Current Status and Future Developments in Nuclear-Power Industry of the World

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It is well known that electrical-power generation plays the key role in advances in industry, agriculture, technology, and standard of living. Also, strong power industry with diverse energy sources is very important for a country's independence. In general, electrical energy can be mainly generated from: (1) nonrenewable energy sources (75.5% of the total electricity generation) such as coal (38.3%), natural gas (23.1%), oil (3.7%), and nuclear (10.4%); and (2) renewable energy sources (24.5%) such as hydro, biomass, wind, geothermal, solar, and marine power. Today, the main sources for electrical-energy generation are: (1) thermal power (61.4%)—primarily using coal and secondarily using natural gas; (2) "large" hydro-electric plants (16.6%); and (3) nuclear power (10.4%). The balance of the energy sources (11.6%) is from using oil, biomass, wind, geothermal, and solar, and has visible impact just in a few countries. This paper presents the current status of electricity generation in the world, various sources of industrial electricity generation and role of nuclear power with a comparison of nuclear-energy systems to other energy systems. A comparison of the latest data on electricity generation with those several years old shows that world usage of coal, gas, nuclear, and oil has decreased by 1–2%, but usage of renewables has increased by 1% for hydro and 2% for other renewable sources. Unfortunately, within last years, electricity generation with nuclear power has decreased from 14% before the Fukushima Nuclear Power Plant (NPP) severe accident in March 2011 to about 10%. Therefore, it is important to evaluate current status of nuclear-power industry and to make projections on near (5–10 yr) and far away (10–25 yr and beyond) future trends. [DOI: 10.1115/1.4042194]

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1 Statistics on Electricity Generation in the World and Selected Countries

This paper is a logical continuation of our previous publications on this topic [1–4]. It is well known that electricity generation and consumption are the key factors for advances in industry, agriculture, technology, and standard of living (see Figs. 1–4 and Tables 1

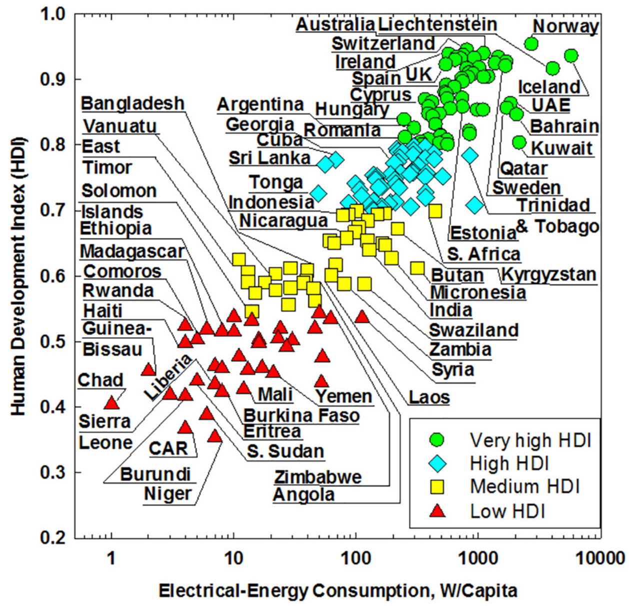


Fig. 1 Impact of electrical-energy consumption (EEC) on human development index (HDI) for all countries of the world (based on data from the Appendix: graph with all countries in the world are shown, but only selected countries are identified). This graph shows clearly strong dependence of HDI from EEC.

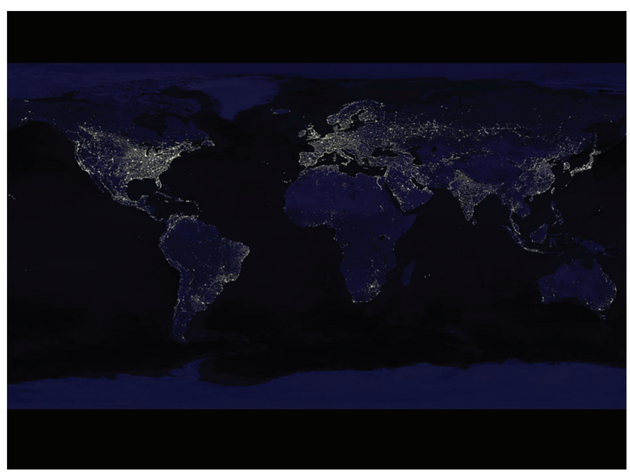


Fig. 2 This composite image showing a global view of Earth at night, was compiled from over 400 satellite images. Lights in image show density of population and EEC. Credit: NASA/NOAA. Last updated: Aug. 4, 2017 [5].

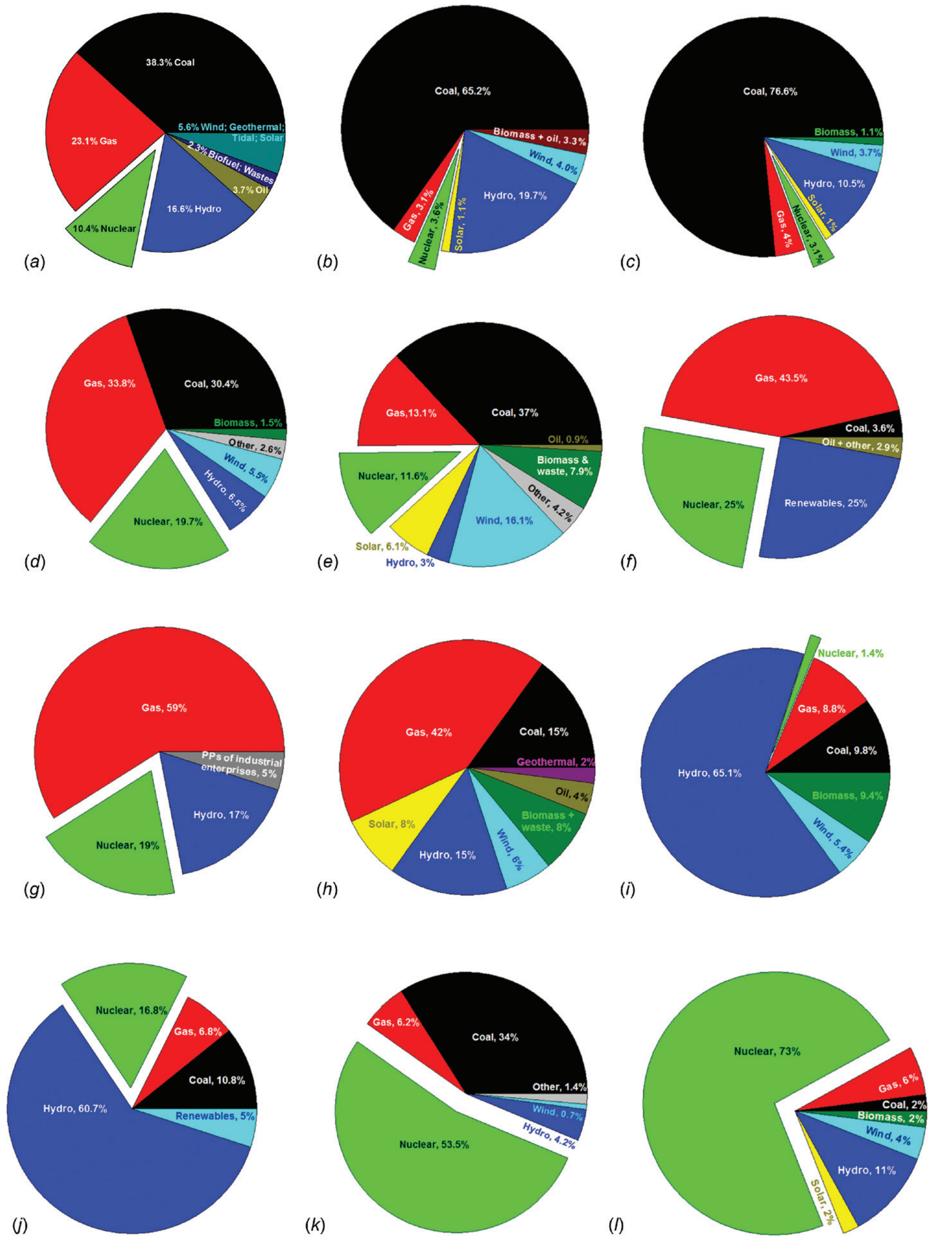


Fig. 3 Electricity generation in the world and selected countries by source (data presented here just for reference purposes): population from Ref. [6] (data for 2018); EEC from Ref. [7] (data mainly from 2017 to 2015; for exact details see the reference); and HDI from Ref. [8] (data from 2017); data in diagrams from 2016: World from Ref. [9]; China, USA, and Germany from Ref. [10]: (*a*) World: population 7659 million (Oct. 19, 2018); EEC 24,816 TW·h per year or 372 W per capita; HDI 0.728 or HDI Rank 98. (*b*) China: population 1415 million; EEC 5920 TW·h per year or 510 W per capita; HDI 0.738 or HDI Rank 86. (*c*) India: population 1354 million; EEC 1048 TW·h per year or 114 W per capita; HDI 0.640 or HDI Rank 130. (*d*) USA: population 327 million; EEC 3,911 TW·h per year or 1377 W per capita; HDI 0.924 or HDI Rank 13. (*e*) Germany: population 82 million; EEC 515 TW·h per year or 753 W per capita; HDI 0.936 or HDI Rank 5. (*f*) UK: population 67 million; EEC 302 TW·h per year or 547 W per capita; HDI 0.922 or HDI Rank 14. (*g*) Russia: population 144 million; EEC 890 TW·h per year or 854 W per capita; HDI 0.816 or HDI Rank 49. (*h*) Italy: population 59 million; EEC 296 TW·h year or 535 W per capita; HDI 0.880 or HDI Rank 28. (*i*) Brazil: population 211 million; EEC 461 TW·h per year or 287 W per capita; HDI 0.759 or HDI Rank 79. (*j*) Canada: population 37 million; EEC 517 TW h per year or 1704 W per capita; HDI 0.926 or HDI Rank 12. (*k*) Ukraine: population 44 million; EEC 133 TW·h per year or 369 W per capita; HDI 0.751 or HDI Rank 88. (*l*) France: population 65 million; EEC 436 TW·h per year or 736 W per capita; HDI 0.901 or HDI Rank 24.

and 21 (in the Appendix)). Also, strong power industry with diverse energy sources is very important for a country's independence. In general, electricity (see Fig. 3) can be mainly generated from: (1) nonrenewable energy sources such as coal, natural gas, oil, and nuclear and (2) renewable energy sources such as hydro, biomass, wind, geothermal, solar, and marine power.

Today, the main sources for global electrical-energy generation (see Fig. 3(*a*)) are: (1) thermal power—primarily using coal

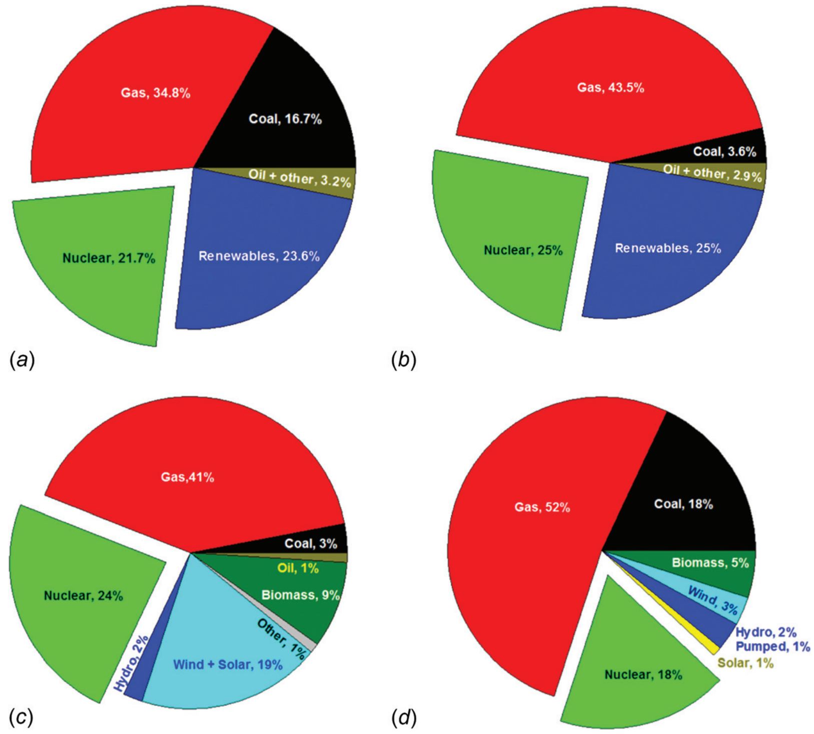


Fig. 4 Electricity generation in UK by source (data presented here just for reference purposes): Data in diagrams for 2015–2017 [11–13] (*a*) UK Q3 2015, (*b*) UK Q3 2016, (*c*) UK Q3 2017 (all renewables 30%), (*d*) UK Jan. 16–22, 2017: population 67 million; EEC 302 TW·h/yr or 547 W per capita; HDI 0.922 or HDI Rank 14

(38.3%) and secondarily using natural gas (23.1%); (2) "large" hydro-electric plants (16.6%); and (3) nuclear power (10.4%). The last 11.6% of the electrical energy is generated using oil (3.7%), and the remainder (7.9%)—from biomass, geothermal, and intermittent wind, solar, and marine energy. Main sources for electrical-energy generation in selected countries are also shown in Figs. 3(*b*)–(*l*) and 4.

A selected comparison of the data in Fig. 3 with those data (mainly related to 2013 or even earlier) presented in our previous publication from 2016 [1] shows that:

(1) World usage of coal, gas, nuclear, and oil has decreased by 1–2%. Usage of renewables has increased by 1% for hydro and 2% for other renewable sources (Fig. 3(*a*)). However, these changes are not so significant within a number of years.
(2) China has significantly decreased usage of coal for electricity generation from 80% to 65%; and increased usage of hydro power from 15% to 20%, gas from 1% to 3%, nuclear from 2% to 4%, wind from 0% to 4%, and solar from 0% to 1%, which is a very good trend, i.e., decreasing usage of "dirty" coal for electricity generation (Fig. 3(*b*)).
(3) The U.S. have decreased usage of coal from 39% to 30%; increased usage of gas from 28% to 34%; nuclear, hydro power, and other renewables are approximately on the same level, i.e., 20%; 7%, and 7%, respectively, which is also a good trend (Fig. 3(*d*)).
(4) Russia has increased usage of gas for electricity generation from 49% to 59%, nuclear from 17% to 19%, and hydro power from 16% to 17% (Fig. 3(*g*)). Due to these increases, the usage of coal has substantially decreased from 16% to less than 5%.
(5) Germany has visibly decreased usage of coal for electricity generation from 47% to 37%; however, at the same time, the usage of nuclear power was also decreased from 16% to 12% (Fig. 3(*e*)). This drop in electricity generation was mainly compensated with wind power, which was increased from 8% to 16% (onshore wind farms—13.3% and offshore—2.8%), gas from 11% to 13%, and solar up to 4% increase.
(6) The United Kingdom has significantly decreased their usage of coal for electricity generation from 17 to 3% within 2015–2017 (Fig. 3(*f*); also, more detailed comparison, based on data for Q3 per each year, is shown in Figs. 4(*a*)–4(*c*)). The usage of coal was substituted mainly with gas, and, partially, with nuclear and renewables. However, in January 2017 quite unusual events have happened, which affected significantly the electricity generation from various sources (Fig. 4(*d*)). At that time, the UK grid faced a "perfect storm," which co-inside with a temporary shutdown of a number of NPPs in France, nuclear trips in the UK, and a broken interconnector with France. On the top of that, on Jan. 16, 2017, wind diminished for the whole week. These special and unexpected conditions could definitely lead to a complete blackout. However, gas- and coal-fired power plants have saved the grid (usage of gas for electricity generation has increased by ~11% and of coal—by ~15%).
(7) France has not significantly changed their usage of various sources for electricity generation (Fig. 3(*l*)) over the same period.

Therefore, considering fast changes in climate, possible catastrophic events such as powerful hurricanes, melting ice-caps in mountains, and changes in solar activity, countries should not rely on unreliable renewable sources such as hydro, wind, solar, and

Fig. 5 Aerial view of the largest NPP in the world—6384-MW_{el} Bruce NPP (courtesy of Bruce NPP[1]). (The Douglas Point NPP was Canada's first full-scale NPP and the second CANDU reactor. Its success was a major milestone for Canada to enter into global nuclear-power scene. Construction began on Feb. 1, 1960 and decommission date: May 4, 1984.)

marine unless there is a significant backup with reliable energy source(s) independent of Mother Nature (in the case of UK there were thermal power plants and NPPs).

Just for comparison purposes, Table 2 lists 20 largest power plants of the world by installed capacity, and Table 3 lists largest operating power plants of the world by energy source, based on installed capacity.

Two very important parameters [1,3] of a power plant are:

(1) Overall (gross) or net efficiency (see Table 4): Gross efficiency of a unit during a given period of time is the ratio of the gross electrical energy generated by a unit to the energy consumed during the same period by the same unit. The difference between gross and net efficiencies is an internal need for electrical energy of a power plant, which might be not so small (5% or even more).

(2) Capacity factor of a plant: Net capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time (usually, during a year) and its potential output, if it had operated at a full nameplate capacity the entire time. To calculate the capacity factor, the total amount of energy a plant produced during a period of time should be divided by the amount of energy the plant would have produced at the full capacity. Capacity factors vary significantly depending on the type of a plant (see Table 5). Average capacity factors of the largest power plants in the world are listed in Table 2.

How various energy sources generate electricity in a grid can be illustrated based on the Province of Ontario (Canada) system. Currently, the Province of Ontario (Canada) has completely eliminated coal-fired power plants from its electrical grid. Some of them were closed, others—converted to natural gas. Figure 6(*a*) shows installed capacity, and Fig. 6(*b*) shows electricity generation by energy source in the Province of Ontario (Canada) in 2015. Analysis of Fig. 6(*a*) shows that in Ontario major installed capacities in 2015 were nuclear (38%), gas (29%), hydro (25%), and renewables (mainly wind) (8%). However, electricity (see Fig. 6(*b*)) was mainly generated by nuclear (60%), hydro (24%), natural gas (8.7%), and renewables (mainly wind) (4.9%).

As a result, Ontario has committed to a massive \$25B refurbishment and multiyear life extension of its existing NPPs, on the grounds that "There are currently no alternative generation portfolios that could provide the same supply of low emissions baseload electricity generation at a comparable price to the Nuclear Refurbishment Plan." (Ontario Financial Accountability Office, "Nuclear Refurbishment Report," Nov. 21, 2017 [15]).

Figure 7 shows power generated (*a*) and capacity factors (*b*) of various energy sources in Ontario (Canada) electrical grid in winter (Feb. 11, 2015), in spring (Apr. 16, 2015), and in summer (June 17, 2015). Analysis of the data in Fig. 7 shows that nuclear, hydro, gas, wind, biofuel, and solar are the major sources for electricity generation. However, in winter, solar might not be visible (see Figs. 7(a_1) and 7(b_1)). Somewhere in spring, solar became visible in a grid (see Figs. 7(a_2) and 7(b_2)). Therefore, a detailed analysis of the Ontario grid operation is provided below for a summer day (see Figs. 7(a_3) and 7(b_3)).

Electricity that day from midnight till 3 o'clock in the morning was mainly generated with nuclear, hydro, gas, wind, and biofuel. After 3 o'clock, biofuel power plants have increased slightly electricity generation followed by hydro and gas-fired power plants due to increased consumption of electricity in the province. Also, at the same time, wind power plants have also slightly increased electricity generation by the Mother Nature. However, after 7 o'clock wind power started to fluctuate and, eventually, decreased significantly. After 6 o'clock in the morning, solar power plants started to generate electricity.

During a day, hydro, gas-fired, and biofuel power plants had variable electricity generation to compensate changes in consumption of electrical energy and variations in generating electricity from wind and solar power plants. After 9 o'clock in the

[1] www.brucepower.com

Table 1 Population, EEC and HDI in selected countries

HDI[a] rank (2017)	Country	HDI[a] (2017)	EEC[b] (2015-2017) W/capita	EEC[b] (2015-2017) GW·h	Population in millions (2018)
Very high HDI					
1	Norway	0.953	2740	133,100	5.35
2	Switzerland	0.944	809	58,450	8.54
3	Australia	0.939	1112	223,600	24.77
4	Ireland	0.938	576	23,790	4.80
5	Germany	0.936	753	514,600	82.29
6	Iceland	0.935	5777	17,980	0.34
8	Sweden	0.933	1467	125,400	9.98
12	Canada	0.926	1704	516,600	36.95
13	USA	0.924	1377	3,911,000	326.76
14	UK	0.922	547	301,600	66.57
19	Japan	0.909	841	933,600	127.18
23	South Korea	0.903	1109	497,000	51.16
24	France	0.901	736	436,100	65.23
34	United Arab Emirates (UAE)	0.863	1848	110,600	9.54
40	Saudi Arabia	0.853	1102	292,800	33.55
49	Russia	0.816	854	890,100	143.96
56	Kuwait	0.803	2176	54,110	4.19
High HDI					
60	Iran	0.798	300	220,900	82.01
64	Turkey	0.791	294	213,200	81.91
74	Mexico	0.774	220	245,200	130.76
78	Venezuela	0.761	288	73,990	32.38
79	Brazil	0.759	287	460,800	210.86
86	China	0.752	510	5,920,000	1415.05
88	Ukraine	0.751	369	133,400	44.01
	World	0.728	370	24,816,000	7658.82
Medium HDI					
114	South Africa	0.699	445	207,700	57.40
130	India	0.640	128	1,048,000	1354.05
137	Republic of Congo	0.606	13	901	5.40
150	Pakistan	0.562	46	85,900	200.81
Low HDI					
158	Rwanda	0.524	4	644	12.50
161	Madagascar	0.519	6	1108	26.26
162	Uganda	0.516	8	2936	44.27
168	Haiti	0.498	4	372	11.11
169	Afghanistan	0.498	16	2866	36.37
173	Ethiopia	0.463	7	8143	107.53
177	Guinea-Bissau	0.455	2	32	1.91
179	Eritrea	0.440	5	330	5.18
184	Sierra Leone	0.419	3	163	7.72
185	Burundi	0.417	4	304	11.21
186	Chad	0.404	1	200	15.35
187	South Sudan	0.388	6	694	12.91
188	Central African Republic	0.367	4	162	4.73
189	Niger	0.354	7	1072	22.31

[a]HDI—Human Development Index by United Nations (UN); HDI is a comparative measure of life expectancy, literacy, education, and standards of living for countries worldwide. HDI is calculated by the following formula: $\mathrm{HDI} = \sqrt[3]{\mathrm{LEI} \times \mathrm{EI} \times \mathrm{II}}$, where LEI—Life Expectancy Index, EI—Education Index, and II—Income Index. It is used to distinguish whether the country is a developed, a developing or an underdeveloped, and also to measure the impact of economic policies on quality of life.

[b]EEC, $\frac{\mathrm{W}}{\mathrm{capita}} = \frac{(\mathrm{EEC}, (\mathrm{GWh/yr})) \times (10^9/(365\,\mathrm{days} \times 24\,\mathrm{h}))}{(\mathrm{population}, \mathrm{millions}) \times 10^6}$; EEC compares the total electricity generated annually plus imports and minus exports, expressed in gigawatt-hours (GW·h).

Note: Population from Ref. [6] (data for 2018); EEC from Ref. [7] (data mainly from 2017 to 2015; for exact details see the reference); and HDI from Ref. [8] (data from 2017). Data for all countries in the world are listed in the Appendix, Table 21.

evening, energy consumption started to drop in the province, and at the same time, wind power increased. Therefore, gas-fired, hydro, and biofuel power plants decreased energy generation accordingly.

It should be noted that NPPs operated at about 100% of installed capacity providing reliable basic power to the grid. This example shows clearly that any grid that includes NPPs and/or renewable-energy sources must also include "fast-response" power plants such as gas-fired, coal-fired and/or large hydropower plants to compensate changes in consumption of electrical energy per day and variations in electricity supply by wind and/or solar power plants.

Usually, NPPs operate continuously on the maximum load, because of a high capital costs and low operating costs. The relative cost of electrical energy generated by any system is not only dependent on building capital costs and operating expenses, but

Table 2 Twenty largest power plants of the world by installed capacity [2]

No.	Plant	Country	Capacity MW_{el}	Average annual generation $TW \cdot h_{year}$	Capacity factor %	Plant type
1	Three Gorges Dam[a]	China	22,500	93.5_{2016}	47	Hydro
2	Itaipu Dam[a]	Brazil/Paraguay	14,000	103.1_{2016}	84	Hydro
3	Xiluodu[a]	China	13,860	55.2_{2015}	46	Hydro
4	Guri Dam	Venezuela	10,235	$47_{average}$	52	Hydro
5	Tucurui Dam	Brazil	8370	21.4_{1999}	29	Hydro
6	Kashiwazaki-Kariwa (not in service)	Japan	7965	(60.3_{1999})	(86)	Nuclear
7	Robert-Bourassa Dam	Canada	7722	$26.5_{average}$	39	Hydro
8	Grand Coulee Dam	USA	6809	$20.2_{average}$	34	Hydro
9	Xiangjiaba	China	6448	30.7_{2015}	54	Hydro
10	Longtan Dam	China	6426	17.3_{2015}	31	Hydro
11	Sayano-Shushenskaya	Russia	6400	26.9_{2016}	48	Hydro
12	Bruce (Fig. 5)	Canada	6384	47.6_{2015}	85	Nuclear
13	Kori	South Korea	6040	39.3_{2015}	74	Hydro
14	Krasnoyarsk Dam	Russia	6000	$18.4_{average}$	35	Hydro
15	Hanul	South Korea	5928	48.2	93	Nuclear
16	Hanbit	South Korea	5875	47.6	93	Nuclear
17	Nuozhadu Dam	China	5850	$23.9_{estimate}$	47	Hydro
18	Zaporizhia	Ukraine	5700	48.2	96	Nuclear
19	Kashima	Japan	5660	—	—	Fuel oil, natural gas
20	Shoaiba	Saudi Arabia	5600	—	—	Fuel oil

[a]It should be noted that, currently, the largest under construction power plants are hydroelectric ones—Baihetan Dam (16,000 MW_{el}) in China and Belo Monte Dam (11,233 MW_{el}) in Brazil. Also, there are two known in the world proposals for future power plants: (1) Grand Inga Dam in Democratic Republic of Congo with possible maximum installed capacity of 39,000 MW_{el} and (2) Penzhin Tidal Power Plant Project in Russia with possible maximum installed capacity of 87,000 MW_{el}.

Table 3 Largest operating power plants of the world (based on installed capacity) by energy source [2]

Rank	Plant	Country	Capacity MW_{el}	Plant type
1	Three Gorges Dam	China	22,500	Hydro (dam)
2	Bruce NPP (Fig. 5)	Canada	6384	Nuclear
3	Taichung	Taiwan	5780	Coal
4	Shoaiba	South Arabia	5600	Fuel oil
5	Surgut-2[a]	Russia	5597	Natural gas
6	Gansu	China	5160	Wind (onshore)
7	Jirau	Brazil	3750	Hydro (run-of-the-river)
8	Bath County[b]	USA	3003	Hydro (pumped storage)
9	Eesti	Estonia	1615	Oil shale
10	Tengger Desert Solar Park	China	1547	Solar (flat panel photovoltaic)
11	The Geysers	USA	1517	Geothermal
12	Shatura[a]	Russia	1500	Peat[a]
13	Ironbridge	UK	740	Biofuel[a]
14	Walney	UK	659	Wind (offshore)
15	IPP3[a]	Jordan	573	Internal combustion engines
16	Ivanpah	USA	377	Solar (concentrated thermal)
17	Sihwa Lake	South Korea	254	Tidal
18	Vasavi Basin Bridge	India	200	Diesel
19	Golmud 2	China	60	Concentrated photovoltaic
20	Sotenäs	Sweden	3	Marine (wave)

[a]It should be noted that actually, some thermal power plants use multifuel options, for example, Surgut-2 (15% natural gas); Shatura (peat—11.5%, natural gas—78%, fuel oil—6.8%, and coal—3.7%) power plants.
[b]Pumped-storage hydro-electricity, or pumped hydro-electric energy storage, is a type of hydro-electric power plant used by electric grids for load balancing. During off-peak hours (or during periods of lower electricity prices), usually at night, water is pumped from a lower elevation reservoir to a higher elevation one. During peak hours (or periods of high electricity prices), the plant is used as a regular hydro-electricity plant. It should be noted that such plants usually consume energy overall, but the plant increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest).

also dependent on the capacity factor. The higher the capacity factor—the better, as generating costs fall proportionally. However, some renewable-energy sources with exception of large hydro-electric power plants can have significantly lower capacity factors compared to those of thermal- and nuclear-power plants (see Table 5).

Also, it should be noted here that countries having a large percentage of variable power sources such as wind and solar, run the risk of an electrical-grid collapse due to unpredicted power instabilities (see the abovementioned example for UK (Fig. 4)). Moreover, the following detrimental factors are usually not considered during estimation of variable power-sources costs: (1) costs of

Table 4 Typical ranges of thermal efficiencies (gross) of modern thermal and NPPs [1]

No.	Power plant	Gross thermal efficiency
1	Combined-cycle power plant (combination of Brayton gas-turbine cycle (fuel—natural gas or liquefied natural gas (LNG); combustion-products parameters at the gas-turbine inlet: $P_{in} \approx 2.5$ MPa, $T_{in} \approx 1650\,^\circ$C) and Rankine steam-turbine cycle (steam parameters at the turbine inlet: $P_{in} \approx 12.5$ MPa ($P_{cr} = 22.064$ MPa), $T_{in} \approx 620\,^\circ$C ($T_{cr} = 374\,^\circ$C))	Up to 62%
2	Supercritical-pressure coal-fired power plant (Rankine-cycle steam inlet turbine parameters: $P_{in} \approx 25$–38 MPa ($P_{cr} = 22.064$ MPa), $T_{in} \approx 540$-$625\,^\circ$C ($T_{cr} = 374\,^\circ$C; and $P_{reheat} \approx 4$–6 MPa, $T_{reheat} \approx 540$-$625\,^\circ$C)	Up to 55%
3	Internal-combustion-engine generators (diesel cycle and Otto cycle with natural gas as a fuel)	Up to 50%
4	Subcritical-pressure coal-fired power plant (older plants; Rankine-cycle steam: $P_{in} = 17$ MPa, $T_{in} = 540\,^\circ$C ($T_{cr} = 374\,^\circ$C; and $P_{reheat} \approx 3$–5 MPa, $T_{reheat} = 540\,^\circ$C)	Up to 43%
5	Carbon-dioxide-cooled reactor NPP (generation-III) (reactor coolant: $P = 4$ MPa, $T = 290$–$650\,^\circ$C; and steam: $P_{in} = 17$ MPa ($T_{sat} = 352\,^\circ$C) and $T_{in} = 560\,^\circ$C; and $P_{reheat} \approx 4$ MPa, $T_{reheat} = 560\,^\circ$C)	Up to 42%
6	Sodium-cooled fast reactor (SFR) (BN-600/BN-800) NPP (steam: $P_{in} = 14.2$ MPa ($T_{sat} = 338\,^\circ$C), $T_{in} = 505\,^\circ$C; and $P_{reheat} \approx 2.5$ MPa, $T_{reheat} = 505\,^\circ$C)	Up to 40%
7	Pressurized-water-reactor NPP (Generation-III+) (reactor coolant: $P = 15.5$ MPa, $T_{out} = 327\,^\circ$C; steam: $P_{in} = 7.8$ MPa, $T_{in} = 293\,^\circ$C; and $P_{reheat} \approx 2$ MPa, $T_{reheat} \approx 265\,^\circ$C)	Up to 36-38%
8	Pressurized-water-reactor NPP (Generation-III, current fleet) (reactor coolant: $P = 15.5$ MPa, $T_{out} = 292$–$329\,^\circ$C; steam: $P_{in} = 6.9$ MPa, $T_{in} = 285\,^\circ$C); and $P_{reheat} \approx 1.5$ MPa, $T_{reheat} \approx 255\,^\circ$C)	Up to 34-36%
9	Boiling-water-reactor NPP (Generation-III, current fleet) ($P_{in} = 7.2$ MPa, $T_{in} = 288\,^\circ$C); and $P_{reheat} \approx 1.7$ MPa, $T_{reheat} \approx 258\,^\circ$C)	Up to 34%
10	Pressurized heavy water reactor (PHWR) NPP (generation-III, current fleet) (reactor coolant: $P = 11$ MPa and $T = 260$–$310\,^\circ$C; steam: $P_{in} = 4.7$ MPa, $T_{in} = 260\,^\circ$C; and $P_{reheat} \approx 0.6$ MPa, $T_{reheat} \approx 250\,^\circ$C)	Up to 32%
11	Concentrated solar thermal power plants with heliostats, solar receiver (heat exchanger) on a tower, and molten-salt heat-storage system. Molten salt maximum temperature is $\sim 565\,^\circ$C. Subcritical-pressure Rankine-steam-turbine power cycle used.	Up to 20%

Table 5 Average (typical) capacity factors of various power plants (for the U.S. data, see [14])

No.	Power plant type	Location	Year	Capacity factor, %
1	Nuclear	USA	2017	92
		Russia	2014	81
		UK	2015	75
		World	2017	81
2	Geothermal	USA	2017	76
3	Bioenergy	USA	2017	51–71
4	Combined cycle	USA	2017	55
5	Coal fired	USA	2017	54
6	Hydroelectric	USA	2017	45
		World (average)	2011–2013	~45
7	Wind	USA	2017	37
		World	2011–2013	20–40
8	Concentrated solar thermal	USA	2017	22
		Spain (molten salt with storage)	2014	63
9	Photovoltaic solar	USA	2017	27
		UK	2015	12
10	Wave	UK	2015	3

fast-response power plants with service crews on site 24/7 as a back-up power; and (2) faster amortization/wear of equipment of fast-response plants.

The major driving force for all advances in thermal power plants is directed towards increasing thermal efficiency (see Table 4) in order to reduce operating fuel costs and minimize specific emissions, and by that parameter thermal power plants have the highest thermal efficiencies in the power industry: up to 62% for combined-cycle power plants and up to 55% for supercritical-pressure coal-fired power plants.

Despite all advances in thermal power-plants design and operation worldwide, they are still considered as environmentally "unfriendly" due to significant carbon-dioxide emissions (for example, the largest in the world 5780-MW_{el} Taichung coal-fired power plant (Taiwan) is the world's largest emitter of carbon dioxide with over 40×10^6 ton per year) [1,19]) and air pollution as a result of the combustion process. In addition, coal-fired power-plants produce significant amounts of slag and ash, and other greenhouse gases such as SO_2, which contributes to acid rains. Comparison of various electricity-generating power plants based on carbon footprint is shown in Fig. 8, deaths per terawatt for various energy sources—in Fig. 9, and per cent of various wastes in total amount—in Table 6. Therefore, nuclear power looks quite attractive based on the abovementioned comparisons.

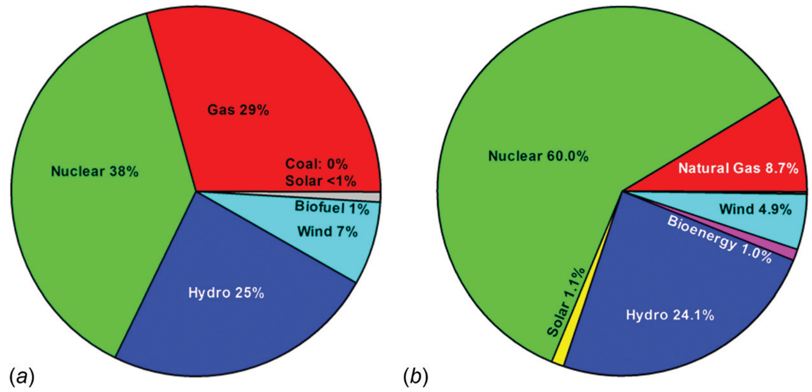


Fig. 6 Installed capacity (*a*) and electricity generation (*b*) by energy source in Ontario (Canada) (population ~13 million people), 2014–2015 (based on data from Ontario Energy Board [16] and Ontario Energy Report [2,17]

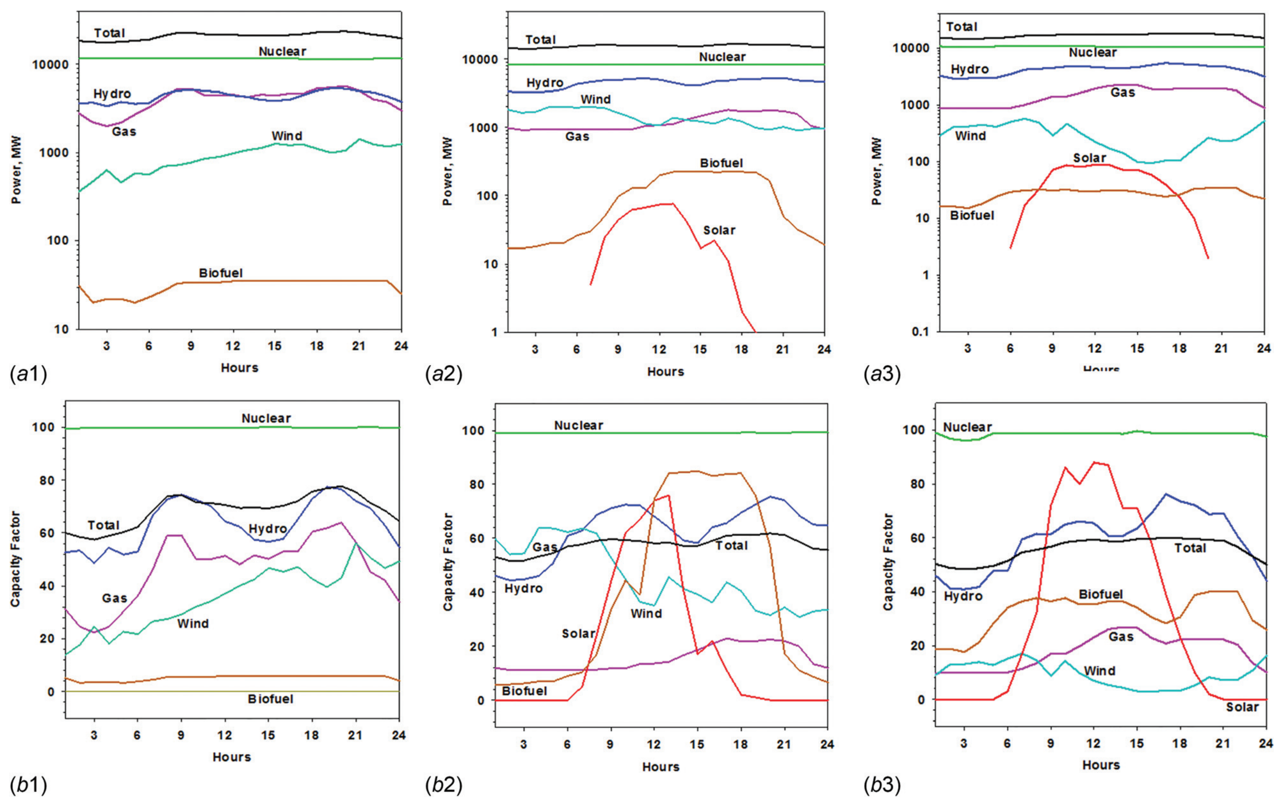


Fig. 7 Power generated (*a*) and capacity factors (*b*) of various energy sources in Ontario (Canada) in selected winter, spring, and summer working days of 2015 (based on data from [18]) (shown here just for reference purposes) [1,2]

2 Modern Nuclear-Power Reactors and Nuclear Power Plants

Nuclear power is often considered to be a nonrenewable-energy source as the fossil fuels, such as coal and gas. However, nuclear resources can be used for significantly longer time than some fossil fuels, and in some cases almost indefinitely, if recycling of unused or spent uranium fuel, thoria-fuel resources, and fast-neutron-spectrum reactors are used. The major advantages of nuclear power [1] are:

(1) concentrated and reliable source of almost infinite energy, which is independent of weather conditions (however, it should be noted that in summer of 2018, which was very hot on a record due to fast climate changes, some reactors/NPPs were forced to decrease power loads or even were

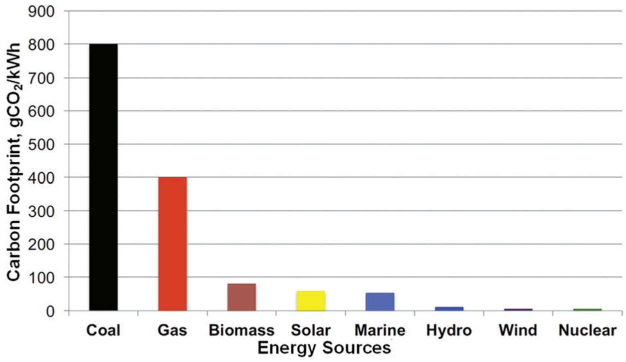


Fig. 8 Carbon footprint for various energy sources (courtesy of Dr. J. Roberts, University of Manchester, Manchester, UK; based on the data from Ref. [20]). If carbon capture and storage is used then the carbon footprint can be decreased for coal and gas by about six times. (For details on carbon footprint of NPPs—see Fig. 10).

shut down for some time, because of lower levels of water in rivers, etc., and/or of relatively high water temperatures including not only in-land water resources, but, also, sea/ocean waters);

(2) high capacity factors are achievable, often in excess of 90% with long operating cycles, making units suitable for continuous base-load operation (Table 5);
(3) essentially negligible operating emissions of carbon dioxide (see Fig. 8) and relatively small amount of wastes generated (see Table 6) compared to alternate fossil-fuel thermal power plants;
(4) relatively small amount of fuel required compared to that of fossil-fuel thermal power plants (see Table 7); and
(5) NPPs can supply relatively cheap electricity for recharging of electrical vehicles during night hours as they usually operate on full load (capacity) 24/7 (see Fig. 7).

As a result, nuclear power is considered as the most viable source for electricity generation within next 50–100 yr. However,

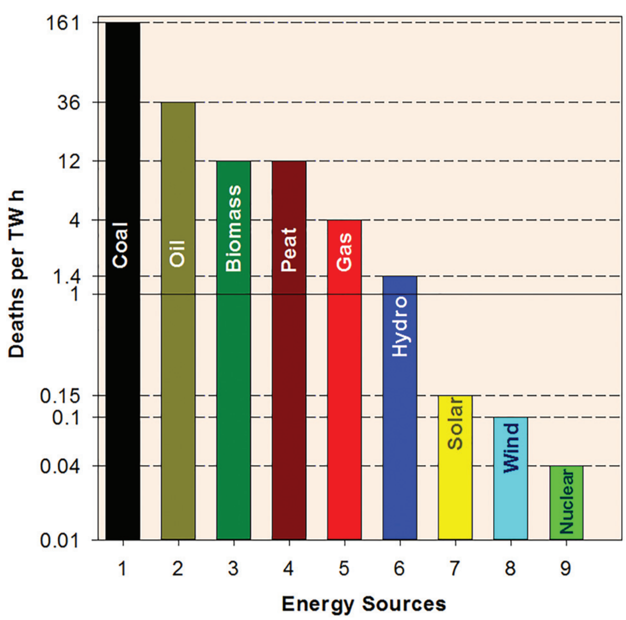


Fig. 9 Deaths per TW·h for various energy sources (based on data from Ref. [21])

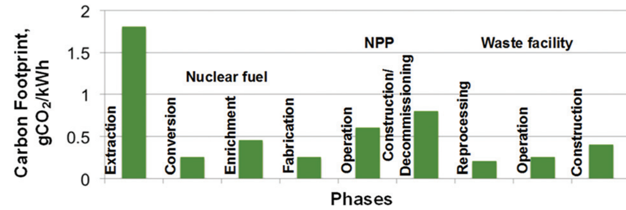


Fig. 10 Carbon footprint of NPP various phases (courtesy of Dr. J. Roberts, University of Manchester; based on the data from British Energy for Torness AGR NPP)

nuclear power must operate and compete in energy markets based on relative costs and strategic advantages of the available fuels and energy types.

Current statistics of all world nuclear-power reactors connected to electrical grids are listed in Tables 8–12, and shown in Figs. 12–15. Analysis of the current statistical data on nuclear-power reactors shows that, currently, 31 countries in the world have operating nuclear-power reactors (within these countries: 18 plan to build new reactors, and 13 do not plan to build new reactors) and 5 countries without nuclear-power reactors (Bangladesh, Belarus', Egypt, Turkey, and UAE) are working toward introducing nuclear energy on their soils (see Table 10).

The largest group of nuclear-power reactors by type is pressurized water reactors (PWRs) (301 from 452 reactors or 67% of the total number), and quite significant number of PWRs are planned to be built (about 77) (for details, see Table 8). The second largest group of reactors is boiling water reactors (BWRs)/advanced BWRs (ABWRs) (72 reactors or 16% of the total number). The third group is PHWRs (48 reactors or 11% of the total number). Considering the number of forthcoming reactors, the number of BWRs/ABWRs and PHWRs will possibly decrease within next 20–25 yr. Furthermore, within next 10–15 yr or so, all advanced gas-cooled reactors (AGRs) (carbon-dioxide-cooled) and light-water-cooled graphite-moderated reactors (LGRs) will be shut down forever. However, instead of carbon-dioxide-cooled AGRs helium-cooled reactors will be built and put into operation.

Analysis of the data in Tables 9 and 10 shows that real nuclear "renaissance" is in China (32 reactors built and put into operation within past 8 yr!), in Russia (addition of 5 reactors), and in South Korea (addition of 3 reactors). Meanwhile, the most significant drop in a number of reactors is in Japan (12 reactors were shut down) (only about 9 reactors out of 42 are currently in operation), in Germany (10 reactors), in U.S. (6 reactors), in UK (4 reactors), and in Canada (3 reactors). In addition, Germany and Canada have no plans to build new reactors (for details on other countries, see Tables 9 and 10).

Table 11 lists current activities in various countries worldwide on new nuclear-power-reactors build. Analysis of the data in

Table 6 Percent of various wastes in total amount

No.	Wastes	% of total amount
1	Mining and quarrying	27.30
2	Agriculture	20.13
3	Demolition and construction	18.51
4	Industrial	12.73
5	Dredged spoils	7.64
6	Household	6.94
7	Commercial	6.48
8	Sewage sludge	0.23
9	Radioactive	0.04

Note: Data courtesy of Dr. J. Roberts, University of Manchester; partially based on the data from Ref. [22].

Table 7 Approximate tonnage of wastes per 1000-MW_{el} power per year for nuclear and coal-fired power plants

Nuclear power plant	Coal-fired power plant
Fuel	
25 ton of UO_2	2.6×10^6 ton of coal (5×1400 ton trains a day)
Wastes	
35 ton high level wastes	6,500,000 ton of CO_2
310 ton intermediate level wastes	900 ton of SO_2
460 ton low level wastes	4500 ton of NO_x
	320,000 ton of ash
	400 ton of toxic heavy metals

Note: Data courtesy of Dr. J. Roberts, University of Manchester.

Table 8 Number of nuclear-power reactors connected to electrical grid and forthcoming units as per December 2018[a] and before the Japan earthquake and tsunami disaster[b]

		No. of units		Installed capacity, GW_{el}		Forthcoming units	
No.	Reactor type (some details on reactors)	As of December 2018	Before March 2011	As of December 2018	Before March 2011	No. of units	GW_{el}
1	PWRs (largest group of nuclear reactors in the world—67%)	301 ↑	268	286 ↑	248	77	84
2	BWRs or advanced BWRs (second largest group of reactors in the world—16%; ABWRs were the first Generation-III+ reactors put into operation in 1996–97)	72 ↓	92	72 ↓	84	6	8
3	PHWRs (third largest group of reactors in the world—11%; mainly CANDU-reactor type)	48 ↓	50	23 ↓	25	8	5
4	LGRs (3%) (Russia, 11 RBMKs and 4 EGPs; **these pressure-channel boiling-water-cooled reactors will be shut down in the nearest future and will not be built again**)	15↑	15	10	10	0	0
5	AGRs (3%) (UK, 14 reactors); (**all these CO_2-cooled reactors will be shut down in the nearest future and will not be built again**)	14 ↓	18	8 ↓	9	1[a]	0.2[c]
6	Liquid-metal fast-breeder reactors (LMFBRs)(Russia, SFRs—BN-600 and BN-800 (see Fig. 11))	2 ↑	1	1.3 ↑	0.6	3	0.6
In total		452 ↑	444	402↑	378	97	101

[a]Data up to Dec. 31, 2017 are based on Nuclear News (March 2018) [23]; data on reactors put into operation in 2018 are from World Nuclear Association (WNA) [24] and International Atomic Energy Agency (IAEA) [25].
[b]Nuclear News, March 2011 [26] (technical parameters of various reactors are shown in [1,27,28] and by WNA and IAEA).
[c]Forthcoming reactor is a helium-cooled reactor—high temperature reactor pebble-bed modular (HTR-PM) (China).
Note: Data in the table include 42 reactors in Japan, 33 of which are not in service as per December, 2018. Arrows mean decrease or increase in a number of reactors.

Table 11 clearly shows that China and Russia are the front runners in new nuclear builds in their countries and abroad. And it is not a big surprise, because both governments provide a significant and long-term support with various funds for nuclear-power R&D and their nuclear vendors, especially, to build NPPs abroad plus credits and other incentives for foreign countries, which would like to introduce nuclear power on their soils.

Last several years and, especially, year of 2018, were very important for the nuclear-power industry of the world. As such, Russia put into operation a number of Generation III+ VVERs

Table 9 Number of nuclear-power reactors connected to grid by nation (11 nations ranked by nuclear-reactor installed capacities) as per October 2018[a] and before the Japan earthquake and tsunami disaster[b]

No.	Nation	No. of units (PWRs/BWRs) As of December 2018	No. of units Before March 2011	Installed capacity, GW_{el} As of December 2018	Installed capacity, GW_{el} Before March 2011	Changes in number of reactors from March 2011
1	USA	98 (65/33)	104	102	103	↓ **Decreased by 6 reactors**
2	France	58 (58/-)	58	63	63	No changes
3	China	45 (43/-/2[c])	13	42	10	↑ **Increased by 32 reactors**
4	Japan[d]	42 (19/23)	54	40	47	↓ **Decreased by 12 reactors**
5	Russia	37 (20/-/15[e]/2[f])	32	29	23	↑ **Increased by 5 reactors**
6	South Korea	23 (20/-/3[c])	20	23	18	↑ **Increased by 3 reactors**
7	Canada	19 (-/-/19[c])	22	14	15	↓ **Decreased by 3 reactors**
8	Ukraine	15 (15/-)	15	13	13	No changes
9	Germany	7 (6/1)	17	10	20	↓ **Decreased by 10 reactors**
10	Sweden	8 (5/3)	10	9	9	↓ **Decreased by 2 reactors**
11	UK	15 (1/-/14[g])	19	9	10	↓ **Decreased by 4 reactors**
In total		367 (252/60/15[e]/2[f]/22[c]/14[g])	364	353	331	↑ **Increased by 3 reactors and installed capacity increased by 33 GW_{el}**

[a]Data up to Dec. 31, 2017 are based on Nuclear News (March 2018) [23]; data on reactors put into operation in 2018 are from WNA [24] and IAEA [25].
[b]Nuclear News, March 2011 [26]. Data for all countries with nuclear-power reactors are listed in Table 10.
[c]PHWRs.
[d]As per December, 2018, only nine reactors are in operation (for details on Japan nuclear-power industry, see the JSME Greeting to NERS readers by Professor K. Okamoto at the beginning of the January 2019 NERS issue).
[e]Number of LGRs.
[f]LMFBRs.
[g]AGRs.
Note: Arrows mean decrease or increase in a number of reactors.

(PWRs) (for technical parameters, see Tables 13 and 14) and the SFR-BN-800 reactor in 2016 (for technical parameters, see Table 15 and Fig. 11) and continue to lead the SFR technologies in the world.

China put into operation many reactors/NPPs including the largest in the world Generation III+ PWR—EPR (Areva design) with amazing installed capacity of 1660 MW_{el} (see Table 12 for a list of largest operating nuclear-power reactors in the world with installed capacities from 1400 MW_{el} and above, and Table 16 for basic parameters of EPR). In addition, several AP-1000 reactors (Westinghouse design), also, a Generation III+ design, were put into operation in China first time in the world (for major differences between Generation III and Generation III+ reactors, see a comparison of basic parameters of ABWR and BWR by Hitachi-GE Nuclear Energy (Table 17)). In general, Generation III+ reactors/NPPs have installed capacities from 1000+ to 1660 MW_{el}, enhanced safety, and can reach slightly higher thermal efficiencies up to 36–37% (38%) compared to those of generation III reactors/NPPs. In addition, Table 18 lists basic data on APR-1400 (Doosan design)—Generation III+ PWR from South Korea, which operates there, and seven more will be put into operation soon: three in South Korea and four in UAE (Table 10).

Year of 2019 and following years will be also very important ones, because a unique GCR—a helium-cooled reactor—HTR-PM should be put into operation China. Also, a number of Generation III+ reactors around the world are expected to be put into operation as well, plus, at least one, or a number of SFR(s) can be added to the fleet of nuclear-power reactors (see Table 10 or the latest March issue of Nuclear News [23]). In addition, a number of nonnuclear-energy countries will have operating nuclear-power reactors (Table 10).

Figure 12 shows impact of the major NPPs accidents within the last 50 yr on new builds. Analysis of the data in this figure shows that we might face a very significant drop (up to three times) in a number of operating nuclear-power reactors somewhere between 2030 and 2040 (see Fig. 16); if we assume that current operating term of reactors is on average 45 yr, and the rate of building and putting into operation new reactors is ~21 reactors per 5 yr. Even with higher rates of new nuclear-capacities additions, we will have a tangible decrease in a number of operating reactors. If this forecast(s) is correct, the nuclear-power industry will face very difficult times ahead. Conservative projections for selected countries in terms of a number of reactors, which might be shut down within future years, are shown in Figs. 17 and 18.

It should be once more emphasized that, in general, current problems in the world nuclear-power industry are: significant delays in putting into operation new, mainly, Generation III+ reactors, indecision of governments in terms of support of nuclear-based electricity generation; and radioactive-waste management and safe storage.

Currently, operating NPPs with water-cooled nuclear reactors, which are the largest group of all reactors' types (~96% of 452 nuclear-power reactors), have lower thermal efficiencies (32–36% (38%)) compared to those NPPs with liquid metal-cooled (SFRs) (up to 40%) and gas-cooled reactors (AGRs) (up to 42%), and way below of those of modern advanced thermal power plants (see Table 4). Therefore, to be competitive on energy markets, it is necessary to make this type of NPPs more efficient.

The major problem with low thermal efficiency of NPPs with water-cooled reactors is that at the turbine inlet we have only saturated steam of low parameters (maximum steam parameters as of today are: $P_{sat} \approx 7$ MPa and $T_{sat} = 285.8\,^{\circ}$C). Areva has planned to have the pressure of 7.8 MPa ($T_{sat} = 293.7\,^{\circ}$C) at the turbine inlet of the largest in the world by the installed capacity EPR (1660 MW_{el}), which can push the gross thermal efficiency of a NPP up to 37–38%.

Therefore, we need to have bright future for these the most "popular" NPPs. The conventional way, which the thermal-power industry has passed at the end of 50 s, was increasing a pressure at the steam-turbine inlet from a subcritical to supercritical one and having steam superheat up to 625 °C. This approach allowed to move from about 43% gross thermal efficiency to about 55% for supercritical-pressure coal-fired power plants (see Table 4). Due to this one of the six concepts of the Generation IV nuclear-power

Table 10 Number of nuclear-power reactors connected to electrical grid and forthcoming units as per December 2018[a]

		# Units (type)	Net MW_{el}	# Units	Net MW_{el}	Type
No.	Nation	(connected to grid)		(forthcoming)		
1	**Argentina**	**3 (PHWRs)**	**1632**	**1**	**25**	**PWR**
2	Armenia	1 (PWR)	375	0	0	—
3	**Bangladesh**	**–**	**—**	**2**	**2400**	**PWR**
4	**Belarus**	**–**	**—**	**2**	**2218**	**PWR**
5	Belgium	7 (PWRs)	5913	0	0	—
6	**Brazil**	**2 (PWRs)**	**1884**	**1**	**1245**	**PWR**
7	Bulgaria	2 (PWRs)	1926	0	0	—
8	Canada	19 (PHWRs)	13,554	0	0	—
9	**China**	**45 (43 PWRs; 2 PHWRs)**	**42,000**	**21**	**22,576**	**20 PWRs, 1 GCR**[b]
10	Czech Republic	6 (PWRs)	3930	0	0	—
11	**Egypt**	**–**	**—**	**4**	**4760**	**PWR**
12	**Finland**	**4 (2 PWRs; 2 BWRs)**	**2764**	**2**	**2800**	**PWR**
13	**France**	**58 (PWRs)**	**63,130**	**1**	**1600**	**PWR**
14	Germany	7 (6 PWRs; 1 BWR)	9515	0	0	–
15	**Hungary**	**4 (PWRs)**	**1889**	**2**	**2400**	**PWR**
16	**India**	**22 (18 PHWRs; 2 BWRs; 2 PWRs)**	**6225**	**8**	**5187**	**6 PHWRs; 1 PWR;1 LFMBR**
17	**Iran**	**1 (PWR)**	**915**	**2**	**2000**	**PWR**
18	**Japan**[c]	**42 (19 PWRs; 18 BWRs; 5 ABWRs)**	**39,752**	**2**	**2650**	**BWR**
19	Mexico	2 (BWRs)	1552	0	0	–
20	Netherlands	1 (PWR)	482	0	0	–
21	**Pakistan**	**5 (4 PWRs; 1 PHWR)**	**1320**	**3**	**3028**	**PWR**
22	**Romania**	**2 (PHWRs)**	**1300**	**2**	**1440**	**PHWR**
23	**Russia**	**37 (20 PWRs; 15 LGRs; 2 LMFBRs)**	**28,961**	**7**	**4802**	**6 PWRs;1 LMR**[d]
24	**Slovakia**	**4 (PWRs)**	**1814**	**2**	**880**	**PWR**
25	Slovenia	1 (PWR)	688	0	0	–
26	South Africa	2 (PWRs)	1860	0	0	–
27	**South Korea**	**23 (20 PWRs; 3 PHWRs)**	**21,832**	**5**	**6760**	**PWR**
28	Spain	7 (6 PWRs; 1 BWR)	7121	0	0	–
29	Sweden	8 (3 PWRs; 5 BWRs)	8629	0	0	–
30	Switzerland	5 (3 PWRs; 2 BWRs)	3333	0	0	–
31	**Taiwan**	**4 (2 PWRs; 2 BWRs)**	**3844**	**2**	**2600**	**BWR**
32	**Turkey**	**–**	**—**	**4**	**4800**	**PWR**
33	**Ukraine**	**15 (PWRs)**	**13,107**	**3**	**3020**	**PWR**
34	**UAE**	**–**	**—**	**4**	**5380**	**PWR**
35	**UK**	**15 (1 PWR; 14 AGRs)**	**8883**	**2**	**3200**	**PWR**
36	**USA**	**98 (65 PWRs; 33 BWRs)**	**101,502**	**6**	**7100**	**4 PWRs;2 BWRs**
In total		**452**	**400,852**	**97**	**100,931**	**—**

Summary: **31 countries have operating nuclear-power reactors, and 5 countries plan to build nuclear-power reactors (in green color). In addition, 30 countries are considering, planning or starting nuclear-power programs, and about 20 countries have expressed their interest in nuclear power.** However, 13 countries with NPPs do not plan to build nuclear-power reactors (in black color). Moreover, such countries as Switzerland and some others might not proceed with new builds. In particular, President of France, Mr. E. Macron, said that France will shut down 14 nuclear reactors by 2035 and would cap the amount of electricity derives from NPPs to 50% from current 73%.

[a]Data up to Dec. 31, 2017 are based on Nuclear News (March 2018) [23] and data on reactors put into operation in 2018 are from WNA [24] and IAEA [25].
[b]GCR is a helium-cooled reactor—HTR-PM (China).
[c]For details on Japan nuclear-power industry, please see the JSME Greeting to NERS readers by Professor K. Okamoto at the beginning of the January 2019 NERS issue.
[d]LMR is an SVBR-100 reactor (Lead-Bismuth Fast Reactor (in Russian abbreviations)).

reactors is a supercritical water-cooled reactor [1,28,35,36]. Also, there is an interim approach, which is only applicable to pressure-channel reactors—to introduce a nuclear steam superheat inside a reactor, which was tested in 1960s and 1970s in USA, Russia, and some other countries [37].

3 Small Modular Reactors

Small modular reactors (SMRs) are today's a very "hot" topic in nuclear engineering worldwide [1,38]. According to the IAEA ARIS (Advanced Reactors Information System) data, there are about 55 SMRs designs/concepts, which can be classified as: (1) water-cooled SMRs (land based)—19; (2) water-cooled SMRs (marine based)—6; (3) high-temperature gas-cooled SMRs—10; (4) molten-salt SMRs—9; (5) fast-neutron-spectrum SMRs—10; and (6) other SMRs—1. From all these 55 SMRs only two KLT-40S reactors have been constructed, installed on a barge, and should be put into operation in 2019; CAREM (Central Argentina de Elementos Modulares) SMR (PWR-type; 25 (32) MW_{el}; CNEA (Comisión Nacional de Energía Atómica), Argentina) is under construction now, and FUJI (200 MW_{el}, MSR International Thorium Molten-Salt Forum (ITMSF), Japan) is possibly within an experimental phase.

In general, as of today, a number of small nuclear-power reactors by installed capacity (10–300 MW_{el}) operate around the world (see Table 19). Moreover, some of them operate successfully for about 50 yr! However, they cannot be named as SMRs. Also, France, Russia, UK, USA, and other countries have great experience in successful development, manufacturing, and operation of submarines, icebreakers, and ships propulsion reactors. Therefore, many modern designs/concepts of SMRs are based on these achievements. (Also, it should be mentioned that a number of SMRs concepts are based on the Generation IV nuclear-power-reactors concepts [1].)

Table 11 Current activities worldwide on new nuclear-power-reactors build

No.	Country/nuclear vendor	Countries, which looking forward for new builds (number of planned units)
1	China/various vendors (nuclear-power activities are supported by the Chinese government)	China (21 + 1?[b]), Pakistan (3), Romania (2), UK (2) In total: 28 + 1?
2	Russia/Rosatom (outside Russia—ASE (AtomStroyExport) is the Russian Federation's nuclear-power equipment and service exporter. It is a fully owned subsidiary of Rosatom. Nuclear-power activities are financially supported by the Russian government.)	Russia (4 + 3?), Belarus (2), Finland (1), Iran (2), Hungary (2), India (1), China (2), Turkey (4), Egypt (4?), Bangladesh (2), India (1) In Total: 21 + 7?
3	USA/Westinghouse, GE	China (2), USA (4 + 2?), Taiwan (2?) In total: 6 + 4?
4	South Korea/various vendors	UAE (4), South Korea (3) In total: 7
5	India/various vendors	India (6) In total: 6
6	France/Areva	China (1), Finland (1), France (1), UK (2) In total: 5
7	Japan/Hitachi, Toshiba	Japan (1 + 1?), USA (2) In total: 3 + 1?
8	Slovakia/Skoda	Slovakia (2) In total: 2
9	Canada/AECL (Candu Energy, Inc., Mississauga, ON, Canada)	Romania (2) In total: 2
10	Germany/KWU (KraftWerk Union AG)	Brazil (1?) In total: 1?
11	Argentina/CNEA (Comisión Nacional de Energía Atómica)	Argentina (1?) In total: 1?

[a]Based on Nuclear News, March 2018 [23].
[b]?—Means "Commercial start date—indefinitely" (Nuclear News, 2018 [23]).

Table 12 Largest in the world operating nuclear-power reactors [23]

Name	No. units	Net MW_{el}	Reactor type	Com. start	Reactor supplier	Country
Oskarshamn	1	1400	BWR	1985	ABB-Atom	Sweden, Oskarshamn, Kalmar
Philippsburg	1	1402	PWR	1985	KWU	Germany, Philippsburg, Baden-Württemberg
Isar	1	1410	PWR	1988	KWU	Germany, Essenbach, Bavaria
Brokdorf	1	1410	PWR	1986	KWU	Germany, Brokdorf, Schleswig-Holstein
Shin-Kori	1	1416	PWR	2016	Doosan	South Korea, Gijang
Civaux	2	1495	PWR	2002	Framatom	France, Civaux, Vienne
Chooz	2	1500	PWR	2000	Framatom	France, Chooz, Ardennes
Taishan	1	1660	PWR	2018	Areva	China, Guangdong

Table 13 Reference parameters of Generation III+ VVER

Parameter	Value
Thermal power	3200 MW_{th}
Electric power	1160 MW_{el}
NPP thermal efficiency	36%
Primary coolant pressure	16.2 MPa
Coolant temperature at reactor inlet	298 °C
Coolant temperature at reactor outlet	329 °C
Steam-generator pressure/temperature	6.27 MPa / 278 °C
Main equipment service life	60 yr
Replaced equipment service life	Not less than 30 yr
Capacity factor	Up to 90%
Length of fuel cycle	4–5 yr
Frequency of refueling	12–18 months
Fuel assembly maximum burn-up	Up to 60-70 MW day/kgU
Annual average length of scheduled shut-downs (for refueling, scheduled maintenance work)	16–40 days per year
Refueling length	$\leq$16 days per year
Number of not scheduled reactor shutdowns	$\leq$1 per year
Frequency of severe core damage	$<10^{-6}$ per year
Frequency of limiting emergency release	$<10^{-7}$ per year
Efficient time of passive safety and emergency control system operation without operator's action and power supply	$\geq$24 h
Operating basis earthquake/SSE, magnitude of MSK-64 scale	6 and 7
RP main stationary equipment is designed for SSE of magnitude	8

Note: Mainly based on data from paper by Ryzhov et al. (2010) [29] [1].

Table 14 Additional typical parameters of latest VVER-1000 series 300 and 400 [1]

Parameter	Value
Pressure vessel ID	4.14 m
RPV wall thickness	0.19 m
RPV height without cover	10.9 m
Core equivalent diameter	3.12 m
Core height	3.56 m
Volumetric heat flux	110 MW/m^3
Average volumetric flow rate in assembly	515±55 m^3/h
No. of fuel assemblies	163
No. of rods per assembly	317
Fuel mass	80 ton of UO_2
Fuel enrichment	4%
Part of fuel reloaded during year	1/3

As such, Russia has adjusted their proven marine reactor—KLT-40S for operation as an SMR for electricity generation and heat supply (also, a desalination of water is possible). Figure 19 shows a schematic of KLT-40S reactor and its systems; Fig. 20—photo of reactor KLT-40S with four steam generators and reactor-coolant circulation pumps; Fig. 21—KLT-40S reactor-core cross section; Fig. 22—photo of the floating nuclear thermal-power plant (FNThPP) with two KLT-40S reactors; and Table 20—main parameters of KLT-40S.

The barge with two KLT-40S SMRs will be towed to and then put into operation at Pevek, Russia's northernmost city in 2019, where it will gradually replace the Bilibino NPP (see Table 19) and the Chaunskaya combined heat and power plant, which are being retired. Commercial start of these two SMRs is planned for 2019 [23]. Currently, the FNThPP is temporary located in the port of Murmansk (Russia), where, on Nov. 4, 2018, first KLT-40S has reached the minimum controlled power level.

It is very difficult to believe that SMRs somewhere in the future will replace nuclear-power reactors, but they have their own "niche," in particularly, electricity and heat supplies (also, desalination of water possible) for remote settlements, military bases, mines, etc. around the world.

In general, SMR-based NPPs will have lower thermal efficiencies compared to those of similar type regular NPPs; higher level of

Table 15 Key-design parameters of Russian SFRs—BN reactors [1]

No.	Parameters	BN-600[a]	BN-800[b] (see Fig. 11)	BN-1200[c]
1	Thermal power (MW_{th})	1470	2100	2800
2	Electrical power (MW_{el})	600	880	1220
3	Basic components:			
	No. of turbines × type	3 × K-200-130	1 × K-800-130	1 × K-1200-160
	No. of generators × type	3 × ТГВ-200-М	1 × ТЗВ-800-2	1 × ТЗВ-1200-2
4	Pressure vessel			
	Diameter (m)	12.86	12.96	16.9
	Height (m)	12.60	14.82	20.72
5	Number of heat-transfer loops	3	3	4
6	T of reactor coolant: sodium, primary loop—T_{in}/T_{out} (°C)	377/550	354/547	410/550
7	T of intermediate coolant: sodium, secondary loop—T_{in}/T_{out} (°C)	328/518	309/505	355/527
8	T of power-cycle working fluid: water/steam—T_{in}/T_{out} (°C)	240/505	210/490	275/510
9	P at SG outlet (MPa)	13.7	14.0	17.0
10	Scheme of steam reheat with	Sodium	Steam	Steam
11	Basic unchangeable components service term (yr)	30	40	60
12	NPP thermal efficiency (gross) (%)	42.5	41.9	43.6
13	NPP thermal efficiency (net) (%)	40.0	38.8	40.5

[a]BN-600 is currently in operation at the Beloyarsk NPP (BNPP); BN-600 commercial start—1981.
[b]BN-800—commercial start in 2016 (BNPP).
[c]BN-1200—concept/design of future Russian SFR with objective to move to a close fuel cycle in nuclear-power industry.

Fig. 11 Reactor hall of BN-800 reactor (Courtesy of Rosatom, Photo by A. Savransky) [30]

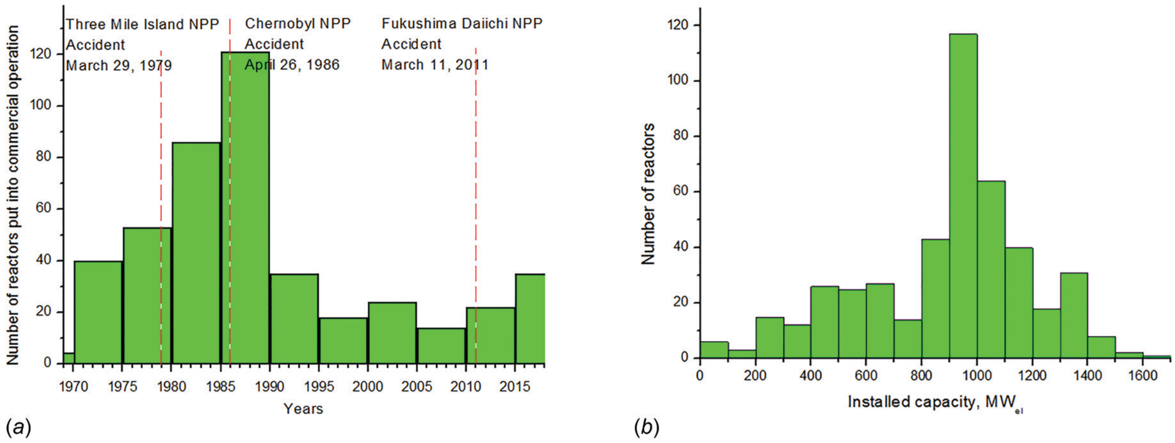


Fig. 12 (*a*) Number of nuclear-power reactors of the world put into commercial operation versus years as per November 2018 (based on data from Nuclear News [23,32]) [1]; Four reactors (India $2 \times 150\,MW_{el}$; Switzerland $1 \times 365\,MW_{el}$; and USA $1 \times 613\,MW_{el}$ and $1 \times 650\,MW_{el}$) have been put into operation in 1969, i.e., they operate for almost 50 yr. It is clear from this diagram that the Chernobyl NPP accident has tremendous negative impact on nuclear-power industry, which is lasting for decades, and, currently, we have additional negative impact of the Fukushima Daiichi NPP accident. (*b*) Number of nuclear-power reactors in the world by installed capacity as per November 2018 [23,33]. For better understanding of this diagram, the largest number of reactors has installed capacities within the range of 900–999 MW_{el}.

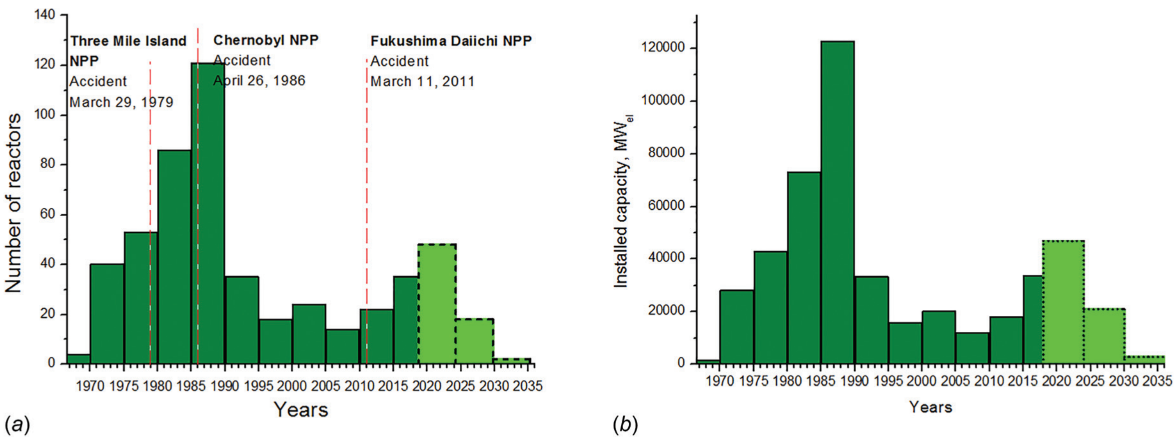


Fig. 13 Number of reactors built in the world [34] (based on the data from Ref. [23]): (*a*) and their installed capacities and (*b*) from 1969 till 2018 (solid lines and dark green columns) and planned reactors and installed capacities until 2035 (dashed lines and green columns) (for details, see Fig. 14)

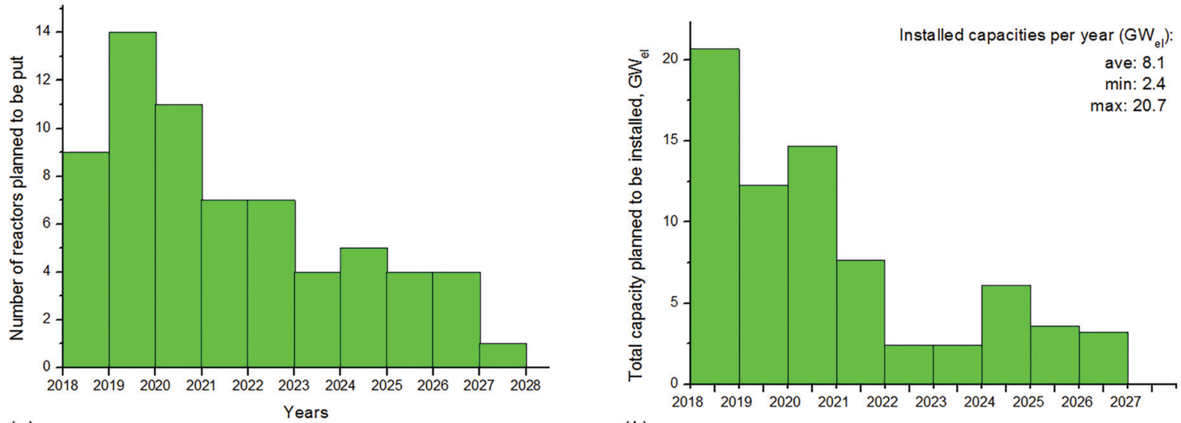
fuel enrichment compared to water-cooled nuclear-power reactors to be able to operate for longer periods between refuelings, etc.

4 Economic and Competitiveness Issues for Nuclear Power Plants

Key to successful deployment of *any* such new or next generation nuclear concepts or designs is the ability to compete against available energy alternates, especially, in local or national power markets.

Market share is fundamentally determined by price advantage relative to competitors, and conversely, the driving forces for innovation and cost reduction are those of the competitive marketplace [40]. Traditional overall electricity demand, market economics, comparative plant costing, and regulations are covered in great detail elsewhere [41–44]. To determine the optimization of cost and size in competitive power markets, the competition for power and energy generation is low capital cost of natural-gas combined-cycle plants with multiple module layouts; and large advanced supercritical-pressure-coal units, both with cycle efficiencies reaching near 60% [43], which are cheaper (on an overnight capital, levelized unit energy cost (LUEC) or cost of energy (COE) basis). The reactor island is a small fraction of the total plant or project costs, so it is evident that technology choice is not the key, as the market has no "favorites." The real issue is fully optimizing the overall cost and efficiency of the design and performance of any "Technology X" units to meet power- and financial-market requirements, not choosing or developing something that is superficially attractive, but too expensive.

Adverse external key-market developments and challenges to increased nuclear deployment include: (1) the emergence of even



(*a*) (*b*)

Fig. 14 Number of reactors planned to be built [34] (based on data from Ref. [23]): (*a*) and their planned installed capacities and (*b*) from 2018 till 2027

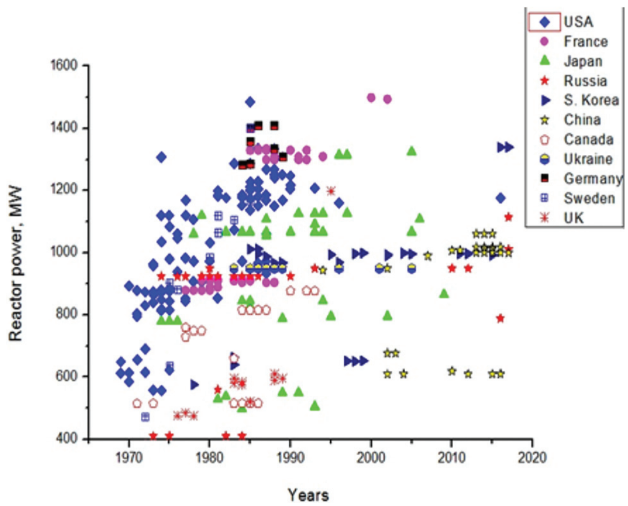


Fig. 15 Age of nuclear-power reactors in selected countries (11 nations with the largest installed capacities of reactors) as per March 2017 (based on the data from Ref. [33]) (shown here data on 363 reactors with the total installed capacity of 342 GW_{el} Net) (also, for other details, see Table 10). Some symbols might represent more than one reactor, because in some cases, a number of reactors with the same installed capacity (power) have been put into commercial operation within the same year.

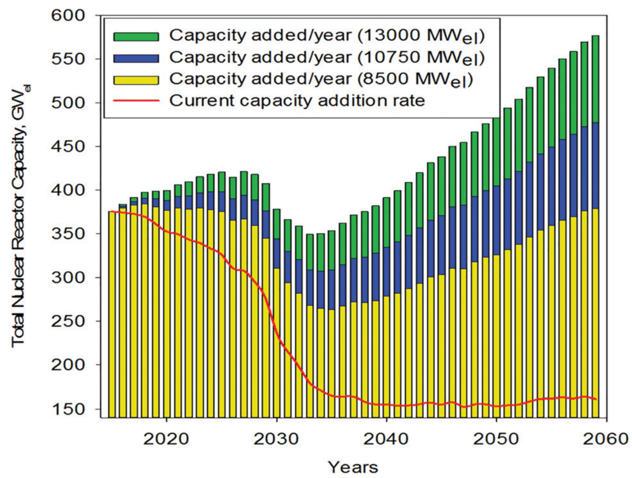
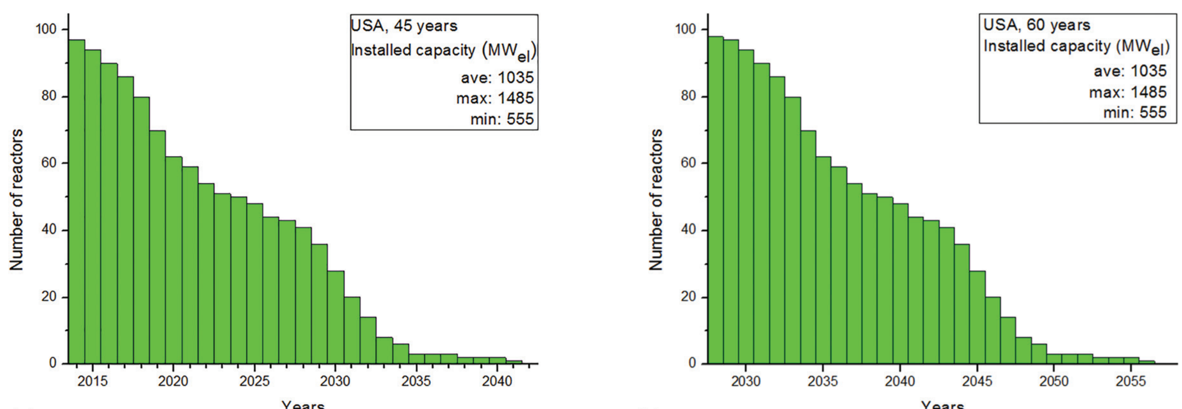


Fig. 16 Possible scenarios for future of nuclear power; based on 45 yr in service of current reactors and adding new reactors with rate of ~21 reactor per 5 yr (red line) [1]



(*a*) (*b*)

Fig. 17 Possible conservative scenarios for future of nuclear power in USA, if no additional reactors are built [34]; based on 45 yr (*a*) and 60 yr (*b*) in service of current reactors (based on the data from Ref. [23])

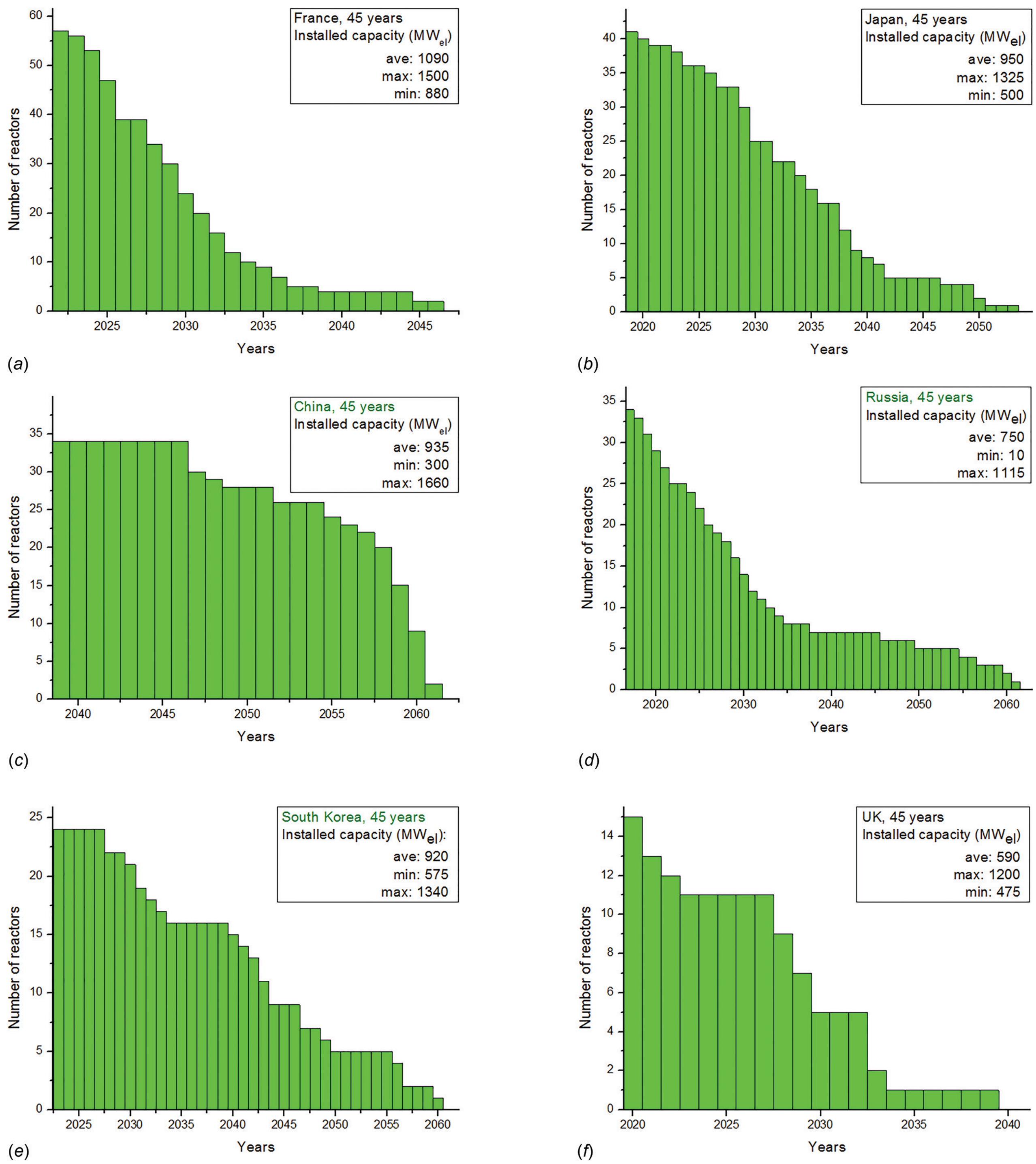


Fig. 18 Possible conservative scenarios for future of nuclear power in France (*a*), Japan (*b*), China (*c*), Russia (*d*), South Korea (*e*), and UK (*f*), if no additional reactors are built; based on 45 yr in service of current reactors [34] (based on the data from Ref. [23])

lower cost "fracking" technology for natural-gas production; (2) closure and insolvency threats for some U.S. NPPs; (3) the Fukushima NPP accident; (4) the effective bankruptcy and financial/corporate reorganization of three large nuclear-plant manufactures; (5) new build activity dominated by state-supported manufacturers with financing, and/or political guarantees; (6) the utilization of mandatory portfolios, feed-in tariffs and reverse metering preferentially for wind and solar generation. The requirements and internal challenges for any new nuclear concepts/design/technology are, and always will be [1,2,45]:

- safer than previous "generations";
- low financial risk exposure and capital cost;
- ease and speed of build;
- readily licensable;
- simple to operate and secure;

Table 16 Basic data on AREVA's Generation III+ PWR–EPR[a] [31]

Characteristics	Data
Reactor core	
Thermal power	4590 MW_{th}
Electric power	1600+ MW_{el}
Gross thermal efficiency	36–37%
Active fuel length	4.2 m
No. of fuel assemblies	241
No. of fuel rods	63,865
Fuel assembly array	17 × 17
No. of rod cluster control assemblies	89
Average linear power	166.7 W/cm
Operation cycle length up to	24 months
Reactor coolant system	
No. of loops	4
Nominal flow	28,315 m^3/h
Reactor-pressure-vessel inlet temperature	295.2 °C
Reactor-pressure-vessel outlet temperature (T_{sat} =344.8 °C at 15.5 MPa)	330 °C
Primary side operating pressure	15.5 MPa
Secondary side saturation pressure at nominal conditions (SG outlet) (T_{sat} = 292.5 °C)	7.72 MPa
Service life	60 yr

[a]In China, Taishan NPP two EPRs are 1660 MW_{el} (one in service from 2018); planned EPRs with 1600 MW_{el}—one in Finland and one in France, and two in UK.

Table 17 Key specifications of ABWR (Generation III+) and BWR (Generation III) NPPs

Parameters	Item	ABWR	BWR-5
Output	Plant output	1350 MW_{el}	1100 MW_{el}
	Reactor thermal output	3926 MW_{th}	3293 MW_{th}
Thermal efficiency (gross)	%	34	33.4
Reactor core	Fuel assemblies	872	764
	Control rods	205 rods	185 rods
Reactor equipment	Recirculation system	Internal pump method	External recirculation type
	Control rod drive	Hydraulic/electric motor drive methods	Hydraulic drive
Reactor containment vessel		Reinforced concrete with built-in liner	Free-standing vessel
Residual heat removal system		Three systems	Two systems
Turbine systems	Thermal cycle	Two-stage reheat	Nonreheat
	Turbine (blade length)	1.32 m (52 in.)	1.09 m (43 in.)
	Moisture separation method	Reheat type	Nonreheat type
	Heater drain	Drain up type	Cascade type

Note: Courtesy of Hitachi-GE Nuclear Energy [1].

- assured fuel supply and sustainability;
- providing social value and acceptance; and, of course;
- be competitive with respect to lowest costs generation.

The general concept for multiple small units adopts the "learning curve" approach, which has been previously shown to apply for manufacturing, nuclear, and other markets [46,47].

The standard models of discounted cash flow provide generating costs as a function of capital and operating expenses, discount or loan rate, construction time, and other "fixed" and variable costs to determine income and the return on investment [2,41–44]. Having set the sales potential, target markets, and performance goals, the approach must combine the plant and market economics in three simple, but interwoven steps for any given conceptual technology:

- *Step 1*: Assess the optimum capital, operating, and generating costs as a function of plant output size to determine the system design targets and technical requirements.
- *Step 2*: Minimize risk in the cash flow scenario assuming given build constraints and options for single and multiple units to establish investment needs and suitable power purchase agreements or contracts.
- *Step 3*: Determine the build profile of unit/plant number and output matching the power market and customer generating needs, establishing the optimum niche and market specific

Table 18 Basic data on APR-1400[a] Generation III+ PWR [28]

Characteristics	Data
Reactor core	
Thermal power	3983 MW_{th}
Electric power	1400 MW_{el}
Gross thermal efficiency	34–35%
Active fuel length	3.81 m
No. of fuel assemblies	241
Fuel assembly array	16 × 16
No. of fuels rods in fuel assembly	236
No. of fuel rods	56,876
Fuel	UO_2
Core equivalent diameter	3.65 m
Operation cycle length more than	18 months
Fuel rod outer diameter/sheath-wall thickness	9.5 mm/0.57 mm
Burnable absorber material	Gd_2O_3–UO_2
Reactor coolant system	
No. of pumps	4
Nominal flow	21,618 m^3/h
Reactor inlet temperature	291 °C
Reactor outlet temperature (T_{sat} = 344.8 °C at 15.5 MPa)	324 °C
Operating pressure	15.5 MPa
Power cycle	
Number of steam generators	4
Steam pressure at full power	6.89 MPa
Stem saturated temperature at full power	285 °C

[a]Put into operation in South Korea; more reactors planned to be put into operation in South Korea and UAE (Table 10).

Table 19 Smallest in the world operating nuclear-power reactors (10–300 MW_{el})

NPP	No. of units	Net MW_{el}	Reactor Type	Reactor Model	Commercial start	Location	Reactor supplier
<50 MW_{el}							
Bilibino	4	11	LGR	EGP-6	1974; 1975; 1976; 1977	Russia, Chukotka	MTM
50 – 99 MW_{el}							
Rajasthan	1	90	PHWR	CANDU	1973	India, Kota, Rajasthan	AECL/DAE
Kanupp	1	90	PHWR	CANDU	1972	Pakistan, Karachi, Sind	GE Canada
100–199 MW_{el}							
Tarapur	2	150	BWR	BWR-1/Mark II	1969; 1969	India, Maharashtra	GE
Rajasthan	1	187	PHWR	Four-loop	1981	India, Kota, Rajasthan	AECL/DAE
200–300 MW_{el}							
Rajasthan	4	202	PHWR	Four-loop	2000; 2000; 2010; 2010	India, Kota, Rajasthan	Nuclear Power Corp. of India, Ltd.
Kaiga	4	202	PHWR	Four-loop	2000; 2000; 2007; 2011	India, Karnataka	Nuclear Power Corp. of India, Ltd.
Kakrapar	2	202	PHWR	Four-loop	1993; 1995	India, Gujarat	Nuclear Power Corp. of India, Ltd.
Narora	2	202	PHWR	Four-loop	1991; 1992	India, Uttar Pradesh	Nuclear Power Corp. of India, Ltd.
Madras	2	205	PHWR	Eight-loop	1984; 1986	India, Kalpakkam, Tamil Nadu	Nuclear Power Corp. of India, Ltd.
Qinshan	1	298	PWR	CNP-300	1994	China, Haiyan, Zhejiang	MHI
Chasnupp	2	300	PWR	CNP-300	2000; 2011	Pakistan, Mianwali, Punjab	CNNC

Note: Based on data from Nuclear News, 2018 [23].

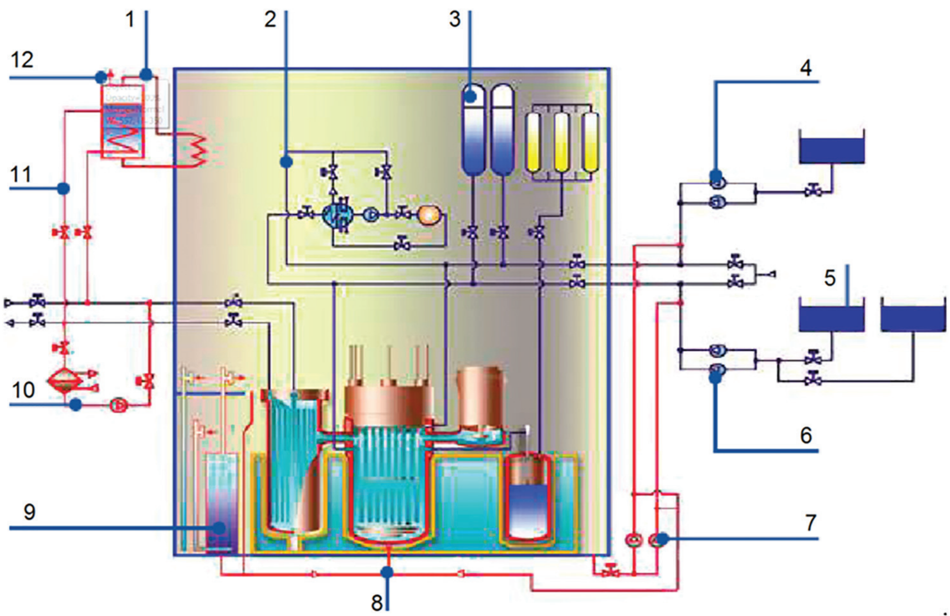


Fig. 19 Schematic of KLT-40S reactor and its systems (based on original figures from AO OKBM by the name of I. I. Afrikantov, Brochure on KLT-40S [39] and from Ref. [37] (in red—newly introduced safety systems): 1—passive system of containment emergency pressure decrease (condensing system); 2—active emergency cooling system through heat exchangers of loops I—III; 3—passive emergency core cooling system (hydraulic accumulators); 4—active emergency core cooling system from feedwater pumps; 5—active system for injecting liquid absorber; 6—active emergency core cooling system from feedwater pumps; 7—active emergency core cooling system through recirculation pumps; 8—system of reactor caisson filling with water; 9—containment passive emergency pressure decrease system (bubbling); 10—active emergency shutdown cooling system (through process condensers); 11—passive emergency shutdown cooling system; 12—to atmosphere.

share; then iterate back through the steps 1, 2, and 3 as needed to meet the goals, if necessary changing or even adopting a different technology.

This feedback process must be completed before committing to preliminary design work and reevaluated periodically during the overall design and engineering process. This systematic method provides a coherent business model for both supplier and customer and is also useful as a rapid audit and estimating tool, and to weed out uncompetitive options (details can be found in Ref. [48]).

Capital- and operating-cost reduction is the obvious first target, while licensing, siting, fuel, and decommissioning costs are difficult to reduce substantially. So the objectives are to simplify and "modularize" the design, reducing capital and operating costs, and shortening construction times. Very often, customers require a reference plant for cost, safety, and design comparison purposes. Hence the emphasis for any bid on reducing, optimizing and managing fixed capital and operation and maintenance costs, and on multiple builds based on a "standardized" design for which the usual economic methods exist [44]. The fundamental problem is that a decrease in plant output increases the LUEC/LCOE,

Fig. 20 Reactor KLT-40S (КЛТ-40С in Russian abbreviations) (in center) with four steam generators (larger cylinders) and four reactor-coolant circulation pumps (smaller cylinders) (Photo courtesy of Rosatom) [30]

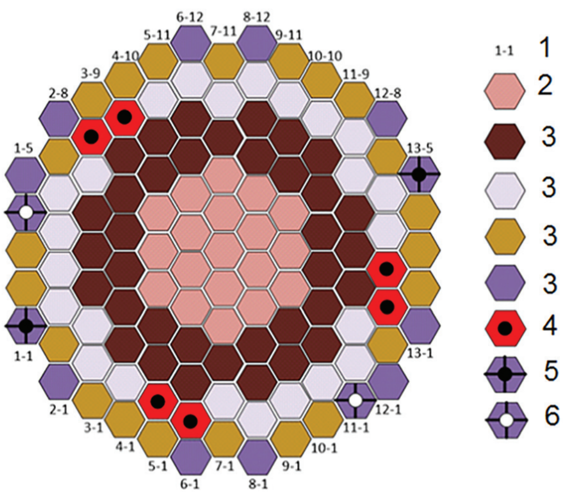


Fig. 21 KLT-40S reactor-core cross section (prepared by UOIT student A. Khan; based on original figure from AO OKBM by the name of I. I. Afrikantov [39]): 1—cell number; 2—main assembly in central zone; 3—main assemblies; 4—assembly with emergency shut-down rod; 5—assembly for neutron-absorber location; 6—assembly peripheral zone for location of extra sensors for neutron-flux control.

because many of the balance of plant and other variable and fixed costs (of site, safety, infrastructure, engineering, decommissioning, and staffing) do not decrease proportionately, so ultimately become dominant as output shrinks.

However, recent build experience in Europe, USA, and China shows that some large plants often require over the nominal 60-months completion time, or experience significant delays in construction or schedule times. Long schedules and delays are the major factor that must be avoided, incurring approximately a linear LUEC/LCOE increase with project timescale. For a given interest rate, it is necessary to optimize the build scenario for the potential of sequentially adding some number of multiple units that can be of any selected size and, hence, cost. This implies the "order book" approach, which is necessary to initiate and commit the program beforehand, as practiced in the aircraft manufacturing

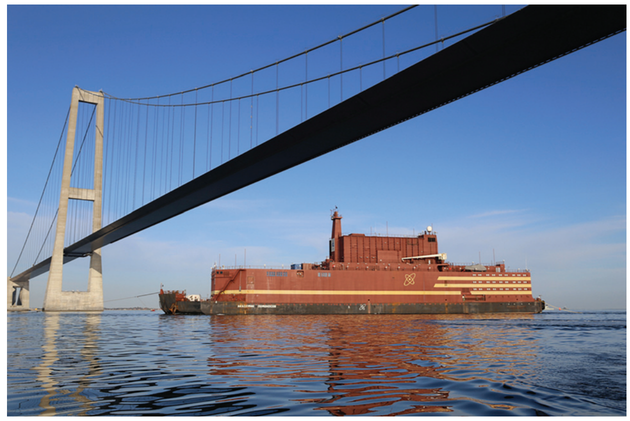


Fig. 22 Photo of FNThPP (Плавающая Атомная Тепловая ЭлектроСтанция (ПАТЭС) (in Russian abbreviations)) on barge with two KLT-40S reactors (Photo courtesy of Rosatom) [30]. Barge: length—140 m; width—30 m; height of board—10 m; draught—5.6 m; displacement—approximately 21,000 ton; underwater foundation pit in m—175 (*L*) × 45 (*W*) × 9 (*D*); operating term of FNThPP—40 yr; number of servicing personal—approximately 70; and construction term—4 yr.

industry. Otherwise the first-of-a-kind engineering, design, licensing, and setup costs all have to be absorbed by the first few units. In addition, the cost of multiple units must be reduced by the "learning effect" of an experienced production line for the Nth-of-a-kind units [46,47].

To "fill the order book" is design and market specific, but the maximum ~50% reduction possible from mass production matches that required to offset the cost of smaller plants/units [48,49]. This result is theoretically based and describes actual data worldwide (Fig. 23).

The net-cash flow for a multiple-unit build program is calculated as the difference between outgoing operating and debt expenses and the income from power sales, and will be investor and market specific.

Investment in module "factories" is expensive, requires large up-front commitment (for say, options for 100 standardized units per the aircraft industry "order book" approach), and the downside risks must be carefully managed, since, that cost must also be subtracted, or amortized (realized) by or from the sale of many units. Hence, it is self-evident that although small and units cost more for their power and energy, only with multiple builds do they carry significantly less financial risk and for much shorter exposure times.

Although every market is geographically different, they share the same goal of attaining a dynamic balance between supply and demand [41–43]. This balance has to occur both during the daily short-term swings in demand, bringing plants "on line"; and, also, in the longer term for meeting future demand projections and units being added and/or retired. The overall approach to meeting demand is obviously "cheapest first," or a merit order [41,43,50], except, when there is a mandatory feed-in-tariff or reverse metering obligation, or no choice. For any technology, the fraction of the total market power demand that is available for or at a specific cost advantage is proportional to the incremental area under the merit order curve. The result is that the fractional market share is exponentially (and not linearly) dependent on the LUEC/LCOE cost advantage [46].

Obviously, the fractional market share is partly determined by price advantage for a whole range of alternate fuels, at both the national and local levels. For example, new nuclear builds must compete with: coal plants in China, Virginia, and Alberta; hydropower in Washington and Quebec; natural-gas turbines and LNG in USA, Asia, and Europe; state-supported nuclear from and in Russia, China, France, and Korea; with renewable portfolios and

Table 20 Main parameters of KLT-40S SMR [37,39]

Parameters	KLT–40S
Reactor type	PWR
Reactor coolant/moderator	Light water
Thermal power (MW_{th})	150
Electric power, gross/net (MW_{el})	38.5/35
Thermal efficiency (%)	~26
Expected capacity factor (%)	60–70
Maximum output thermal power (Gcal/h)	73
Production of desalinated water[a] (m^3/day)	40,000–100,000
Operating range of power (%)	10–100
Normal-mode power variation (%/s)	0.1
Primary circuit pressure (MPa)	12.7
Primary circuit T_{in}/T_{out} (°C)	280/316
Reactor coolant massflow rate (ton/h)	680
Primary circuit circulation mode	Forced
Power cycle	Indirect Rankine cycle
P_{steam} at SG outlet (MPa)	3.72
T_{sat} at P_{steam} (°C)	246.1
Overheated T_{steam} at SG outlet (°C)	290
Steam massflow rate (ton/h)	240
T feedwater in–out (°C)	70–130 (170)
RPV height/diameter (m)	4.8/2.0
Maximum mass of reactor pressure vessel (ton)	46.5
Fuel type/assembly array	UO_2 pellets in silumin matrix
Fuel assembly active length (m)	1.2
Number of fuel assemblies	121
Core service life (h)	21,000
Refueling interval[b] (yr)	~3
Refueling outage (days)	30–36
Fuel enrichment (%)	18.6
Fuel burnup (GWd/t)	45.4
Predicted core damage frequency (event/reactor year)	$0.5 \cdot \times 10^{-7}$
Seismic design	9 point on MSK scale

[a]In case of floating nuclear-power desalination complex.
[b]The FNThPP will save up to 200,000 metric tons of coal and 100,000 ton of fuel oil per year. Every 12 years, the FNThPP will be towed back to the manufacturing plant and overhauled there.

FITs in Europe and Canada; and with diesel fuels in remote locations. Detailed energy projections out to 2040 show modest nuclear growth, and state [51]:" Natural gas demand rises the most, largely to help meet the increasing needs for electricity and support increasing industrial demand."

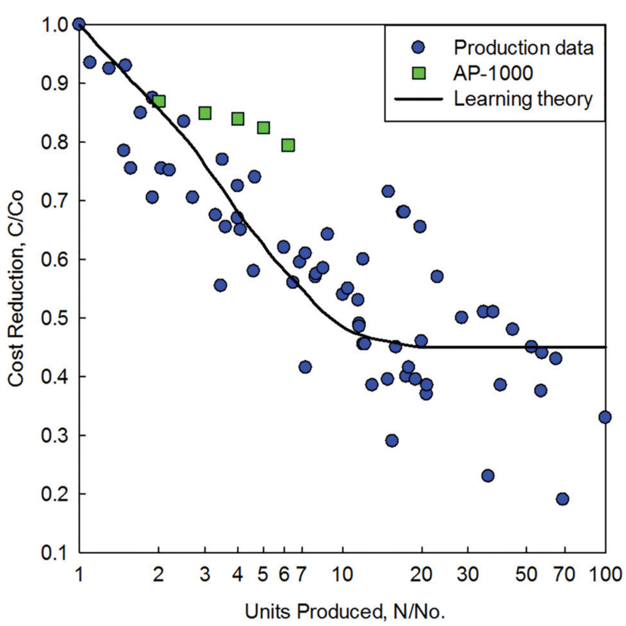


Fig. 23 Cost reduction versus units produced: composite technology learning curve (based on the data from Refs. [46], [48], and [49]): C/Co—unit cost/initial unit cost and N/No.—number of units produced/initial number

No clear market or price advantage for current SMR concepts has been shown in recent comparative studies that have been independently published [50,52], emphasizing the need for enhanced competitiveness. The OECD (Organization for Economic Co-operation and Development) estimate is that the global market share by 2035 could be the "high case" 9%, or 3% for the "low case" for some hypothetical/generic SMR "Technology X" [50]. The middle of this range is the worldwide 6% nuclear share or market entry already historically attained, when there is essentially little or no cost advantage [49], so is within the uncertainties due to local market vagaries and variations.

Several key challenges still remain today and in the future, some of which are well known low capital cost and high efficiency of modern natural gas and supercritical-pressure coal-fired power plants, including modular gas turbines and mobile power concepts, are likely to dominate many markets for the next 20 years. This timeframe is sufficient for competitive nonconventional and innovative nuclear-technology developments to emerge that challenge many of the paradigms of the past [53].

5 Conclusions

(1) It is well known that electrical-power generation is the key factor for advances in industry, agriculture, technology, and level of living. Also, strong power industry with diverse energy sources is very important for a country's independence.
(2) Major sources for electrical-energy generation in the world today are: (1) thermal— primary coal (38.3%) and secondary natural gas (23.1%); (2) "large" hydro (16.6%);

and (3) nuclear (10.4%). The remaining 11.6% of the electrical energy is generated using oil (3.7%) and renewable sources (biomass, wind, geothermal, and solar energy) (7.9%) in selected countries.

(3) Other energy sources such as renewable wind-, solar-, marine-power have a visible impact just in some countries, especially, where there are government incentives with electricity prices guaranteed by legislation and power-purchase contracts. However, these apparently attractive renewable-energy sources (wind, solar, tidal, etc.) are not reliable as full-time energy sources for industrial-power generation. To overcome this problem, an electrical grid must also include "fast-response" power plants such as gas- (coal-) fired and/or large hydro-power plants.

(4) In general, the major driving force for all advances in thermal and nuclear power plants is thermal efficiency and generating costs. Ranges of gross thermal efficiencies of modern power plants are as the following: (1) combined-cycle thermal power plants—up to 62%; (2) supercritical-pressure coal-fired thermal power plants—up to 55%; (3) carbon-dioxide-cooled reactor NPPs—up to 42%; (4) SFR NPP—up to 40%; (5) subcritical-pressure coal-fired thermal power plants—up to 43%; and (6) modern water-cooled-reactor NPPs—30–36% (38%).

(5) Combined-cycle thermal power plants with natural-gas fuel are considered as relatively clean fossil-fuel-fired plants compared to coal and oil power plants, and are dominating new capacity additions, because of their relatively lower carbon-dioxide production and lower costs using natural gas, LNG, or natural gas derived from "fracking" processes.

(6) Nuclear power is, in general, a nonrenewable source unless fuel recycling, thoria fuel, and/or fast-neutron-spectrum reactors are adopted, which means that nuclear resources can be used significantly longer than some fossil fuels. Currently, this source of energy is considered as the most viable one for base-load electrical generation for the next 50–100 yr.

(7) However, all current generations-II and -III and oncoming generation-III+ NPPs, especially, those equipped with water-cooled reactors, are not competitive with modern thermal power plants in terms of thermal efficiency (30–36% (38%) for current NPPs with water-cooled reactors and 55–62% for supercritical-pressure coal-fired and combined-cycle power plants, respectively).

(8) Enhancements are needed beyond the current building plans for NPPs. These new designs must compete in the world markets, and if possible, without government subsidies or power-price guarantees. New generation NPPs must have thermal efficiencies close to those of modern thermal power plants, i.e., within a range of at least 40–50%, and incorporate improved safety measures and designs.

(9) The major advantages of nuclear power are well known, including cheap reliable base-load power, high capacity factor, low carbon-dioxide emissions, and minor environmental impact. However, these factors are offset today by a competitive disadvantage with natural gas and the occurrence of three significant nuclear accidents (Fukushima, Chernobyl, and Three Mile Island NPPs). The latter have caused significant social disruption together with high capital costs.

(10) Currently, 31 countries have operating nuclear-power reactors, and 5 countries plan to build nuclear-power reactors. In addition, 30 countries are considering, planning or starting nuclear-power programs, and about 20 countries have expressed their interest in nuclear power. However, 13 countries with NPPs do not plan to build new nuclear-power reactors. Moreover, such countries as Taiwan, Switzerland, and some others might not proceed with new builds.

(11) In October 2018, 451 nuclear-power reactors operated around the world. This number includes 300 PWRS, 72 BWRs, 48 PHWRs, 14 AGRs, 15 LGRs, and 2 LMFBRs. Considering the number of forthcoming reactors, the number of BWRs/ABWRs and PHWRs will possibly decrease within next 20–25 years. Furthermore, within next 10–15 years or so, all AGRs (carbon-dioxide-cooled) and LGRs will be shut down forever. However, instead of carbon-dioxide-cooled AGRs helium-cooled reactors will be built and put into operation.

(12) In 2018, several very important milestones have been achieved—first EPR and AP-1000 NPPs have been put into operation in China. In 2019, it is expected that China will put into operation first in the world nuclear-power helium-cooled pebble-bed reactor. Also, in 2016, second SFR-BN-800 was put into operation in Russia.

(13) Analysis of the current statistics on nuclear-power reactors of the world shows that we might face a very significant drop (up to three times) in a number of operating nuclear-power reactors somewhere between 2030–2040; if we assume that current operating term of reactors is on average 45 years, and the rate of building and putting into operation new reactors is $\sim$21 reactors per 5 years. Even with higher rates of new nuclear-capacities additions, we will have a tangible decrease in a number of operating reactors. If this forecast(s) is correct, the nuclear-power industry will face very difficult times ahead.

(14) SMRs are today's a very "hot" topic in nuclear engineering worldwide [1,37]. According to the IAEA, there are about 55 SMRs designs/concepts proposed in the world. There is a possibility that in 2019, Russia will put into operation first two SMRs-KLT-40S reactors barge-based as a floating NPP for the Northern regions.

(15) In spite of all current advances in nuclear power, NPPs have the following deficiencies: (1) generate radioactive wastes; (2) have relatively low thermal efficiencies, especially, NPPs equipped with water-cooled reactors (up to 1.6 times lower than that for modern advanced thermal power plants; (3) risk of radiation release during severe accidents; and (4) production of nuclear fuel is not an environment-friendly process. Therefore, all these deficiencies should be addressed in next generation—generation IV reactors and NPPs.

Nomenclature

P = pressure, MPa
T = temperature, $^\circ$C

Subscripts

cr = critical
el = electrical
in = inlet
out = outlet
sat = saturated or saturation
th = thermal

Abbreviations

ABWR = advanced boiling water reactor
AECL = Atomic Energy of Canada Limited
AGR = advanced gas-cooled reactor
AP = Advanced Plant (USA)
APR = Advanced Pressurized-Water Reactor (South Korea)
ARIS = Advanced Reactors Information System
ASME = American Society of Mechanical Engineers
B = billion
BN = fast sodium (reactor) (in Russian abbreviations)

BWR = boiling water reactor
CANDU = Canada Deuterium Uranium (reactor)
CAR = Central African Republic
COE = cost of energy
Corp. = corporation
CNNC = Chian National Nuclear Corporation
D = depth
DAI = Department of Atomic Energy (India)
EEC = electrical-energy consumption
EGP = Power Heterogeneous Loop Reactor (in Russian abbreviations)
EPR = European Pressurized-Water Reactor (France)
FNThPP = floating nuclear thermal-power plant
GCR = gas-cooled reactor
GE = General Electric (USA)
HDI = human development index
HTR PM = high temperature reactor pebble-bed modular (reactor)
IAEA = International Atomic Energy Agency
ID = inside diameter
JSME = Japan Society of Mechanical Engineers
K = condensing (in Russian abbreviations)
L = length
LGR = light-water-cooled graphite-moderated reactor
LMFBR = liquid-metal fast-breeder reactor
LMR = liquid-metal-cooled reactor
LNG = liquefied natural gas
Ltd = limited
LUEC = levelized unit energy cost
MHI = Mitsubishi Heavy Industries (Japan)
MSK = Medvedev–Sponheuer–Karnik scale
MTM = Ministry of Heavy Machine Building (in Russian abbreviations) (Russia)
NASA = National Aeronautics and Space Administration (USA)
NERS = (ASME Journal of) Nuclear Engineering and Radiation Science
NOAA = National Oceanic and Atmospheric Administration (USA)
NPP = nuclear power plant
OECD = Organization for Economic Co-operation and Development
PHWR = pressurized heavy-water reactor
PV = photovoltaic
PWR = pressurized water reactor
Q = quarter
RBMK = Reactor of Large Capacity Channel Type (in Russian abbreviations) (Russia)
R&D = research and development
RPV = reactor pressure vessel
SFR = sodium fast reactor
SG = steam generator
SMR = small modular reactor, also, small and medium size reactor
SSE = safe shutdown earthquake
SVBR = lead-bismuth fast reactor (in Russian abbreviations)
FIT = feed-in-tariff
TГВ = turbine generator with hydrogen (/water) cooling (in Russian abbreviations)
UAE = United Arab Emirates
UK = United Kingdom
UOIT = University of Ontario Institute of Technology
VVER = water power reactor (in Russian abbreviations) (Russia)
W = width
WNA = World Nuclear Association

Appendix

Table 21 Population, EEC, and HDI in all countries of the world[a]

HDI[b] rank (2017)	Country	HDI[b] (2017)	EEC[c] (2015-2017) W/capita	EEC[c] (2015-2017) GW·h	Population in millions (2018)
Very high HDI					
1	Norway	0.953	2740	133,100	5.35
2	Switzerland	0.944	809	58,450	8.54
3	Australia	0.939	1112	223,600	24.77
4	Ireland	0.938	576	23,790	4.80
5	Germany	0.936	753	514,600	82.29
6	Iceland	0.935	5777	17,980	0.34
7	Hong Kong	0.933	668	44,030	7.43
8	Sweden	0.933	1467	125,400	9.98
9	Singapore	0.932	931	48,630	5.79
10	Netherlands	0.931	724	106,000	17.08
11	Denmark	0.929	653	31,410	5.75
12	Canada	0.926	1704	516,600	36.95
13	United States	0.924	1377	3,911,000	326.76
14	United Kingdom	0.922	547	301,600	66.57
15	Finland	0.920	1681	85,150	5.54
16	New Zealand	0.917	1020	38,750	4.74
17	Belgium	0.916	810	81,960	11.49
18	Liechtenstein	0.916	4092	394	0.04
19	Japan	0.909	841	933,600	127.18
20	Austria	0.908	913	70,700	8.75
21	Luxembourg	0.904	1215	6178	0.59
22	Israel	0.903	835	52,780	8.45
23	South Korea	0.903	1109	497,000	51.16
24	France	0.901	736	436,100	65.23
25	Slovenia	0.896	750	16,560	2.08
26	Spain	0.891	550	240,400	46.39
27	Czech Republic	0.888	643	61,160	10.62
28	Italy	0.880	535	296,000	59.29
29	Malta	0.878	549	2103	0.43

Table 21. (Continued)

HDI[b] rank (2017)	Country	HDI[b] (2017)	EEC[c] (2015-2017) W/capita	EEC[c] (2015-2017) GW·h	Population in millions (2018)
30	Estonia	0.871	743	7664	1.31
31	Greece	0.870	561	53,050	11.14
32	Cyprus	0.869	369	4028	1.19
33	Poland	0.865	420	141,300	38.10
34	United Arab Emirates	0.863	1848	110,600	9.54
35	Andorra	0.858	749	222	0.08
36	Lithuania	0.858	395	9848	2.87
37	Qatar	0.856	1718	36,530	2.69
38	Slovakia	0.855	594	25,870	5.45
39	Brunei	0.853	984	3679	0.43
40	Saudi Arabia	0.853	1102	292,800	33.55
41	Latvia	0.847	394	6712	1.93
42	Portugal	0.847	484	47,030	10.29
43	Bahrain	0.846	2069	26,090	1.56
44	Chile	0.843	426	67,950	18.19
45	Hungary	0.838	249	38,660	9.69
46	Croatia	0.831	449	18,650	4.16
47	Argentina	0.825	301	122,500	44.68
48	Oman	0.821	850	27,620	4.82
49	Russia	0.816	854	890,100	143.96
50	Montenegro	0.814	495	516,600	0.63
51	Bulgaria	0.813	495	35,240	7.03
52	Romania	0.811	253	48,280	19.58
53	Belarus	0.808	393	31,750	9.45
54	Bahamas	0.807	558	1681	0.40
55	Uruguay	0.804	340	9420	3.47
56	Kuwait	0.803	2176	54,110	4.19
57	Malaysia	0.802	483	133,000	32.04
58	Barbados	0.800	352	944	0.29
59	Kazakhstan	0.800	565	97,600	18.40
High HDI					
60	Iran	0.798	300	220,900	82.01
61	Palau	0.798	-	-	0.02
62	Seychelles	0.797	367	366	0.01
63	Costa Rica	0.794	215	9113	4.95
64	Turkey	0.791	294	213,200	81.91
65	Mauritius	0.790	220	2680	1.26
66	Panama	0.789	240	8202	4.16
67	Serbia	0.787	430	26,780	8.76
68	Albania	0.785	292	7094	2.93
69	Trinidad & Tobago	0.784	851	9461	1.37
70	Antigua & Barbuda	0.780	365	307	0.10
71	Georgia	0.780	227	12,440	3.91
72	Saint Kitts & Nevis	0.778	436	193	0.06
73	Cuba	0.777	68	17,340	11.49
74	Mexico	0.774	220	245,200	130.76
75	Grenada	0.772	205	185	0.11
76	Sri Lanka	0.770	56	11,720	20.95
77	Bosnia & Herzegovina	0.768	325	11,440	3.50
78	Venezuela	0.761	288	73,990	32.38
79	Brazil	0.759	287	460,800	210.86
80	Azerbaijan	0.757	231	20,270	9.92
81	Lebanon	0.757	292	15,660	6.09
82	Macedonia	0.757	378	6455	2.08
83	Armenia	0.755	190	5331	2.93
84	Thailand	0.755	274	168,300	69.18
85	Algeria	0.754	138	53,440	42.01
86	China	0.752	510	5,920,000	1415.05
87	Ecuador	0.752	149	27,530	16.86
88	Ukraine	0.751	369	133,400	44.01
89	Peru	0.750	144	40,930	32.55
90	Colombia	0.747	145	60,110	49.46
91	Saint Lucia	0.747	208	333	0.18
92	Fiji	0.741	99	828	0.91
93	Mongolia	0.741	210	7103	3.12
94	Dominican Republic	0.736	162	13,250	10.88
95	Jordan	0.735	223	16,130	9.90
96	Tunisia	0.735	153	15,120	11.66
97	Jamaica	0.732	107	3173	2.89
	World	0.728	370	24,816,000	7658.82

Table 21. (Continued)

HDI[b] rank (2017)	Country	HDI[b] (2017)	EEC[c] (2015-2017) W/capita	GW·h	Population in millions (2018)
98	Tonga	0.726	49	47	0.11
99	St. Vincent & The Grenadines	0.723	111	144	0.11
100	Suriname	0.720	370	1948	0.57
101	Botswana	0.712	191	3722	2.33
102	Maldives	0.712	87	326	0.44
103	Dominica	0.715	139	87	0.07
104	Samoa	0.713	210	118	0.20
105	Uzbekistan	0.710	185	48,000	32.36
106	Belize	0.708	129	413	0.38
107	Marshall Islands	0.708	933	577	0.05
108	Libya	0.706	162	8131	6.47
109	Turkmenistan	0.706	280	15,090	5.85
110	Gabon	0.702	137	1907	2.06
111	Paraguay	0.702	161	10,470	6.89
112	Moldova	0.700	139	3669	4.04
Medium HDI					
113	Philippines	0.699	101	77,790	106.51
114	South Africa	0.699	445	207,700	57.40
115	Egypt	0.696	172	150,400	99.37
116	Indonesia	0.694	86	223,500	266.79
117	Vietnam	0.694	149	182,900	96.49
118	Bolivia	0.693	78	8981	11.21
119	Palestine	0.686	-	-	-
120	Iraq	0.685	125	66,000	39.33
121	El Salvador	0.674	105	6344	6.41
122	Kyrgyzstan	0.672	219	10,680	6.13
123	Morocco	0.667	98	26,830	36.19
124	Nicaragua	0.658	84	3177	6.28
125	Cabo Verde	0.654	61	436	0.55
126	Guyana	0.654	124	800	0.78
127	Guatemala	0.650	66	10,020	17.24
128	Tajikistan	0.650	164	12,940	9.10
129	Namibia	0.647	173	3771	2.58
130	India	0.640	128	1,048,000	1354.05
131	Micronesia	0.627	194	179	0.11
132	East Timor	0.625	11	125	1.32
133	Honduras	0.617	68	7215	9.41
134	Kiribati	0.612	29	22	0.12
135	Bhutan	0.612	317	2009	0.82
136	Bangladesh	0.608	40	48,980	166.36
137	Republic of Congo	0.606	13	901	5.40
138	Vanuatu	0.603	22	68	0.28
139	Laos	0.601	63	4239	6.96
140	Ghana	0.592	39	11,420	29.46
141	Equatorial Guinea	0.591	13	395	1.31
142	Kenya	0.590	18	9515	50.95
143	São Tomé & Príncipe	0.589	37	61	0.21
144	Swaziland	0.588	117	1500	1.39
145	Zambia	0.588	80	11,620	17.61
146	Cambodia	0.582	29	4952	16.24
147	Angola	0.581	45	8338	30.77
148	Myanmar	0.578	22	11,000	53.85
149	Nepal	0.574	15	4777	29.62
150	Pakistan	0.562	46	85,900	200.81
151	Cameroon	0.556	28	5702	24.67
152	Solomon Islands	0.546	14	84	0.62
Low HDI					
153	Papua New Guinea	0.544	50	1015	8.41
154	Tanzania	0.538	10	4976	59.01
155	Syria	0.536	112	13,960	18.28
156	Zimbabwe	0.535	62	7630	16.91
157	Nigeria	0.532	14	24,570	195.87
158	Rwanda	0.524	4	644	12.50
159	Lesotho	0.520	46	763	2.26
160	Mauritania	0.520	24	1108	4.54
161	Madagascar	0.519	6	1108	26.26
162	Uganda	0.516	8	2936	44.27
163	Benin	0.515	10	1121	11.48
164	Senegal	0.505	23	3014	16.29
165	Comoros	0.503	5	50	0.83

Table 21. (Continued)

HDI[b] rank (2017)	Country	HDI[b] (2017)	EEC[c] (2015-2017) W/capita	EEC[c] (2015-2017) GW·h	Population in millions (2018)
166	Togo	0.503	16	1213	7.99
167	Sudan	0.502	30	10,260	41.51
168	Haiti	0.498	4	372	11.11
169	Afghanistan	0.498	16	2866	36.37
170	Ivory Coast	0.492	27	5669	24.9
171	Malawi	0.477	11	1972	19,16
172	Djibouti	0.476	53	377	0.97
173	Ethiopia	0.463	7	8143	107.53
174	Gambia	0.460	17	223	2.16
175	Guinea	0.459	8	930	13.05
176	Democratic Republic of Congo	0.457	13	7190	84.00
177	Guinea-Bissau	0.455	2	32	1.91
178	Yemen	0.452	21	3634	28.91
179	Eritrea	0.440	5	330	5.18
180	Mozambique	0.437	52	13,860	30.52
181	Liberia	0.435	7	39	4.85
182	Mali	0.427	12	2023	19.11
183	Burkina Faso	0.423	8	1321	19.75
184	Sierra Leone	0.419	3	163	7.72
185	Burundi	0.417	4	304	11.21
186	Chad	0.404	1	200	15.35
187	South Sudan	0.388	6	694	12.91
188	Central African Republic	0.367	4	162	4.73
189	Niger	0.354	7	1072	22.31

[a]Population from Ref. [7] (data for 2018); EEC from Ref. [8] (data mainly from 2017–2015; for exact details see the reference); and HDI from [9,10] (data from 2017).

[b]HDI—human development index by United Nations (UN); HDI is a comparative measure of life expectancy, literacy, education, and standards of living for countries worldwide. HDI is calculated by the following formula: $\mathrm{HDI} = \sqrt[3]{\mathrm{LEI} \times \mathrm{EI} \times \mathrm{II}}$, where LEI—life expectancy index, EI—education index, and II—income index. It is used to distinguish whether the country is a developed, a developing, or an under-developed country, and also to measure the impact of economic policies on quality of life.

[c]EEC, $\frac{\mathrm{W}}{\mathrm{capita}} = \frac{(\mathrm{EEC}, (\mathrm{GWh/yr})) \times (10^9/(365\,\mathrm{days} \times 24\,\mathrm{h}))}{(\mathrm{population, millions}) \times 10^6}$; EEC compares the total electricity generated annually plus imports and minus exports, expressed in gigawatt-hours (GW·h).

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