Updated: 2/6/2024

Typical Generation Costs

1. Introduction

New generation must be continuously planned and built to keep pace with load growth and the retirement of old facilities. However, the concern over greenhouse gases has motivated an extremely strong public interest in finding ways to reduce CO_2 emissions, and electric utilities are responding to this interest in various ways.

A few generation technologies promising in reducing carbon emissions are summarized below, in approximate increasing order of LCOE shown in Fig. 1a from 2021 [1], and in Fig. 1b from 2023 [2]. These figures were already seen in "Engineering Economics" notes, pg. 43).

1. Wind
2. Solar PV, utility scale
3. Natural gas combined cycle (NGCC)
4. Geothermal
5. Canadian hydro
6. Nuclear
7. Integrated gasification combined cycle (IGCC) with CCS
8. Pulverized coal (PC) with CCS
9. Concentrated solar (solar thermal tower with storage)

Very important issues for each of these technologies is the capital and operational costs, well quantified by the LCOE. Although Lazard's provides LCOE, it does not publish the capital and O&M costs behind LCOE. There are two main sources used for obtaining this information. These are

1. The US Energy Information Administration (EIA).
2. The NREL Annual Technology Database (ATB).

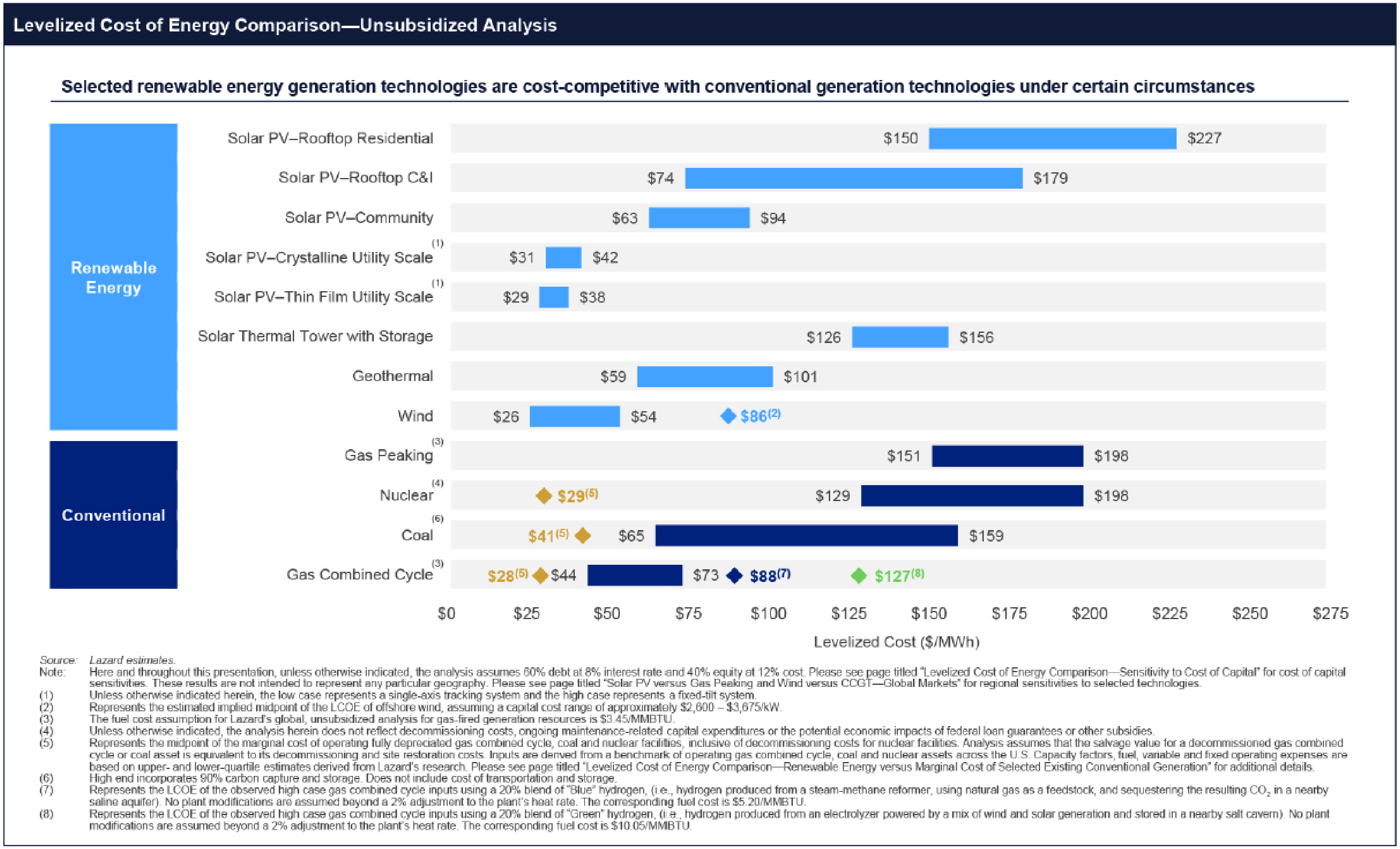


Fig. 1a: Lazard's LCOE Assessment for Generation Technologies, 2020 [1]

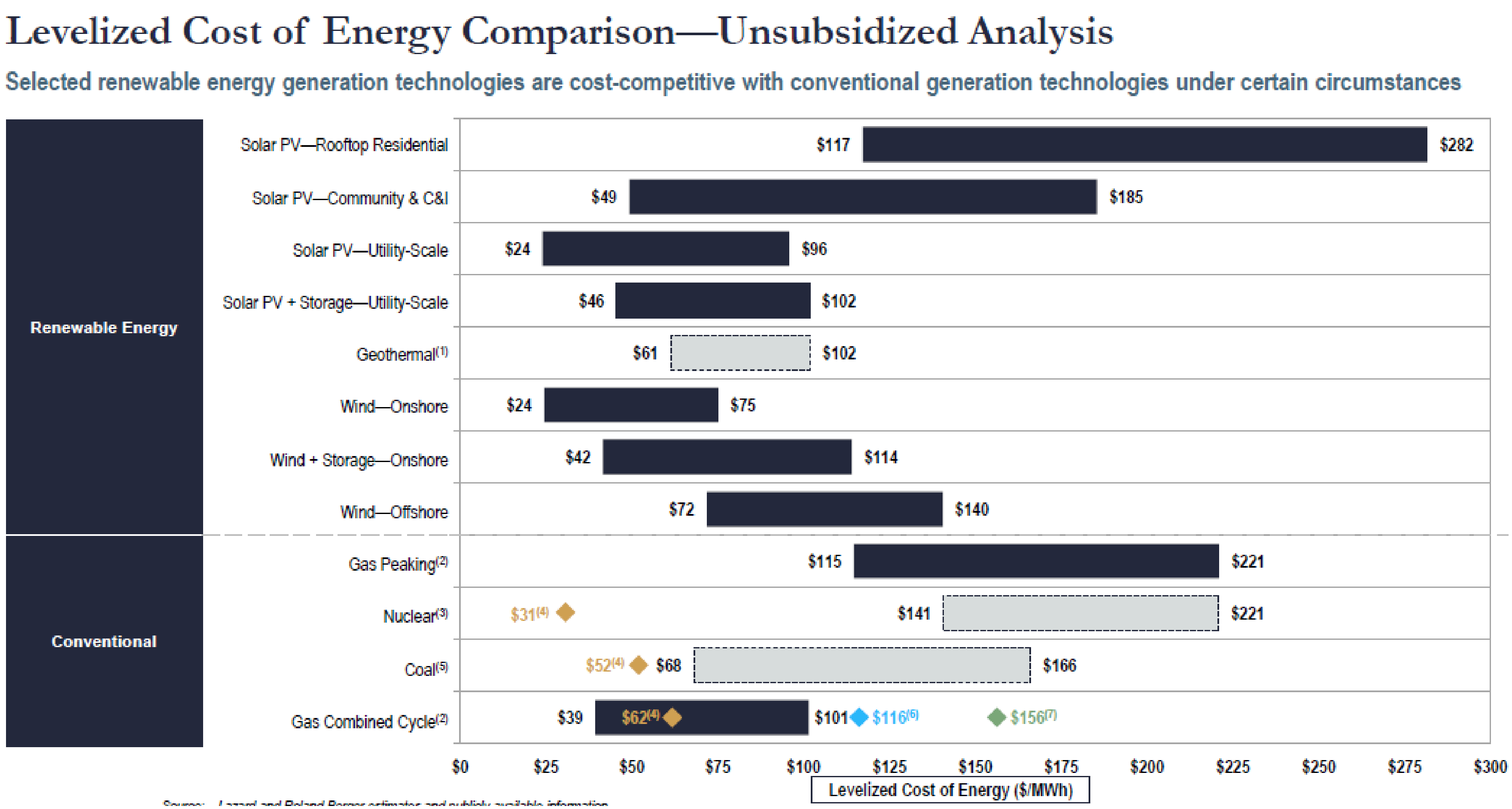


Fig. 1b: Lazard's LCOE Assessment for Generation Technologies, 2023 []

2. EIA data

The DOE EIA provides comprehensive generation capital and O&M data and have been doing so for a number of years. These data are obtained via consulting agencies directly contracted by EIA to develop it. I have included data from 2008 [3], 2010 [4], 2013 [5], 2015 [6], 2020 [7].

Table 1: 2008 Cost of new generation technologies

Technology	Online Year[1]	Size (mW)	Leadtime (Years)	Base Overnight Cost in 2007 ($2006/kW)	Contingency Factors: Project Contingency Factor[2]	Contingency Factors: Technological Optimism Factor[3]	Total Overnight Cost in 2007[4] (2006 $/kW)	Variable O&M[5] ($2006 mills/kWh)	Fixed O&M[5] ($2006/kW)	Heatrate[6] in 2007 (Btu/kWhr)	Heatrate nth-of-a-kind (Btu/kWr)
Scrubbed Coal New[7]	2011	600	4	1,434	1.07	1.00	1,534	4.46	26.79	9,200	8,740
Integrated Coal-Gasification Combined Cycle (IGCC)[7]	2011	550	4	1,657	1.07	1.00	1,773	2.84	37.62	8,765	7,450
IGCC with Carbon Sequestration	2011	380	4	2,302	1.07	1.03	2,537	4.32	44.27	10,781	8,307
Conv Gas/Oil Comb Cycle	2010	250	3	683	1.05	1.00	717	2.01	12.14	7,196	6,800
Adv Gas/Oil Comb Cycle (CC)	2010	400	3	654	1.08	1.00	706	1.95	11.38	6,752	6,333
ADV CC with Carbon Sequestration	2010	400	3	1,254	1.08	1.04	1,409	2.86	19.36	8,613	7,493
Conv Combustion Turbine[8]	2009	160	2	476	1.05	1.00	500	3.47	11.78	10,833	10,450
Adv Combustion Turbine	2009	230	2	450	1.05	1.00	473	3.08	10.24	9,289	8,550
Fuel Cells	2010	10	3	4,653	1.05	1.10	5,374	46.62	5.50	7,930	6,960
Advanced Nuclear	2016	1350	6	2,143	1.10	1.05	2,475	0.48	66.05	10,400	10,400
Distributed Generation -Base	2009	5	2	972	1.05	1.00	1,021	6.93	15.59	9,200	8,900
Distributed Generation -Peak	2010	2	3	1,168	1.05	1.00	1,227	6.93	15.59	10,257	9,880
Biomass	2011	80	4	2,490	1.07	1.05	2,809	6.53	62.70	8,911	8,911
MSW - Landfill Gas	2010	30	3	1,773	1.07	1.00	1,897	0.01	111.15	13,648	13,648
Geothermal[7,9]	2011	50	4	1,057	1.05	1.00	1,110	0.00	160.18	35,376	33,729
Conventional Hydropower[9]	2011	500	4	1,410	1.10	1.00	1,551	3.41	13.59	10,022	10,022
Wind	2010	50	3	1,340	1.07	1.00	1,434	0.00	29.48	10,022	10,022
Wind Offshore	2011	100	4	2,547	1.10	1.03	2,872	0.00	87.05	10,022	10,022
Solar Thermal[7]	2010	100	3	3,499	1.07	1.00	3,744	0.00	55.24	10,022	10,022
Photovoltaic[7]	2009	5	2	5,380	1.05	1.00	5,649	0.00	11.37	10,022	10,022

[1]Online year represents the first year that a new unit could be completed, given an order date of 2007.

[2]A contingency allowance is defined by the American Association of Cost Engineers as the "specific provision for unforeseeable elements if costs within a defined project scope; particularly important where previous experience has shown that unforeseeable events which will increase costs are likely to occur."

[3]The technological optimism factor is applied to the first four units of a new, unproven design. It reflects the demonstrated tendency to underestimate actual costs for a first-of-a-kind unit.

[4]Overnight capital cost including contingency factors, excluding regional multipliers and learning effects. Interest charges are also excluded. These represent costs of new projects initiated in 2007.

[5]O&M = Operations and maintenance.

[6]For hydro, wind, and solar technologies, the heatrate shown represents the average heatrate for conventional thermal generation as of 2006. This is used for purposes of calculating primary energy consumption displaced for these resources, and does not imply an estimate of their actual energy conversion efficiency.

[7]Capital costs are shown before investment tax credits are applied.

[8]Combustion turbine units can be built by the model prior to 2009 if necessary to meet a given region's reserve margin.

[9]Because geothermal and hydro cost and performance characteristics are specific for each site, the table entries represent the cost of the least expensive plant that could be built in the Northwest Power Pool region, where most of the proposed sites are located.

Sources: The values shown in this table are developed by the Energy Information Administration, Office of Integrated Analysis and Forecasting, from analysis of reports and discussions with various sources from industry, government, and the Department of Energy Fuel Offices and National Laboratories. They are not based on any specific technology model, but rather, are meant to represent the cost and performance of typical plants under normal operating conditions for each plant type. Key sources reviewed are listed in the 'Notes and Sources' section at the end of the chapter.

Table 2: 2010 Cost of new generation technologies

Technology	Online Year[1]	Size (mW)	Leadtime (Years)	Base Overnight Cost in 2009 ($2008/kW)	Contingency Factors: Project Contingency Factor[2]	Contingency Factors: Technological Optimism Factor[3]	Total Overnight Cost in 2009[4] (2008 $/kW)	Variable O&M[5] ($2008 mills/kWh)	Fixed O&M[5] ($2008/kW)	Heatrate[6] in 2009 (Btu/kWhr)	Heatrate nth-of-a-kind (Btu/kWr)
Scrubbed Coal New[7]	2013	600	4	2,078	1.07	1.00	2,223	4.69	28.15	9,200	8,740
Integrated Coal-Gasification Combined Cycle (IGCC)[7]	2013	550	4	2,401	1.07	1.00	2,569	2.99	39.53	8,765	7,450
IGCC with Carbon Sequestration	2016	380	4	3,427	1.07	1.03	3,776	4.54	47.15	10,781	8,307
Conv Gas/Oil Comb Cycle	2012	250	3	937	1.05	1.00	984	2.11	12.76	7,196	6,800
Adv Gas/Oil Comb Cycle (CC)	2012	400	3	897	1.08	1.00	968	2.04	11.96	6,752	6,333
ADVCC with Carbon Sequestion	2016	400	3	1,720	1.08	1.04	1,932	3.01	20.35	8,613	7,493
Conv Combustion Turbine[8]	2011	160	2	653	1.05	1.00	685	3.65	12.38	10,788	10,450
Adv Combustion Turbine	2011	230	2	617	1.05	1.00	648	3.24	10.77	9,289	8,550
Fuel Cells	2012	10	3	4,744	1.05	1.10	5,478	49.00	5.78	7,930	6,960
Advanced Nuclear	2016	1350	6	3,308	1.10	1.05	3,820	0.51	92.04	10,488	10,488
Distributed Generation-Base	2012	2	3	1,334	1.05	1.00	1,400	7.28	16.39	9,050	8,900
Distributed Generation-Peak	2011	1	2	1,601	1.05	1.00	1,681	7.28	16.39	10,069	9,880
Biomass	2013	80	4	3,414	1.07	1.05	3,849	6.86	65.89	9,451	7,765
Geothermal[7,9]	2010	50	4	1,666	1.05	1.00	1,749	0.00	168.33	32,969	30,326
MSW - Landfill Gas	2010	30	3	2,430	1.07	1.00	2,599	0.01	116.80	13,648	13,648
Conventional Hydropower[9]	2013	500	4	2,084	1.10	1.00	2,291	2.49	13.93	9,884	9,884
Wind	2009	50	3	1,837	1.07	1.00	1,966	0.00	30.98	9,884	9,884
Wind Offshore	2013	100	4	3,492	1.10	1.02	3,937	0.00	86.92	9,884	9,884
Solar Thermal[7]	2012	100	3	4,798	1.07	1.00	5,132	0.00	58.05	9,884	9,884
Photovoltaic[7]	2011	5	2	5,879	1.05	1.00	6,171	0.00	11.94	9,884	9,884

[1]Online year represents the first year that a new unit could be completed, given an order date of 2009. For wind, geothermal and landfill gas, the online year was moved earlier to acknowledge the significant market activity already occuring in anticipation of the expiration of the Production Tax Credit.

[2]A contingency allowance is defined by the American Association of Cost Engineers as the "specific provision for unforeseeable elements if costs within a defined project scope; particularly important where previous experience has shown that unforeseeable events which will increase costs are likely to occur."

[3]The technological optimism factor is applied to the first four units of a new, unproven design. It reflects the demonstrated tendency to underestimate actual costs for a first-of-a-kind unit.

[4]Overnight capital cost including contingency factors, excluding regional multipliers and learning effects. Interest charges are also excluded. These represent costs of new projects initiated in 2009.

[5]O&M = Operations and maintenance.

[6]For hydro, wind, and solar technologies, the heatrate shown represents the average heatrate for conventional thermal generation as of 2008. This is used for purposes of calculating primary energy consumption displaced for these resources, and does not imply an estimate of their actual energy conversion efficiency.

[7]Capital costs are shown before investment tax credits are applied.

[8]Combustion turbine units can be built by the model prior to 2011 if necessary to meet a given region's reserve margin.

[9]Because geothermal and hydro cost and performance characteristics are specific for each site, the table entries represent the cost of the least expensive plant that could be built in the Northwest Power Pool region, where most of the proposed sites are located.

Sources: The values shown in this table are developed by the Energy Information Administration, Office of Integrated Analysis and Forecasting, from analysis of reports and discussions with various sources from industry, government, and the Department of Energy Fuel Offices and National Laboratories. They are not based on any specific technology model, but rather, are meant to represent the cost and performance of typical plants under normal operating conditions for each plant type. Key sources reviewed are listed in the "Notes and Sources" section at the end of the chapter.

Table 3: 2013 Cost of new generation technologies

	Plant Characteristics		Plant Costs (2012$)			
	Nominal Capacity (MW)	Heat Rate (Btu/kWh)	Overnight Capital Cost ($/kW)	Fixed O&M Cost ($/kW-yr)	Variable O&M Cost ($/MWh)	NEMS Input
Coal						
Single Unit Advanced PC	650	8,800	$3,246	$37.80	$4.47	N
Dual Unit Advanced PC	1,300	8,800	$2,934	$31.18	$4.47	Y
Single Unit Advanced PC with CCS	650	12,000	$5,227	$80.53	$9.51	Y
Dual Unit Advanced PC with CCS	1,300	12,000	$4,724	$66.43	$9.51	N
Single Unit IGCC	600	8,700	$4,400	$62.25	$7.22	N
Dual Unit IGCC	1,200	8,700	$3,784	$51.39	$7.22	Y
Single Unit IGCC with CCS	520	10,700	$6,599	$72.83	$8.45	N
Natural Gas						
Conventional CC	620	7,050	$917	$13.17	$3.60	Y
Advanced CC	400	6,430	$1,023	$15.37	$3.27	Y
Advanced CC with CCS	340	7,525	$2,095	$31.79	$6.78	Y
Conventional CT	85	10,850	$973	$7.34	$15.45	Y
Advanced CT	210	9,750	$676	$7.04	$10.37	Y
Fuel Cells	10	9,500	$7,108	$0.00	$43.00	Y
Uranium						
Dual Unit Nuclear	2,234	N/A	$5,530	$93.28	$2.14	Y
Biomass						
Biomass CC	20	12,350	$8,180	$356.07	$17.49	N
Biomass BFB	50	13,500	$4,114	$105.63	$5.26	Y
Wind						
Onshore Wind	100	N/A	$2,213	$39.55	$0.00	Y
Offshore Wind	400	N/A	$6,230	$74.00	$0.00	Y
Solar						
Solar Thermal	100	N/A	$5,067	$67.26	$0.00	Y
Photovoltaic	20	N/A	$4,183	$27.75	$0.00	N
Photovoltaic	150	N/A	$3,873	$24.69	$0.00	Y
Geothermal						
Geothermal – Dual Flash	50	N/A	$6,243	$132.00	$0.00	N
Geothermal – Binary	50	N/A	$4,362	$100.00	$0.00	N
Municipal Solid Waste						
Municipal Solid Waste	50	18,000	$8,312	$392.82	$8.75	N
Hydroelectric						
Conventional Hydroelectric	500	N/A	$2,936	$14.13	$0.00	N
Pumped Storage	250	N/A	$5,288	$18.00	$0.00	N

Table 4: 2015 Cost of new generation technologies

Technology	Online Year[1]	Size (MW)	Lead time (years)	Base Overnight Cost in 2014 (2013 $/kW)	Project Contin-gency Factor[2]	Techno-logical Optimism Factor[3]	Total Overnight Cost in 2014[4] (2013 $/kW)	Variable O&M[5] (2013 $/mWh)	Fixed O&M (2013 $/ kW/yr.)	Heatrate [6] in 2014 (Btu/ kWh)
Scrubbed Coal New	2018	1300	4	2,726	1.07	1.00	2,917	4.47	31.16	8,800
Coal-Gasification Integrated Comb Cycle (IGCC)	2018	1200	4	3,483	1.07	1.00	3,727	7.22	51.37	8,700
IGCC with Carbon sequestion	2018	520	4	5,891	1.07	1.03	6,492	8.44	72.80	10,700
Conv Gas/Oil Comb Cycle	2017	620	3	869	1.05	1.00	912	3.60	13.16	7,050
Adv Gas/Oil Comb Cycle (CC)	2017	400	3	942	1.08	1.00	1,017	3.27	15.36	6,430
Adv CC with Carbon sequestration	2017	340	3	1,845	1.08	1.04	2,072	6.78	31.77	7,525
Conv Comb Turbine[8]	2016	85	2	922	1.05	1.00	968	15.44	7.34	10,783
Adv Comb Turbine	2016	210	2	639	1.05	1.00	671	10.37	7.04	9,750
Fuel Cells	2017	10	3	6,042	1.05	1.10	6,978	42.97	0.00	9,500
Adv Nuclear	2022	2234	6	4,646	1.10	1.05	5,366	2.14	93.23	10,479
Distributed Generation-Base	2017	2	3	1,407	1.05	1.00	1,477	7.75	17.44	9,015
Distributed Generation - Peak	2016	1	2	1,689	1.05	1.00	1,774	7.75	17.44	10,015
Biomass	2018	50	4	3,399	1.07	1.01	3,659	5.26	105.58	13,500
Geothermal[7,9]	2018	50	4	2,331	1.05	1.00	2,448	0.00	112.85	9,516
Municipal Solid Waste Conventional	2017	50	3	7,730	1.07	1.00	8,271	8.74	392.60	14,878
Hydropower[9]	2018	500	4	2,410	1.10	1.00	2,651	5.76	15.15	9,516
Wind	2017	100	3	1,850	1.07	1.00	1,980	0.00	39.53	9,516
Wind Offshore	2018	400	4	4,476	1.10	1.25	6,154	0.00	73.96	9,516
Solar Thermal[7]	2017	100	3	3,787	1.07	1.00	4,052	0.00	67.23	9,516
Photovoltaic[7,10]	2016	150	2	3,123	1.05	1.00	3,279	0.00	24.68	9,516

Table 5: 2020 Cost of new generation technologies

Technology	First available year[1]	Size (MW)	Lead time (years)	Base overnight cost[2] (2020 $/kW)	Techno-logical optimism factor[3]	Total overnight cost[4,5] (2020 $/kW)	Variable O&M[6] (2020 $/MWh)	Fixed O&M (2020$/ kW-yr)	Heat rate[7] (Btu/kWh)
Ultra-supercritical coal (USC)	2024	650	4	3,672	1.00	3,672	4.52	40.79	8,638
USC with 30% carbon capture and sequestration (CCS)	2024	650	4	4,550	1.01	4,595	7.11	54.57	9,751
USC with 90% CCS	2024	650	4	5,861	1.02	5,978	11.03	59.85	12,507
Combined-cycle—single shaft	2023	418	3	1,082	1.00	1,082	2.56	14.17	6,431
Combined-cycle—multi shaft	2023	1,083	3	957	1.00	957	1.88	12.26	6,370
Combined-cycle with 90% CCS	2023	377	3	2,471	1.04	2,570	5.87	27.74	7,124
Internal combustion engine	2022	21	2	1,813	1.00	1,813	5.72	35.34	8,295
Combustion turbine—aeroderivative[8]	2022	105	2	1,169	1.00	1,169	4.72	16.38	9,124
Combustion turbine—industrial frame	2022	237	2	709	1.00	709	4.52	7.04	9,905
Fuel cells	2023	10	3	6,277	1.09	6,866	0.59	30.94	6,469
Nuclear—light water reactor	2026	2,156	6	6,034	1.05	6,336	2.38	122.26	10,455
Nuclear—small modular reactor	2028	600	6	6,183	1.10	6,802	3.02	95.48	10,455
Distributed generation—base	2023	2	3	1,560	1.00	1,560	8.65	19.46	8,935
Distributed generation—peak	2022	1	2	1,874	1.00	1,874	8.65	19.46	9,921
Battery storage	2021	50	1	1,165	1.00	1,165	0.00	24.93	NA
Biomass	2024	50	4	4,077	1.00	4,078	4.85	126.36	13,500
Geothermal[9,10]	2024	50	4	2,772	1.00	2,772	1.17	137.50	8,946
Municipal solid waste—landfill gas	2023	36	3	1,566	1.00	1,566	6.23	20.20	8,513
Conventional hydropower[10]	2024	100	4	2,769	1.00	2,769	1.40	42.01	NA
Wind[5]	2023	200	3	1,846	1.00	1,846	0.00	26.47	NA
Wind offshore[9]	2024	400	4	4,362	1.25	5,453	0.00	110.56	NA
Solar thermal[9]	2023	115	3	7,116	1.00	7,116	0.00	85.82	NA
Solar photovoltaic (PV) with tracking[5,9,11]	2022	150	2	1,248	1.00	1,248	0.00	15.33	NA
Solar PV with storage[9,11]	2022	150	2	1,612	1.00	1,612	0.00	32.33	NA

[1] Represents the first year that a new unit could become operational.
[2] Base cost includes project contingency costs.
[3] The technological optimism factor is applied to the first four units of a new, unproven design; it reflects the demonstrated tendency to underestimate actual costs for a first-of-a-kind unit.
[4] Overnight capital cost includes contingency factors and excludes regional multipliers (except as noted for wind and solar PV) and learning effects. Interest charges are also excluded. The capital costs represent current costs for plants that would come online in 2021.
[5] Total overnight cost for ind and solar PV technologies in the table are the average input value across all 25 electricity market regions, as weighted by the respective capacity of that type installed during 2019 in each region to account for the substantial regional variation in wind and solar costs (as shown in Table 4). The input value used for onshore wind in AEO2021 was $1,268 per kilowatt (kW), and for solar PV with tracking it was $1,232/kW, which represents the cost of building a plant excluding regional factors. Region-specific factors contributing to the substantial regional variation in cost include differences in typical project size across regions, accessibility of resources, and variation in labor and other construction costs throughout the country.
[6] O&M = Operations and maintenance.
[7] The nuclear average heat rate is the weighted average tested heat rate for nuclear units as reported on the Form EIA-860, *Annual Electric Generator Report*. No heat rate is reported for battery storage because it is not a primary conversion technology; conversion losses are accounted for when the electricity is first generated; electricity-to-storage losses are accounted for through the additional demand for electricity required to meet load. For hydropower, wind, solar, and geothermal technologies, no heat rate is reported because the power is generated without fuel combustion and no set British thermal unit conversion factors exist. The model calculates the average heat rate for fossil-fuel generation in each year to report primary energy consumption displaced for these resources.
[8] Combustion turbine aeroderivative units can be built by the model before 2022, if necessary, to meet a region's reserve margin.
[9] Capital costs are shown before investment tax credits are applied.
[10] Because geothermal and hydropower cost and performance characteristics are specific for each site, the table entries show the cost of the least expensive plant that could be built in the Northwest region for hydro and Great Basin region for geothermal, where most of the proposed sites are located.
[11] Costs and capacities are expressed in terms of net AC (alternating current) power available to the grid for the installed capacity.
Sources: Input costs are primarily based on a report provided by external consultants: Sargent & Lundy, December 2019. Hydropower site costs for non-powered dams were most recently updated for AEO2018 using data from Oak Ridge National Lab

Table 6: 2023 Cost of new generation technologies

Technology	First available year[a]	Size (MW)	Lead time (years)	Base overnight cost[b] (2022$/ kW)	Techno-logical optimism factor[c]	Total overnight cost[d,e] (2022$/kW)	Variable O&M[f] (2022$/ MWh)	Fixed O&M (2022$/ kWy)	Heat rate[g] (Btu/kWh)
Ultra-supercritical coal (USC)	2026	650	4	$4,507	1.00	$4,507	$5.06	$45.68	8,638
USC with 30% carbon capture and sequestration (CCS)	2026	650	4	$5,577	1.01	$5,633	$7.97	$61.11	9,751
USC with 90% CCS	2026	650	4	$7,176	1.02	$7,319	$12.35	$67.02	12,507
Combined-cycle—single-shaft	2025	418	3	$1,330	1.00	$1,330	$2.87	$15.87	6,431
Combined-cycle—multi-shaft	2025	1,083	3	$1,176	1.00	$1,176	$2.10	$13.73	6,370
Combined-cycle with 90% CCS	2025	377	3	$3,019	1.04	$3,140	$6.57	$31.06	7,124
Internal combustion engine	2024	21	2	$2,240	1.00	$2,240	$6.40	$39.57	8,295
Combustion turbine—aeroderivative[h]	2024	105	2	$1,428	1.00	$1,428	$5.29	$18.35	9,124
Combustion turbine—industrial frame	2024	237	2	$867	1.00	$867	$5.06	$7.88	9,905
Fuel cells	2025	10	3	$6,771	1.08	$7,291	$0.66	$34.65	6,469
Nuclear—light water reactor	2028	2,156	6	$7,406	1.05	$7,777	$2.67	$136.91	10,447
Nuclear—small modular reactor	2028	600	6	$7,590	1.10	$8,349	$3.38	$106.92	10,447
Distributed generation—base	2025	2	3	$1,915	1.00	$1,915	$9.69	$21.79	8,912
Distributed generation—peak	2024	1	2	$2,300	1.00	$2,300	$9.69	$21.79	9,894
Battery storage	2023	50	1	$1,270	1.00	$1,270	$0.00	$45.76	NA
Biomass	2026	50	4	$4,996	1.00	$4,998	$5.44	$141.50	13,500
Geothermal[i, j]	2026	50	4	$3,403	1.00	$3,403	$1.31	$153.98	8,881
Conventional hydropower[j]	2026	100	4	$3,421	1.00	$3,421	$1.57	$47.06	NA
Wind[e]	2025	200	3	$2,098	1.00	$2,098	$0.00	$29.64	NA
Wind offshore[i]	2026	400	4	$5,338	1.25	$6,672	$0.00	$123.81	NA
Solar thermal[i]	2025	115	3	$8,732	1.00	$8,732	$0.00	$96.10	NA
Solar photovoltaic (PV) with tracking[e, i, k]	2024	150	2	$1,448	1.00	$1,448	$0.00	$17.16	NA
Solar PV with storage[i, k]	2024	150	2	$1,808	1.00	$1,808	$0.00	$32.42	NA

The overnight cost data of Tables 1-6 have been summarized in Table 7.

Table 7: Summary of data in Tables 1-6

	Base Overnight Cost $/kW)					
Technology	**2008 (2006$)**	**2010 (2008$)**	**2013 (2012$)**	**2015 (2013$)**	**2020 (2020$)**	**2023 (2023$)**
Ultra-critical coal	1434	2078	2934	2726	3672	4507
IGCC	1657	2461	3784	3483		
IGCC with CCS	2302	3427	6599	5891		
Conv Gas Oil CC (multishaft)	683	937	917	869	957	
Adv Gas/Oil CC	654	897	1023	942		
Adv CC with CCS	1254	1720	2095	1845		3140
Conv CT - aeroderivative	476	653	973	922	1169	1428
Adv CT - industrial frame	450	617	676	639	709	867
Nuclear -small modular reactor						8349
Adv Nuclear - lite watr reactor	2143	3308	5530	4646	6336	7777
Geothermal	1057	1666	4362	2331	2772	3403
Wind onshore	1340	1837	2213	1850	1268	2098
Wind offshore	2547	3492	6230	4476	5453	6672
Solar thermal	3499	4798	5067	3787	7116	8732
Solar PV with tracking	5380	5879	3873	3123	1248	1448

Fig. 2 illustrates these data. Some caveats:

- The first bar is 2008 report, the second is 2010 report, the third is 2013 report, the fourth is 2015 report, the fifth is 2020 report. The sixth is 2023 report.
- The data are in current (nominal) dollars in the given year and so reflect the effect of inflation (particularly salient when comparing 2023 figures to those of previous years).
- It is clear that
    - solar thermal, advanced nuclear, small modular reactors, and IGCC with CCS have the highest overnight costs;
    - combined cycle technologies, followed by combustion turbines, then onshore wind, and more recently, solar PV (utility scale), have the lowest overnight costs.

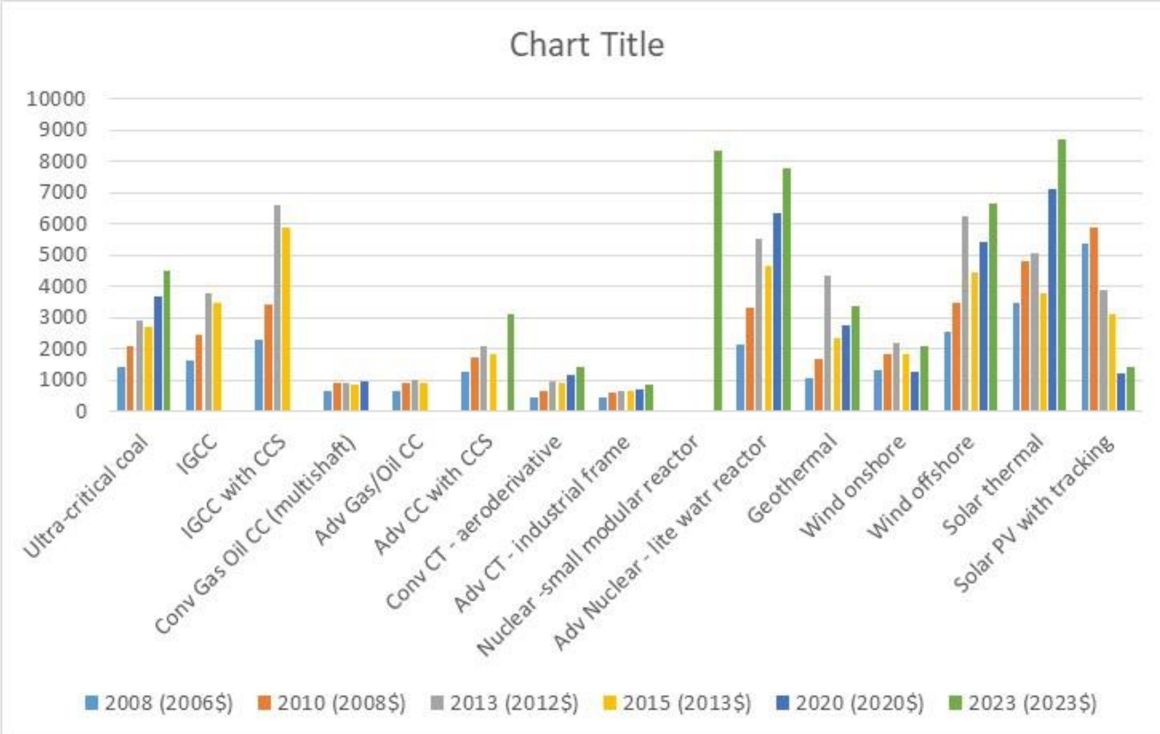
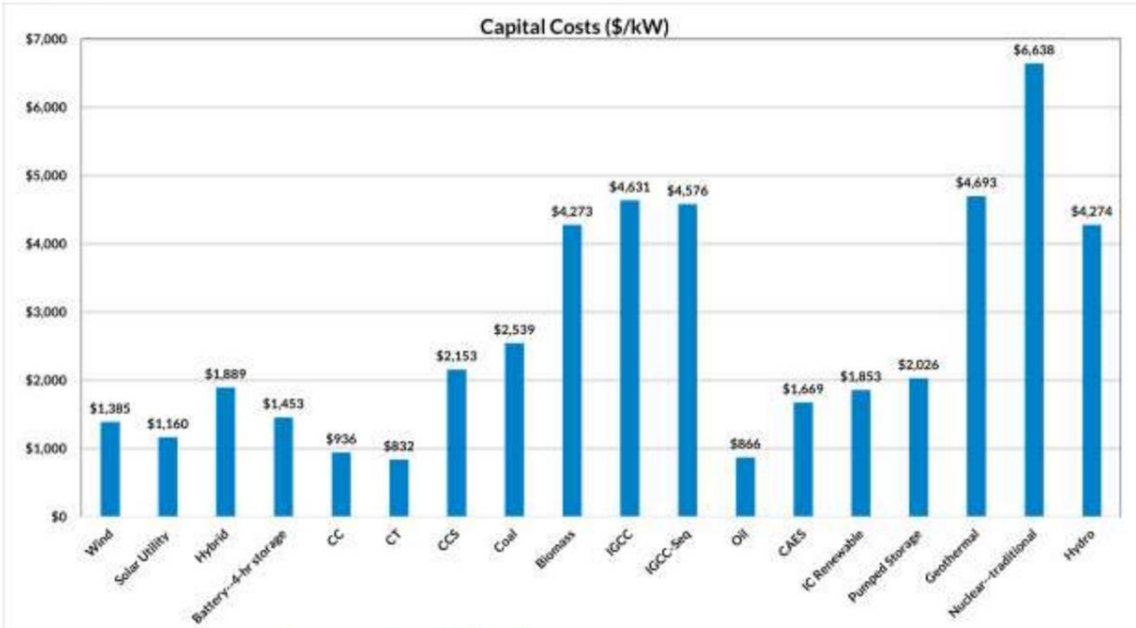


Fig. 2: Summary of EIA generation overnight cost data 2008-2023

3. NREL Annual Technology Baseline (ATB)

The NREL ATB database [8] is heavily used by people from all over the world. The Mid-Continent Independent System Operator (MISO) uses it in their planning studies; see, for example, Appendix E of the MTEP 2020 [9], and also MISO's 2023 Futures Report [10], where, on p. 109, the text and figure of Fig. 3a is presented.

MISO used the 2022 National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB).[47] to calculate the capital costs for all resources except for oil,.[48] compressed air energy storage (CAES),.[49] and internal combustion (IC) renewable.[50] costs. MISO utilized moderate cost values within the 2022 ATB, which are in 2020 dollars. These values were converted to 2022 dollars and projected into the 20-year study period to create cost trajectories. For Hybrid unit costs, 2022 ATB Solar PV + Battery costs are included.



All relevant resource types are presented prior to factoring in the effects of the PTC and ITC.

Fig 3a: ATB overnight cost data presented in MISO report [10]

There is some overlap between NREL ATB and the EIA data mentioned in Section 2, but this overlap is mainly confined to the fossil, nuclear, and biopower cost estimates. Cost estimates for renewables are developed by the ATB team at NREL; sources used in this development effort can be found at https://atb.nrel.gov/electricity/2023/approach_&_methodology.

The NREL ATB data can be accessed at

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

in any of several forms.

1. ***<u>LCOE data</u>***: LCOE ranges may be obtained, similar to that of what Lazards (see Fig. 1) provides, as indicated in Fig. 3b (for 2018) and Fig. 3c (for 2021).

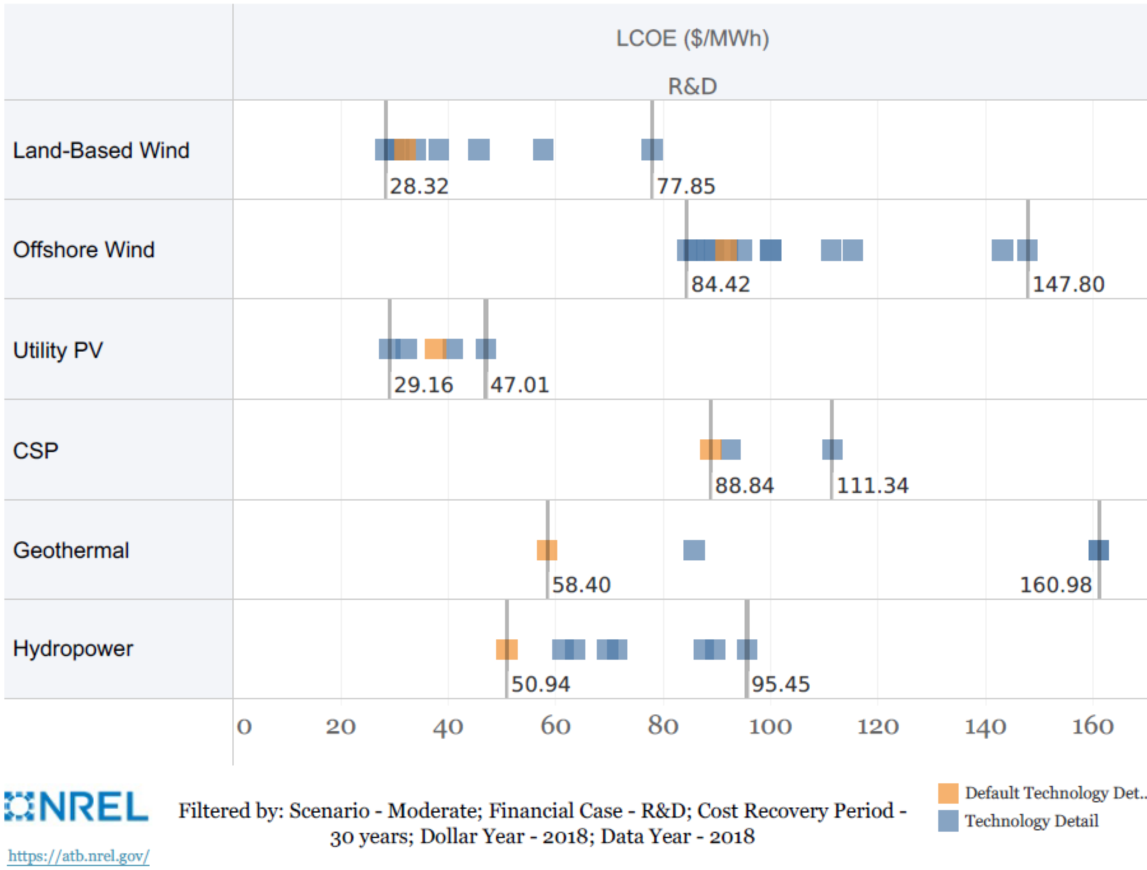


Fig. 3b: NREL LCOE ranges, 2018

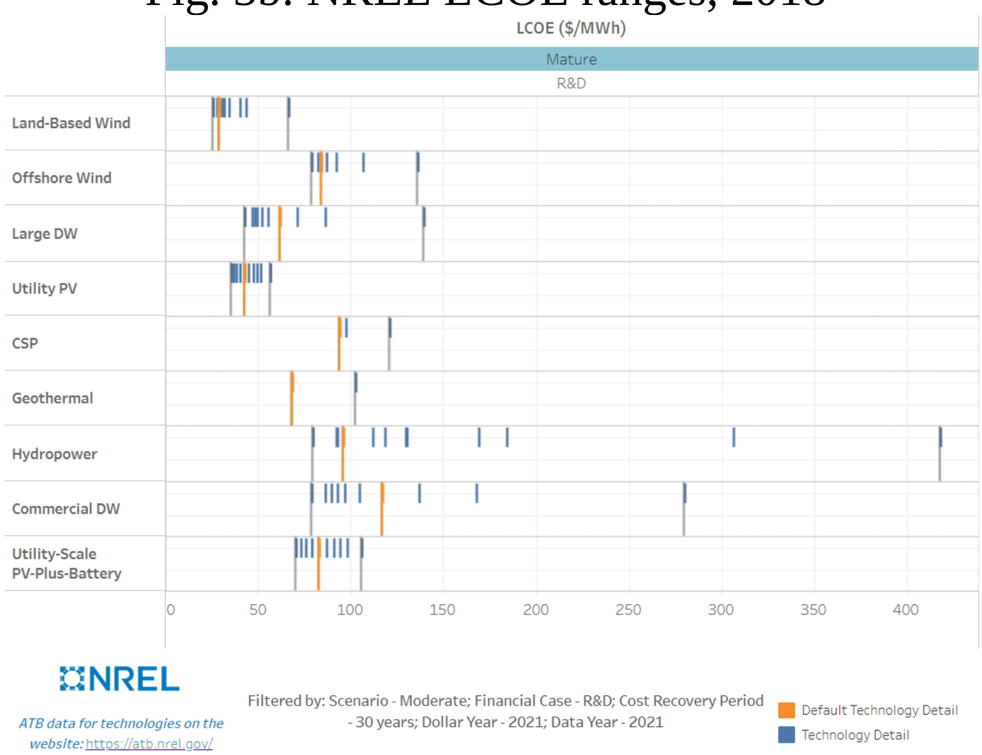


Fig. 3c: NREL LCOE ranges, 2021

2. ***Report-like form***: A textual report-like treatment of data for each technology may be obtained, see https://atb.nrel.gov/electricity/2023/land-based_wind.
For example, when we click to see the "Land-based wind," several pages of descriptive text, plots, and tables become available. I have copied into Fig. 4a below a portion of this report-like material for "Land-based wind" data retrieved in 2021, and I have copied into Fig. 4b below a portion of this report-like material for "Land-based wind" data retrieved in 2024.

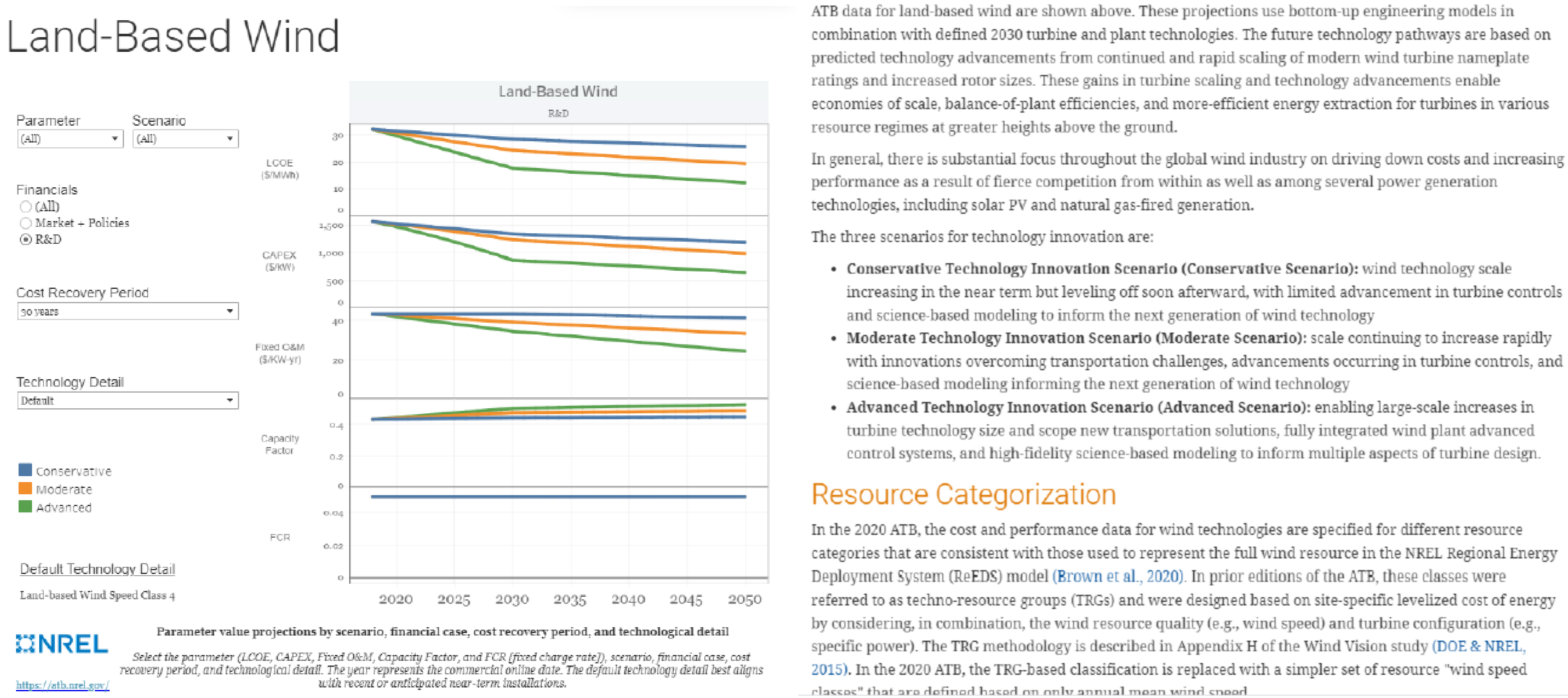
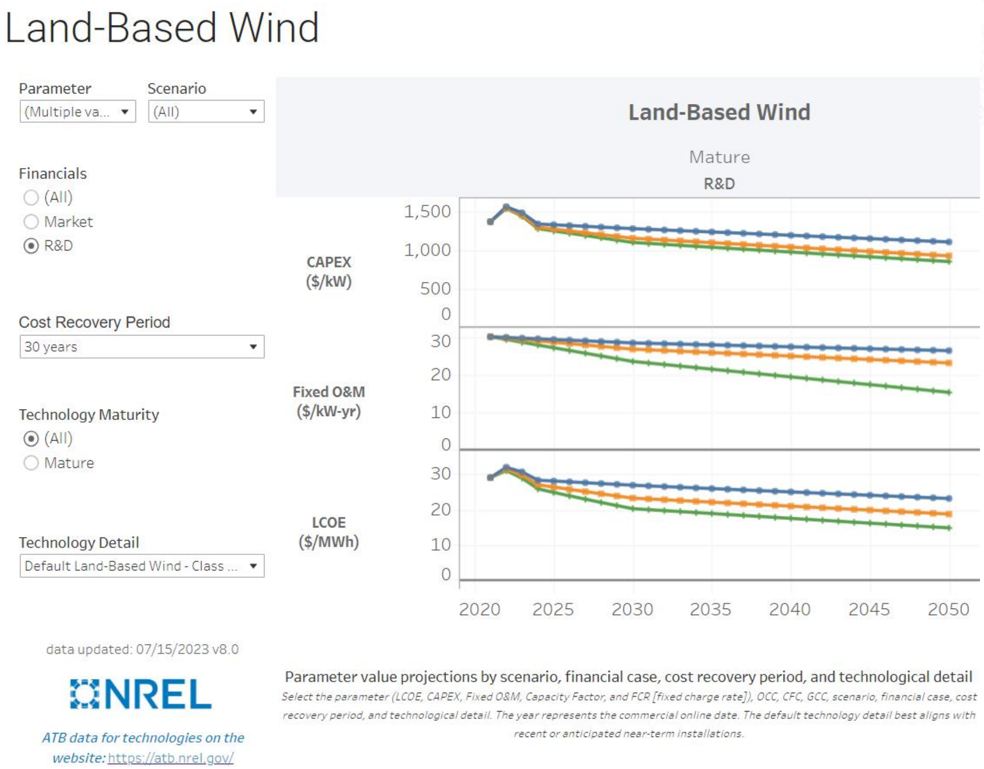


Fig. 4a: Report-like information for land-based wind (retrieved in 2021)



2023 ATB data for land-based wind are shown above. These projections use bottom-up engineering models in combination with representative 2030 wind turbine and plant technologies. The predicted future technology pathways are based on a series of innovations to overcome transportation challenges, advance wind turbine controls, and apply science-based modeling for next-generation wind turbines. These technology advancements enable economies of scale, balance-of-plant efficiencies, and more-efficient energy extraction for various turbine configurations in different wind resource regimes. Details on the representative 2030 wind turbines characteristics are presented in the Representative Technology section of this page.

Scenario Descriptions

The 2023 ATB scenarios are different from the methods used in previous editions of the ATB. In prior editions, each scenario for land-based wind assumed one wind turbine technology characterization and projected innovations to overcome transportation challenges, advance wind turbine controls, and increase adoption of science-based modeling. In the 2023 ATB, multiple wind turbine technology configurations are developed separately, which allows for different technologies to be used within each scenario.

The scenarios now consider four different technology configurations (see the Representative Technology section of this page for details) each with three cost and performance projections:

- **Conservative Cost and Performance Scenario (Conservative Scenario):** Cost and performance trajectories for each technology are based on conservative historical learning rates. Learning rates for capital expenditures vary by technology based on the Moderate Scenario's bottom-up engineering-based cost modeling of each technology in 2030.
- **Moderate Cost and Performance Scenario (Moderate Scenario):** From 2021 to 2030, cost and performance trajectories for each technology are based on bottom-up scaling relationships and process-based balance-of-system and turbine component cost models for each technology in 2021 and 2030. From 2030 to 2050, cost and performance trajectories for each technology are based on moderate historical learning rates.
- **Advanced Cost and Performance Scenario (Advanced Scenario):** Cost and performance trajectories for each technology are based on aggressive historical learning rates. Learning rates for capital expenditures vary by technology based on the Moderate Scenario's bottom-up engineering-based cost modeling of each technology in 2030.

Fig. 4b: Report-like information for land-based wind (retrieved in 2024)

3. ***Spread-sheet form***: All technology data is available within a ~5MB Excel file containing 25 separate worksheets. The names of these worksheets are:
   i. Preface and contents
   ii. Financial definitions
   iii. Financial and CRP inputs
   iv. Land-based wind
   v. Offshore wind
   vi. Distributed wind
   vii. Solar – Utility PV
   viii. Solar – PV Distributed Commercial
   ix. Solar – PV Distributed Residential
   x. Solar – CSP
   xi. Geothermal
   xii. Hydropower
   xiii. Coal_FE
   xiv. Natural gas_FE
   xv. Natural Gas Fuel Cell_FE
   xvi. Coal retrofits
   xvii. Natural gas retrofits
   xviii. Utility scale battery storage
   xix. Commercial battery storage
   xx. Residential battery storage
   xxi. Utility scale PV-plus battery
   xxii. Pumped storage hydropower
   xxiii. WACC Calculation
   xxiv. Tax credits
   xxv. Summary
   xxvi. Summary CAPEX
   xxvii. Summary Capacity Factor
   xxviii. Summary FCR
   xxix. Summary LCOE
   xxx. Summary FOM
   xxxi. Summary VOM
   xxxii. Summary Fuel
   xxxiii. LCOE Range

4. Last comments

4.1. Last comments - generation technologies

A useful document on costs of new fossil-fired generation technologies, developed using the modeling software Aspen [11], and published in 2007, can be found at [12]. A summary table from this document is given below as Table 10. Though dated, there are two points to this data that are still relevant today:

1. CCS is expensive. Comparing columns 1 and 2 data, 3 and 4 data, and so on, provides insight into the impact of CCS. Although CCS significantly reduces CO_2 emissions for all plant types, it requires (i) reduction in net power output (capacity); (ii) reduction in efficiency (increase in heatrate); (iii) increase in water usage; (iv) increase in LCOE; (v) increase in "total plant cost" (this is the capital cost).
2. Modeling software (Aspen in this case) for techno-economic modeling of this nature is very available, although it requires significant power plant knowledge and start-up time to learn it. Its power is that it provides ability to perform rigorous cost analysis before actually investing in that technology.

Table 10: Cost, Performance, and Environmental Summary

	Integrated Gasification Combined Cycle						Pulverized Coal Boiler				NGCC	
	GEE		CoP		Shell		PC Subcritical		PC Supercritical		Advanced F Class	
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14
CO_2 Capture	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Gross Power Output (kW_e)	770,350	744,960	742,510	693,840	748,020	693,555	583,315	679,923	580,260	663,445	570,200	520,090
Auxiliary Power Requirement (kW_e)	130,100	189,285	119,140	175,600	112,170	176,420	32,870	130,310	30,110	117,450	9,840	38,200
Net Power Output (kW_e)	640,250	555,675	623,370	518,240	635,850	517,135	550,445	549,613	550,150	545,995	560,360	481,890
Coal Flowrate (lb/hr)	489,634	500,379	463,889	477,855	452,620	473,176	437,699	646,589	411,282	586,627	N/A	N/A
Natural Gas Flowrate (lb/hr)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	165,182	165,182
HHV Thermal Input (kW_{th})	1,674,044	1,710,780	1,586,023	1,633,771	1,547,493	1,617,772	1,496,479	2,210,668	1,406,161	2,005,660	1,103,363	1,103,363
Net Plant HHV Efficiency (%)	38.2%	32.5%	39.3%	31.7%	41.1%	32.0%	36.8%	24.9%	39.1%	27.2%	50.8%	43.7%
Net Plant HHV Heat Rate (Btu/kW-hr)	8,922	10,505	8,681	10,757	8,304	10,674	9,276	13,724	8,721	12,534	6,719	7,813
Raw Water Usage, gpm	4,003	4,579	3,757	4,135	3,792	4,563	6,212	12,187	5,441	10,444	2,511	3,901
Total Plant Cost ($ x 1,000)	1,160,919	1,328,209	1,080,166	1,259,883	1,256,810	1,379,524	852,612	1,591,277	866,391	1,567,073	310,710	564,628
Total Plant Cost ($/kW)	1,813	2,390	1,733	2,431	1,977	2,668	1,549	2,895	1,575	2,870	554	1,172
LCOE (mills/kWh)[1]	78.0	102.9	75.3	105.7	80.5	110.4	64.0	118.8	63.3	114.8	68.4	97.4
CO_2 Emissions (lb/hr)	1,123,781	114,476	1,078,144	131,328	1,054,221	103,041	1,038,110	152,975	975,370	138,681	446,339	44,634
CO_2 Emissions (tons/year) @ CF[1]	3,937,728	401,124	3,777,815	460,175	3,693,990	361,056	3,864,884	569,524	3,631,301	516,310	1,661,720	166,172
CO_2 Emissions (tonnes/year) @ CF[1]	3,572,267	363,896	3,427,196	417,466	3,351,151	327,546	3,506,185	516,667	3,294,280	468,392	1,507,496	150,750
CO_2 Emissions (lb/MMBtu)	197	19.6	199	23.6	200	18.7	203	20.3	203	20.3	119	11.9
CO_2 Emissions (lb/MWh)[2]	1,459	154	1,452	189	1,409	149	1,780	225	1,681	209	783	85.8
CO_2 Emissions (lb/MWh)[3]	1,755	206	1,730	253	1,658	199	1,886	278	1,773	254	797	93
SO_2 Emissions (lb/hr)	73	56	68	48	55	58	433	Negligible	407	Negligible	Negligible	Negligible
SO_2 Emissions (tons/year) @ CF[1]	254	196	237	167	194	204	1,613	Negligible	1,514	Negligible	Negligible	Negligible
SO_2 Emissions (tonnes/year) @ CF[1]	231	178	215	151	176	185	1,463	Negligible	1,373	Negligible	Negligible	Negligible
SO_2 Emissions (lb/MMBtu)	0.0127	0.0096	0.0125	0.0085	0.0105	0.0105	0.0848	Negligible	0.0847	Negligible	Negligible	Negligible
SO_2 Emissions (lb/MWh)[2]	0.0942	0.0751	0.0909	0.0686	0.0739	0.0837	0.7426	Negligible	0.7007	Negligible	Negligible	Negligible
NOx Emissions (lb/hr)	313	273	321	277	309	269	357	528	336	479	34	34
NOx Emissions (tons/year) @ CF[1]	1,096	955	1,126	972	1,082	944	1,331	1,966	1,250	1,784	127	127
NOx Emissions (tonnes/year) @ CF[1]	994	867	1,021	882	982	856	1,207	1,783	1,134	1,618	115	115
NOx Emissions (lb/MMBtu)	0.055	0.047	0.059	0.050	0.058	0.049	0.070	0.070	0.070	0.070	0.009	0.009
NOx Emissions (lb/MWh)[2]	0.406	0.366	0.433	0.400	0.413	0.388	0.613	0.777	0.579	0.722	0.060	0.066
PM Emissions (lb/hr)	41	41	38	40	37	39	66	98	62	89	Negligible	Negligible
PM Emissions (tons/year) @ CF[1]	142	145	135	139	131	137	247	365	232	331	Negligible	Negligible
PM Emissions (tonnes/year) @ CF[1]	129	132	122	126	119	125	224	331	211	300	Negligible	Negligible
PM Emissions (lb/MMBtu)	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0130	0.0130	0.0130	0.0130	Negligible	Negligible
PM Emissions (lb/MWh)[2]	0.053	0.056	0.052	0.057	0.050	0.057	0.114	0.144	0.107	0.134	Negligible	Negligible
Hg Emissions (lb/hr)	0.0033	0.0033	0.0031	0.0032	0.0030	0.0032	0.0058	0.0086	0.0055	0.0078	Negligible	Negligible
Hg Emissions (tons/year) @ CF[1]	0.011	0.012	0.011	0.011	0.011	0.011	0.022	0.032	0.020	0.029	Negligible	Negligible
Hg Emissions (tonnes/year) @ CF[1]	0.010	0.011	0.010	0.010	0.010	0.010	0.020	0.029	0.019	0.026	Negligible	Negligible
Hg Emissions (lb/TBtu)	0.571	0.571	0.571	0.571	0.571	0.571	1.14	1.14	1.14	1.14	Negligible	Negligible
Hg Emissions (lb/MWh)[2]	4.24E-06	4.48E-06	4.16E-06	4.59E-06	4.03E-06	4.55E-06	1.00E-05	1.27E-05	9.45E-06	1.18E-05	Negligible	Negligible

[1] Capacity factor is 80% for IGCC cases and 85% for PC and NGCC cases

[2] Value is based on gross output

[3] Value is based on net output

A more visual representation of these data is seen in Fig. 15. Here, TS&M costs represents the transport, storage, and monitoring cost of the carbon sequestration process, and the vertical axis units, mills/kWhr, (where a mill=$0.001), is the same as $/MWhr. Comparing bars 1 and 2, bars 3 and 4, etc., enables one to observe that CCS causes all costs to increase except fixed costs. The largest cost increase is in the capital costs.

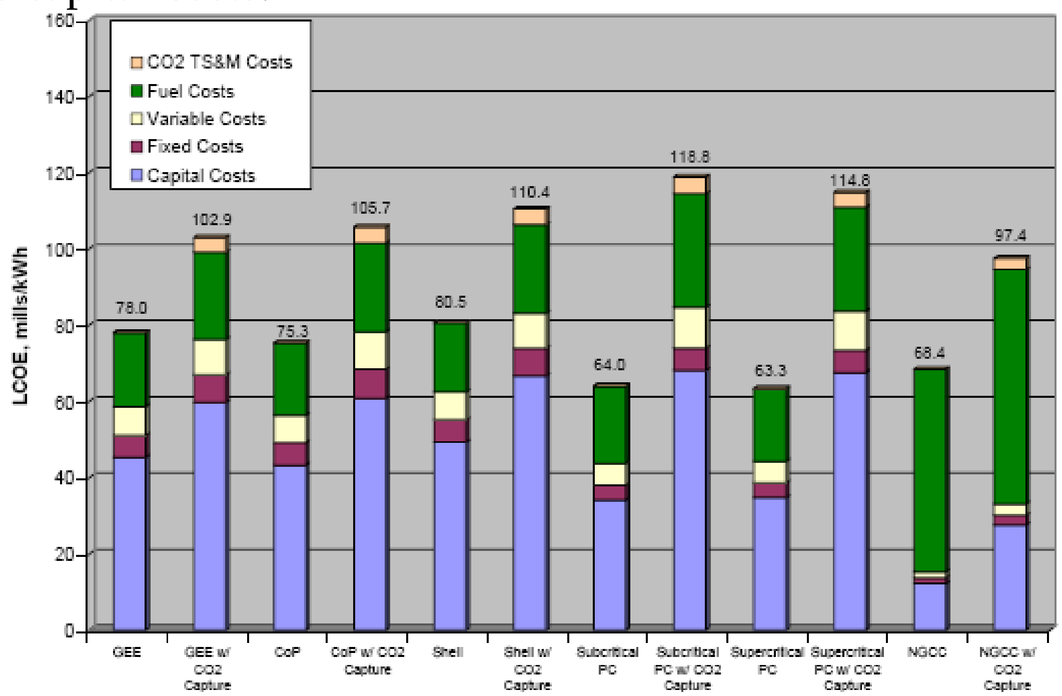


Fig. 15: Levelized Cost of Electricity

4.2. Last comments - trans technologies

We have said nothing about transmission costs in this document because our focus in this document has been on generation costs. For now, I simply refer you to the best transmission cost resource document of which I know, the MISO Transmission Cost Estimation Guide [13]. We will have more to say about transmission cost later in the course.

References:

[1] Lazard's LCOE, Nov., 2020, https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/.
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