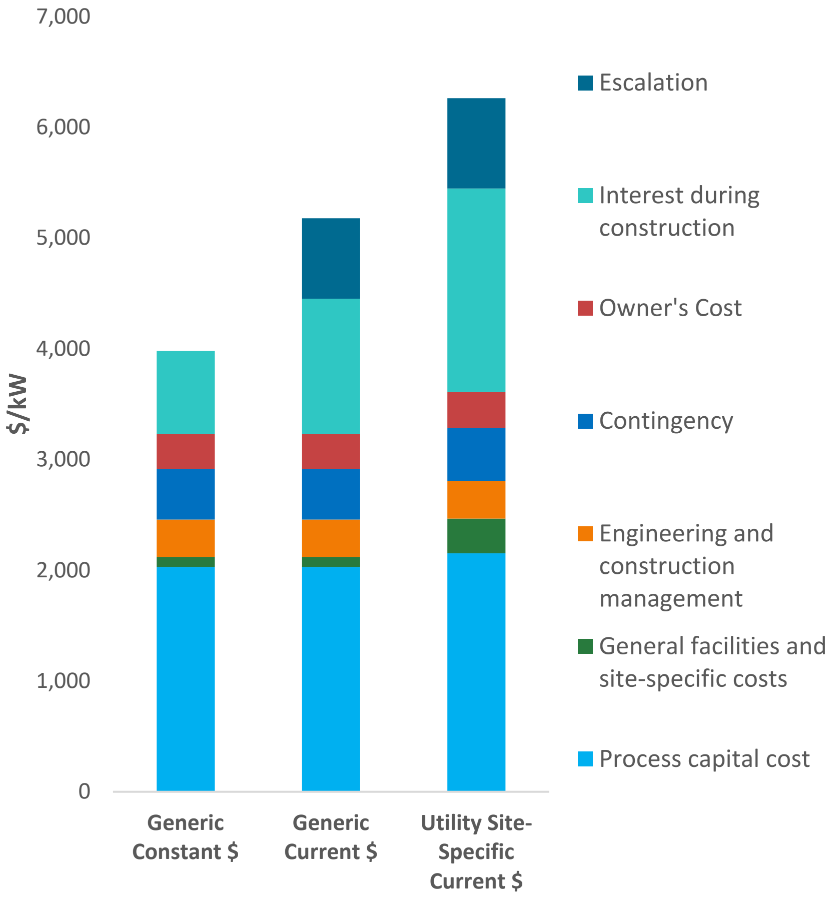




Illustrative comparisons of Generation Technologies from *Energy Supply Reference Card: 2023* (3002027620)

Cost Estimate Basis and Assumptions

- All costs are reported in constant Q3-2023$ as generic cost estimates excluding site specific assumptions.
- **Cost ranges represent a range of potential plant configurations and equipment types included in EPRI studies and are not intended to indicate an uncertainty range.** These cost ranges were cross-referenced with data from other publicly available sources, where applicable, to validate and define a reliable cost range for each technology. EPRI studies and other relevant public sources used for this analysis are listed in the *References* section of this report.
- Cost estimates assume mature technology, i.e., no extra cost for 1st-of-a-kind demonstration is included.
- Cost estimates reflect construction and operation in the Midwest U.S. (Kenosha, Wisconsin) except for non-dispatchable renewable technologies, which incorporate a range of location-based capacity factor assumptions.
- Financing assumptions and technology-specific plant lifetimes and recovery periods used for TCR and LCOE calculations can be found in Appendix A.3.
- Capital costs can vary significantly depending on choice of analysis, i.e., current vs. constant dollars. Site-specific estimates can also impact the capital cost. A comparison of key cost elements is shown here for illustrative purposes.



Example comparison of generic versus site-specific estimates and constant versus current dollars

Cost & Performance Results and Sensitivities

Representative Cost and Performance of Dispatchable Power Generation Technologies – Present (2023)

All Costs in Constant Q3 2023$	Net Plant Capacity, MW	Capacity Factor[1], %	Net Heat Rate, Btu/kWh	CO_2 Emissions, Metric Tons/MWh	Total Plant Cost, $/kW	Total Capital Required[2], $/kW	Fixed O&M, $/kW-yr	Variable O&M, $/MWh	Fuel Price, $/MMBtu	LCOE[3], $/MWh
Pulverized Coal	650-750	85	8,550-8,900	0.79-0.83	3,060-3,730	3,700-4,500	115-150	6-7	2	75-90
Pulverized Coal with CCS[4]	610-750	85	11,480-12,560	0.10-0.12	5,000-6,800	6,000-8,200	150-250	18-19	2	121-160
NGCC	350-1,080	85	6,150-6,680	0.33-0.35	830-1,040	970-1,220	22-35	2.4-3.3	3	34-40
NGCC with CCS[4]	930-950	85	6,950-7,140	0.04	1,850-2,080	2,150-2,400	45-50	9-9.5	3	57-62
Combustion Turbine[5]	230-400	10	9,080-10,300	0.48-0.55	765-900	875-1,030	15-21	7-10	3	125-147
RICE	75-220	10	8,600-8,750	0.46-0.47	1,475-1,870	1,700-2,150	28-51	8.3-8.4	3	208-272
Nuclear	1,120-3,200	90	9,480-10,670	-	8,200-8,700	10,750-11,400	175-240	11-13[6]	0.75	133-140
Small Modular Reactor	480-875	90	8,060-10,900	-	7,000-9,160	8,600-11,260	185-265	10-12[6]	0.75	111-143
Biomass	50-150	75	11,400-13,300	1.00-1.20[7]	3,850-5,850	4,550-6,850	120-165	5.5-9	5	131-163
Biomass with CCS[4]	50-150	75	15,600-17,350	0.13-0.17[7]	7,950-12,750	9,620-15,360	235-345	27-33	5	242-332
H_2-Fired Aeroderivative CT	40	10	10,350-10,450	-	1,560-1,880	1,840-2,200	90-110	5-6	12.7	400-450
H_2-Fired Combined Cycle	550	85	6,500-6,600	-	920-1,100	1,100-1,360	60-75	5-6	12.7	105-115

1. Coal, NGCC, nuclear, biomass and H_2 combined cycle turbines are assumed to operate as baseload units whereas simple cycle combustion turbines (natural gas and H_2-fired) and RICE are assumed as peaking power generating sources.
2. Total Capital Required (TCR) is based on overnight capital costs plus owner's costs and interest during construction. Escalation during construction is not included. TCR does not include tax credits or other incentives. Where applicable, it is assumed that the plant cost is based on commercially proven equipment and no process contingencies are included in the estimate. For those technologies that have not yet reached a sufficient level of maturity including small modular reactors (SMR), H_2-fired turbines, and those with CCS, certain process contingencies in present (2023) capital costs are considered.
3. LCOE includes estimated capital costs, fuel costs, and O&M costs. LCOE does not include tax credits or other incentives. Financing rates are based on Investor-Owned Utility (IOU) financial assumptions included in Appendix A.3. Because the LCOE is calculated on a constant-dollar (Q3 2023) basis, no inflation/escalation for fuel, capital cost, and O&M is assumed.
4. For cases with CCS, a carbon capture rate of 90% is considered. A $10/tonne cost of captured CO_2 is added to variable O&M to account for transportation and storage costs.
5. Natural gas-fired combustion turbines considered in this report are industrial frame turbines in simple-cycle configuration. Aeroderivative turbines, which operate with greater flexibility but at higher costs, are not included.
6. Variable O&M cost for large scale nuclear and SMR technologies includes ongoing capital expenditures for sustaining activities, regulatory reforms, infrastructure upgrades, information technology expenses, and overall plant enhancements.
7. Biomass heat rate and emissions can vary significantly based on fuel source and life cycle emission assumptions. Conventionally, the release of carbon from biogenic sources is assumed to be balanced by the uptake of carbon when the feedstock is grown, resulting in zero net CO_2 emissions over some period of time. For this reason, Biomass is often considered carbon-neutral and Biomass with CCS is often considered to be a net negative carbon technology.

CCS = Carbon capture and storage, NGCC = Natural gas combined cycle, RICE = Reciprocating internal combustion engine, CT = Combustion turbine

Representative Cost and Performance of Storage and Non-Dispatchable Power Generation Technologies – Present (2023)

All Costs in Constant Q3 2023$	Net Plant Capacity, MW	Capacity Factor[1], %	Net Heat Rate, Btu/kWh	CO_2 Emissions, Metric Tons/MWh	Total Plant Cost, $/kW	Total Capital Required[2], $/kW	Fixed O&M, $/kW-yr	Variable O&M, $/MWh	Fuel Price[3]	LCOE[4], $/MWh
Battery Energy Storage	20-100 MW, 4hr	17	-	-	1,260-1,420	1,420-1,590	43-46[6]	-	50	195-208
Onshore Wind[5]	50-250	30-50	-	-	1,460-1,725	1,620-1,910	38-56	-	-	35-71
Offshore Wind[5]	900	51-53	-	-	4,200-6,450	5,000-7,500	85-125	-	-	104-130
Solar Photovoltaic (PV)[5]	50-150	20-35	-	-	1,280-1,465	1,425-1,630	16-20	-	-	40-69
Solar PV Plus Storage	150 MW_{AC} Solar PV 100 MW, 4hr Storage	20.5-33.5	-	-	2,070-2,160	2,260-2,360	59-61[6]	-	-	73-123

1. Non-dispatchable technologies' capacity factors are based on a representative range of resource availability assumptions. Battery energy storage system (BESS) capacity factor is based on one cycle per day assumption.
2. TCR is based on overnight capital costs plus owner's costs and interest during construction. Escalation during construction is not included. TCR does not include tax credits or other incentives. Where applicable, it is assumed that the plant cost is based on commercially proven equipment and no process contingencies are included in the estimate.
3. Battery "fuel cost" represents charging cost (in $/MWh) to account for electricity cost used to charge the battery.
4. LCOE includes estimated capital costs, fuel costs, and O&M costs. LCOE does not include tax credits or other incentives. Financing rates are based on IOU financial assumptions included in Appendix A.3. Because the LCOE is calculated on a constant-dollar (Q3 2023) basis, no inflation/escalation for fuel, capital cost, and O&M is assumed.
5. For wind and solar PV, production is set by resource availability, not load demand. LCOE values presented here do not include integration costs (for example, costs associated with additional reserves, balancing, conventional generation cycling, and so on). Care should be taken when comparing LCOEs of these technologies to those of dispatchable technologies.
6. Fixed O&M cost for battery energy storage systems includes battery augmentation to maintain the energy capacity over the project life.

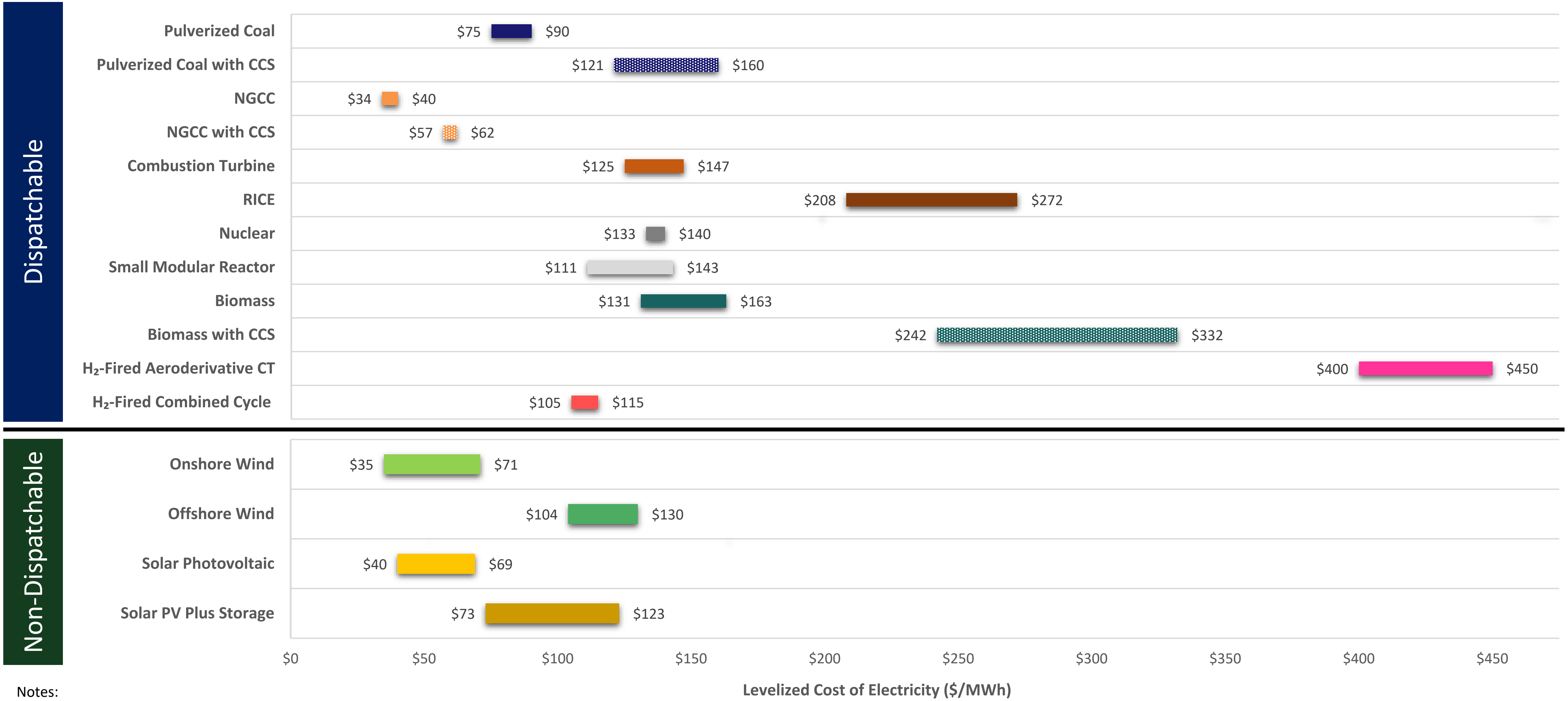
Representative Cost and Performance of Hydrogen Fuel Production Technologies – Present (2023)

All Costs in Constant Q3 2023$	Plant Capacity[1], kg/day	Capacity Factor[2], %	Book Life[3], Years	Efficiency[4], %	Total Plant Cost, $/kg-day	Total Capital Required[5], $/kg-day	Fixed O&M, $/kg-day-yr	Variable O&M, $/kg	Fuel Price[6]	LCOH[7], $/kg
Alkaline Electrolysis	1,500-50,000	90	20	60-62	2,850-6,750	3,250-7,600	98-315	0.64-0.98	50	4.6-6.8
PEM Electrolysis	1,500-50,000	90	20	58-60	6,450-9,650	7,250-10,800	215-408	1.60-1.80	50	7.1-8.9
SMR with CCS[8]	50,000-300,000	90	30	60-70	1,120-3,260	1,340-3,860	52-229	0.09-0.11	3	1.1-2.4
Coal Gasification with CCS[8]	50,000-300,000	90	30	50-60	5,580-9,180	6,630-10,860	255-482	0.23-0.30	2	3.0-4.7
Biomass Gasification with CCS[8]	50,000	90	30	50-55	8,350-9,500	9,900-11,250	445-490	0.22-0.25	5	5.2-6.0

1. Plant capacities are representative for consistent comparisons across technologies. Projects are under development that exceed these ranges.
2. Capacity factor is based on assumption that the plant is to operate nearly continuously.
3. Book life represents the period over which the initial capital investment to build a plant is recovered. The book life can differ from plant's technical life or service life.
4. Efficiency is based on lower heating value (LHV) of hydrogen produced.
5. TCR is based on overnight capital costs plus owner's costs and interest during construction. Escalation is not included. TCR does not include tax credits or other incentives. Where applicable, it is assumed that the plant is based on commercially proven equipment and no process contingencies are included in the estimate. For those technologies that have not yet reached a sufficient level of maturity, including PEM Electrolysis and Biomass Gasification, some process contingencies are considered.
6. Assumed fuel prices are: Electricity – $50/MWh, Natural gas – $3/MMBtu (HHV), Coal – $2/MMBtu (HHV), Biomass – $5/MMBtu (HHV). Electricity price for electrolysis applications could vary significantly depending on market and source of electricity.
7. Levelized cost of hydrogen (LCOH) includes estimated capital costs, fuel costs, and O&M costs. LCOH does not include tax credits or other incentives. Financing rates are based on IOU financial assumptions included in Appendix A.3. Because the LCOH is calculated on a constant-dollar (Q3 2023) basis, no inflation/escalation for fuel, capital cost, and O&M is assumed.
8. For cases with CCS, the capture rate of 90% is considered. $10/tonne cost of captured CO_2 is added to variable O&M to account for transportation and storage costs.

PEM = Proton exchange membrane, SMR = Steam methane reforming

Levelized Cost of Electricity – Present (2023)



Notes:

- LCOE values based on current/near-term construction project execution cost.
- LCOE values do not include tax credits or other incentives.
- The cost ranges encompass a variety of potential plant configurations and equipment types considered in EPRI studies. Cost ranges are not intended to signify uncertainty ranges.
- The LCOE values provided here exclude integration costs such as those associated with additional reserve, system balancing, conventional generation cycling, etc. Relying solely on the LCOE metric does not adequately assess the economic competitiveness of various power generation technologies. Caution is advised when comparing LCOEs of non-dispatchable technologies with dispatchable technologies.

Representative Cost and Performance of Dispatchable Power Generation Technologies – Future (2035)[1]

All Costs in Constant Q3 2023$	Net Plant Capacity, MW	Capacity Factor[2], %	Net Heat Rate, Btu/kWh	CO_2 Emissions, Metric Tons/MWh	Total Plant Cost, $/kW	Total Capital Required[3], $/kW	Fixed O&M, $/kW-yr	Variable O&M, $/MWh	Fuel Price, $/MMBtu	LCOE[4], $/MWh
Pulverized Coal with CCS[5]	610-750	85	10,770-11,800	0.10-0.11	4,600-6,300	5,600-7,650	129-223	16-17	2	111-146
NGCC	350-1,080	85	6,040-6,480	0.32-0.34	775-975	900-1,140	19-31	2.4-3.3	3	32-38
NGCC with CCS[5]	930-950	85	6,700-6,900	0.04	1,700-1,900	2,000-2,200	36-40	8-8.5	3	52-57
Combustion Turbine[6]	230-400	10	9,080-10,300	0.48-0.55	725-850	825-970	14-19	7-10	3	119-140
RICE	75-220	10	8,600-8,750	0.46-0.47	1,400-1,775	1,600-2,050	26-47	8.3-8.4	3	200-260
Nuclear	1,120-3,200	90	9,480-10,670	-	7,900-8,400	10,350-11,000	170-235	11-13[7]	0.75	130-137
Small Modular Reactor	480-875	90	8,060-10,900	-	5,500-7,250	6,800-8,900	165-240	10-12[7]	0.75	94-121
Biomass	50-150	75	11,400-13,300	1.00-1.20[8]	3,730-5,640	4,380-6,600	120-165	5.5-9	5	130-160
Biomass with CCS[5]	50-150	75	15,600-17,350	0.13-0.17[8]	7,670-12,300	9,280-14,820	235-343	25-30	5	236-322
H_2-Fired Aeroderivative CT	40	10	10,350-10,450	-	1,300-1,570	1,550-1,860	80-95	5-6	12.7	350-400
H_2-Fired Combined Cycle	550	85	6,400-6,500	-	800-970	960-1,160	55-65	5-6	12.7	100-110

1. Projected costs aim to reflect potential advancements achievable through widespread commercial deployment, along with further investments in RD&D endeavors to enhance commercial and near-commercial technology choices. In some cases, experience curves gleaned from international experience are used to support projections for cost estimates.
2. Coal, NGCC, nuclear, biomass and H_2 combined cycle turbines are assumed to operate as baseload units whereas simple cycle combustion turbines (natural gas and H_2-fired) and RICE are assumed as peaking power generating sources.
3. TCR is based on overnight capital costs plus owner's costs and interest during construction. Escalation during construction is not included. TCR does not include tax credits or other incentives. For all future cases, it is assumed that the plant cost is based on commercially proven equipment and no process contingencies are included in the estimate.
4. LCOE includes estimated capital costs, fuel costs, and O&M costs. LCOE does not include tax credits or other incentives. Financing rates are based on IOU financial assumptions included in Appendix A.3. Because the LCOE is calculated on a constant-dollar (Q3 2023) basis, no inflation/escalation for fuel, capital cost, and O&M is assumed.
5. For cases with CCS, a carbon capture rate of 90% is considered. A $10/tonne cost of captured CO_2 is added to variable O&M to account for transportation and storage costs.
6. Natural gas-fired combustion turbines considered in this report are industrial frame turbines in simple-cycle configuration. Aeroderivative turbines, which operate with greater flexibility but at higher costs, are not included.
7. Variable O&M cost for large scale nuclear and SMR technologies includes ongoing capital expenditures for sustaining activities, regulatory reforms, infrastructure upgrades, information technology expenses, and overall plant enhancements.
8. Biomass heat rate and emissions can vary significantly based on fuel source and life cycle emission assumptions. Conventionally, the release of carbon from biogenic sources is assumed to be balanced by the uptake of carbon when the feedstock is grown, resulting in zero net CO_2 emissions over some period of time. For this reason, Biomass is often considered carbon-neutral and Biomass with CCS is often considered to be a net negative carbon technology.

Representative Cost and Performance of Storage and Non-Dispatchable Power Generation Technologies – Future (2035)[1]

All Costs in Constant Q3 2023$	Net Plant Capacity, MW	Capacity Factor[2], %	Net Heat Rate, Btu/kWh	CO_2 Emissions, Metric Tons/MWh	Total Plant Cost, $/kW	Total Capital Required[3], $/kW	Fixed O&M, $/kW-yr	Variable O&M, $/MWh	Fuel Price[4]	LCOE[5], $/MWh
Battery Energy Storage	20-100MW, 4hr	17	-	-	800-910	910-1,020	28-30[7]	-	50	146-154
Onshore Wind[6]	50-250	32-52	-	-	1,200-1,420	1,325-1,575	34-50	-	-	28-57
Offshore Wind[6]	900	56-58	-	-	2,750-4,220	3,280-4,920	68-95	-	-	65-80
Solar Photovoltaic (PV)[6]	50-150	21-36	-	-	920-1,050	1,020-1,170	11-15	-	-	27-48
Solar PV Plus Storage	150MW_{AC} Solar PV 100MW, 4hr Storage	22-35	-	-	1,420-1,490	1,550-1,620	39-40[7]	-	-	47-80

1. Projected costs aim to reflect potential advancements achievable through widespread commercial deployment, along with further investments in RD&D endeavors to enhance commercial and near-commercial technology choices. In some cases, experience curves gleaned from international experience are used to support projections for cost estimates.
2. Non-dispatchable technologies' capacity factors are based on a representative range of resource availability assumptions. BESS capacity factor is based on one cycle per day assumption.
3. TCR is based on overnight capital costs plus owner's costs and interest during construction. Escalation during construction is not included. TCR does not include tax credits or other incentives. It is assumed that the plant cost is based on commercially proven equipment and no process contingencies are included in the estimate.
4. Battery "fuel cost" represents charging cost (in $/MWh) to account for electricity cost used to charge the battery.
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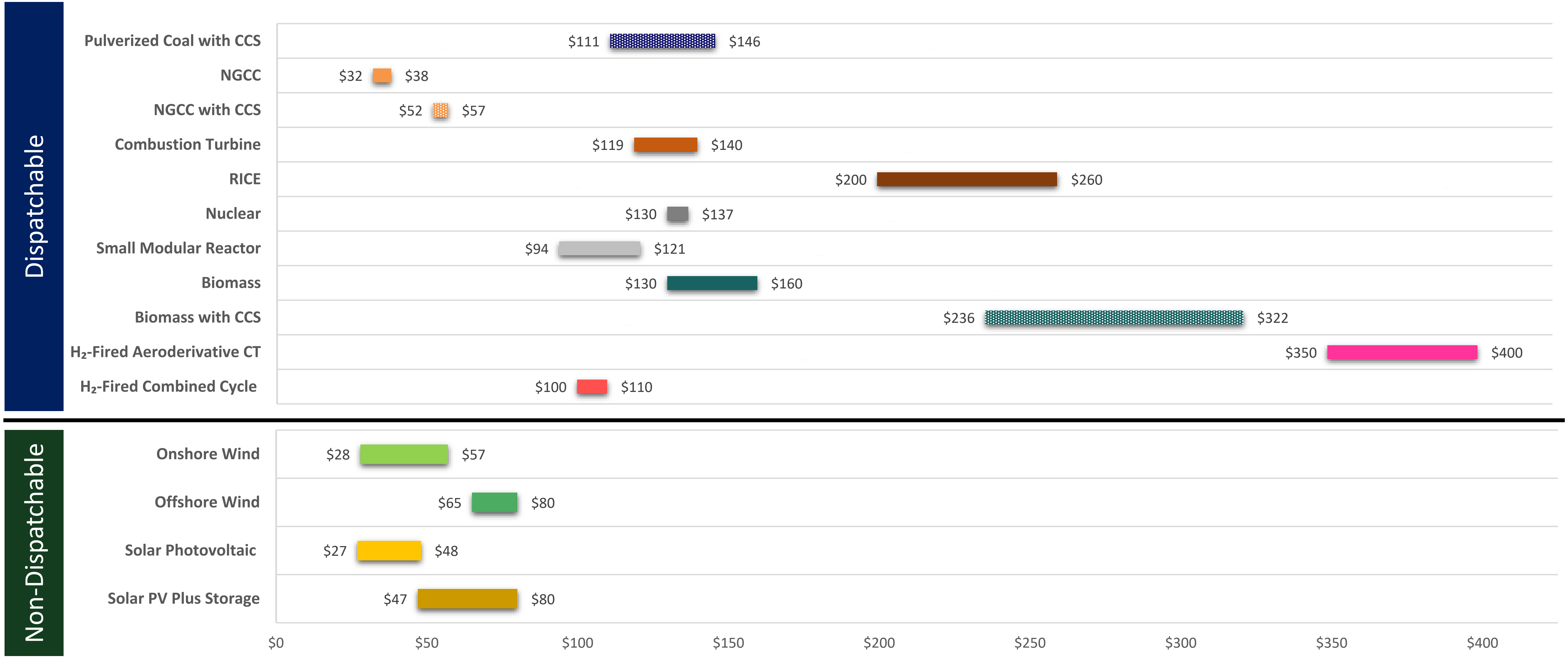
6. For wind and solar PV, production is set by resource availability, not load demand. LCOE values presented here do not include integration costs (for example, costs associated with additional reserves, balancing, conventional generation cycling, and so on). Care should be taken when comparing LCOEs of these technologies to those of dispatchable technologies.
7. Fixed O&M cost for battery energy storage systems includes battery augmentation to maintain the energy capacity over the project life.

Levelized Cost of Electricity – Future (2035)

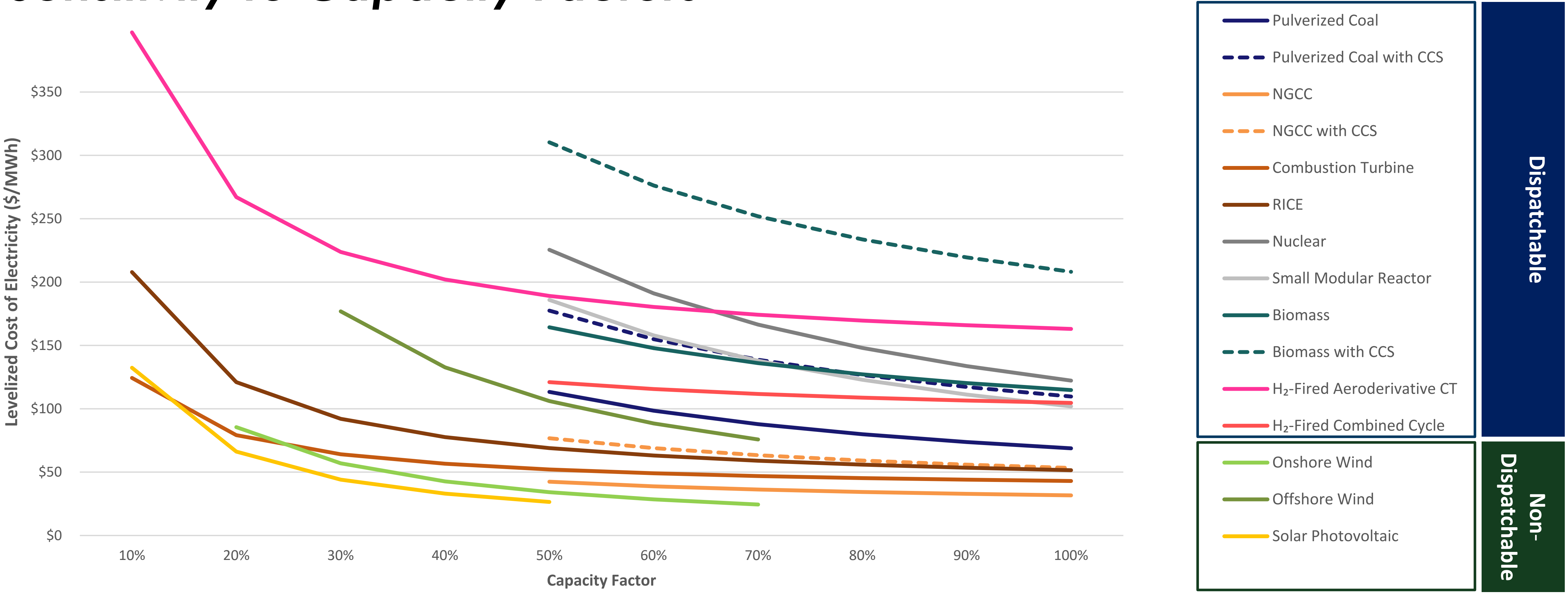


Notes:

- LCOE values calculated based on projected costs that anticipate potential advancements achievable through widespread commercial deployment, along with further investments in RD&D endeavors to enhance commercial and near-commercial technology choices.
- LCOE values do not include tax credits or other incentives.
- The cost ranges encompass a variety of potential plant configurations and equipment types considered in EPRI studies. Cost ranges are not intended to signify uncertainty ranges.
- The LCOE values provided here exclude integration costs such as those associated with additional reserve, system balancing, conventional generation cycling, etc. Relying solely on the LCOE metric does not adequately assess the economic competitiveness of various power generation technologies. Caution is advised when comparing LCOEs of non-dispatchable technologies with dispatchable technologies.

Levelized Cost of Electricity – Present (2023)

Sensitivity to Capacity Factors

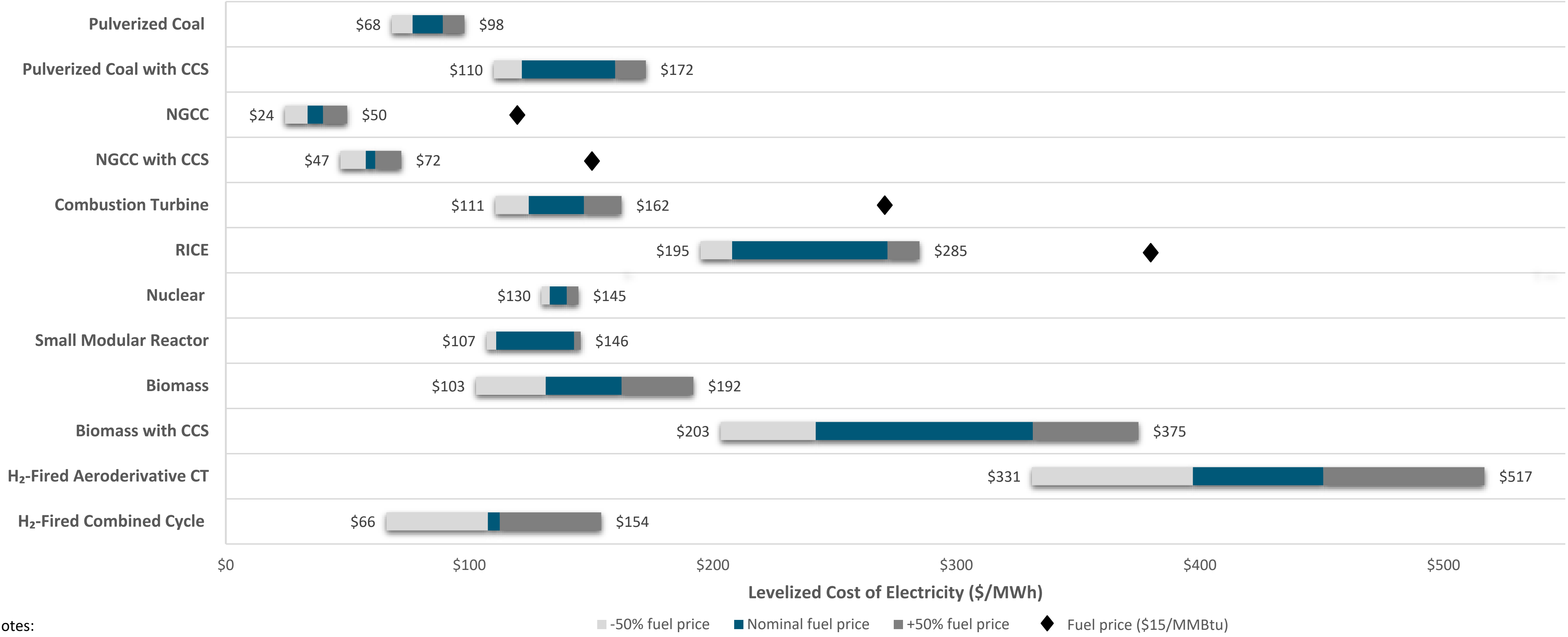


Notes:
- The LCOE values are depicted for the range of capacity factors that is either realistic or applicable.
- Reflects the present (2023) low LCOE of each selected technology for the range of capacity factors.

Capacity factor assumptions drive LCOE for peaking and capital-intensive technologies

Levelized Cost of Electricity – Present (2023)

Sensitivity to Fuel Prices



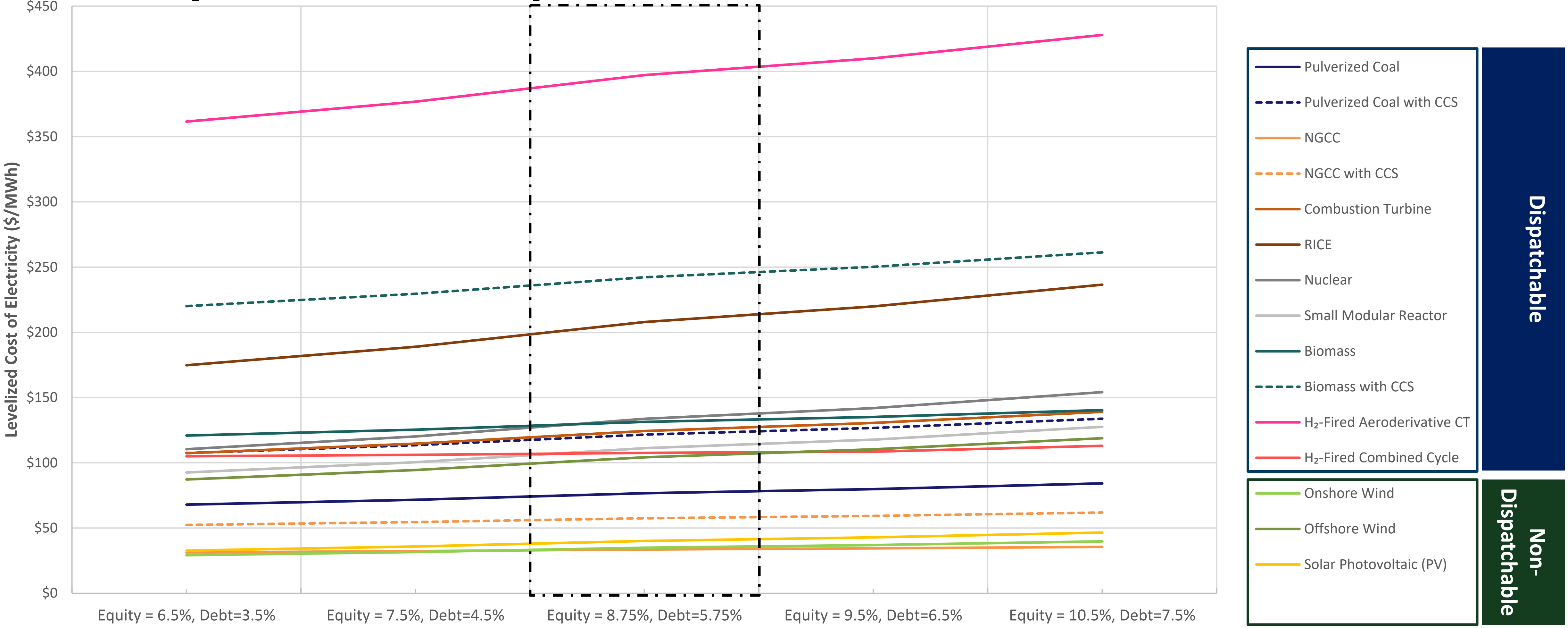
Notes:

The analysis assumes following fuel cost range for various generation resources:

- Coal - $1.00/MMBtu – $3.00/MMBtu (± 50% of the $2.00/MMBtu nominal price used in the analysis).
- Natural gas - $1.50/MMBtu – $4.50/MMBtu (± 50% of the $3.00/MMBtu nominal price used in analysis), as well as a single point for $15/MMBtu to represent significantly higher natural gas prices observed outside the U.S.
- Nuclear fuel - $0.38/MMBtu – $1.13/MMBtu (± 50% of the $0.75/MMBtu nominal price used in analysis).
- Biomass - $2.50/MMBtu – $7.50/MMBtu (± 50% of the $5.00/MMBtu nominal price used in the analysis).

Generation technologies characterized by high heat rates exhibit greater sensitivity to fuel prices

Levelized Cost of Electricity – Present (2023)
Sensitivity to Cost of Capital

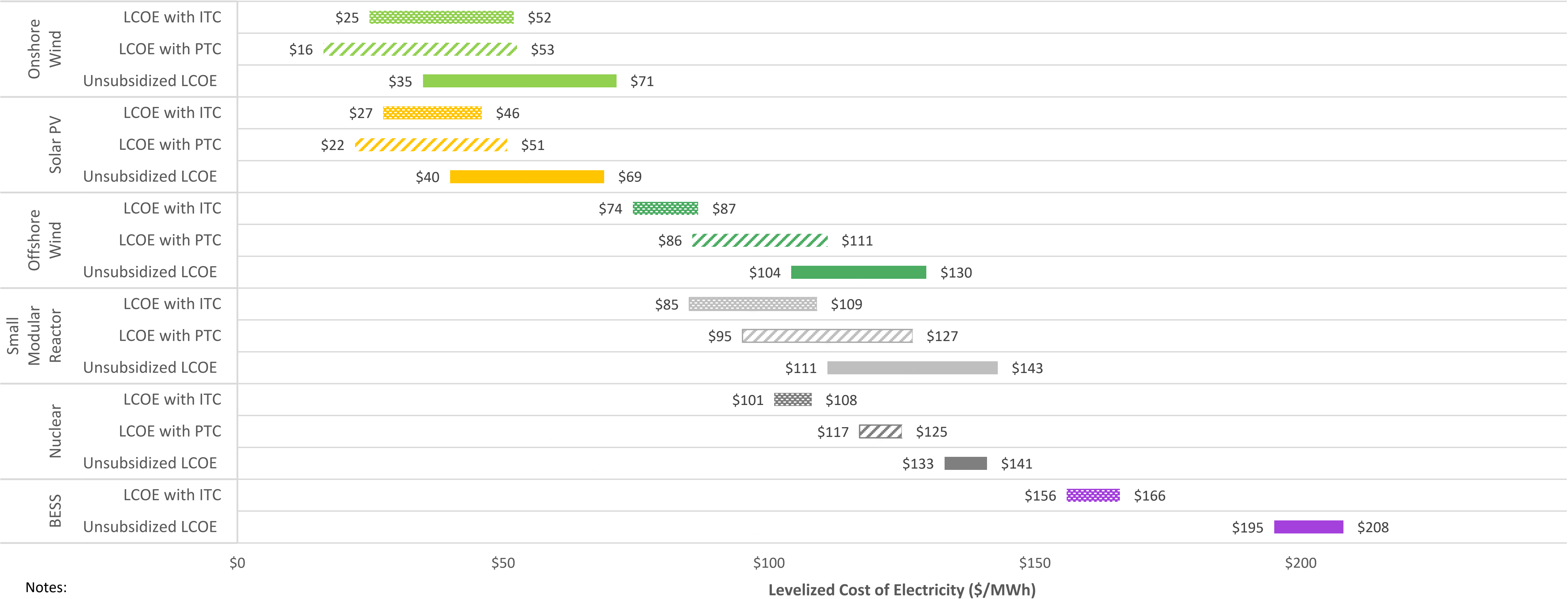


Notes:

- Analysis assumes 40% debt and 60% equity. Other financial assumptions are same as stated in Appendix A.3.
- Reflects the low LCOE of each technology for respective cost of capital assumption.

The cost of capital is a critical driver of LCOE, particularly impacting capital-intensive and peaking technologies

Levelized Cost of Electricity – Present (2023)
Impact of IRA Tax Credits



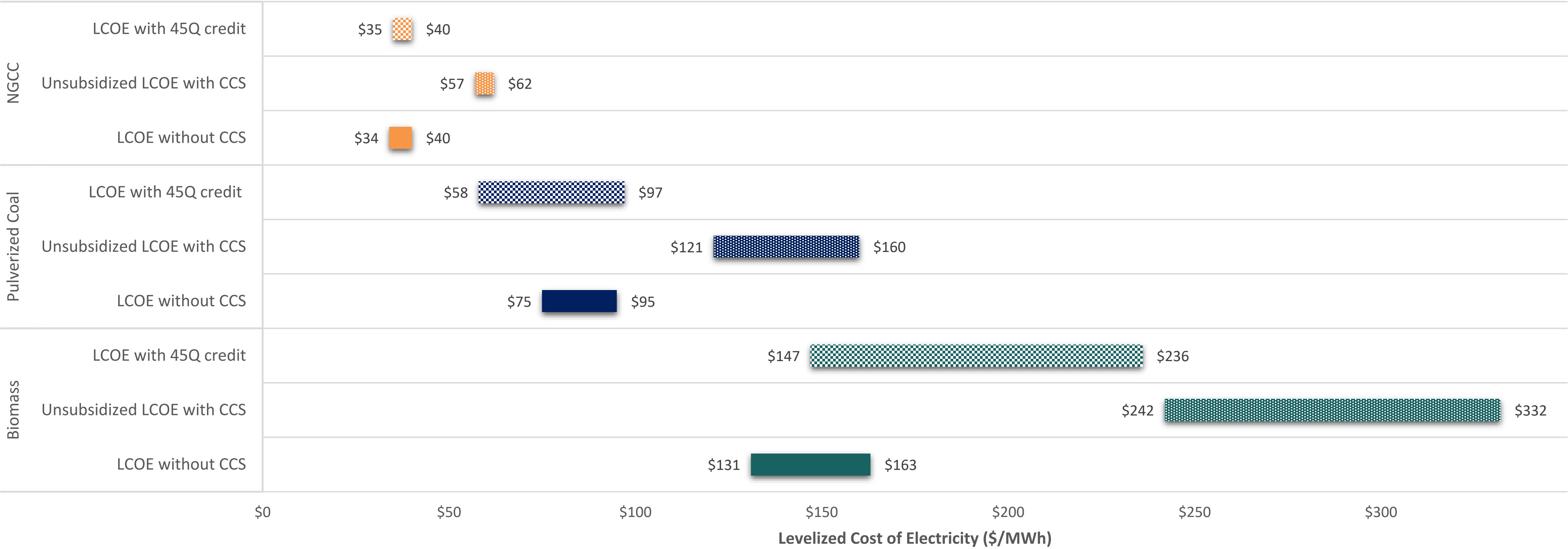
Notes:

- Under the Inflation Reduction Act (IRA) of 2022, Investment Tax Credit (ITC) of 30% is considered as one-time credit and tied to capital costs for all above shown technologies and Production Tax Credit (PTC) of $27.5/MWh (2022$) for a 10-year period is considered for all above shown technologies except BESS.
- The sensitivity cases assume that prevailing wages and apprenticeship requirements are met by the project. Capital costs do not include the additional costs of complying with prevailing wages and apprenticeship requirements.
- No additional bonus tax credit for domestic content, energy or low-income communities is considered in the analysis. No base credit is considered in unsubsidized case.

Technologies with relatively high capital costs, such as nuclear and offshore wind, may typically benefit more from ITC. PTC is typically more advantageous for onshore wind, while the benefits of PTC versus ITC for solar PV depend on available solar resource

Levelized Cost of Electricity – Present (2023)

Impact of IRA Tax Credits



Notes:

- The analysis assumes applicable 45Q credit amount under the IRA of 2022 for CO_2 capture and geological sequestration of $85 per metric ton captured.
- The sensitivity cases assume that prevailing wages and apprenticeship requirements are met by the project. Capital costs do not include the additional costs of complying with prevailing wages and apprenticeship requirements.
- The equipment is assumed to be placed in service after 12/31/2022 and construction beginning prior to 1/1/2033. The claim period is 12-year after the facility is placed in service.

The IRA 45Q tax credit enhances the economic viability of CCS technologies by narrowing the LCOE gap between facilities equipped with and without CCS technology

Technology Overviews

Technology Overviews

The following tables provide a high-level overview of the technology process, maturity level, current deployment, and potential future development of the technologies included in the cost and performance estimate tables. Appendix A.4 includes additional details on Technology Readiness Levels (TRLs) as assessed in the technology maturity discussion.

Technology information is also provided for four technologies not included in the preceding EPRI cost tables: hydroelectric power, pumped storage hydropower, geothermal, and concentrating solar thermal power (CSP). While these technologies have been deployed at scale and are considered mature technologies, EPRI has not conducted recent techno-economic studies to develop current cost estimates and their costs are highly site-specific. Cost estimates of these technologies based on publicly available sources are presented in Appendix A.5. Subsequent updates of this report may include EPRI-based cost and performance estimates for these technologies as they are developed.

Pulverized Coal (PC)

Basic Process Description

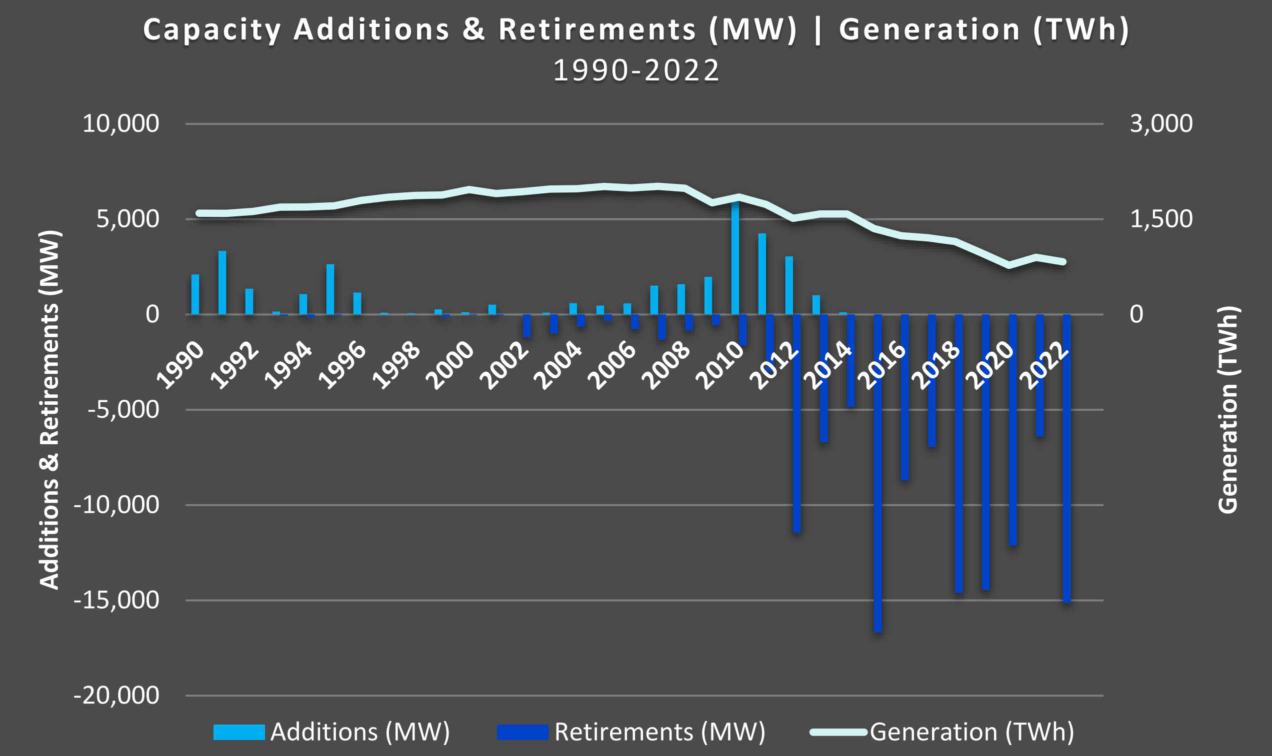
Finely ground coal is fed into a boiler, where it is combusted to release heat. This heat generates steam, which is then passed through a steam turbine that is connected to a generator to produce electricity. Typical PC units use sub-bituminous and bituminous coal, which may be pre-treated through some type of washing.

Current Technology Maturity

TRL 9

- PC technology is mature.
- Every segment of the coal technology value chain – from fuel supply to power generation and waste product disposal – has been commercially proven.
- PC with CO_2 capture is less mature (and discussed later in this report).

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data obtained from EIA Electric Monthly.
NOTE: The majority of coal capacity in the U.S. (over 300 GW total) was installed prior to 1990.

Potential Future Development

- Unabated coal power plants face more stringent environmental regulations in the U.S. and elsewhere, resulting in limited new deployment.
- Innovation in PC technology continues, focusing on increasing steam pressure and temperature to enable higher plant thermal efficiency. Supercritical and ultra-supercritical are the current state-of-the-art in PC technology.
- Advanced ultra-supercritical PC technology, which could emerge in the 2030s, could enable even greater plant efficiency, decreased greenhouse gas and local air pollutant emissions, and more economical integration of CO_2 capture technology since the increased performance would reduce the volume of CO_2 required to be captured, transported, and stored.

Natural Gas Combustion Turbine (NGCT)

Basic Process Description

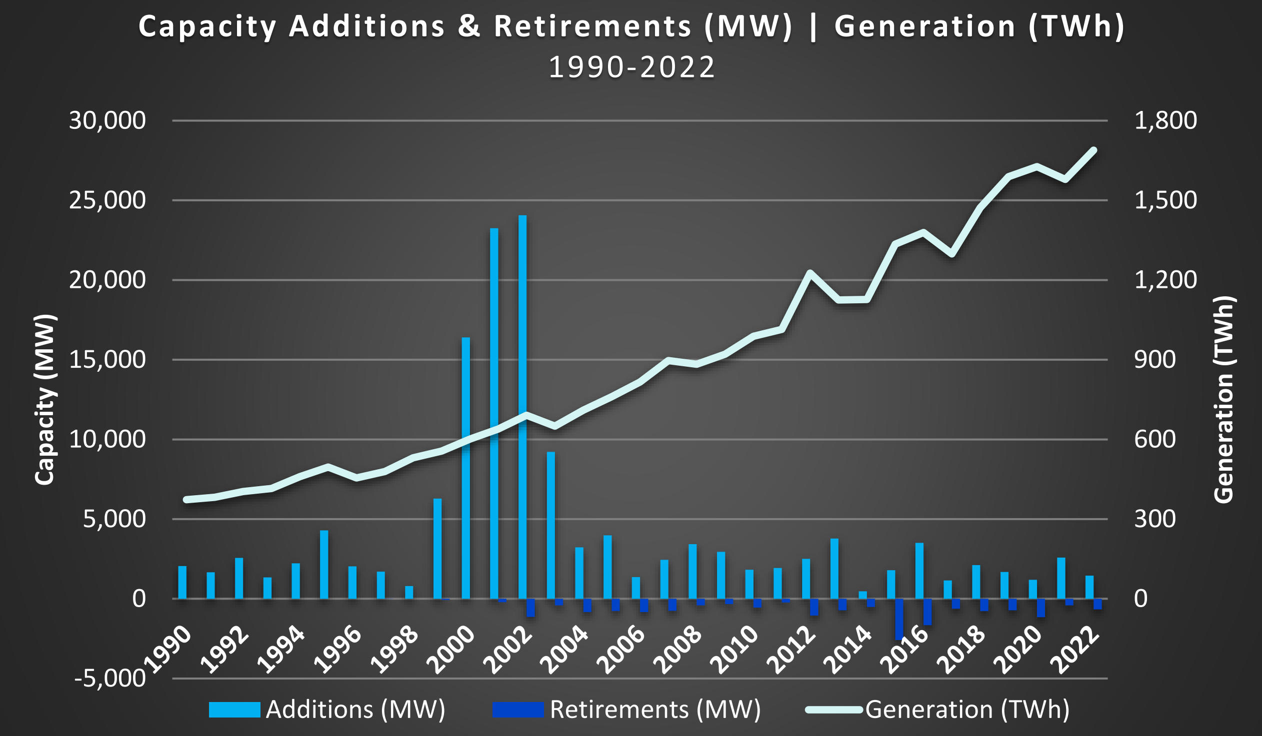
Natural gas is burned under pressure in a combustor, producing hot gases that pass through an expansion turbine that is coupled to an electric generator. The exhaust gases from an NGCT are discharged into the atmosphere without recirculating/extracting additional energy. Electric companies use both heavy frame and aeroderivative turbines, with frame turbines being larger and more suited for mid-load operation and aeroderivatives being smaller and better suited for cyclic operation.

Current Technology Maturity

TRL 9

- NGCT technology is mature.
- Every segment of the natural gas technology value chain – from fuel supply and delivery to power generation – has been commercially proven.

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data obtained from EIA Electric Monthly.
NOTE: Generation data reflect combined natural gas open- and combined-cycle TWhs.

Potential Future Development

- Continued advances in materials, casting and manufacturing techniques, and cooling technologies may allow gas turbines to operate at even higher temperatures, resulting in better efficiencies and greater electric output.
- H and J class technologies are "advanced" class and represent the state-of-the-art for heavy frame gas turbines. These turbines allow for greater reductions in direct emissions and are well-equipped to provide large amounts of dispatchable and highly flexible generation. State-of-the-art aeroderivatives are also characterized by high efficiency, reduced emissions, and superior operational flexibility.
- Many electric sector stakeholders see hydrogen (H_2) as the most pivotal area of development for gas turbines (see "H_2 Turbines" section). Alternative low-carbon fuel applications such as ammonia, methanol, synthetic drop-in fuels, and renewable liquid fuels to fuel firm capacity resources are also being explored.

Natural Gas Combined Cycle (NGCC)

Basic Process Description

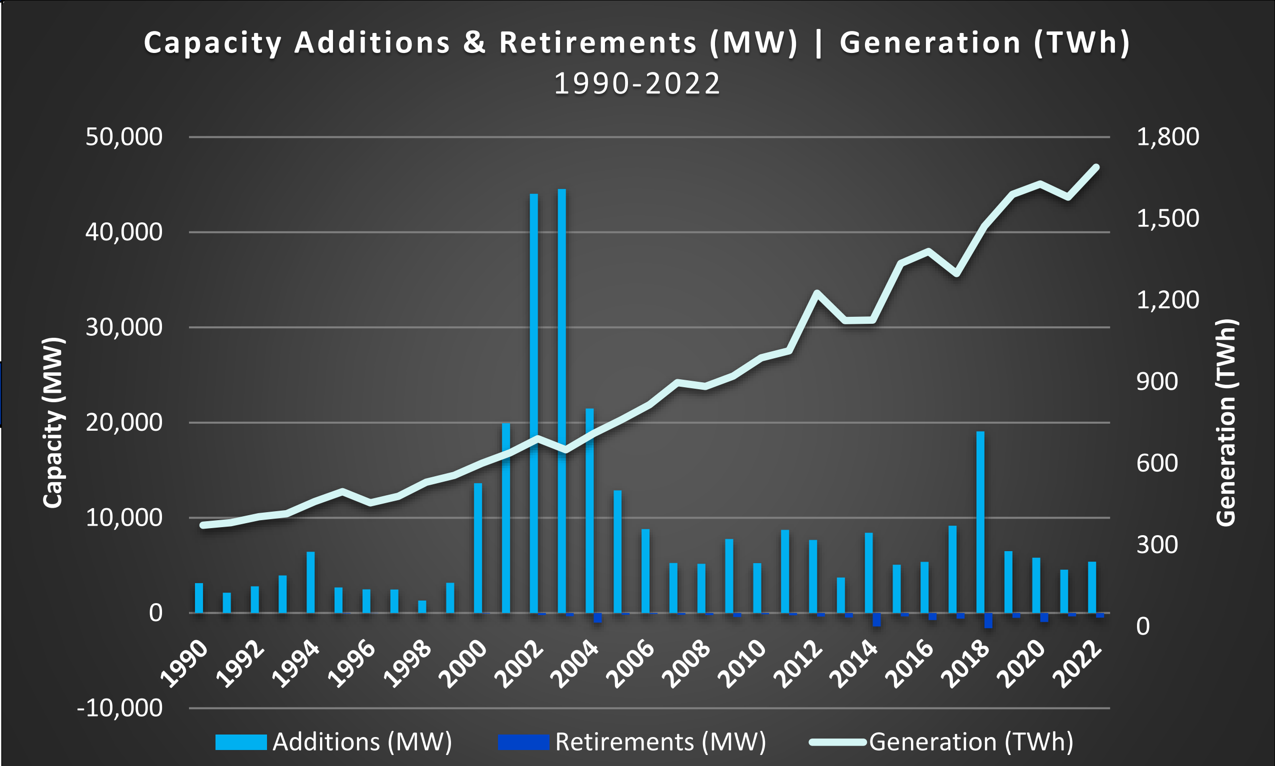
NGCTs can be paired with heat recovery steam generators (HRSGs) and steam turbines to configure a combined cycle unit, where the exhaust gas from the CT is redirected to the HRSG. The hot gas passing through the HRSG generates high-pressure steam, which is routed to a steam turbine to generate additional electric power. Significant improvements are realized in efficiency and electrical output over NGCT/open-cycle technology.

Current Technology Maturity

TRL 9

- NGCC technology is mature.
- Every segment of the natural gas technology value chain – from fuel supply and delivery to power generation – has been commercially proven.
- NGCC with CO_2 capture is less mature (and discussed later in this report).

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data obtained from EIA Electric Monthly.

NOTE: Generation data reflect combined natural gas open- and combined-cycle TWhs.

Potential Future Development

- As with NGCT, continued advances in materials, casting and manufacturing techniques, and cooling technologies may allow gas turbines to operate at even higher temperatures, resulting in better efficiencies and greater electric output.
- NGCCs may also benefit from developments in HRSG technology and advanced control systems. Advanced power generation/steam cycles are also impactful areas of potential development for NGCCs.

Reciprocating Internal Combustion Engine (RICE)

Basic Process Description

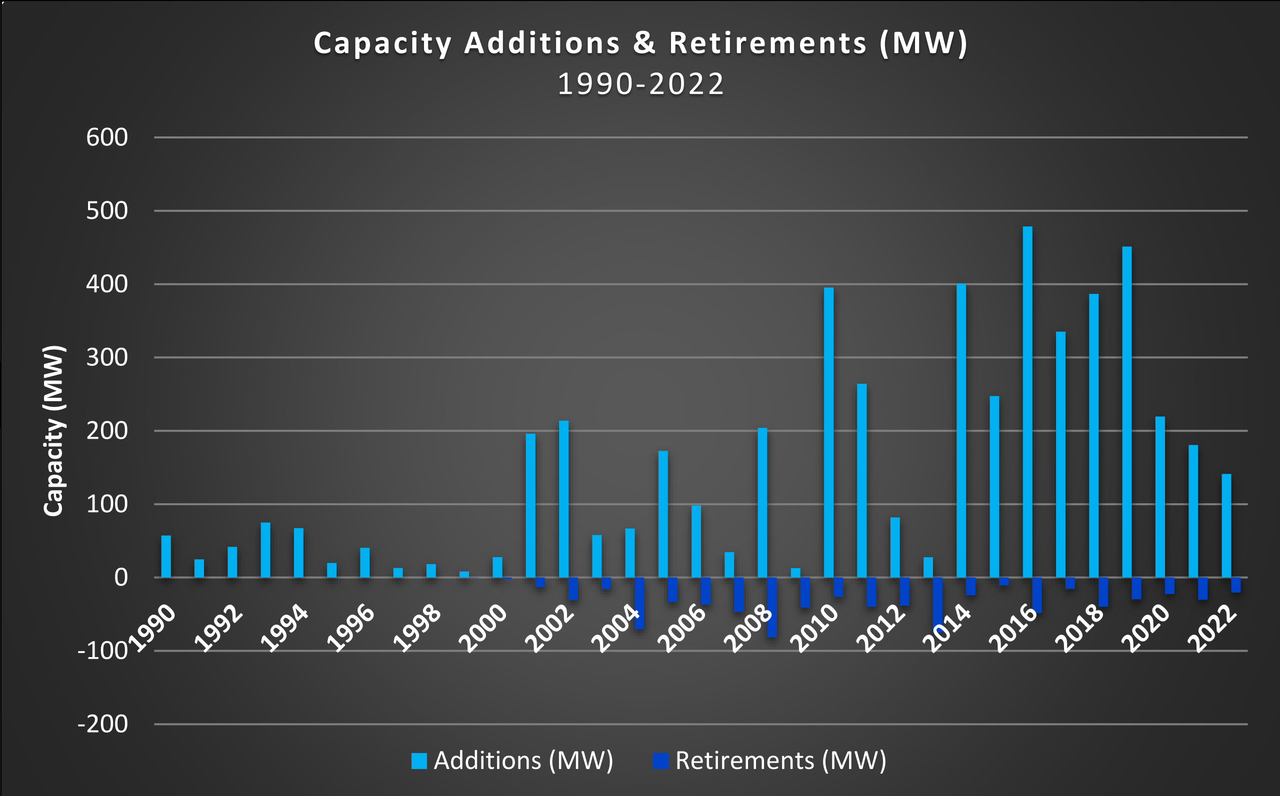
A RICE converts fuel into energy by burning it in a closed chamber. The energy produced is used to power a piston that moves back and forth in a cylinder (reciprocates), converting the energy into mechanical motion. The piston is connected to a generator, which converts the motion into electrical energy. RICEs used for stationary power generation are generally spark-ignited Otto cycles or compression-ignited Diesel cycles, although dual-fuel cycles also exist.

Current Technology Maturity

TRL 9

- RICE technology is mature, though RICEs have played a relatively minor role in energy system portfolios to date.
- Every segment of the RICE value chain – from fuel supply and delivery to power generation – has been commercially proven.

U.S. Observed Capacity Trends



Data compiled from EIA-860A and EIA-860M. Discrete RICE generation data is unavailable.

Potential Future Development

- RICEs may hold promise as a smaller-scale but versatile low-carbon power generation technology that could support decarbonization and improve system resiliency. Nearly all major engine manufacturers are exploring engine operation on advanced, low-carbon fuels. Among the low-carbon fuels of interest for RICE plants are H_2, ammonia, biofuels, and synthetic fuels.

Nuclear

Basic Process Description

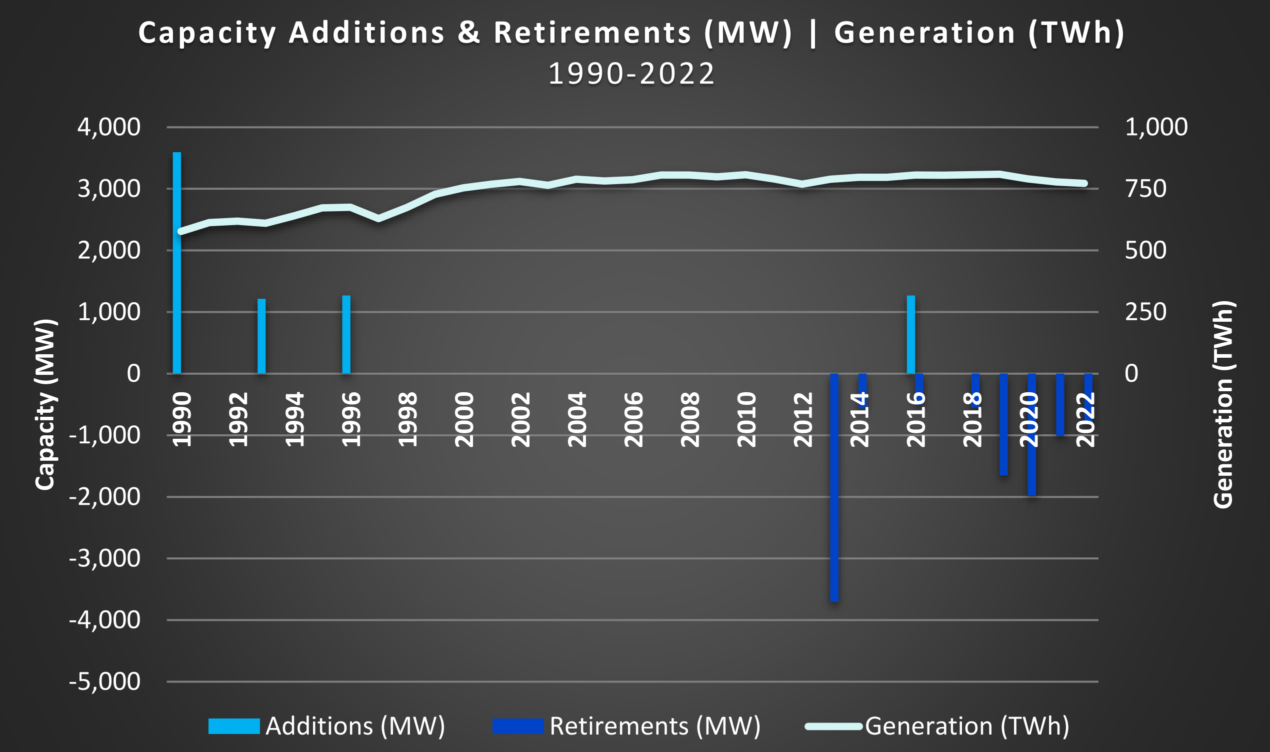
Enriched uranium fuel is split (fissioned) in a reactor, producing heat and steam. The steam drives a turbine-generator to produce electricity. The specific design and coolant vary among reactor types. In a conventional pressurized water reactor (PWR), heat is transferred to a secondary loop to generate steam, while a boiling water reactor (BWR) produces steam directly within the reactor core. The cooling system condenses the steam back into water, completing the cycle.

Current Technology Maturity

TRL 6-9

- Conventional light water-cooled reactor technology is mature and comprises nearly the entire operating fleet globally.
- Advanced Reactors (ARs), which refers to fission reactor designs with significant improvements over the currently operating fleet (including non-light water designs, light water small modular reactors, and microreactors) are in the pre-pilot to pilot stages. Light water-cooled small modular reactors (lwSMRs) are the most commercially advanced ARs.

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data obtained from EIA Electric Monthly.
NOTE: The majority of nuclear capacity in the U.S. (over 100 GW total) was installed prior to 1990.

Potential Future Development

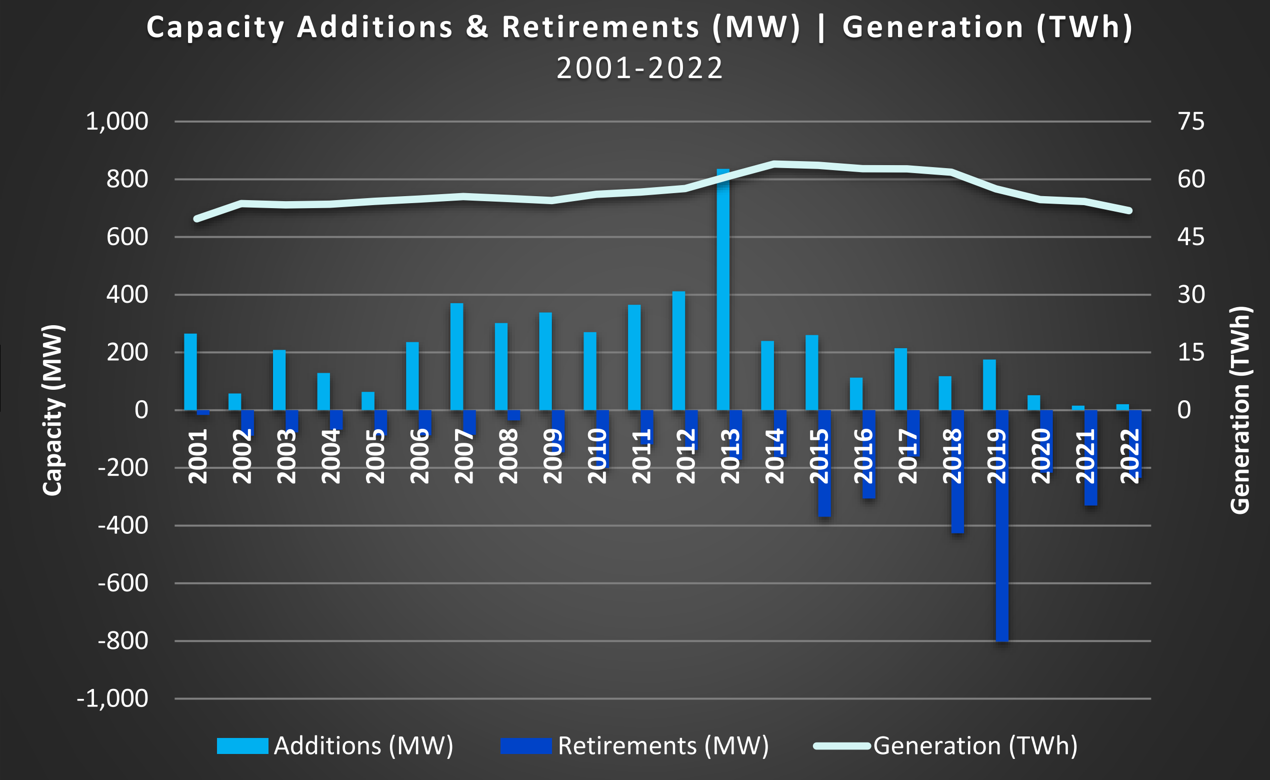
- Government agencies, technology vendors, and other stakeholders are working to support the development and commercial deployment of ARs.
- Technical and non-technical challenges, including advanced materials and fuels supply chain development, risk and uncertainty in regulatory and policy treatment, valuation in energy markets, and public acceptance must be addressed to allow ARs to achieve commercial deployment in future energy systems.

Bioenergy/Biomass

Basic Process Description

Organic material (substances derived from living organisms), such as wood, agricultural residues, or dedicated energy crops, are used as a fuel. Biomass can be converted to electricity through various processes, the most common being direct combustion. This heat is used to generate high-pressure steam in a boiler, which is then directed to a turbine-generator unit to produce electricity.

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data obtained from EIA Data Browser.

Current Technology Maturity

TRL 6-9

- Biomass combustion and anerobic digestion for power generation are mature, while gasification is in the pre-demonstration to early commercial stages.
- The variety of biomass fuel sources and the geographic spread of biomass feedstocks lead to varied levels of value chain maturity. Woody biomass and agricultural residues are generally the most mature with respect to fuel supply chain and energy conversion technology.

Potential Future Development

- Bioenergy with CO_2 capture is being developed by selected technology vendors and an area of promise among many energy sector stakeholders due to the possibility of achieving negative emissions (i.e., the growth of biomass feedstocks absorbs more CO_2 from the atmosphere via the carbon cycle than the electricity generation process emits).
- Blends of biomass and fossil feedstock, such as coal and corn stover gasification, is another area of future research and demonstration for CO_2 emissions reduction.

CO_2 Capture

Basic Process Description

Exhaust gas from the combustion of coal, natural gas, or biomass is treated to separate and capture CO_2 using solvents or sorbents supplied by an integrated CO_2 capture system. The captured CO_2 is then dehydrated and compressed, transported, and either stored underground or utilized for industrial processes. The entire chain is referred to as CO_2 capture, utilization, and storage (CCUS).

Current Technology Maturity

TRL 7-9

- Post-combustion via chemical or physical absorption integrated with PC plants are the most mature CO_2 capture technologies. There are additional, more novel technologies for power generation applications not reflected in this TRL rating.
- Only two commercial power plants with CO_2 capture systems have been deployed globally to date due to complex economics. CO_2 capture has not been commercially deployed on gas-fired plants.
- CO_2 capture has been commercially proven in industrial processes.

Observed Capacity & Generation Trends

To date, there are few commercial power generation projects utilizing CO_2 capture. Therefore, there is minimal data available on capacity and generation trends.

Potential Future Development

- Additional CO_2 capture technologies, such as pre-combustion and oxyfuel combustion, that have been commercially proven in industrial processes are also being pursued in the power generation sector to increase the viability of a greater number of technologies.
- There are numerous projects underway or being planned globally to accelerate the development, demonstration, and deployment of various CO_2 capture technologies on coal-, gas-, and biomass-fired power plants. These projects also seek to improve the economics of CCUS across its value chain, including utilization of captured CO_2.

H_2 Turbines

Basic Process Description

Gaseous H_2 fuel is burned under pressure in a combustor, producing hot gases that pass through an expansion turbine that is coupled to an electric generator. The fundamental principle is like the combustion of fossil fuels except H_2 replaces the fossil fuels (completely if firing 100% H_2, or by <100% if co-firing).

Current Technology Maturity

TRL 6-8

- Co-firing blends of H_2 and natural gas at various ratios has been demonstrated in several utility-scale applications.
- 100% H_2 combustion in utility-scale combustion turbines is estimated to be in the pre-commercial to pilot stages.
- The TRL depends on the volume of H_2 being utilized and the scale of the application. In general, most H_2-fired GTs have been in conjunction with chemical facilities.

Observed Capacity & Generation Trends

To date, there are few commercial-scale projects using 100% H_2- fired turbines for power generation applications. Therefore, there is minimal data to describe capacity and generation trends.

Potential Future Development

- The largest turbine manufacturers in the world have made commitments to develop advanced technologies by 2030 or sooner that would enable additional models of new heavy-duty combustion turbines to fire 100% H_2.
- Some electric companies have formed strategic relationships with original equipment manufacturers to help drive the commercialization of H_2 turbines for large-scale applications to support decarbonization efforts.
- H_2-fired plants may be new build or retrofits of existing plants (potentially, with significant modifications).

Onshore Wind

Basic Process Description

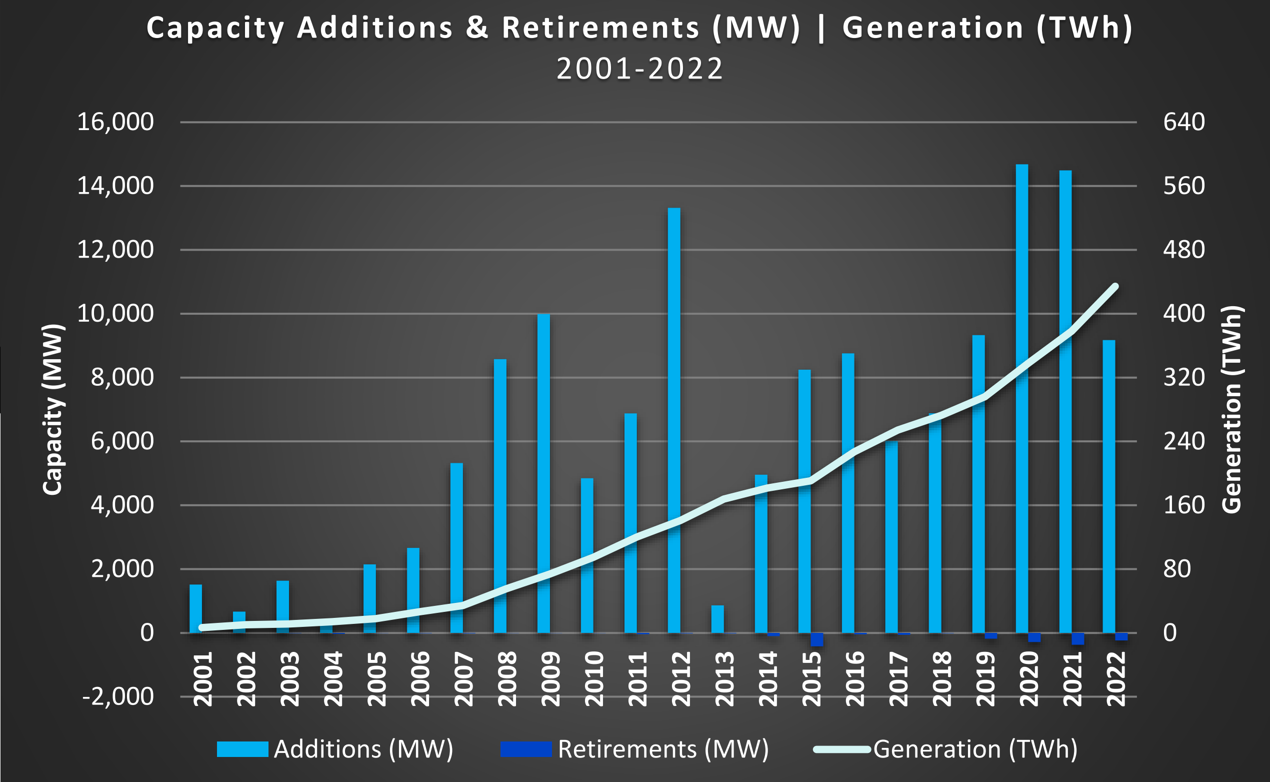
Wind turns a land-based wind turbine's rotor blades, which are connected to a central hub that is connected to a gearbox. The gearbox increases the rotational speed of the rotor blades and sends the energy to a generator. The generator converts the mechanical energy from the rotor blades into electrical energy.

Current Technology Maturity

TRL 9

- Onshore wind turbine technology is fully commercial.
- The onshore wind value chain has been commercially proven.

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data obtained from EIA Data Browser.

Potential Future Development

- Global innovation in wind power technology is expected to continue to focus on increasing the technology's productivity, especially in areas with low wind conditions.
- Advances in wind turbine control technology, reliability, and performance are actively underway on a global scale.
- While the industry has focused on larger turbines, there are signs that growth in turbine size may slow down. As a result, there is a growing emphasis on iterative design to improve reliability, reduce operational costs, and streamline mass production.

Offshore Wind

Basic Process Description

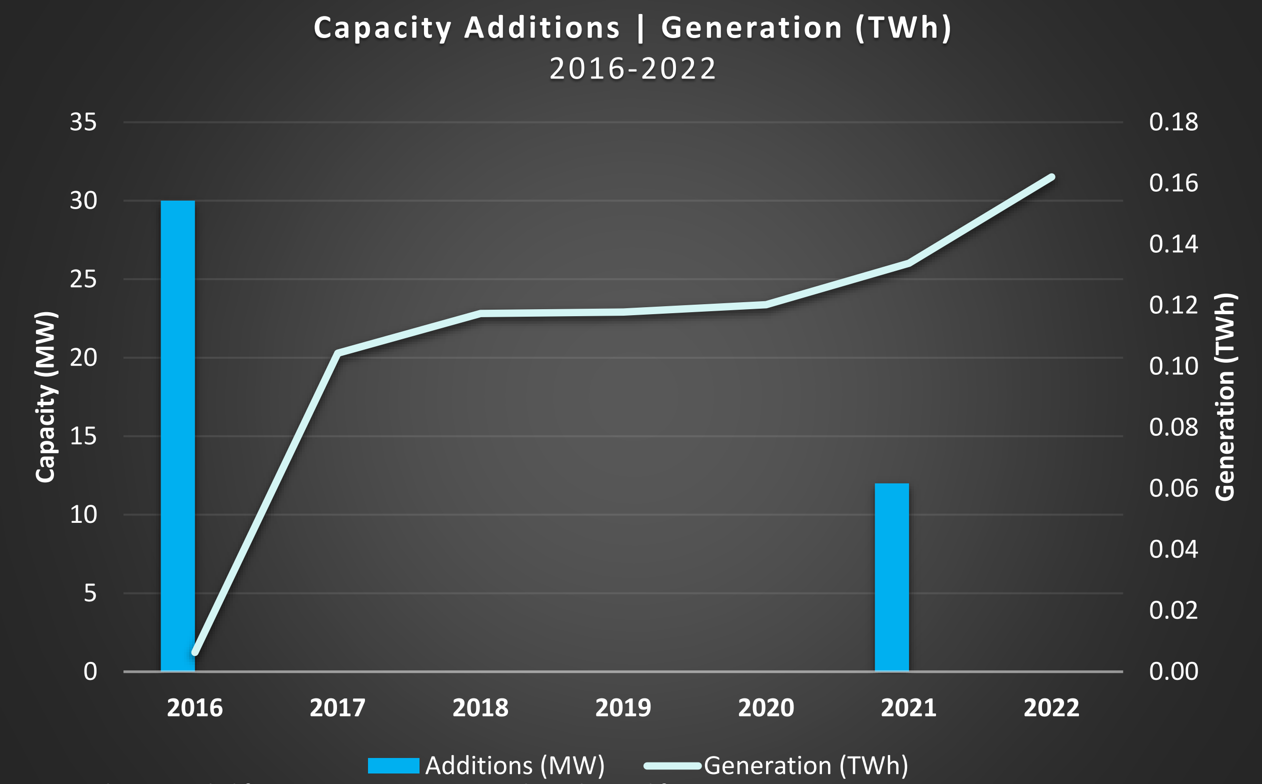
Wind turns a marine-based wind turbine's rotor blades, which are connected to a central hub that is connected to a gearbox. The gearbox increases the rotational speed of the rotor blades and sends the energy to a generator. The generator converts the mechanical energy from the rotor blades into electrical energy.

Current Technology Maturity

TRL 6-9

- Offshore wind turbine technology utilizing fixed-bottom pile foundations is commercial in parts of the world, while floating offshore wind technology is in the demonstration stage.
- Offshore wind technology has not been widely deployed in the U.S. even though the core technology for fixed-bottom designs is relatively advanced in terms of commercialization.

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860M. Generation data obtained from EIA-923.

Potential Future Development

- Offshore wind technology development is expected to be focused on increasing capacity factors, reducing capital costs, improving supply chain, and better integrating with the grid.
- There is currently uncertainty in the industry around continued growth in turbine capacity to increase power output and improve project economics versus focusing on current turbine capacities (on the order of 15 MW) to ramp up supply chain.
- Anticipated reductions in O&M costs stem from economies of scale, refinements in maintenance methodologies, and advancements in turbine control technologies.

Solar Photovoltaic (PV)

Basic Process Description

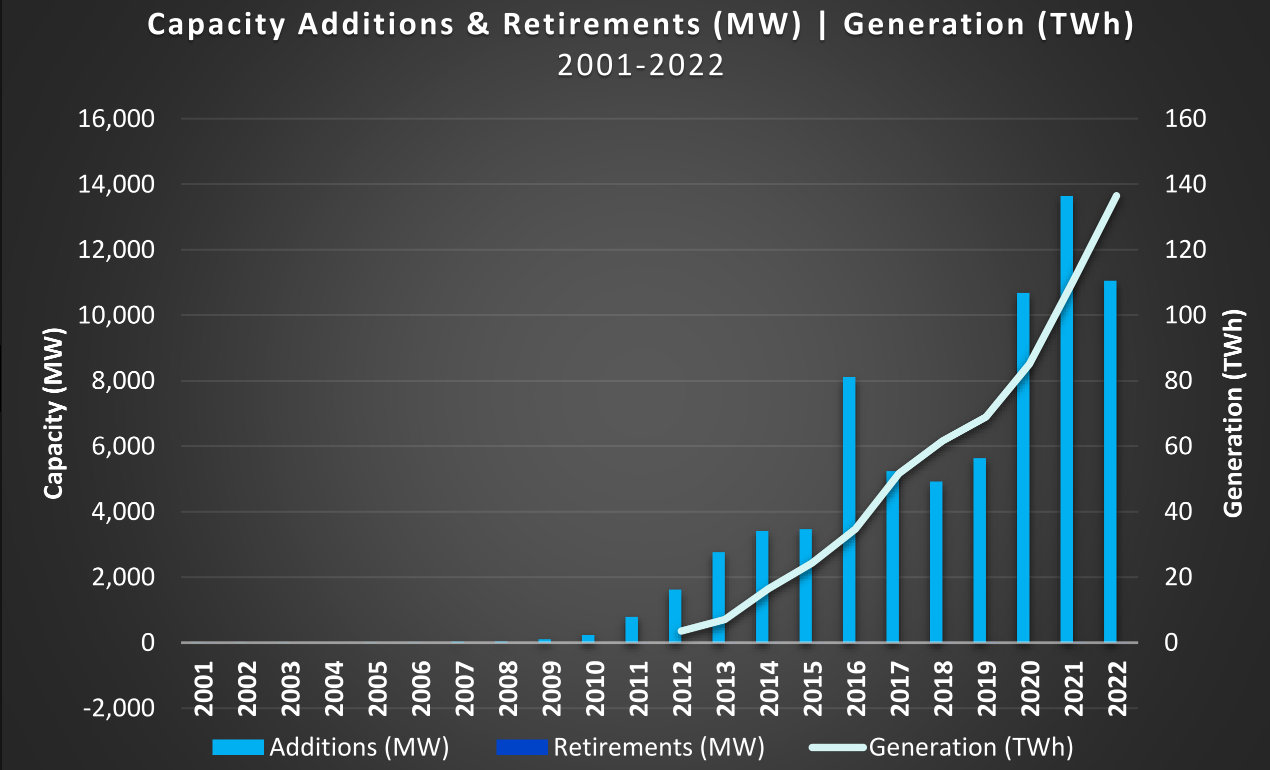
When sunlight hits a solar panel, photons from the sun's rays are absorbed by solar cells and knock electrons free from their atoms, creating a flow of electricity. Free electrons flow through the semiconductor material in solar cells and into the wiring of a solar panel unit, generating direct-current (DC) electricity that is then converted to alternating current (AC) electricity using an inverter.

Current Technology Maturity

TRL 9

- Crystalline silicon module technologies are mature, as are several thin film technologies (e.g., cadmium telluride).
- Emerging high-efficiency, low-cost solar PV technologies (e.g., quantum dot) that are in the applied research stages are not captured in this TRL rating (see Potential Future Development).
- Every segment of the solar PV value chain has been commercially proven, though end-of-life management continues to be developed.

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data starting in 2012 from LBNL Utility-Scale Solar Update.

Potential Future Development

- Ongoing research and development efforts continue to enhance efficiency, reduce costs, and explore new applications through cell and module technology advancements and balance of plant innovations.
- Emerging solar cells are being developed. These designs build upon the current commercially available thin-film technology but are constructed with advanced materials such as organic compounds.
- Solar PV plants are increasingly being paired with lithium ion battery energy storage systems (BESS) to shift the operating profile and generate electricity during peak demand.

Battery Energy Storage Systems (BESS)

Basic Process Description

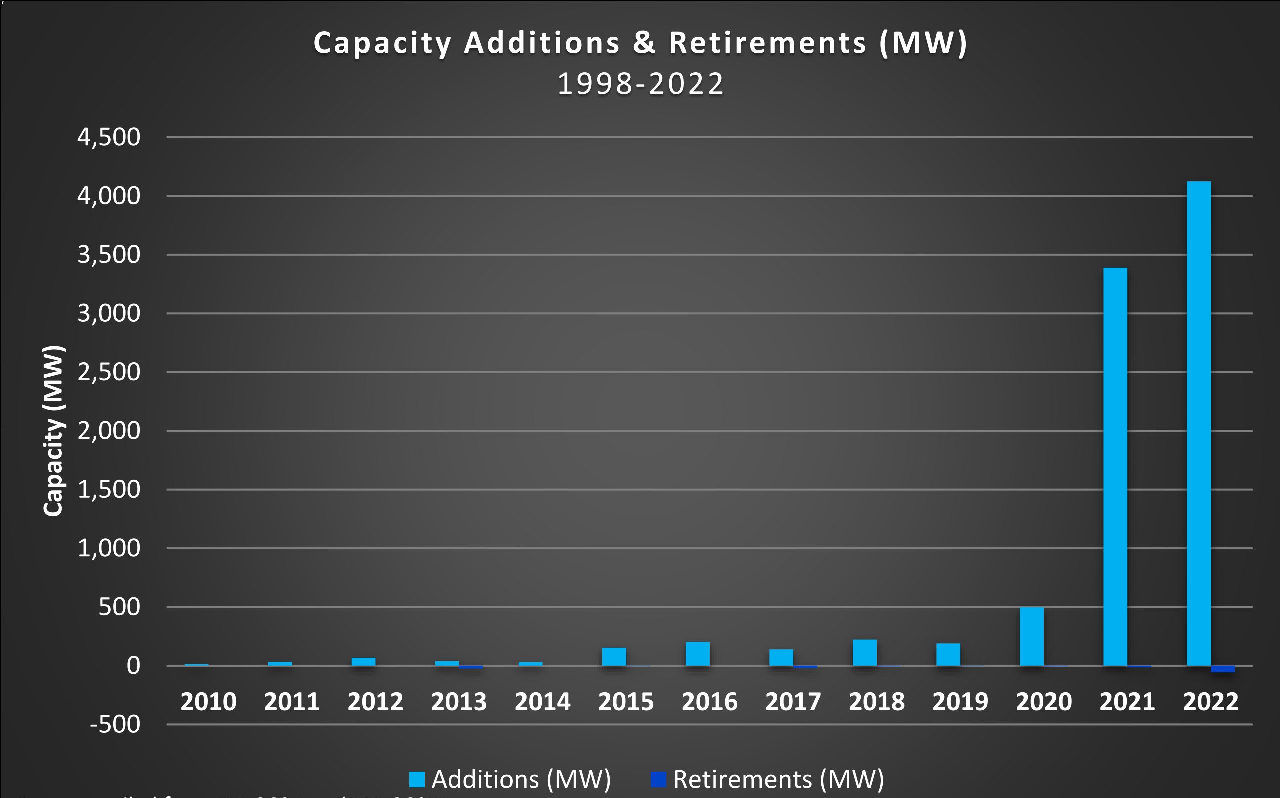
Electricity is stored as chemical potential energy via battery cells. A battery cell allows ions to flow through an electrolyte or a porous membrane that is electrically insulating to deliver energy to an external circuit. Charging batteries with electricity causes the ions to move to a higher energy state and discharging causes them to move to a lower energy state, releasing electrons. Lithium ion batteries (LIBs) are a family of rechargeable batteries that use lithium ions as the primary charge carriers between positive and negative electrodes.

Current Technology Maturity

TRL 9

- There are many LIB battery chemistries, and nearly all conventional liquid-electrolyte LIB designs are mature.
- More novel LIB chemistries and other battery technologies are not captured in this TRL rating (see Potential Future Development)
- All segments of the conventional LIB value chain are mature, though end-of-life management continues to be developed.

U.S. Observed Capacity Trends



Data compiled from EIA-860A and EIA-860M.

Potential Future Development

- Advancements in LIBs have been and may continue to be driven by the needs of the electric vehicle (EV) industry, which is larger in terms of demand and profitability than stationary energy storage. There are often spillovers in innovation from EV LIBs to stationary LIBs. Future improvements in LIBs may be primarily focused on increasing energy density, increasing the power output of lithium ion cells, improving operational safety, reducing overall costs, and reducing reliance on scarce minerals
- Commercial and emerging battery storage technologies beyond LIBs, including iron-air, liquid metal, nickel-hydrogen, sodium-sulfur, vanadium redox flow, zinc bromine, and solid-electrolyte batteries, are also actively being developed.

Solar PV + BESS

Basic Process Description

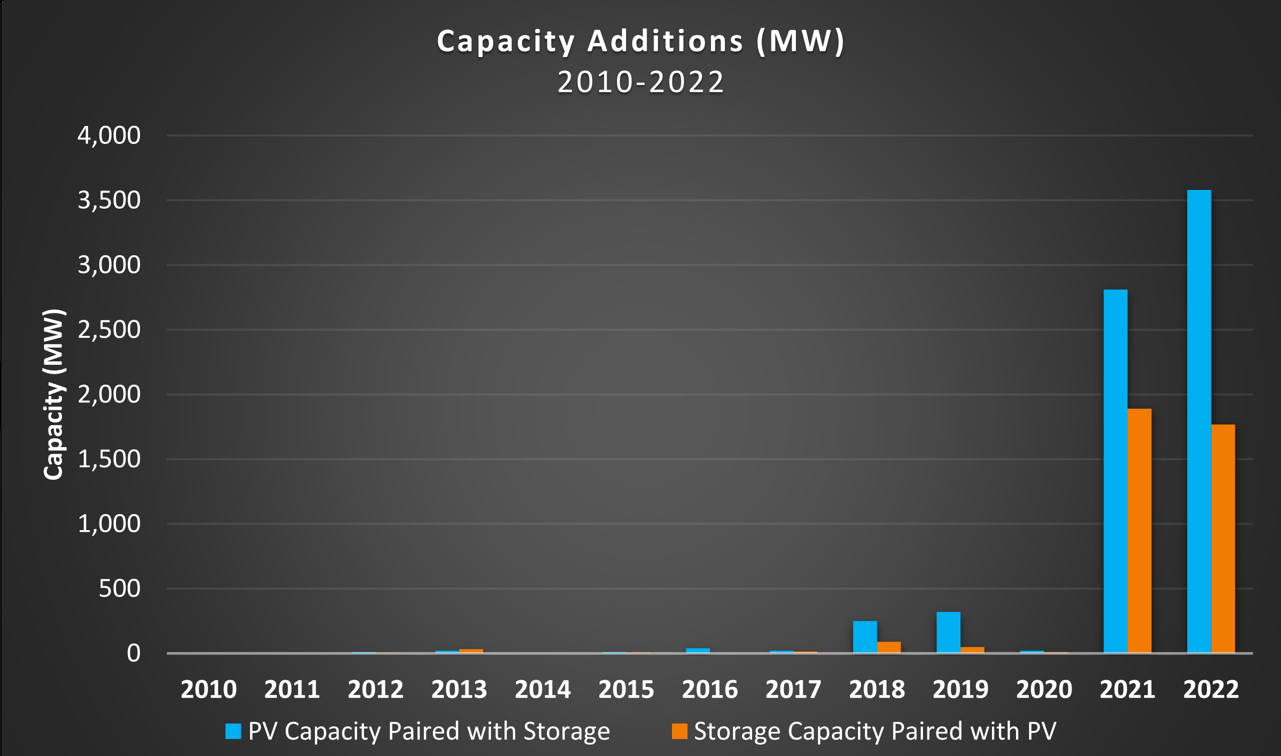
A solar PV plant is connected to a BESS in one integrated hybrid system. The PV panels generate electricity, which can be used to meet current demand or charge the battery so that it can supply power when needed later. When the battery is fully charged, the system delivers energy directly to the grid.

Current Technology Maturity

TRL 9

- Hybrid systems utilizing conventional PV and lithium ion BESS technologies are commercial.
- Most of the value chain of solar PV + BESS has been proven, but increased attention is being given to system integration and end-of-life management.

U.S. Observed Capacity Trends



Data compiled from Lawrence Berkeley National Laboratory. Storage durations range from 15 minutes to 4 hours, with an average storage duration of 3.1 hours.

Potential Future Development

- Due to favorable economics at the project and electric system level, increased deployment of hybrid solar PV + BESS systems is expected.
- Improvements in PV and BESS technologies (e.g., higher energy density for batteries) could improve performance of solar PV + BESS systems.
- PV + BESS can be connected to each other through AC- or DC-coupling. Most projects installed to date are AC-coupled. However, DC-coupled systems may become more prevalent in the future with recently-developed inverter technology.

H_2 Fuel Production

Basic Process Description

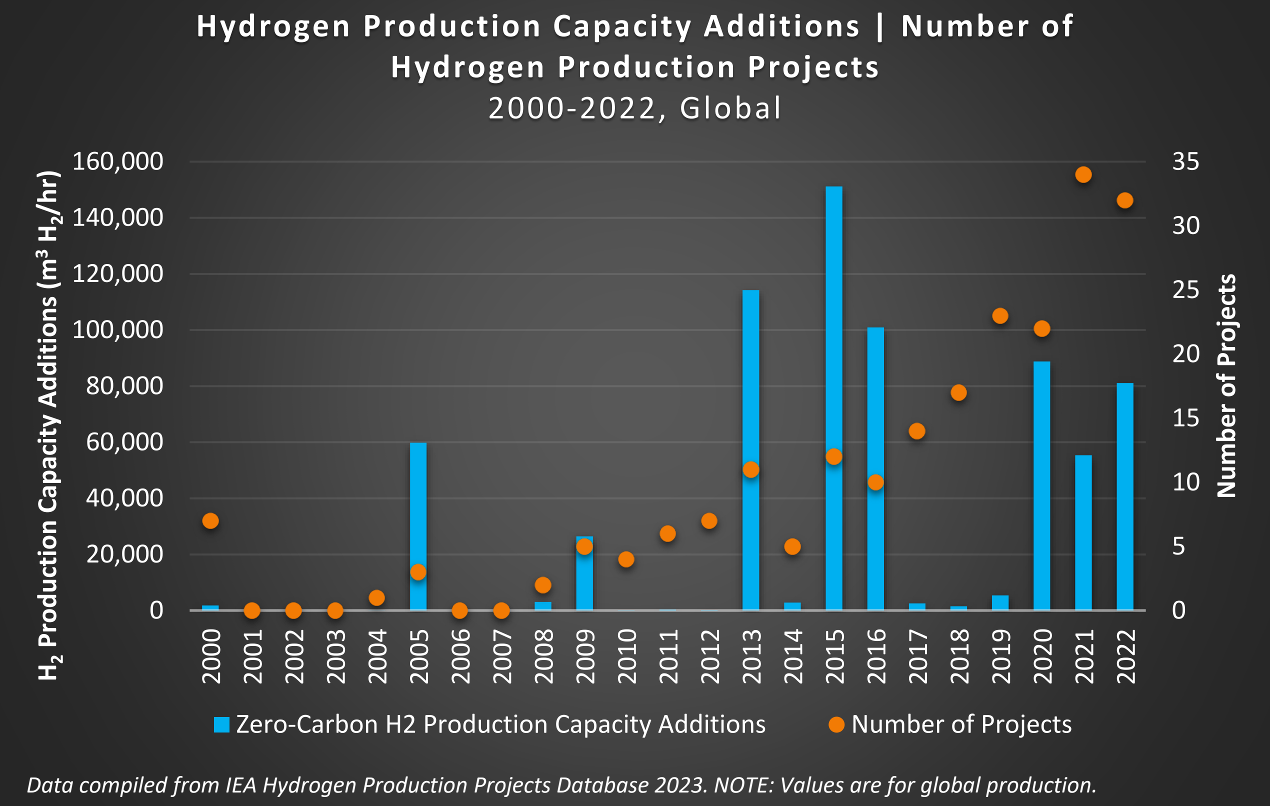
H_2 can be produced using several different processes. Thermochemical processes use heat and chemical reactions to release hydrogen from organic materials, such as fossil fuels and biomass, or from water. Electrolytic processes involve splitting water (H_2O) into H_2 and oxygen (O_2) using electricity in an electrolysis cell. Biological processes involve the conversion of biomass to H_2 using microbial processes.

Current Technology Maturity

TRL 6-9

- Large-scale H_2 production using fossil fuels (without carbon capture) is mature. Steam methane reforming is the most established, followed by autothermal reforming then partial oxidation (both are thermochemical). Coal gasification has achieved commercial status particularly in China.
- Alkaline electrolysis is the most advanced electrolytic process (fully commercial), followed by polymer electrolyte membrane (demonstration-early commercial), and solid oxide (pre-commercial/pilot).

Global Observed Capacity Trends



Data compiled from IEA Hydrogen Production Projects Database 2023. NOTE: Values are for global production.

Potential Future Development

- Further development and optimization of coal and biomass blended gasification with CO_2 capture and reforming paired with CO_2 capture technology is under development, potentially improving its deployment prospects.
- Efforts to improve the cost competitiveness, efficiency, and flexibility of electrolyzer technologies to allow for increased deployment in renewables integration and other applications are expected to continue, especially as more countries look to achieve deep decarbonization.
- There are additional, less mature and/or notable technologies not discussed in this report that could develop in the future (e.g., methane pyrolysis).

Hydroelectric Power

Basic Process Description

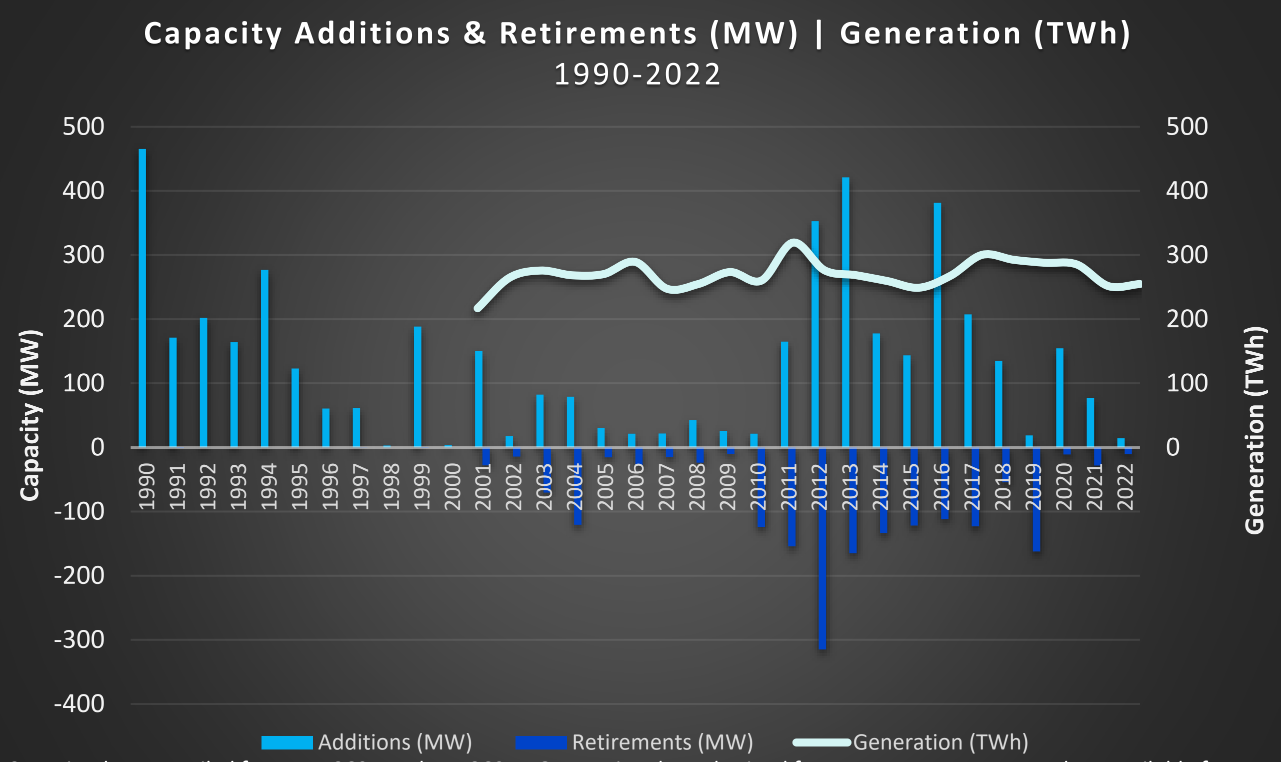
Hydroelectric power is generated by leveraging an elevation difference between an upper and lower reservoir created by a dam or diversion structure. The potential energy stored in the water is then converted into kinetic energy by flowing through the penstock and ultimately through the spiral case before entering the hydroelectric turbine. The rotational motion is transferred through a shaft into a synchronous generator, which produces electricity.

Current Technology Maturity

TRL 9

- Hydroelectric power is mature. It is the oldest commercial-scale renewable energy technology in the U.S. and elsewhere.
- Most new hydropower capacity added in the U.S. over the past few decades has come from uprating existing projects in addition to small hydro and adding generation capacity to non-powered dams.

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data obtained from EIA Data Browser; no data available for period 1990-2000. NOTE: The majority of hydroelectric capacity in the U.S. (nearly 78 GW total) was installed prior to 1990.

Potential Future Development

- Powering non-powered dams in the U.S. has the potential to add up to 8 GWs of generation capacity. Some hydroelectric turbine manufacturers are developing modular and standardized low-head designs that could support economical project installations on non-powered dams, which are often smaller with respect to physical size and water flow.
- Development of methods to reduce the impact of hydropower on migrating fish and improved inspection and monitoring systems/plant digitalization are also areas of active research.

Note: Cost estimates of hydroelectric power technology based on publicly available sources are presented in Appendix A.5.

Pumped Storage Hydropower (PSH)

Basic Process Description

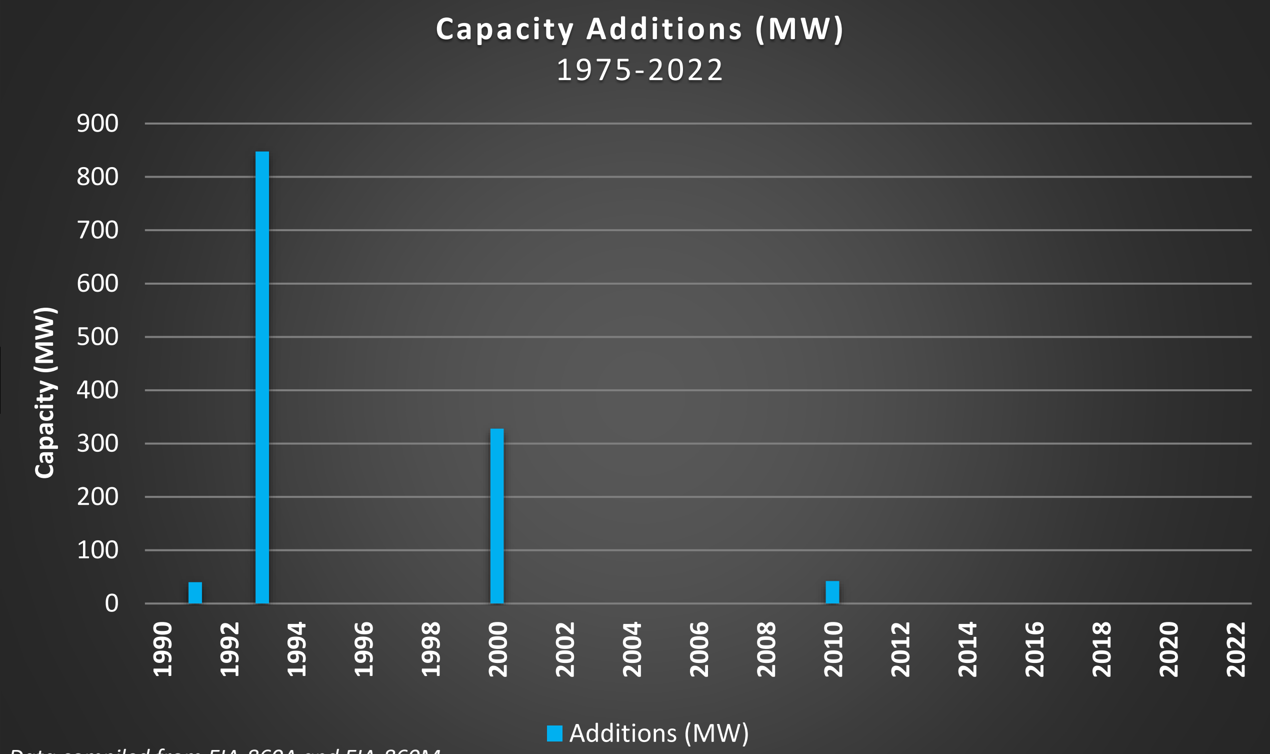
PSH uses water to store and generate electricity by pumping it between two reservoirs at different elevations. Energy is stored by pumping water from the lower reservoir to the higher reservoir. Electricity is generated by releasing water from the high reservoir through a hydroelectric turbine and into the lower reservoir

Current Technology Maturity

TRL 9

- PSH is a mature technology. It is the oldest commercial bulk energy storage technology and makes up the majority of deployed grid-scale storage capacity today.
- All segments of the PSH value chain have been commercially proven.

U.S. Observed Capacity Trends



Data compiled from EIA-860A and EIA-860M.
NOTE: The majority of PSH capacity in the U.S. (over 19 GW total) was installed prior to 1990.

Potential Future Development

- Novel or unconventional PSH system design and operational principles, including non-freshwater PSH and underground PSH, are being explored to facilitate the integration of increasing quantities of intermittent renewable energy sources into the grid.
- RD&D efforts focused on variable-speed, reversible hydroelectric turbines are ongoing with an aim to increase response times and operational adaptability, as the current dominant fixed-speed technology is limited in its reaction time (ramp up and down) and range of operations.

Note: Cost estimates of pumped hydro storage technology based on publicly available sources are presented in Appendix A.5.

Geothermal

Basic Process Description

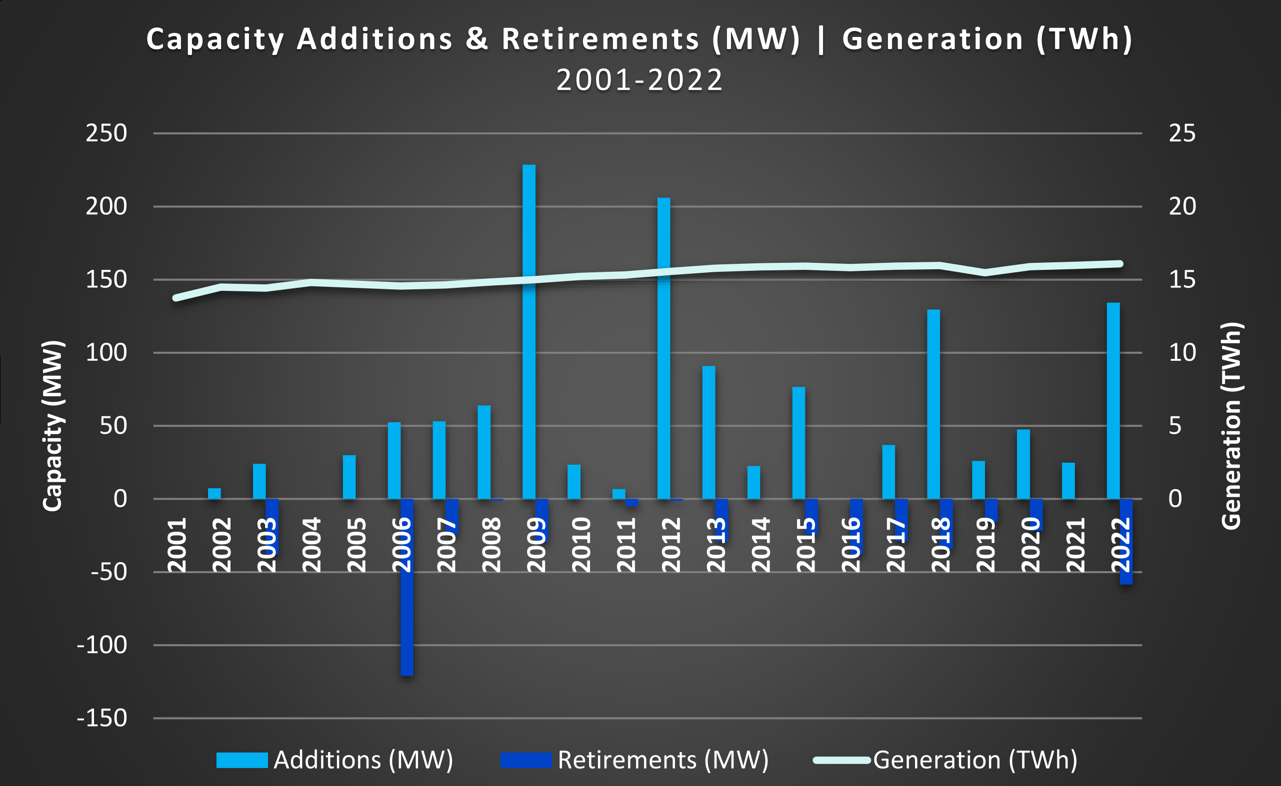
Hot water or steam are pumped from underground under high pressure to the earth's surface to produce steam, which is then directed to drive a turbine-generator unit to produce electricity. There are three main types of geothermal power plant technologies: dry steam, flash steam, and binary cycle, and two main types of geothermal reservoirs: hydrothermal and enhanced geothermal systems (EGS). Hydrothermal reservoirs involve a naturally occurring heated fluid with sufficient permeability while an EGS reservoir has heat but lacks sufficient fluid flow and requires engineering to enhance permeability.

Current Technology Maturity

TRL 8-9

- Flash steam and binary cycle energy conversion technologies for hydrothermal geothermal reservoirs are fully commercial and early commercial, respectively. Both technologies have played a minor role in energy system portfolios to date.
- More novel technologies like EGS are not reflected in this TRL rating.

U.S. Observed Capacity & Generation Trends



Capacity data compiled from EIA-860A and EIA-860M. Generation data obtained from EIA Data Browser.

Potential Future Development

- Some industry stakeholders view EGS as a major area of potential growth. EGS refers to a spectrum of approaches to enable the utilization of geothermal resource deposits with low permeability by engineering a subsurface fracture system to enhance fluid connectivity. EGS are in the R&D to demonstration stages.
- The process to stimulate wells for EGS is like "fracking" in the context of oil and gas extraction. The oil and gas and geothermal industries share similarities that could provide new opportunities for geothermal expansion—from advances in drilling and well construction to co-production in existing oil and gas basins.
- Non-technical challenges (e.g., economics, public acceptance) may need to be addressed to increase the viability of geothermal energy.

Note: Cost estimates of geothermal technology based on publicly available sources are presented in Appendix A.5.

Concentrating Solar Thermal Power (CSP)

Basic Process Description

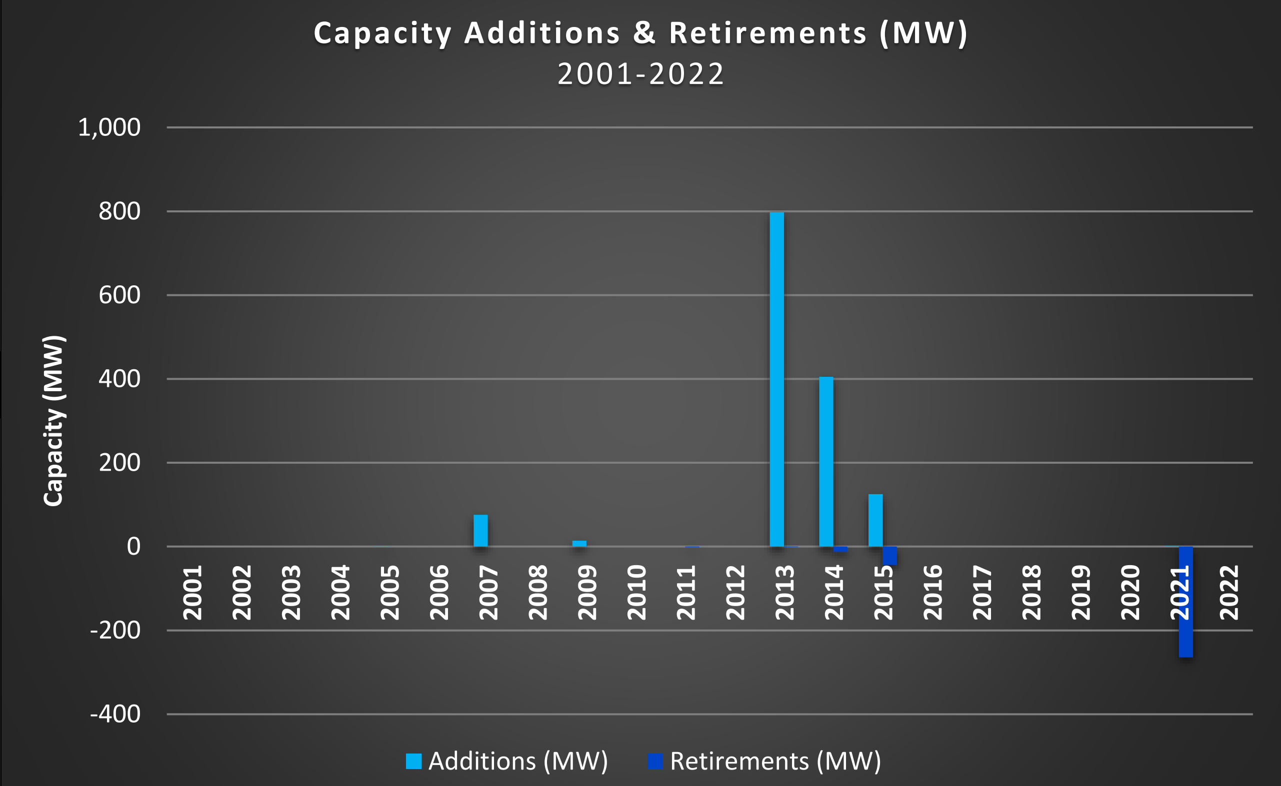
Mirrors are used to concentrate sunlight onto a small area, increasing the intensity of the solar radiation. The concentrated solar energy is then used to heat a working fluid, which can either generate steam to power a turbine and produce electricity or store heat via thermal energy storage to produce electricity at a later time.

Current Technology Maturity

TRL 7-9

- Parabolic trough and power tower technology are fully commercial, while linear Fresnel technology is in the early commercial stage.
- Molten salt thermal energy storage is also fully commercial.
- The CSP value chain is relatively mature, but has experienced multiple starts/stops in deployment.

U.S. Observed Capacity Trends



Data compiled from EIA-860A and EIA-860M. Discrete CSP generation data is unavailable.

Potential Future Development

- CSP plants may continue to become larger over time (e.g., hundreds of megawatts) to further help decrease installed costs and make CSP a more viable option for large-scale electricity generation. Modular systems (10-50 MW) are also being considered to decarbonize industrial processes.
- Improved design and efficiency via advanced power cycles (e.g., supercritical CO_2) and high-temperature solid particle working fluids are also under development.

Note: Cost estimates of CSP technology based on publicly available sources are presented in Appendix A.5.

Appendices

A.1. Definitions

Parameter	Definition
Net Plant Capacity	Maximum net capacity that a generating unit can sustain over a specified period of time.
Capacity Factor	The total amount of energy a plant produces during a period of time divided by the amount of energy the plant would have produced at full capacity.
Heat Rate	Amount of energy, expressed in British thermal unit (Btu), required to produce 1 kWh of electric energy. Heat rates in this report are expressed as the higher heating value (HHV) for fuel-burning technologies.
CO_2 Emissions	The amount of CO_2 emitted per unit of electricity generated. Reflects the emissions of CO_2 produced by the plant and does not include lifecycle emissions.
Total Plant Cost	Includes all process and general facilities capital, engineering and home office overhead, EPC fees, project and process contingencies.
Total Capital Required	Includes all capital necessary to complete the entire project and consists of total plant costs, owner's cost, interest during construction, and escalation during construction (for current dollar analyses).
Fixed O&M	Costs of operating labor, maintenance, and overhead charges. Property taxes and insurances are also included in fixed O&M. These costs are essentially independent of actual capacity factor, hours of operation, or amount of electricity produced and are expressed in $/kW-yr.
Variable O&M	Costs of consumables including water, chemicals, and other materials that are consumed in proportion to energy output and are expressed in $/MWh.
Fuel Price	Price of fuel on HHV basis, expressed in $/MMBtu.
Levelized Cost of Electricity (LCOE)	The cost to produce electricity from a generation plant over its lifetime, based on plant construction costs, operation and maintenance costs, fuel costs, and expected annual electricity production, expressed in $/MWh.
Constant Dollar Analysis	Analysis made in a base year without including the effect of inflation (although real escalation is included in future years). Also known as real-dollar analysis.
Current Dollar Analysis	Analysis that includes the effect of inflation and real escalation. Also known as nominal-dollar analysis.

A.2. Technology Assumptions

Technology	Description
Pulverized Coal	Coal-fired power plant utilizing a supercritical thermal cycle and a wet cooling system is considered. The design includes systems for the removal of mercury, SOx/H_2S, NOx, and particulate matter, integrated into the initial capital cost. For cases incorporating CCS, a 90% carbon capture system is considered.
Natural Gas Combined Cycle (NGCC)	Natural gas-fired combined cycle power generation unit in 2x1 multi-shaft configuration is considered. Dry low NOx burner and SCR for NOx control included in capital cost. Mechanical draft cooling tower system is employed. CCS cases include 90% carbon capture system.
Combustion Turbine	Industrial frame combustion turbine (CT) in simple-cycle configuration. SCR for NOx control and oxidation catalyst for VOC removal included in capital costs.
Reciprocating Internal Combustion Engine (RICE)	Large-scale gas-fired reciprocating internal combustion engines with two-stage post-combustion emission control for CO oxidation and NOx removal. Closed-loop air-cooled radiator system used for cooling.
Nuclear	Nuclear power plant utilizing Generation III/III+ nuclear reactors is considered.
Small Modular Reactor (SMR)	SMR plants with light-water SMRs and high-temperature gas cooled reactor (HTGR) SMRs are considered.
Biomass	Biomass-fired power generation facility with single steam generator and condensing steam turbine. Capital cost includes biomass storage and handling systems, BOP systems, and emissions control. CCS cases include 90% carbon capture system.
Onshore Wind	Onshore wind energy generation in different regions with varying wind resources is considered. The cost range includes plant with wind turbine nameplate capacities of 3.3 MW and 4.2 MW, with rotor diameters of 141 and 145 meters, respectively. Hub height ranges from 90 to 100 meters.
Offshore Wind	Offshore wind projects in U.S. Atlantic and Pacific locations are considered, utilizing turbines with a nameplate capacity of 12 MW. The cost range includes both fixed-bottom and floating foundation configurations.
Solar Photovoltaic (PV)	Solar PV plants in various regions of the U.S. are considered, with different solar PV resources. The cost range includes different module technologies including bifacial c-Si, monofacial c-Si, CdTe, and TOPCon, and mounting technologies including fixed-tilt and single-axis tracking with inverter loading ratios (ILR) of 1.3 to 1.4.
Battery Energy Storage	Utility-scale lithium ion battery energy storage system (BESS) with a power rating ranging from 20 MW to 100 MW and 4-hour storage capacity is considered.
Solar PV and Storage	150 MW_{AC} solar PV plant with 100 MW, 4-hour lithium ion battery storage, DC-coupled, is considered. The cost range includes configurations with fixed-tilt and single-axis tracking, with ILRs of 1.4 and 1.3*, respectively. No grid charging is considered, and excess PV generation is stored in batteries to prevent clipping by the inverter.
H_2-Fired Turbines	Combustion turbines fueled entirely by hydrogen are considered. Two configurations are considered: 1) an aeroderivative turbine in open cycle configuration with water injection for NOx control, and 2) an advanced class hydrogen 1x1 combined cycle with dry low NOx burner and SCR.

*DC-coupled solar PV-plus-storage systems with higher ILRs are expected to yield greater total energy output due to the increased capacity of the PV array. However, the preferred architecture for future utility-scale PV-plus-battery systems remains uncertain. Therefore, the analysis assumes the ILR to be the same as in the case of standalone solar PV.

A.3. Levelized Cost of Electricity – Assumptions

Financial Assumptions: Non-Technology-Specific, Investor-Owned Utility (IOU) Financing Rates

Inputs	Rate
Nominal Equity Rate	8.75%
Nominal Debt Rate	5.75%
Debt : Equity	40 : 60
Income Tax Rate	25.7%
Inflation Rate	2%
Nominal Before Tax WACC	7.6%
Real After Tax WACC	5.1%

Technology-Specific Assumptions

Technology	Construction Duration, Yrs.	MACRS Recovery Period, Yrs.	Book life, Yrs.
Pulverized Coal	4	20	30
Pulverized Coal with CCS	4	20	30
NGCC	3	20	30
NGCC with CCS	3	20	30
Combustion Turbine	2	15	30
RICE	1	15	30
Nuclear	6	15	40
Small Modular Reactor	4	15	40
Biomass	3	5	30
Biomass with CCS	4	5	30
Onshore Wind	2	5	30
Offshore Wind	3	5	30
Solar Photovoltaic	1	5	30
Battery Energy Storage	1	5	20
Aeroderivative H_2 CT	2	15	30
Combined Cycle H_2	3	20	30
Electrolyzer for H_2 Production	2	20	20
SMR with CCS for H_2 Production	4	20	30
Coal gasification with CCS for H_2 Production	4	20	30
Biomass with CCS for H_2 production	4	20	30

A.4 Technology Readiness Levels (TRLs)

TRL		Description
1	**Basic Principles Observed and Reported**	• Observation of material properties or other physical/chemical phenomena that can then be translated into applied research and development (R&D).
2	**Formulation of the Application**	• Practical applications of basic physical principles are identified, and generalizations assumed for physical/chemical data not readily available.
3	**Proof of Concept**	• Initiation of active R&D for the specific application and detailed analytical studies to design the application and predict its performance. • Lab studies to physically verify engineering/scientific assumptions of analytical studies.
4	**Component Validation in Laboratory Environment**	• Component-level test assemblies are created from available “pieces” as a functional unit in a laboratory setting and generally consistent with the eventual system.
5	**Component Validation in Relevant Environment**	• Component-level assemblies are designed and function independently as a unit. • Relevant environment is likely to be a lab or a small process development unit that simulates the operational environment.
6	**Process Development Unit:** Prototype Components in a Relevant Environment	• Prototype components are those whose design and function are essentially the same as expected for full-scale deployment. • Full system integration is not required at this stage and the relevant environments may include field power plant settings or smaller pilot/test plant installations.
7	**Pilot Plant:** Integrated, Fully Functional Prototype Incorporating Features of Anticipated Full-Scale Deployment in an Operational Environment	• Includes all components or unit processes expected at full scale and may be deployed as an adjunct to an operating power plant. • Deployed with an operations/control system of a scope comparable to full-scale implementation of the technology.
8	**Commercial Pilot Plant:** Deployment of Technology in Final Form Under Expected Conditions	• Performance guarantees supportable by TRL 7 experience including capacity, material use/production, and energy use/production. • TRL 8 may be bypassed if achieving TRL 7 provides sufficient confidence to technology developers and customers for commercial service requirements of TRL 9.
9	**Normal Commercial Service**	• Full-scale implementation with enforceable performance guarantees including capacity, material use/production, and energy use/production. • Standard industry warranties.

Adapted from *Energy Storage Technology Database Report: 2022—Annual Year-End Snapshot Report (3002024003)*

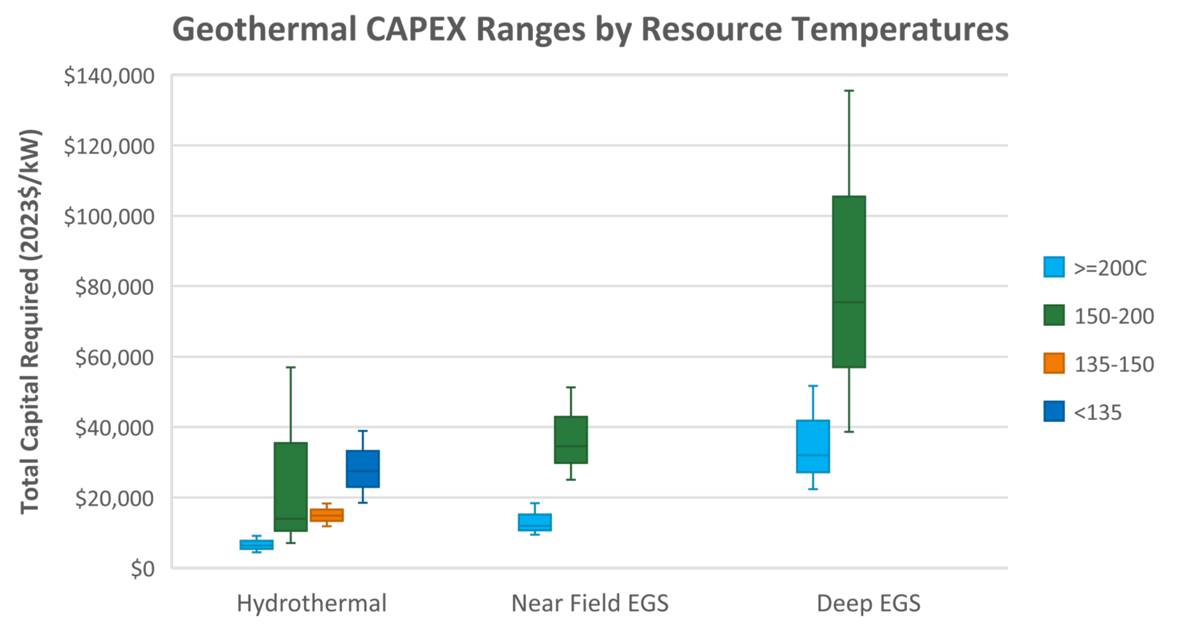
Selected Caveats:

- TRLs are inherently subjective. Ratings may vary from expert to expert.
- TRLs can vary by technology component or value chain segment (e.g., carbon capture vs. storage for CCS), desired technology application (e.g., power generation vs. industrial), application scale, and individual vendor design.
- TRLs do not capture all dimensions of “readiness,” such as manufacturing, market, consumer, or societal readiness. Similarly, TRLs do not reflect cost competitiveness of a technology.

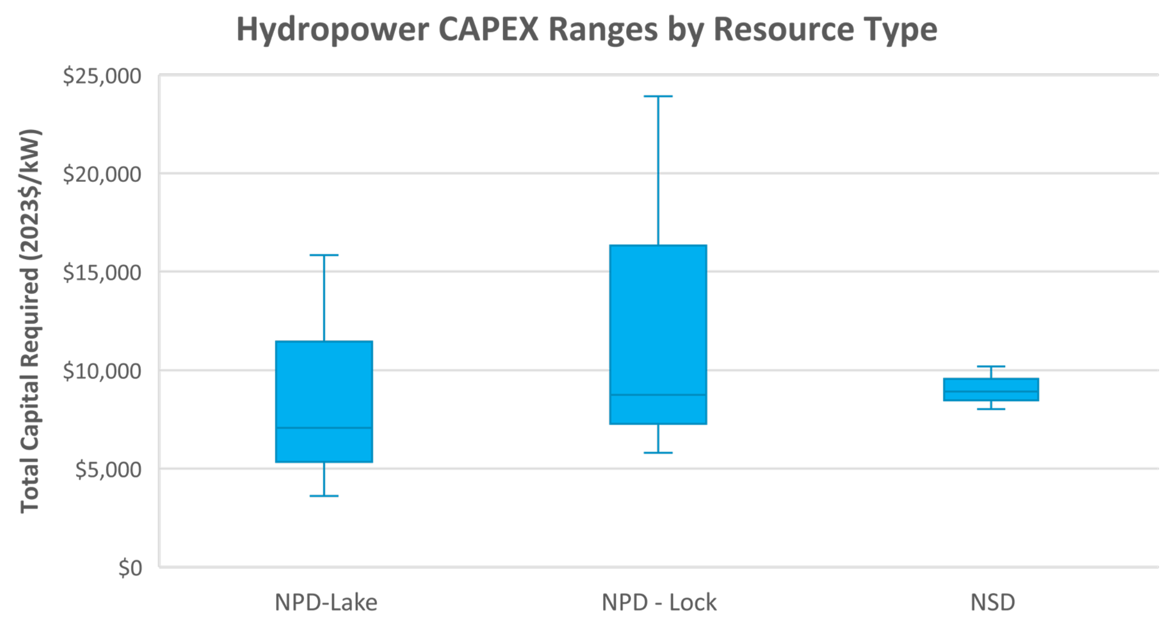
A.5 Representative Costs of Other Technologies – Present (2023)

All Costs in Constant Q3 2023$	Net Plant Capacity, MW	Capacity Factor, %	Book life, yrs	Total Capital Required, $/kW	Fixed O&M, $/kW-yr	Variable O&M, $/MWh	Charging Cost, $/MWh	LCOE, $/MWh
Hydropower	1-60	41-62	50	7,100-9,000*	40-150	-	-	125-149
Pumped Storage Hydropower	100-1,000 MW, 10hr	25-30	50	3,000-3,500	48-68	-	50	155-175
Geothermal	25-40	80-90	30	6,300-75,000*	125-570	-	-	70-820
Concentrated Solar Power – Power Tower	100 MW, 10hr TES	63-65	30	8,500-10,000	180-225	-	-	135-165

Sources: *Annual Technology Baseline 2023,* NREL; *2022 Grid Energy Storage Technology Cost and Performance Assessment*, Viswanathan et al.
*Capital cost ranges are based on average costs for these technologies and resources, but actual costs can vary widely depending on the specific resource, location, and technology assumptions.



Near Field EGS assumes the temperature and depth of conventional hydrothermal plants, but requires enhancements for flow rate and well productivity. Deep EGS assumes deeper resource wells to reach desired temperatures.



Non-Powered Dams (NPD) are existing dams that do not currently have hydropower; NPD Lake = Non-Lock Dams, NPD Lock = Navigation dams with locks; New Stream-Reach Development (NSD) are greenfield hydropower developments along previously undeveloped waterways.

The cost estimates of these technologies are sourced from publicly available data and can vary significantly based on location and technology assumptions

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