Global Progress Toward Renewable Electricity: Tracking the Role of Solar (Version 4)

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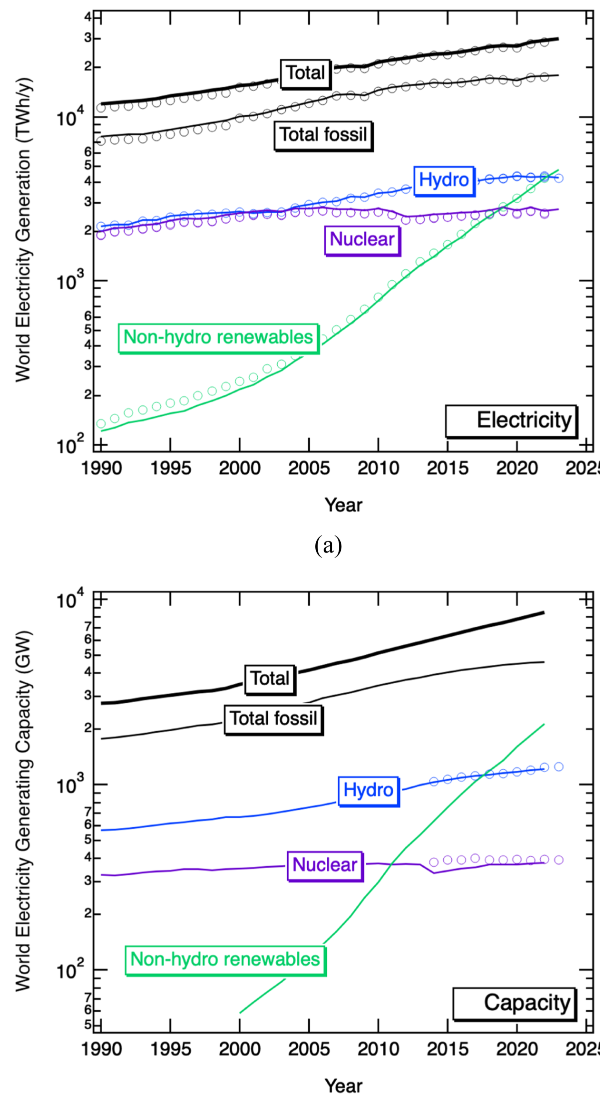
***Abstract*—Photovoltaics (PV) represented ∼61% of newly installed global electricity generating capacity for 2023. The amount of electricity generated by nonhydro renewables (wind, solar, geothermal, and biomass) reached another record high and exceeded generation by global hydropower for the first time in history. Fractional year-to-year growth in both PV installations and PV-generated electricity continued at remarkable levels (∼35% and ∼24%, respectively), while grid scale battery storage grew even faster (∼120%). Combined fractional electricity generation from all low carbon sources (hydro, nuclear, and renewables) reached ∼39%. Following its initial publication in 2021, this annual article will continue to collect information from multiple sources and present it systematically as a reference for IEEE JOURNAL OF PHOTOVOLTAICS readers.**

***Index Terms*—Renewable energy, energy storage, solar energy, solar power generation.**

I. Introduction

GLOBAL electricity generation grew 2.5% in 2023, slightly exceeding the 2% global growth in primary energy consumption. Total 2023 generation from all sources was ∼29 925 TWh, comprising ∼17.4% of total energy consumption, a small increase from the 2022 value of 17.2% [1]. Generation from nonhydro renewable energy sources (solar, wind, geothermal, and biomass) reached a new milestone, exceeding generation from hydropower and contributing ∼16% of global electricity, with wind and solar as the primary contributors. Newly installed global generating capacity in 2023 for combined hydro, photovoltaic (PV), and wind was ∼87% of the total, as shown in Fig. 2(c), with PV at more than 50% for the second year in a row. The 73rd Statistical Review of World Energy characterized 2023 as a year of “Record consumption of fossil fuels and record emissions from energy, but also record generation from renewables, driven by increasingly competitive wind and solar energy.”

PV continues to be the most rapidly growing generation technology in the energy transition. Using the Statistical Review of World Energy data, global installed PV grew 35% (from 1053 to 1419 GW_{AC}), while electricity production from all solar sources (PV dominated) grew 24% (from 1322 to 1642 TWh). The percentage of global electricity generated by PV was 5.5% for 2023, based on the ratio of gross electricity generation from solar to gross electricity generation from all sources reported in



(a) (b)

Fig. 1. (a) Annual electricity generation and (b) electricity generating capacity. Data are tabulated in Tables I and II with lines for the bolded data and open circles for the other sources.

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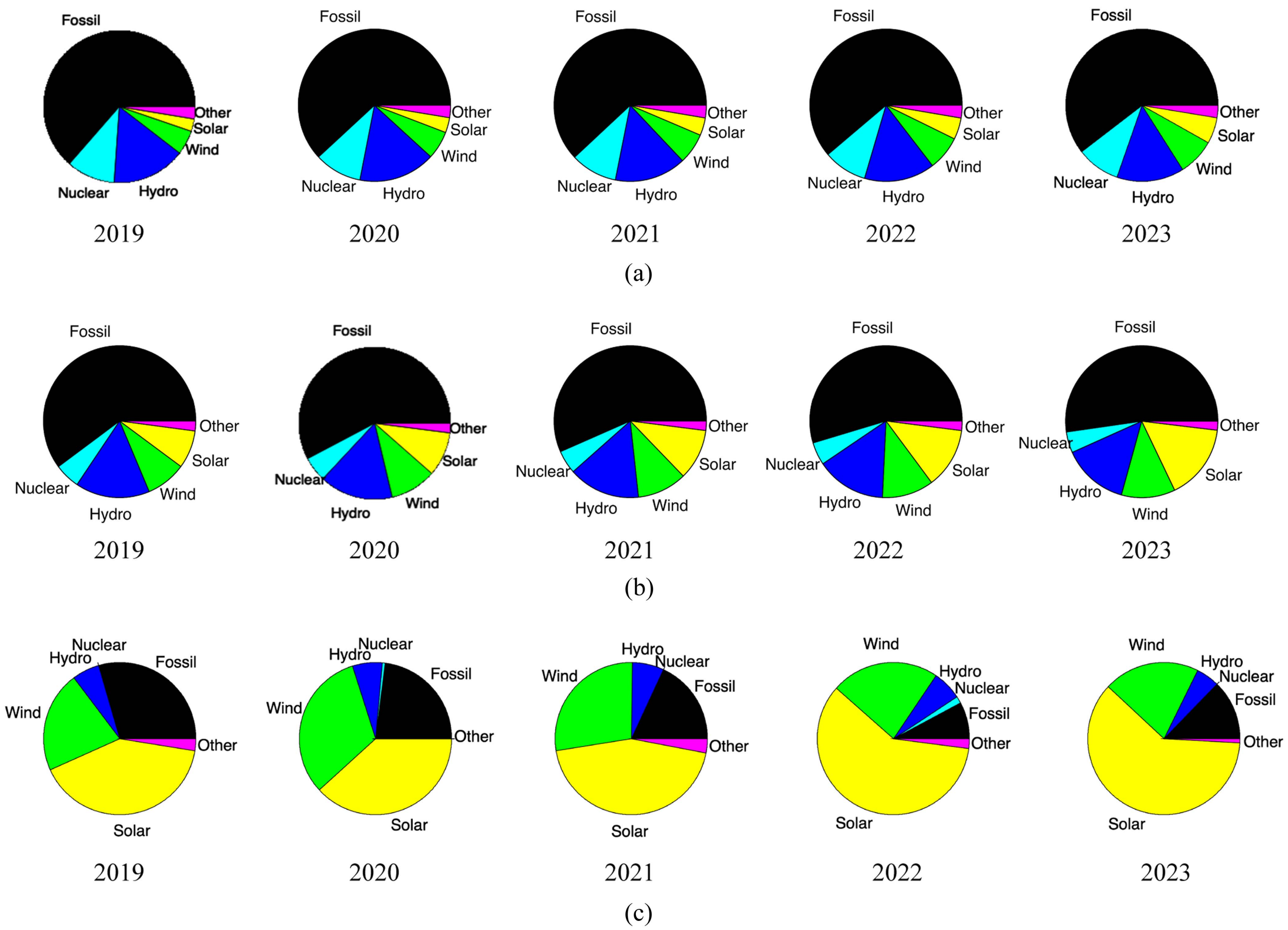

Fig. 2. Pie charts showing global share of (a) electricity generation, (b) electricity-generation capacity, and (c) net expansions of electricity-generating capacity. All are by technology for the indicated years. Data taken from Tables I, II, VIII, and IX and summarized in Tables III–VII.

[1]. This value was 4.5% for 2022, highlighting the still small but rapidly growing (22% fractional growth) global electricity contribution from PV.

The goal of this annual article is to present data, in consistent graphical and tabular form, tracking the global progress toward renewable energy. As discussed in the initial 2021 publication [2], multiple institutions provide global energy data on a yearly basis. These organizations have varying missions and reporting times for annual updates. They also vary in their use of original sources and methodologies. Sometimes methodologies change over time, and some organizations share and cross reference each other's data. Assembling this collection of frequently cited sources in one place illustrates both major trends and the nature and degree of variations within the source group.

Here, we provide 2023 updates to the following three sets of graphs:

1) annual generation and capacity by broad fuel source for global electricity (see Section II);
2) yearly generation and newly installed capacity for specific fuel sources with a focus on renewables (see Section III);
3) generation and capacity over time with a more detailed breakout of fuel sources including PV (see Section IV).

In Version 3, we began to track energy storage as new sources of battery storage data are becoming available (see Section V). Data are included from six primary sources: the Energy Institute (EI) Statistical Review of World Energy [1]; the international data presented by the U.S. Energy Information Administration (EIA) [3]; the World Nuclear Association [4]; the International Energy Agency (IEA) [5]; the International Renewable Energy Agency (IRENA) [6]; and REN21 [7]. Short summaries of the mission and history for many of these organizations were provided in the Appendix of the 2021 publication [2]. The timing of this yearly update is triggered by the release of the Statistical Review of World Energy, which occurred this year on 20 June 2024.

II. Tracking Progress Toward Renewable Electricity

Fig. 1 shows yearly global electricity generation (a) and generating capacity (b) from 1990 to 2023. Source data are presented in Tables I and II respectively. Data from the Statistical Review of World Energy, 73rd edition [1] are indicated in Fig. 1(a) by solid lines, with open circles used to mark other data sources. For Fig. 1(b), solid lines represent the data in bold in Table II, with open circles used to mark the other data sources. Data

TABLE I
GLOBAL ELECTRICITY GENERATION BY TECHNOLOGY CATEGORY (TWh FOR INDICATED YEAR)

Category	Fossil		Nuclear			Hydro			Nonhydro RE		Total	
Source	BP/EI	EIA	BP/EI	EIA	WNA	BP/EI	EIA	REN21	BP/EI	EIA	BP/EI	EIA
Year												
1985	**6339**	6043	**1489**	1426	1328	**1979**	1952		**79**	55	**9886**	9464
1986	**6494**	6104	**1595**	1519	1440	**2006**	1992		**86**	60	**10181**	9660
1987	**6811**	6399	**1735**	1655	1600	**2033**	1996		**92**	66	**10671**	10100
1988	**7057**	6614	**1891**	1796	1727	**2098**	2072		**95**	69	**11141**	10534
1989	**7518**	7054	**1945**	1845	1832	**2088**	2060		**108**	118	**11658**	11062
1990	**7681**	7141	**2001**	1910	1890	**2159**	2144		**121**	134	**11961**	11310
1991	**7791**	7244	**2096**	1998	1988	**2209**	2183		**127**	145	**12222**	11551
1992	**7879**	7288	**2112**	2017	2009	**2209**	2189		**136**	157	**12336**	11633
1993	**7932**	7367	**2185**	2083	2073	**2342**	2314		**142**	163	**12600**	11906
1994	**8193**	7568	**2226**	2127	2111	**2356**	2337		**148**	171	**12924**	12183
1995	**8420**	7804	**2323**	2211	2191	**2484**	2454		**156**	179	**13382**	12627
1996	**8713**	8066	**2407**	2293	2269	**2517**	2490		**161**	185	**13797**	13011
1997	**9003**	8347	**2390**	2273	2264	**2561**	2545		**174**	200	**14129**	13340
1998	**9314**	8621	**2431**	2317	2298	**2581**	2552		**185**	212	**14511**	13678
1999	**9603**	8831	**2524**	2394	2379	**2601**	2589		**199**	228	**14926**	14016
2000	**10120**	9821	**2581**	2451	2444	**2647**	2625		**217**	244	**15565**	15114
2001	**10336**	10026	**2654**	2518	2511	**2579**	2571		**232**	259	**15800**	15345
2002	**10775**	10485	**2696**	2547	2553	**2626**	2616		**261**	290	**16358**	15906
2003	**11387**	11070	**2641**	2519	2505	**2623**	2622		**284**	311	**16936**	16493
2004	**11835**	11535	**2761**	2620	2616	**2817**	2790		**325**	349	**17737**	17266
2005	**12421**	12065	**2769**	2627	2626	**2911**	2910		**364**	393	**18465**	17965
2006	**12931**	12613	**2803**	2661	2661	**3022**	3014		**411**	440	**19167**	18701
2007	**13767**	13427	**2746**	2610	2608	**3073**	3044		**475**	502	**20060**	19554
2008	**13898**	13546	**2738**	2601	2598	**3252**	3179		**550**	579	**20437**	19879
2009	**13697**	13319	**2699**	2566	2558	**3246**	3238		**637**	671	**20279**	19770
2010	**14632**	14293	**2768**	2635	2630	**3430**	3413		**760**	797	**21591**	21110
2011	**15229**	14921	**2652**	2521	2518	**3493**	3473		**905**	949	**22279**	21836
2012	**15658**	15238	**2471**	2350	2346	**3642**	3637		**1064**	1105	**22834**	22302
2013	**15951**	15661	**2490**	2368	2359	**3788**	3766	3791	**1240**	1310	**23469**	23078
2014	**16237**	15981	**2541**	2422	2410	**3889**	3837	3874	**1409**	1475	**24076**	23686
2015	**16227**	16024	**2575**	2451	2441	**3880**	3852	3884	**1634**	1669	**24315**	23966
2016	**16510**	16194	**2614**	2491	2477	**4014**	3989	4013	**1845**	1924	**24984**	24561
2017	**16859**	16543	**2637**	2518	2503	**4071**	4033	4058	**2173**	2239	**25738**	25292
2018	**17416**	16886	**2700**	2570	2563	**4190**	4156	4178	**2479**	2530	**26783**	26105
2019	**17317**	16799	**2796**	2677	2657	**4243**	4190	4226	**2792**	2829	**27147**	26459
2020	**16832**	16291	**2689**	2593	2553	**4359**	4322	4344	**3152**	3182	**27033**	26349
2021	**17790**	17307	**2803**	2673	2653	**4289**	4262	4276	**3667**	3649	**28548**	27850
2022	**17978**	17541	**2680**	2589	2545	**4323**	4353	4298	**4207**	4207	**29188**	28644
2023	**18199**		**2738**			**4240**		4210	**4748**		**29925**	

Source data for Table 1 can be found at:
https://www.energyinst.org/statistical-review
https://www.eia.gov/international/data/world/electricity/electricity-generation
https://www.world-nuclear.org/information-library/facts-and-figures/nuclear-generation-by-country.aspx
https://www.ren21.net/reports/global-status-report/

source variations, of interest for detailed understanding and analysis, are seen in the tabulated data, but are generally not significant when plotted on the logarithmic scale over this period of time.

Electricity generation [see Fig. 1(a)], a measure of energy provided, is presented in Terawatt-hour, where 1 TWh = 3.6×10^{15} J. Installed nameplate capacity [see Fig. 1(b)] is the rated output of a generator or other electric power production equipment under specific conditions designated by the manufacturer. The "capacity factor" is the ratio of the actual output of a system or collection of systems under true operating conditions (reflecting, e.g., variable resource, facility downtime, performance variations, large scale climate effects, etc.) and the output of that electricity source operating continuously at its commercial product or plant rating. Capacity factors for electricity generating technologies vary significantly, both within a technology depending on the performance, and between technologies as determined by the physics of the particular energy conversion process and the variability of the electricity demand. Actual electricity generation [see Fig. 1(a)] is the most relevant information for understanding and tracking the evolution of the energy system in terms of contributing fuel sources. Installed capacity [see Fig. 1(b)] allows one to track the status of global installations and new technology investment.

Different organizations report source data using different fuel subcategories. In Fig. 1, the Statistical Review values for total fossil generation and capacity are determined by summing component data for oil, gas, coal and "other" (where "other"

TABLE II
GLOBAL ELECTRICITY GENERATION CAPACITY BY TECHNOLOGY CATEGORY (GW)

Category	Fossil	Nuclear		Hydro		Nonhydro RE	Total
Source	EIA	EIA	WNA	EIA	REN21	EIA	EIA
Year							
1985	**1566**	**253**		**538**			**2393**
1986	**1597**	**278**		**552**			**2466**
1987	**1626**	**299**		**569**			**2537**
1988	**1668**	**312**		**583**			**2605**
1989	**1727**	**320**		**573**			**2686**
1990	**1764**	**325**		**566**			**2736**
1991	**1792**	**325**		**570**			**2773**
1992	**1832**	**329**		**578**			**2830**
1993	**1877**	**336**		**591**			**2899**
1994	**1925**	**339**		**604**			**2968**
1995	**1962**	**342**		**616**			**3022**
1996	**2022**	**349**		**626**			**3100**
1997	**2074**	**349**		**640**			**3165**
1998	**2117**	**346**		**650**			**3218**
1999	**2168**	**349**		**666**			**3291**
2000	**2288**	**352**		**668**		**58**	**3480**
2001	**2370**	**355**		**680**		**67**	**3588**
2002	**2478**	**360**		**690**		**76**	**3721**
2003	**2576**	**362**		**710**		**87**	**3852**
2004	**2680**	**368**		**731**		**99**	**3997**
2005	**2770**	**370**		**753**		**117**	**4134**
2006	**2918**	**372**		**774**		**137**	**4329**
2007	**3034**	**372**		**801**		**161**	**4500**
2008	**3146**	**372**		**830**		**196**	**4678**
2009	**3269**	**372**		**860**		**246**	**4885**
2010	**3417**	**376**		**890**		**298**	**5123**
2011	**3554**	**369**		**917**		**375**	**5362**
2012	**3671**	**373**		**948**		**457**	**5597**
2013	**3782**	**372**		**993**		**534**	**5832**
2014	**3912**	**333**	382	**1029**	1036	**636**	**6063**
2015	**4024**	**344**	391	**1061**	1071	**756**	**6340**
2016	**4137**	**352**	392	**1089**	1095	**888**	**6629**
2017	**4225**	**358**	400	**1110**	1112	**1038**	**6897**
2018	**4334**	**370**	392	**1133**	1135	**1188**	**7191**
2019	**4409**	**370**	392	**1151**	1150	**1354**	**7450**
2020	**4489**	**372**	394	**1173**	1168	**1604**	**7805**
2021	**4548**	**376**	389	**1195**	1197	**1848**	**8142**
2022	**4574**	**378**	394	**1216**	1237	**2130**	**8483**
2023			393		1244		

Source data for Table II can be found at:
https://www.eia.gov/international/data/world/electricity/electricity-capacity
https://world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme for the December 2023 number
https://www.ren21.net/reports/global-status-report/

is reported to include uncategorized generation, statistical differences, and sources not specified elsewhere, e.g., pumped hydro, nonrenewable waste, and heat from chemical sources). Nonhydro renewable totals are calculated by subtracting the sum of total fossil, nuclear, and hydro from the total electricity value. This addresses the fact that individual values for certain nonhydro renewable components (PV, wind, concentrating solar power, geothermal, etc.) were not uniformly reported in earlier years, although that situation continues to evolve rapidly. The EIA values are taken directly from the website [3] by selecting the desired categories.

Several recent developments are illustrated this year in Fig. 1. As noted, electricity generation from combined nonhydro renewables in 2023 slightly exceeded generation from hydropower. Generation from the global nuclear power fleet and global hydro continued a relatively flat trajectory, with hydropower recording a small (∼2% fractional) decrease from 2022 to 2023. Finally, Fig. 1(b) shows the continued rapid global increase in nonhydro renewable capacity.

III. TRACKING THE RATE OF CHANGE

In Fig. 2, we plot global data for the past five years (2019–2023) for (a) fraction of electricity generation by source, (b) fraction of current total installed electricity generating capacity, and (c) fraction of net expansions of electricity generating capacity for the given year. Data for fossil, nuclear, and hydro are drawn from Table I and are summarized per year in Tables III–VII. Data for wind, solar, and other technologies are drawn from Table VIII as well as summarized in Tables III–VII, with the electricity

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE III
GLOBAL 2019 DATA SUMMARY FOR CREATING PIE CHARTS IN FIG. 2

Technology	Electricity (TWh)	Electricity (%)	Capacity (GW)	Capacity (%)	Net expansion (GW)	Net expansion (%)
Fossil	17 317	63.8%	4409	60.2%	81	29.5%
Nuclear	2796	10.3%	392	5.4%	0	0.0%
Hydro	4243	15.6%	1151	15.7%	16	5.7%
Wind	1421	5.2%	623	8.5%	59	21.4%
Solar	705	2.6%	595	8.1%	112	40.9%
Other*	665	2.4%	151	2.1%	7	2.5%
Total	27 147	100.0%	7321	100%	275	100%

*Biomass and geothermal.

TABLE IV
GLOBAL 2020 DATA SUMMARY FOR CREATING PIE CHARTS IN FIG. 2

Technology	Electricity (TWh)	Electricity (%)	Capacity (GW)	Capacity (%)	Net expansion (GW)	Net expansion (%)
Fossil	16 832	62.3%	4 489	58.6%	80	23.3%
Nuclear	2689	9.9%	394	5.1%	2	0.6%
Hydro	4359	16.1%	1173	15.3%	22	6.4%
Wind	1595	5.9%	734	9.6%	111	32.3%
Solar	855	3.2%	728	9.5%	133	38.6%
Other*	703	2.6%	147	1.9%	-4	-1.1%
Total	27 033	100.0%	7665	100%	344	100%

*Biomass and geothermal.

TABLE V
GLOBAL 2021 DATA SUMMARY FOR CREATING PIE CHARTS IN FIG. 2

Technology	Electricity (TWh)	Electricity (%)	Capacity (GW)	Capacity (%)	Net expansion (GW)	Net expansion (%)
Fossil	17 790	62.3%	4548	56.9%	59	18.4%
Nuclear	2803	9.8%	389	4.9%	-5	-1.5%
Hydro	4289	15.0%	1195	15.0%	22	6.9%
Wind	1860	6.5%	825	10.3%	91	28.1%
Solar	1052	3.7%	874	10.9%	145	45.0%
Other*	756	2.6%	158	2.0%	10	3.2%
Total	28 549	100.0%	7988	100%	323	100%

*Biomass and geothermal.

TABLE VI
GLOBAL 2022 DATA SUMMARY FOR CREATING PIE CHARTS IN FIG. 2

Technology	Electricity (TWh)	Electricity (%)	Capacity (GW)	Capacity (%)	Net expansion (GW)	Net expansion (%)
Fossil	17 978	61.6%	4574	55.0%	26	7.7%
Nuclear	2680	9.2%	394	4.7%	5	1.4%
Hydro	4323	14.8%	1216	14.6%	21	6.4%
Wind	2108	7.2%	901	10.8%	77	23.0%
Solar	1322	4.5%	1073	12.9%	199	59.7%
Other*	777	2.7%	164	2.0%	7	1.9%
Total	29 188	100.0%	8322	100%	334	100%

*Biomass and geothermal.

TABLE VII
GLOBAL 2023 DATA SUMMARY FOR CREATING PIE CHARTS IN FIG. 2

Technology	Electricity (TWh)	Electricity (%)	Capacity (GW)	Capacity (%)	Net expansion (GW)	Net expansion (%)
Fossil	18 198	60.8%	4646	52.3%	72	12.7%
Nuclear	2738	9.1%	393	4.4%	-1	-0.2%
Hydro	4240	14.2%	1244	14.0%	28	4.9%
Wind	2325	7.8%	1017	11.4%	116	20.5%
Solar	1642	5.5%	1419	16.0%	346	61.1%
Other*	782	2.6%	169	1.9%	5	0.9%
Total	29 925	100.0%	8888	100%	566	100%

*Biomass and geothermal.

TABLE VIII
GLOBAL ELECTRICITY GENERATION BY FUEL (TWh FOR INDICATED YEAR)

Fuel	Coal	Gas	Oil	Wind		Solar (all))		Solar (PV)		Biomass		Geothermal		Bio&Geo
Source	BP/EI	BP/EI	BP/EI	BP/EI	EIA	BP/EI	EIA	IEA	IRENA	EIA	REN21	EIA	REN21	REN21
Year														
1985	3748.4	1426.3	1110.8	0.1	0.1		0.0			31.7		22.4		
1986	3839.0	1432.7	1168.3	0.1	0.1		0.0			34.3		25.0		
1987	4058.1	1516.5	1183.2	0.2	0.2		0.0			38.2		26.9		
1988	4200.7	1541.0	1256.5	0.3	0.3		0.0			40.4		27.2		
1989	4377.0	1728.6	1350.2	2.6	2.6	0.3	0.3			81.7		32.8		
1990	4460.2	1788.7	1366.0	3.6	3.6	0.4	0.4			93.9		35.7		
1991	4557.1	1814.1	1351.4	4.1	4.1	0.5	0.5	0.09		102.7		36.9		
1992	4649.8	1828.4	1329.6	4.7	4.6	0.5	0.5	0.10		113.3		38.1		
1993	4727.8	1862.4	1268.5	5.7	5.6	0.6	0.6	0.13		116.7		39.0		
1994	4891.7	1923.7	1303.7	7.1	7.3	0.6	0.6	0.15		123.0		38.9		
1995	5038.7	2034.9	1261.7	8.3	7.9	0.6	0.7	0.17		131.5		38.1		
1996	5279.5	2100.1	1247.4	9.2	9.3	0.7	0.8	0.20		133.8		40.6		
1997	5395.6	2270.3	1245.2	12.0	12.1	0.7	0.8	0.23		143.9		42.0		
1998	5511.2	2407.8	1295.5	15.9	16.1	0.8	0.9	0.28		149.0		44.6		
1999	5630.7	2600.2	1267.9	21.2	21.3	0.9	1.0	0.35		156.4		47.7		
2000	5991.8	2772.1	1245.9	31.4	31.3	1.1	1.2	0.6		159.2		51.4		
2001	6071.6	2950.5	1210.3	38.4	38.4	1.4	1.5	0.8		167.4		51.0		
2002	6323.0	3151.5	1194.7	52.4	52.8	1.8	1.9	1.1		183.0		51.8		
2003	6768.3	3301.8	1202.8	63.3	64.5	2.3	2.3	1.4		190.3		53.5		
2004	6989.4	3550.7	1180.9	85.6	84.7	3.0	3.0	1.8		205.4		55.7		
2005	7361.1	3741.0	1193.6	104.6	104.3	4.2	4.1	2.5		227.2		56.4		
2006	7763.0	3959.5	1085.6	133.5	133.5	5.8	5.7	3.7		242.8		57.8		
2007	8253.8	4284.0	1105.7	171.5	171.3	7.8	7.6	5.3		261.7		60.4		
2008	8270.3	4427.8	1081.9	221.4	221.4	12.7	12.5	7.3	11.9	281.8		63.1		
2009	8118.1	4460.5	1002.6	276.8	277.8	21.1	20.8	11.7	20.1	306.6		65.1		
2010	8639.9	4887.0	966.3	346.4	339.4	33.9	33.3	32.0	32.1	358.5		64.7		
2011	9083.7	4939.3	1062.9	440.7	435.0	65.7	66.2	63.7	62.4	381.5		65.5		
2012	9113.9	5257.8	1143.3	530.5	521.5	101.5	103.8	98.8	96.3	411.6		66.6		
2013	9583.0	5136.3	1084.7	635.5	645.1	138.6	145.3	139.4	131.4	450.4		67.8		468
2014	9758.6	5289.7	1036.3	705.9	717.3	197.3	198.9	184.5	183.7	485.5	429	72.5		508
2015	9415.0	5635.1	1021.5	831.3	828.7	256.0	251.7	251	242.2	511.1	464	76.2	75	550
2016	9435.1	5923.6	939.1	962.1	957.6	328.4	328.3	329	314.6	558.5	504	78.2	78.5	558
2017	9746.2	6039.5	850.6	1141.9	1127.7	445.3	439.2	443	425.3	590.1	555	80.6	85	592
2018	10129.4	6300.0	764.8	1270.5	1267.1	574.7	565.9	589	549.7	611.8	581	84.1	89.3	626
2019	9897.5	6486.3	719.1	1421.4	1399.8	705.5	700.5	679	676.2	642.3	591	85.8	95	659
2020	9497.6	6459.1	656.0	1594.7	1568.5	854.9	853.2	826	830.7	670.3	602	88.9	97	696
2021	10226.6	6622.4	718.2	1859.6	1803.0	1051.6	1037.0	1026	1034	718.1	656	89.5	99	746
2022	10324.4	6668.9	742.6	2108.0	2093.5	1321.9	1279.8	1293		740.2	676	92.0		765
2023	10513.0	6746.3	698.1	2325.3		1641.6					697			787

Total, nuclear, and hydro are tabulated in Table Ia.
Source data for Table VIII can be found at:
https://www.energyinst.org/statistical-review
https://www.eia.gov/international/data/world/electricity/electricity-generation
https://www.ren21.net/reports/global-status-report/
https://public.tableau.com/views/IRENARETimeSeries/Charts?:embed=y&:showVizHome=no&publish=yes&:toolbar=no
https://www.iea.org/energy-system/renewables/solar-pv

generation data in Fig. 2(a) taken from Tables I and VIII and the electricity-generation capacity data in Fig. 2(b) taken from Tables II and IX. The net expansions of the electricity-generating capacity data in Fig. 2(c) are obtained by subtracting the data in Fig. 2(b) for each year from the following year. The choice of datasets to use for Fig. 2 and tabulated in Tables III–VII is detailed in the Appendix. Some values in Tables III–VII are not directly available and were calculated from multiple source data. The choice of data sources for the most recent (i.e., 2023) pie charts is driven in part by when various sources release new data.

The pie charts illustrate a major ongoing theme: the global electricity system continues to be dominated by fossil energy [see Fig. 2(a)] but is undergoing an increasingly rapid rate of change in terms of newly installed capacity [see Fig. 2(c)]. By plotting electricity generation, generating capacity, and net capacity expansions (new installation minus any decommissioning), we highlight both where we stand today and the new installations that will drive the future electricity generating mix.

In the 2023 article [8], we commented on the very small capacity growth in fossil based generation during 2021, based on EIA reporting at the time, but also suggested that those values might be updated. That was, in fact, the case. Fossil capacity values reported by EIA changed (updated from 4433 to 4489 GW for end of year 2020, and from 4436 to 4548 GW for end of year 2021). This changed the net fossil capacity increase in 2021 to 59 GW, a value more consistent with earlier data and the most recently reported increase from 2022 to 2023. A similar update to 2022 values could occur over the next year. This is a reminder that updates to the pie charts, in particular Fig. 2(c), are necessary, since they depend on the most recent data as well

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TABLE IX
GLOBAL ELECTRICITY-GENERATING CAPACITY BY TECHNOLOGY (GW)

Fuel	Wind			Solar (all)		Solar (PV)			Biomass		Geothermal		
Source	BP/EI (AC)	EIA (AC)	REN21 (AC)	EIA (AC)	IRENA (AC)	BP/EI (AC)	REN21 (DC)	IEA (DC)	EIA (AC)	REN21 (AC)	BP/EI (AC)	EIA (AC)	REN21 (AC)
Year													
1985													
1986													
1987													
1988													
1989		**1.5**											
1990		**1.8**									5.9		
1991		**1.9**											
1992		**1.8**						0.05					
1993		**1.8**						0.065					
1994		**1.7**						0.09					
1995	4.8	**1.7**						0.11			6.8		
1996	6.1	**1.7**				0.2		0.15					
1997	7.6	**1.6**				0.2		0.2					
1998	9.9	**1.7**				0.3		0.27					
1999	13.4	**2.3**				0.4		0.37					
2000	17.0	**16.9**		**1.3**	1.2	0.8		0.57	**32.0**		8.2	**8.2**	
2001	23.9	**24.0**		**1.5**	1.5	1.1		0.79	**33.5**		7.9	**7.9**	
2002	30.7	**30.7**		**1.8**	1.8	1.4		1.2	**35.1**		8.1	**8.1**	
2003	38.6	**38.7**		**2.3**	2.3	2.0		1.6	**37.4**		8.2	**8.2**	
2004	47.7	**47.7**		**3.3**	3.4	3.1		2.7	**40.3**		8.2	**8.2**	
2005	58.4	**58.4**		**4.7**	4.9	4.5		4.1	**45.4**		8.6	**8.6**	
2006	73.1	**73.1**		**6.1**	6.5	6.1		5.9	**49.5**		8.8	**8.8**	
2007	91.5	**91.5**		**8.3**	9.0	8.5		8.0	**52.6**		9.0	**9.0**	
2008	115.5	**115.6**		**14.4**	15.3	14.7		14.3	**56.7**		9.3	**9.3**	
2009	150.1	**150.1**		**22.4**	23.6	22.8		22.4	**63.4**		9.8	**9.8**	
2010	181.1	**180.9**		**39.3**	41.6	41.6		39.3	**67.9**		10.0	**10.2**	
2011	220.2	**220.1**		**70.0**	74.0	73.9		70.4	**74.8**		10.1	**10.4**	
2012	267.3	**266.9**		**99.0**	104.2	104.2		100.0	**80.2**		10.5	**10.7**	
2013	299.9	**299.8**		**135.0**	141.4	140.5		137.6	**88.4**		10.7	**11.0**	
2014	349.4	**349.2**		**180.4**	180.8	180.7		177.6	**94.8**	86	11.2	**11.4**	
2015	416.3	**416.1**	433	**228.2**	229.1	228.9		228.0	**99.4**	91	11.8	**12.1**	
2016	467.0	**466.8**	487	**300.4**	301.2	301.1	303	304.7	**108.6**	97	12.1	**12.4**	13.5
2017	515.0	**514.1**	539	**395.4**	396.3	395.9	405	407.4	**115.0**	105	12.7	**13.0**	12.8
2018	563.8	**564.2**	591	**488.9**	492.6	489.3	512	511.7	**121.5**	111	13.2	**13.5**	13.2
2019	622.8	**620.5**	650	**591.4**	595.5	592.2	621	632.2	**127.6**	117	13.9	**14.1**	14.0
2020	733.7	**733.1**	745	**719.7**	728.4	720.4	767	767.0	**137.0**	124	14.1	**14.4**	14.2
2021	824.6	**823.9**	829	**860.8**	873.9	861.5	942	910	**148.3**	138		**14.7**	14.5
2022	901.2	**898.8**	906	**1056.4**	1073.1	1053.1	1183	1185	**159.6**	143		**14.9**	14.7
2023	1017.2		1023		1419.0	1419.0	1590	1600		149			14.8

Total, nuclear, and hydro are tabulated in Table Ib.
Source data for Table IX can be found at:
https://www.energyinst.org/statistical-review
https://www.eia.gov/international/data/world/electricity/electricity-capacity
https://www.ren21.net/reports/global-status-report/
https://public.tableau.com/views/IRENARETimeSeries/Charts?:embed=y&:showVizHome=no&publish=yes&:toolbar=no
https://iea-pvps.org/snapshot-reports/snapshot-2024/
https://www.irena.org/Data

as values significantly smaller in magnitude than the values that determine the distributions in Fig. 2(a) and (b).

The overall trend, however, of a decrease of fossil generation capacity as a fraction of global new installation is clear. This is perhaps best seen by taking a five year average, which should minimize the effect of the recent year time variations. Comparing the five year average fossil fractional contribution to overall new capacity from the first version of this article (covering 2016–2020) with this year's version (2019–2023), we find that value dropping from ∼30% to ∼18%, a fairly dramatic shift over a 4 year period.

IV. Tracking the Role of PV

Fig. 3 shows yearly global electricity generation (a) and generating capacity (b) from 1990 to 2023, now breaking out the contributing technologies to the "nonhydro renewables" in Fig. 1. Source data are presented in Tables VIII and IX, respectively. In Fig. 3(a), the solid lines again represent data from [1], with open circles used to mark other data sources. For Fig. 3(b), solid lines represent the data in bold in Table IX, with open circles used to mark the other data sources. We note again that source variations, although of interest for detailed understanding and analysis, are relatively minor when assessing major trends over the time frames of interest for the global energy transformation.

Global PV capacity now slightly exceeds that of hydro, although the higher hydrocapacity factor means that hydropower remains the largest single source of renewable electricity. If wind and PV continue their recent growth trajectories, one sees from Fig. 3(a) that both are on track to reach and exceed levels of electricity generation from nuclear and hydro in the next ∼3–5 years.

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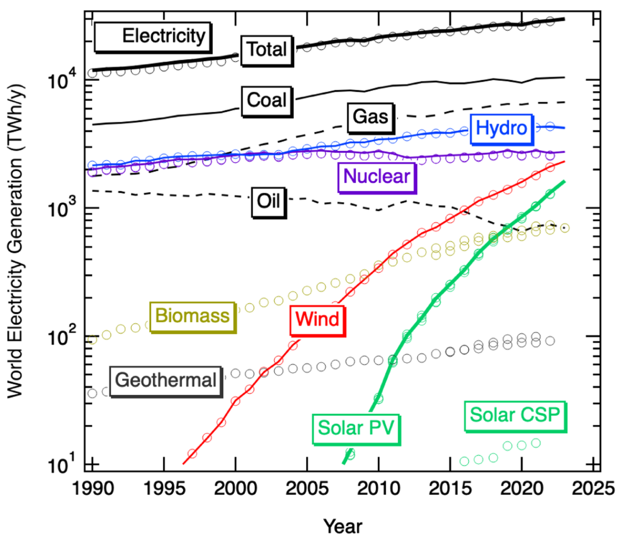
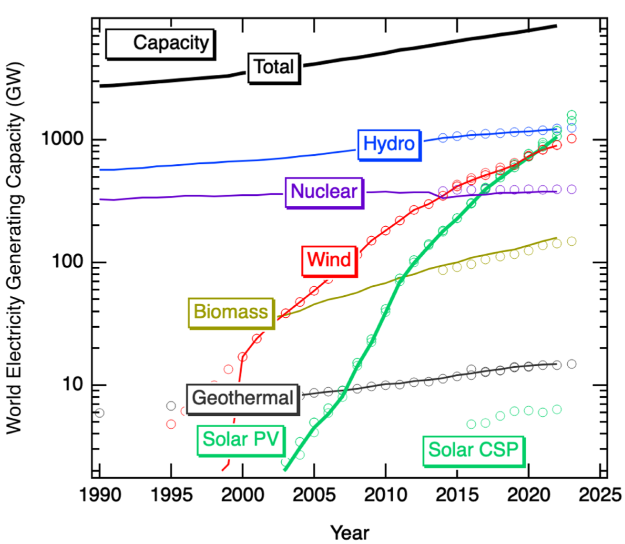


(a)



(b)

Fig. 3. (a) Annual electricity generation and (b) electricity generating capacity by fuel. Data are tabulated in Tables VIII and IX (see Appendix) with lines for the bolded data and open circles for the other sources.

Five different sources for solar (Statistical Review of World Energy, EIA, IEA, IRENA, and REN21) are presented in Table IX. Variations here can arise for multiple reasons. Among these are variations in reporting PV capacity as W_{DC} or W_{AC}; differences that arise in reports of PV shipments versus installations, variations in cross-border electricity accounting, or handling of the balance between new and retired resources; and changing methodologies in source reporting. Those with interests in pursuing these variations can find further details in the primary sources. We note that the EI report has now added data on historical solar capacity, crediting IRENA source data. Previously we presented values from both British Petroleum/Energy Institute (BP/EI) and IRENA in the table. This year, it appears that IRENA has combined PV and concentrating solar power (CSP) to report "all solar." PV is over two orders of magnitude greater than CSP, both in terms of installed capacity and electricity produced, but this variation in solar and PV categorization can cause some differences in the reported data. Tables VIII and IX indicate whether solar data are a combination of these technologies or PV only. These tables also indicate our assessment of which data are W_{DC} or W_{AC}. However, we note that there may be inconsistencies in the documentation of dc and ac PV ratings and that some sources may include a mixture of ac and dc data.

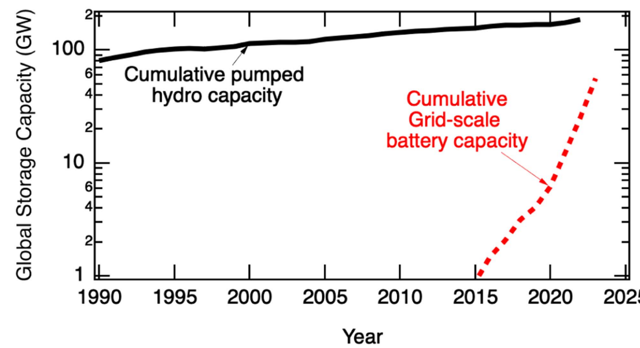


Fig. 4. Global pumped-hydro storage capacity (EIA, thick black line) and grid-scale batteries as reported by the Statistical Review of World Energy.

V. Tracking Energy Storage

Pumped hydropower has long been and remains the dominant energy storage technology supporting the electricity grid, with grid scale battery energy storage system (BESS) only recently becoming a significant addition. Fig. 4 shows the rapid recent growth in grid scale battery storage systems, along with EIA data for the cumulative global pumped hydropower capacity. Of the 55.7-GW cumulative BESS reported, the largest installations are in China (49% at 27.1 GW), followed by the US (15.8 GW) and combined capacity in Europe (7.0 GW). For comparison, pumped hydro capacities for the top three countries are ∼50 GW (China), 22 GW (Japan), and 17 GW (US) [9].

As we noted last year [8], a more important metric may be the amount of electricity that is delivered by these assets, consistent with Figs. 1 and 3. We will continue to monitor for publicly available sources reporting this data and begin presenting data in tabular form when multiple sources are identified.

VI. Conclusion

The year 2023 was marked by significant and sustained year-to-year growth rates in global PV capacity, electricity generation, and related grid-scale battery storage. The trajectory for electricity generation growth in Fig. 3(a) suggests that PV, along with wind, is on a path to reach and exceed levels comparable with nuclear and hydro in the next 3–5 years, providing the global energy system with four independent sources for low-carbon electricity generation.

PV provided approximately 5.5% of 2023 global electricity generation, based on EI numbers, although one should note that other organizations report higher values year to year [10]. To place this growth in context: PV generated electricity increased in 2023 from 1322 to 1642 TWh (an increase of 320 TWh and 24% fractional growth); global electricity generation increased from 29 188 to 29 925 TWh (an increase of 737 TWh and 2.5% fractional growth). Assuming continued or more likely greater electricity demand associated with economic growth, electrification, and expansion of data centers and use of artificial intelligence, the rate of PV growth will need to be sustained, taking full advantage of compound growth rates, to meet future demand and facilitate the transition to a predominantly low carbon electricity system. Indeed, while PV is growing rapidly, it is not yet quite able to meet all of the new load each year, resulting in continued investment in more fossil fuel powered generation.

The average fractional contribution of PV in many countries, so-called grid penetration, continues to grow. At the end of 2022, nine countries had PV penetration levels in excess of 10% on their national grids; at the end of 2023 that number was estimated to be 18 [10]. The European Union as a whole has also reached the 10% threshold. As these fractional contributions increase, integration of battery storage becomes increasingly important to time shift the delivery of electricity. Fractional growth in battery storage for 2023 was in excess of 100%. Tracking future levels of both pumped hydro and battery storage will be of increasing interest.

The global PV R&D community continues to play a significant role. New efficiency cell level records in CdTe and silicon heterojunctions were announced in 2023, along with many new records in the area of emerging perovskite technology; Si/perovskite hybrid tandem record cells now exceed a remarkable 34% as of July 2024. Monocrystalline Si continues to be the dominant PV technology, and important research continues in reliability, bifaciality, development of a circular economy for PV, and integration of PV into areas such as agrivoltaics, building-integration, and floating PV.

Finally, we note that the amount of new annual PV installations for 2023, as indicated in Table III, reached 326 GW_{AC} or 410 GW_{DC}. Multiple commercial sources tracking PV growth have reported record 2023 PV shipments of over 500 GW. This value, 0.5 TW, represents another milestone in PV manufacturing. Future growth in PV-generated electricity depends on continued momentum across this full evolutionary chain—PV manufacturing to PV shipments to PV installation to PV electricity. Monitoring these trends and reporting this progress remain the focus of this article, “tracking the role of solar” in the energy transition.

Appendix

The sources of the data reported in Figs. 1–3 were described in detail in the Version 1 [2, Appendix]. The same sources, as enumerated in Section I, were consulted for Version 4, following the release of the 73rd Statistical Review of World Energy on June 20, 2024. Updated data from other sources were downloaded starting July 7, 2024.

As noted, many of these sources revise their data in retrospect, as new information comes in and/or reporting accuracy increases. Where updated tabulated data are available for download, we have incorporated updates from previous years into our Version 4 tables. The data presented in Figs. 1–3 are tabulated in Tables I–IX. The selection of data for Tables III–VII has little effect on the creation of Fig. 2(a) and (b) but can have a greater effect on the appearance of Fig. 2(c).

The electricity data in Fig. 2(a) and Tables III-VII were taken from The Statistical Review of World Energy. The capacity data in Fig. 2(b) and Table II used WNA data for nuclear, Statistical Review of World Energy data for wind and solar and REN21 data for hydro, biomass and geothermal. Data now reported in the Statistical Review of World Energy for BESS come from Rystad Energy and report utility scale battery storage projects.

EIA fossil fuel capacity data for 2023 were not available as of August 2024, and the Statistical Review of World Energy does not include fossil capacity information, requiring the use of additional sources to create the 2023 pie chart in Fig. 2(c). This year we used newly available data presentations from IRENA, taking the difference in their reported values for 2023 and 2022. This represents a change from previous years when data from REN21 or Global Energy Monitor were used. We plan to use the IRENA data consistently going forward assuming the data presentation and timeliness allow.

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