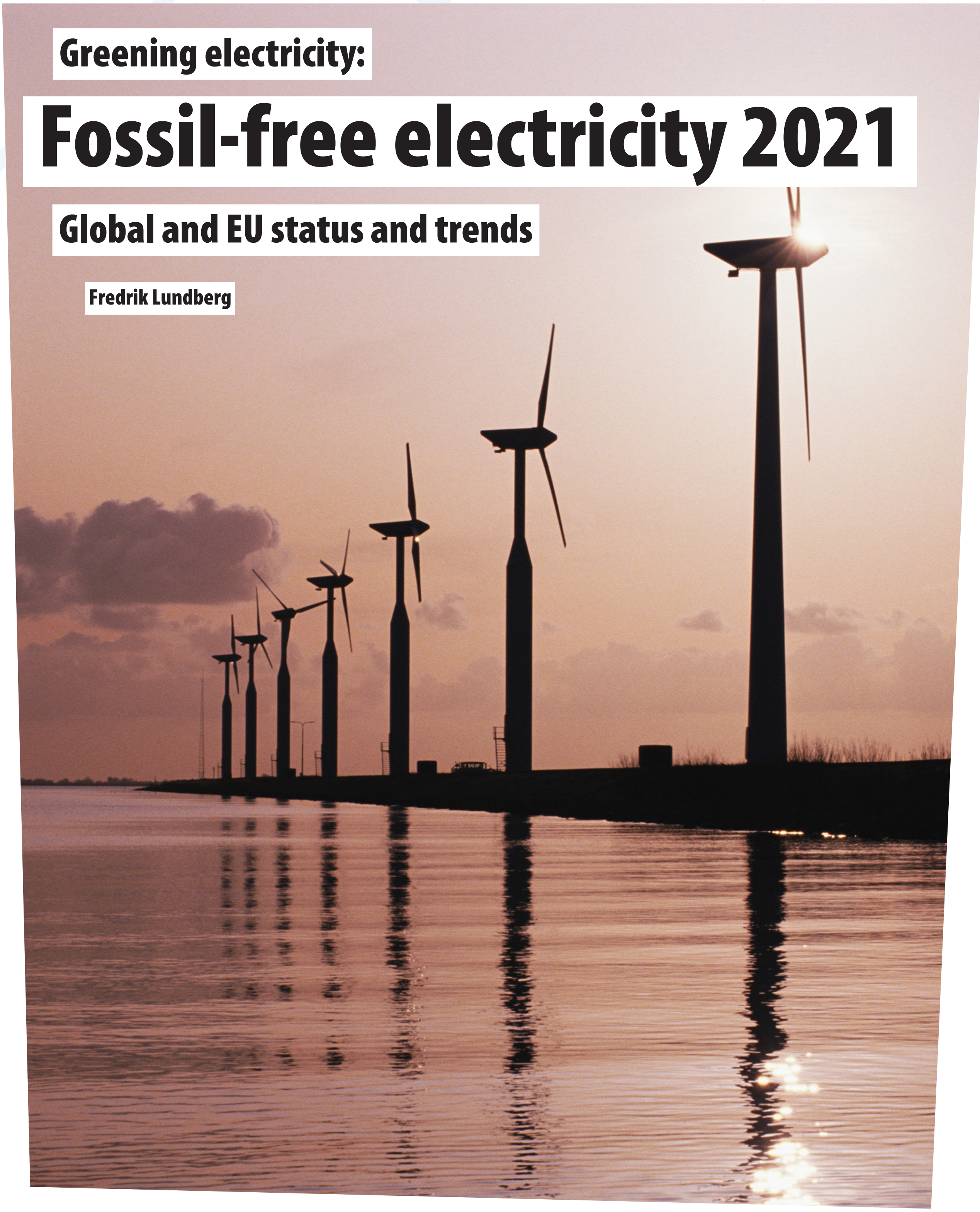
Greening electricity:

Fossil-free electricity 2021

Global and EU status and trends

Fredrik Lundberg



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Wind and solar produced more than 10% of global electricity in 2021, for the first time. They also surpassed nuclear, which fell below 10% for the first time in several decades. Hydro is still the top non-fossil electricity producer, but solar and wind are growing much faster.

In 2021, for the first time, solar and wind power provided more electricity to the world than all nuclear power. This is one of many key points that can be made fromfound in BP's Statistical Review of World Energy June 2022[1], and it is a landmark. It was the first time that solar and wind surpassed 10 per cent of global electricity generation. It was also the first time in many years that nuclear did not exceed 10 per cent.

TWh electricity, World	2010	2020	2021	Average annual growth 2010–2021, %	Share 2021
Nuclear	2,769	2,694	2,800	0.6	9.8
Hydro	3,429	4,346	4,274	1.9	15.0
Renewables	761	3,147	3,657	74.3	12.8
Solar + wind	370	2,362	2,915	120.4	10.2

The remaining 62 per cent is fossil power. What the climate needs is for fossil power to be eliminated by the three non-fossil sources. Of these, renewable power alone is a credible candidate for the job. So far, renewables have only reduced the growth of fossil power. The next doubling of solar and wind will cut fossil power, and emissions, in absolute terms.

Nuclear has moved sideways for almost two decades, globally. It has decreased in the EU. Renewables are now predominantly wind and solar, the least controversial of the renewables. Some of the remaining renewables are also generally seen as benign: particularly geothermal, tidal and some bioenergy.

Hydro is also controversial but not accounted for as renewable in BP statistics. It is the biggest of the three non-fossil sources of electricity, but renewables are growing much faster

Politics and history play a big role in which energy sources different countries choose – much bigger than geographical conditions. Nuclear power is mostly found in countries that have or had nuclear weapons ambitions and is found in countries with high risks of earthquakes and tsunamis, weak infrastructure and extensive corruption, as well those with stable bedrock and management. It is found in rich and poor countries.

1 See https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html

Wind power is mostly found in countries that developed it as an alternative to nuclear power and fossil fuels.

Sunnier countries have more solar power. But there are many examples of countries with very good conditions that have almost no solar power at all: Russia and most of the former Soviet republics in the south, most of the Middle East and, with some exceptions, Africa.

Nuclear Power

Nuclear power, all countries TWh 2021

1	USA	819.1
2	China	407.5
3	France	379.4
4	Russia	222.4
5	South Korea	158
6	Canada	92
7	Ukraine	86.2
8	Germany	69
9	Japan	61.2
10	Spain	56.5
11	Sweden	53.1
12	Belgium	50.6
13	UK	45.9
14	India	43.9
15	Czech rep	30.7
16	Taiwan	27.9
17	Finland	23.8
18	Switzerland	18.5
19	Bulgaria	16.5
20	Hungary	16
21	Pakistan	15.9
22	Slovakia	15.8
23	Brazil	14.7
24	Mexico	11.9
25	Romania	11.3
26	Argentina	10.8
27	United Arab Emirates	10.5
28	Belarus	5.8

29	South Africa	12.1
30	Slovenia	5.7
31	Netherlands	3.8
32	Iran	3.5
33	Armenia	1.9
	World	2,800.3
	European Union	732.2

The USA is by far the largest nuclear nation, as it has been for at least 60 years. The world's first nuclear reactor started operation there in 1942.

The main growth for nuclear power is is happening in China, which had 74.7 TWh of nuclear in 2010 and 407.5 TWh in 2021, i.e. an increase of 333 TWh. Global nuclear growth was only 31 TWh between 2010 and 2021, so the world outside China saw a substantial contraction of nuclear.

The fast growth of nuclear in China should be put in some context. Wind power is much bigger than nuclear in China, 656 TWh against 408 TWh, and solar (at 327 TWh) is closing in.

The Chinese dominance in nuclear seen in BP data is not the whole truth. The top manufacturer and exporter of nuclear power is Russia.

Rosatom builds reactors in Belarus, Iran, Bangladesh, Egypt, Iran and Turkey. Moreover, they build several reactors in China and India, although both countries have indigenous manufacturers. Rosatom had a project in Finland, but it was terminated by the Finnish government soon after the Ukraine invasion. There are imminent plans for new Russian power in Hungary. Of the seven reactors that started construction in the world 2022, five were being built by Rosatom and two by Chinese companies in China[2]. Of the 10 reactors that started construction 2021, five were Russian exports, one was in Russia and the remaining four were Chinese reactors built in China.

Russia has a very long history as an exporter, reaching back to the Soviet era. All nuclear power reactors in Slovakia, the Czech Republic, Bulgaria, Ukraine, Hungary and Armenia, and half of Finland's reactors are made in Russia.

Those countries are dependent on Russian fuel supply, with the exception of Ukraine. Russia is also big in uranium, uranium isotope enrichment, nuclear fuel fabrication and in technology development.

History plays a big role. The first four countries are all nuclear weapons states. Canada's nuclear technology programme also started during World War II. Argentina, Brazil, South Korea, (West) Germany, Japan, Spain, Sweden, Switzerland and Taiwan all had nuclear weapons plans that laid the foundation for civilian nuclear power in these countries. Britain, India and Pakistan are nuclear weapon states. South Africa even had nuclear weapons, but they were dismantled in 1989. Nuclear weapons preceded civil nuclear in most countries, but civil nuclear was also a cover for weapons.

Geography plays almost no role. Obviously nuclear power should be located far from population centres, far from volcanos, where extensive floods are very rare (for riverside

2 https://pris.iaea.org/PRIS/home.aspx

reactors), where tsunamis and other big waves are unheard of (for coastal reactors) and where the earthquake risk is low. They should also preferably be in countries with a competent and independent bureaucracy, low levels of corruption, and with a resilient power grid that can withstand an emergency reactor shutdown at any time, and supply reliable power to the reactor when it is down.

This is not what we see.

Nuclear power per capita, kWh

1	France	5,621
2	Sweden	5,081
3	Belgium	4,366
4	Finland	4,296
5	South Korea	3,054
6	Slovakia	2,899
7	Czech Republic	2,869
8	Slovenia	2,701
9	USA	2,468
10	Canada	2,405
11	Bulgaria	2,391
12	Switzerland	2,126
13	Ukraine	1,968
14	Hungary	1,648
15	Russia	1,550
16	Spain	1,194
17	Taiwan	1,184
18	Arab Emirates	1,051
19	Germany	830
20	United Kingdom	682
21	Armenia	640
22	Belarus	621
23	Romania	591
24	Japan	487
25	China	289

Every year since the 1970s, Sweden has been at the top or in second place, alternating with France. In 2022, it is very possible that Sweden overtook France, since many French reactors were idle during this year due to rust and cracks.

Most of the world's countries have no nuclear power at all, including Italy, Poland and another 11 EU countries. Several of the world's most populous countries got no electricity from nuclear power in 2021: Indonesia, Nigeria, Ethiopia, Bangladesh, Egypt and Turkey, although the latter three have reactors under construction.

Wind Power

Biggest nations in wind power, TWh 2021

1	China	655.6
2	US	383.6
3	Germany	117.7
4	Brazil	72.3
5	India	68.1
6	United Kingdom	64.5
7	Spain	62.4
8	France	37.0
9	Canada	35.1
10	Turkey	31.1
11	Sweden	27.3
12	Australia	26.8
13	Mexico	20.9
14	Italy	20.6
15	Netherlands	17.9
16	Poland	16.2
17	Denmark	16.0
18	Portugal	13.2
19	Argentina	12.9
20	Belgium	11.9
21	Norway	11.8
	World	1,861.9
	European Union	389.5

China is by far the largest in wind power, where it grew 13 times the size it had in 2010. There is also a lot of wind power in the USA. The differences between countries are remarkable. Germany has three times as much wind power as France, which has a larger area and a longer coast. The explanation is obviously that for many years Germany had a political will to produce clean power and in 2004–2014 had the most wind power in the world

It is also striking to note which countries are absent from the table. Russia, the world's largest country by surface area, produced only 2.6 TWh of wind, a quarter of what Greece achieved. Wind power is also spectacularly absent in Japan, at only 8.2 TWh.

The BP statistics do not distinguish between onshore and offshore wind. Offshore wind power was of marginal interest and almost single-handedly developed by the UK. The UK remained the world leader until 2021, when China overtook. It is now growing very fast, by 36 per cent[3] in 2021.

3 https://wfo-global.org/wp-content/uploads/2022/02/WFO_Global-Offshore-Wind-Report-2021.pdf

Offshore wind power used to be limited to relatively shallow waters, but the Norwegian invention of floating wind power has increased the potential greatly, though the numbers are still small compared to other offshore and onshore wind.

More energy is produced by turbines, not merely because the rated capacity has grown. The increasing height and size of wind turbines has increased the capacity factor, often over 50 per cent (for offshore). A few years ago an onshore turbine was limited to 3 MW because it was impossible to transport bigger blades. This logistical issue has been resolved, and 7 MW turbines are now on the market.

Table 4. Wind power per capita, kWh 2021

1	Denmark	2,736
2	Sweden	2,613
3	Norway	2,175
4	Ireland	1,931
5	Finland	1,483
6	Germany	1,416
7	Spain	1,317
8	Portugal	1,284
9	US	1,156
10	Australia	1,041
11	Belgium	1,025
12	Netherlands	1,021
13	Greece	982
14	United Kingdom	957
15	Canada	918
16	Austria	754
17	Estonia	558
18	France	548
19	Croatia	530
20	Luxembourg	530
21	New Zealand	516

Denmark's position is not a surprise. It was Denmark, and later Germany, that pioneered wind power in the 1990s as an alternative to nuclear and fossil power.

Few people are aware that Sweden comes in second place, generating almost twice as much per capita as Germany, and that Norway is third. It is also striking that Western Europe leads the way.

Solar Power

Table 5. Biggest solar PV nations, TWh

1	China	327.0
2	US	165.4
3	Japan	86.3
4	India	68.3
5	Germany	49.0
6	Australia	31.2
7	Spain	26.8
8	Vietnam	25.8
9	Italy	25.1
10	South Korea	21.8
11	Brazil	16.8
12	France	14.6
13	Turkey	12.8
14	United Kingdom	12.4
15	Mexico	11.9
16	Netherlands	11.4
17	Chile	10.6
18	Taiwan	7.9
19	South Africa	7.9
20	Ukraine	6.3
21	Belgium	5.6
	World	1032.5
	European Union	160.6

China is thus not only the world's leading producer of solar cells, panels and silicon. It produces far more solar power at home than any other country. This is the consequence of a strategic political choice, which made China richer and cleaner than it would have been with a different industrial strategy.

China's investment in solar power built on Germany's Energiewende (energy transition), which began with the red-green election victory in 1998.

Russia produced only 2.3 TWh of solar power, less than Switzerland, and not much more than Denmark.

Solar is not just growing in TWh. It has also spread to many more countries. By 2015 there were 22 countries with at least one TWh of solar (and many of them just above). In 2021 there were 42 countries, as listed by BP. Some increases are spectacular:

TWh solar, selected nations	2015	2021
Mexico	0.2	11.9
Turkey	0.8	12.8
Vietnam	<0.1	25.8
Pakistan	0.4	1.5
United Arab Emirates	0.3	5.1
Poland	0.1	3.9
Ukraine	0.5	6.3

The world's first modern solar cell (monocrystalline silicon) was invented in the United States in 1954. Even in 2014 the USA had more solar power than China and Japan combined. Japan was for a long time the leader in all semiconductor technology, including solar cells. It laid the foundations for new investment in solar power in Japan after the Fukushima disaster in 2011.

Besides photovoltaic power there are two other forms of solar energy.

One is thermal solar power (concentrated solar power CSP), which heats water (or some other liquid) and drives the steam through a turbine with a generator. It was once thought to have a huge future, even bigger than PV, in very sunny countries. Those hopes have mainly failed to materialise and compared to PV it is marginal (and not accounted for in the BP statistics) with some 6 GW operating worldwide[4] in 2021, less than one per cent of PV. It may yet have some role to play, because solar heat can be stored in molten salt, for example, so the power is dispatchable. It remains to be seen if this advantage is enough to compete with PV combined with battery storage.

The "other solar" is solar hot water, which is pretty big but does not get much attention. There was 522 GW of solar heat in the world in 2021 according to the IEA[5], compared to 843 GW of PV, even if it is difficult to compare heat with electricity.

The big growth is in PV, where installed capacity grew more than eight-fold from 2012 to 2021, and energy. It may have grown twice as fast in 2022 as it did in 2021[6].

The main growth is at utility scale, in big solar farms, although rooftop installations are also substantial.

New applications are growing. In some of them the shade supplied by the panels is almost as important as the electricity. Agrivoltaics is one combination, floating solar panels on canals and water reservoirs also help to save water as they increase solar output by cooling the panels.

Modules are now often bifacial, picking up light on both sides. An increasing share of the panels follow the sun with single-axis (tilting) or even dual-axis tracking. Such factors largely explain why solar energy generation (in TWh) has increased more than capacity (in GW), from about 0.9 kWh/watt in 2011 to 1.2 kWh/watt in 2021. The improvement per square metre is even higher, as conversion efficiencies have improved.

4 https://www.solarpaces.org/wp-content/uploads/installed_capacity_sept2021.jpg

5 https://www.iea-shc.org/Data/Sites/1/media/documents/press/2022-06-20--solar-heat-worldwide-2022=press-release.pdf

6 https://www.pv-magazine.com/2022/12/23/global-solar-capacity-additions-hit-268-gw-in-2022-says-bnef/

They first improve in the labs for a dozens[7] of different technologies, and some are then commercialised for niche or mainstream applications. The biggest bet for high-efficiency low-cost cells is now on perovskite, alone or as an extra layer with silicon.

This diversity means that if one road ahead is blocked, for example by a price hike for a component metal or because of geopolitics, other roads will open up.

Solar power per capita, kWh

1	Australia	1,212
2	Japan	686
3	Netherlands	652
4	Germany	589
5	Israel	580
6	Spain	566
7	Chile	552
8	Cyprus	544
9	United Arab Emirates	515
10	US	498
11	Greece	485
12	Belgium	484
13	Italy	424
14	South Korea	422
15	Luxembourg	394
16	Hungary	391
17	Switzerland	346
18	Taiwan	336
19	Vietnam	263
20	Austria	237
21	China	232
	World	131

The differences are striking and show that the potential for growth is really huge, as well as likely. Saturation is a long way off, and in many countries growth is yet in its infancy.

Colombia, Iran and Pakistan had less than 10 kWh solar per capita in 2021, for example, though all three have good insolation, vast land areas and large populations. It might be suspected that the focus on oil in Colombia and Iran, and the focus on nuclear in Iran and Pakistan have led their technocrats to shun solar. As for Russia, this is a certainty. But once solar development starts, it can accelerate very fast.

Geography is important. A solar panel delivers twice as much energy in a sunny country as in north Germany. Australia is a very sunny country with lots of space, and that goes for a lot of the top solar countries.

7 See https://www.nrel.gov/pv/cell-efficiency.html

Politics play an even bigger part. Germany has been a pioneer not because of, but in spite of, its geography. But its endorsements of solar has spread to all its not-very-sunny neighbours: Denmark, the Netherlands, Belgium, Austria, Switzerland, Luxembourg, Hungary and Poland. Only the Czech Republic has, so far, resisted.

Denmark, far from the tropics, comes in 22nd place, and even less sunny Sweden in 32nd place with 139 kWh/capita (not in the table). The top solar nation per capita, Australia, has predominantly had an anti-climate, pro-coal government in recent years, but politics is not only federal. Some state governments have supported solar, and obviously the plummeting price of PV has been a driving force.

Hydro power

Hydroelectricity: Generation, excluding most of Africa*, selected countries

	Nation	TWh 2021
1	China	1,300
2	Canada	381
3	Brazil	363
4	US	258
5	Russia	215
6	India	160
7	Norway	143
8	Japan	78
9	Vietnam	76
10	Sweden	71
11	Venezuela	61
12	Colombia	60
13	France	58
14	Turkey	56
15	Italy	43
16	Austria	43
17	Pakistan	38
18	Switzerland	36
19	Mexico	35
20	Malaysia	32
21	Peru	32
22	Spain	30
23	Ecuador	26
24	Indonesia	25
25	New Zealand	24
26	Argentina	20

27	Germany	19
28	Romania	17
29	Chile	17
30	Australia	16
31	Finland	16
32	Iran	15
33	Egypt	15
34	Iceland	14
35	Portugal	12
36	Ukraine	10
37	Philippines	9
38	Kazakhstan	9
39	Croatia	7
40	Sri Lanka	7
	World	4,274
	EU	344

*BP has grouped several African countries together as West Africa, etc

Hydroelectricity is a big source of energy: 4,274 TWh globally, compared to 1,862 TWh of wind and 2,700 TWh of nuclear. It is by far the biggest source of renewable electricity, though its status as renewable is contested. The water is renewable, but the biodiversity of the river and its surroundings is not. There are several social issues, such as displacement of indigenous people and loss of arable land.

The greenhouse balance of a hydro project is complicated in the initial years or decades.

The common NGO view can be summarised as: no new hydro anywhere, especially not in pristine rivers. Existing hydro should usually be accepted.

The distribution of hydro is extremely uneven, and has had consequences for the industrial structure.

Once built, hydro is a cheap source of electricity as it has no fuel costs and has low costs for operation and maintenance. This has led governments to believe that hydro produces cheap electricity, and that it is a good idea to locate aluminium smelters and the like near hydro plants. Such thinking has led to a colossal waste of energy. Norway, and even later Sweden, kept using outdated, inefficient and incredibly dirty Söderberg technology to produce aluminium for several decades more than would have been optimal. Iceland is the top per-capita user of electricity, because it has hydro, followed by Norway. They use a great deal of electricity, not because they need to, but because they can.

Existing hydro also plays an important part in the electricity grid, because it is dispatchable and can be used to balance wind and solar.

As seen above, some of the top per-capita wind power nations are Denmark, Sweden, Norway and Finland, all connected to the huge Norwegian-Swedish hydro resource, which also helps to balance Poland, Germany, the Netherlands, Lithuania and the UK. Germany only has a small hydro resource and Denmark and the Netherlands none at all.

Hydro works like a battery: when wind and solar produce a lot of electricity, hydro production is minimised. The water level rises in the reservoirs. When there is not so much solar and wind, hydro can top up the shortfall.

In normal hydropower stations, the flow rate can only be increased or decreased. The flow cannot normally be reversed, although there are some installations that can do this, known as “pumped hydro”. Around 25 per cent of the energy is lost in the round trip. They were built in the 1970s or 1980s for fast response to nuclear power trips, for example in Wales and Lithuania.

“PHES [pumped hydro energy storage] plants have historically been developed to create electricity demand at night in order to operate base load power plants, such as nuclear power plants, in stable conditions. Therefore, many PHES plants are located midway between nuclear power plants and large demand areas.”[8]

It is worth noting that big hydro is correlated with nuclear power growth from the 1960s onwards in Japan, France, Canada, Sweden, Switzerland, Canada (Ontario), and parts of the United States (mainly the north and Tennessee).

There are other ways to balance wind and solar (or nuclear), by using demand-side management and batteries, but the existence of hydro has helped the expansion of wind and solar power in Northern Europe, Spain, China, South America and other countries.

Hydroelectricity per capita, kWh, selected countries

1	Iceland	37,362
2	Norway	26,449
3	Canada	9,957
4	Sweden	6,838
5	Austria	4,783
6	New Zealand	4,722
7	Switzerland	4,179
8	Finland	2,835
9	Slovenia	2,231
10	Venezuela	2,171
11	Croatia	1,762
12	Brazil	1,695
13	Russia	1,496
14	Latvia	1,450
15	Ecuador	1,437
16	Colombia	1,168
17	Portugal	1,151
18	Malaysia	964
19	Peru	958
20	China	920

8 Ichimura and Kimura https://www.sciencedirect.com/science/article/pii/S2096511719301082

21	Romania	884
22	Chile	861
23	France	859
24	US	776
25	Slovakia	776
26	Vietnam	773
27	Italy	729
28	North Macedonia	691
29	Bulgaria	661
30	Turkey	657
31	Spain	625
32	Japan	618
33	Australia	618
34	Greece	546
35	Kazakhstan	479
36	Argentina	428
37	Sri Lanka	320
38	Mexico	267
39	Ukraine	238
40	Germany	230
	EU	770
	Total World	545

Trends

Electricity use

2020 and 2021 were unique years, because of the Covid pandemic and supply chain challenges due to the lockdowns. For this reason it is more informative to compare 2021 not only with 2020 but also with 2019. The data is for production, which is the same as consumption for the world and almost the same as consumption in the EU.

Table Electricity production/consumption, TWh

Electricity, TWh	2019	2020	2021	Growth 2021/2019, %
World	27,037	26,889	28,466	5
EU	2,894	2,779	2,895	0

For the world as a whole, **electricity production and consumption** have continued to grow every year for a long time. In low-income countries, electricity growth is strongly correlated with rising standard of living. In richer countries we do not see the same pattern. Electricity production in the EU peaked in 2008 at close to 3,000 TWh. It has since decreased by 3–4 per cent.

For the world in general, continued growth is inevitable for the foreseeable future.

But for the EU, there are two opposing trends.

One is rising efficiency, which explains the downward trend over the last few years in rich countries (electricity consumption in Sweden peaked at an admittedly very high level, in 2001). The efficiency gains are due to using heat pumps instead of direct electric heating, better windows, LED lighting, occupancy sensors and a plethora of other electronic gadgets, more efficient motors and pumps etc. The potential for further conservation is huge and keeps growing.

The other trend is increased use of electricity for new purposes. Electric cars are an obvious case, and the use of hydrogen in the steel industry and chemical industry may be of bigger importance. The replacement of gas or oil heating with heat pumps will also add to electricity consumption.

Nuclear Power

Nuclear power has been essentially flat, globally, and is decreasing in the EU.

Nuclear, TWh	2019	2020	2021	Growth 2021/2019, %
World	2,796	2,694	2,800	0
EU	766	683	732	-4

Nuclear peaked globally, at least so far, in 2006, at 2803 TWh. It almost reached the same level in 2021. On the whole, new capacity (mainly in China) has matched shutdowns (mainly in Japan, the EU, Japan, the UK the United States, and Taiwan).

In the EU, nuclear peaked in 2004 at 929 TWh. It was 21 per cent lower, at 732 TWh, in 2021. This trend is sure to continue in 2022, even if France brings all its reactors back on line. Late in 2021 Germany shut down three reactors and will shut down its last three by spring 2023. Belgium shut down two reactors in 2022 and 2023. The four reactors under construction (one in France, two small in Slovakia) or being commissioned (one in Finland) will not make up for the deficit.

Hydro power

Hydropower grew by two per cent per year over the last decade, and new construction is not likely to stop soon, though the environmental and social costs are very high.

Hydro will not grow in the EU, as there are very few unregulated waterways left, and those few are protected.

Climate change will mean more water and more energy in some rivers, which obviously is accompanied by increased disaster risks. It will also mean less water in other rivers.

Wind power

Globally, wind power is growing every year, and in the EU almost every year

Wind power TWh	2019	2020	2021	Growth 2021/2019, %
World	1,421	1,596	1,862	31
EU	364	397	389	7

The lacklustre performance of wind power in the EU 2021 is not a trend. There is an inter-annual random variation, at least regionally, for hydro, nuclear and wind. 2020 was a very windy year in Europe, 2021 much less so, so despite increasing capacity, slightly less electricity was produced than in the previous year. Wind power keeps growing in Europe, and the world.

One possible obstacle for wind power is the need for neodymium and dysprosium for the permanent magnets. If supply is strained and prices remain very high for a long time, other sources will become viable and profitable, possibly with geopolitically motivated subsidies. It may also be possible to eliminate the use of those metals for wind power[9].

Solar power

Solar power, TWh	2019	2020	2021	Growth 2021/2019, %
World	704	846	1,033	47
EU	123	143	161	31

Solar power has grown quickly in the EU and in the world. It seems a safe bet to predict even faster growth for the next few years. The Covid pandemic and supply chain issues made solar cell and module prices go up instead of down. This is about to reverse once again, and soon. The PV manufacturers have invested in more polysilicon production, more solar cell production capacity and more module capacity. There is now a substantial overcapacity in every stage, except maybe installation. The supply side is ready for a huge increase.

The demand is not just price-driven. There is also a strong political element. The US, the EU, China, India and many other countries want to reduce greenhouse gas emissions and get rid of (Russian) gas as soon as possible, and nothing is faster than solar. The US Inflation Reduction Act is creating additional demand, and the EU's Fit for 55 legislative package points in the same direction.

Solar's perceived Achilles heel was that it is not dispatchable, but there are now several ways of integrating ever larger amounts of solar and wind, due to cheaper batteries, by using electric car batteries and through smart combinations of solar and wind, by using hydrogen storage (to flatten solar power peaks) and by demand-side management (to flatten demand peaks, and for "valley filling" in periods of low demand).

9 https://www.sandia.gov/labnews/2022/07/28/propelling-wind-energy-innovation/