# Current Status of Reactors Deployment and Small Modular Reactors Development in the World

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*Due to emerging climate change concerns coupled with increased global energy demand, eventually the world needs to move to low-carbon-emission electricity-generating sources—nonrenewables, such as nuclear power, and renewables, as hydro, wind, geothermal, solar, and tidal. The only source is nuclear power that is reliable, concentrated, and can be of large installed capacity and operate with high capacity factors. This paper updates and presents the current status of nuclear-power deployment and small modular reactors (SMRs) development in the world. Unfortunately, within last 9 years, electricity generation with nuclear power has decreased from ~14% before the Fukushima Nuclear Power Plant (NPP) severe accident in March of 2011 to about ~10%. Therefore, it is important to follow up with and understand the latest trends in nuclear power including SMRs development.* [DOI: 10.1115/1.4047927]

## 1 Introduction

Due to emerging climate change concerns coupled with growing global energy demand, eventually the world needs to move toward manufacturing, transportation, heating and electricity generation with lower carbon emissions including increased use of nuclear power, and hydro, wind, geothermal, solar, and tidal sources [1–4]. However, only nuclear power, is high reliability, and of potentially large installed capacity that can operate with high capacity factors (up to 90 - 100%). The other sources are lower capital cost, but mainly limited by Nature as to lower reliability, capacity factors, and location. It is clear that nuclear power can make a significant, indeed vital contribution to the stated political objectives, industrial positioning and social goals of becoming "Zero Carbon" or "Carbon Neutral" by dates varying from 2030 to 2050. The necessary increased electrification of transportation, industry and whole societies without significantly enhanced emissions is only possible if 1000's of new reactors are, also, actually built quickly.

This paper is a logical continuation of our previous publications on the current status of nuclear-power industry of the world [2–7]. Unfortunately, within last 9 years, electricity generation with nuclear power has decreased from 14% before the Fukushima Nuclear Power Plant (NPP) severe accident in March of 2011 to about 10% (see Fig. 1(*a*)). However, the last couple of years were very important for the world nuclear-power industry, because long-term expected new Generation-III$^+$ nuclear-power reactors/plants were put into operation in China, Russia, and South Korea, and more reactors are planned to be put into operation in these and other countries such as Bangladesh, Belarus', Finland, India, Turkey, United Arab Emirates (UAE), and USA within next 3 – 4 years.

The controversy and difficulty have been the needed capital investment and costs for building large 1000$^+$-MW$_{el}$ units, the potential for significant disruptive accidents (e.g., Fukushima), and the competitive energy market forces from cheap large-scale natural-gas production, especially, in the USA, Russia and elsewhere. As a result, nowadays, there is a lot of discussions, claims, and hopes in the nuclear, conference and political arenas directed toward smaller and variable sized units mass-produced and built in series (so-called, small modular reactors, SMRs). These are considered as a new development in nuclear-power industry of the world despite being commonly available in the combined cycle gas turbine (CCGT) industry. Therefore, to examine the present status, economic position, and future market positioning, it is important to follow up with the latest trends and actual data for both present and future deployments in the world nuclear-power industry, including the status of SMRs development.

Figure 1 shows various sources of electricity generation in the world (Fig. 1(*a*)) and 13 countries with the largest number of nuclear reactors/their installed capacities. These countries are China (Fig. 1(*b*)), India (Fig. 1(*c*)), USA (Fig. 1(*d*)), Russia (Fig. 1(*e*)), Japan (Fig. 1(*f*)), Germany (Fig. 1(*g*)), UK (Fig. 1(*h*)), France (Fig. 1(*i*)), South Korea (Fig. 1(*j*)), Spain (Fig. 1(*k*)), Ukraine (Fig. 1l), Canada (Fig. 1(*m*)), and Sweden (Fig. 1(*n*)). World and all these countries are shown in Fig. 1 according to decreasing population.

Analysis of the data presented in these sector diagrams shows that the world (~38%) (see Fig. 1(*a*)) and, especially, countries with the largest population, i.e., China (~66%) (see Fig. 1(*b*)) and India (~75%) (see Fig. 1(*c*)), as well as Germany (~37%) (see Fig. 1(*g*)) and South Korea (~42%) (see Fig. 1(*j*)) rely heavily on coal for electricity generation! The USA (~39%) (see Fig. 1(*d*)), Russia (~59%) (see Fig. 1(*e*)), Japan (~37%) (see Fig. 1(*f*)), and UK (~44%) (see Fig. 1(*h*)) use mainly natural gas or liquified natural gas (LNG) (Japan) for electricity generation, which is better than to use coal, but still for now we cannot avoid emission of carbon dioxide. On opposite, France (~72%) (see Fig. 1(*i*)), and Ukraine (~54%) (see Fig. 1(*l*)) heavily rely on nuclear power, which is, in general, the lowest emitter of carbon dioxide compared to all other electricity-generating sources including renewables (for details, see Figs. 8 and 10 in Ref. [2]). Canada is the only country from these 13 countries, which heavily rely on hydro-electricity generation (~61%) (see Fig. 1(*m*)), and Sweden—on hydro (~39%) and wind (~10%) (see Fig. 1(*n*)).

## 2 Current Status of the World Nuclear-Power Industry

Current statistics on all world nuclear-power reactors connected to electrical grids are listed in Tables 1–7, and shown in Fig. 2. Statistics from previous years is shown in Refs. [1–7]. Tables 8–10 list basic parameters of various nuclear-power reactors and thermal efficiencies of the corresponding NPPs, respectively. Figure 3 shows simplified *T–s* diagram for a typical pressurized water reactor (PWR), boiling water reactor (BWR), or light-water-cooled graphite-moderated reactor (LGR) NPP turbine cycle.

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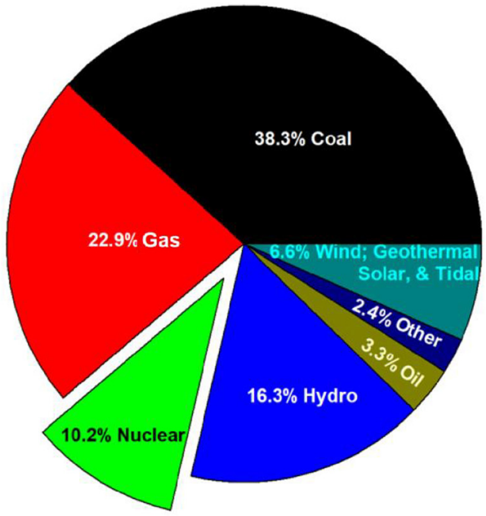
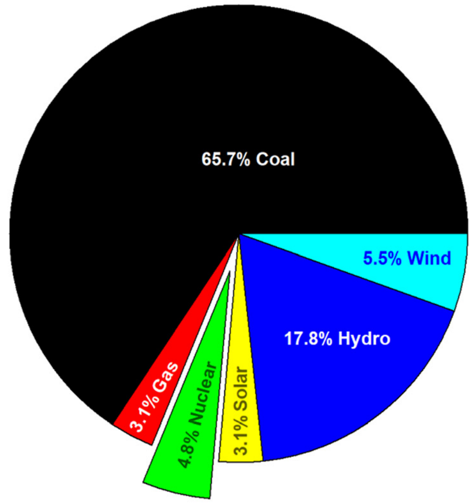
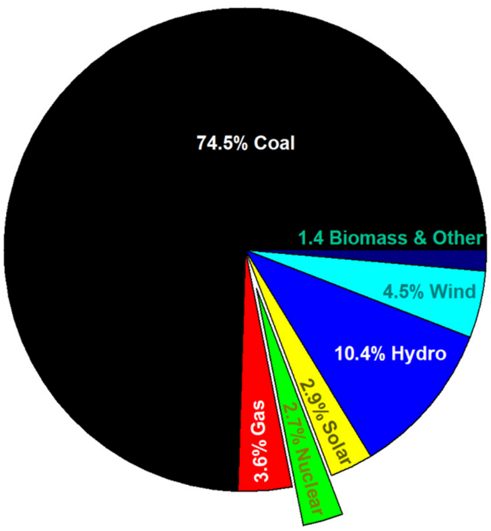


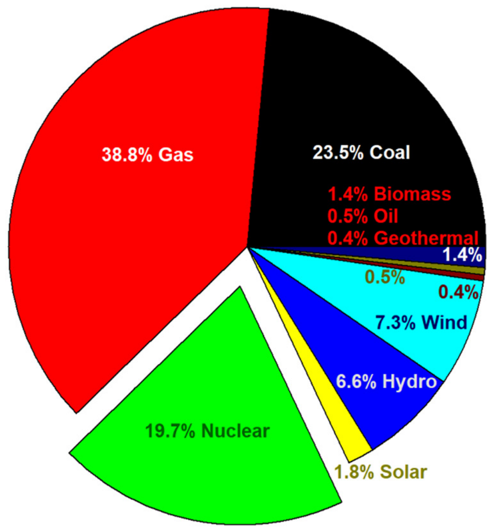

(*a*) **World: Population 7,798 million; EEC 22,347 TW h per year or 327 W per Capita; HDI 0.731 or HDI Rank 93.**




(*b*) **China: Population 1,439 million; EEC 5,935 TW h per year or 461 W per Capita; HDI 0.758 or HDI Rank 85.**




(*c*) **India: Population 1380 million; EEC 1,177 TW h per year or 97 W per Capita; HDI 0.647 or HDI Rank 129.**



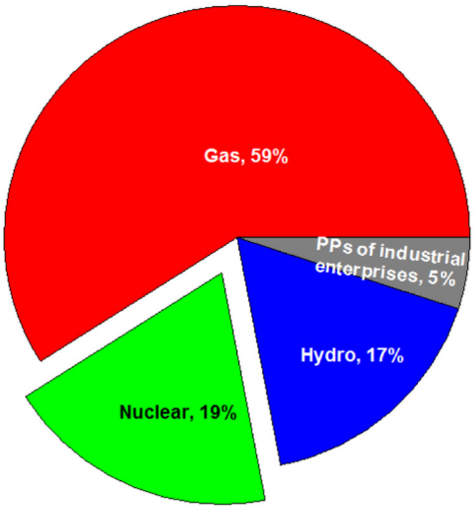

(*d*) **USA: Population 331 million; EEC 4,034 TW h per year (2018) or 1,391 W per Capita; HDI 0.920 or HDI Rank 15.**

**Fig. 1 Electricity generation in the world and selected countries by source (data presented here just for reference purposes): Data in sector diagrams,[1] population (data for July 2020),[2] EEC (data are from 2017),[3] and HDI (data from 2018—Report of 2019)[4,5] can be obtained online. (More diagrams for other countries and for previous years are shown in Refs. [1–3] and [5–7].**

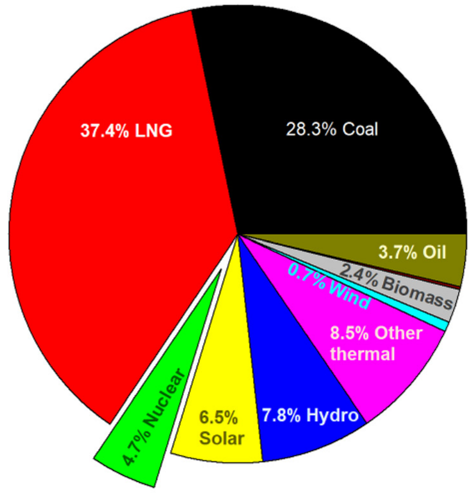
The largest group of nuclear-power reactors by type is PWRs (297 from 439 reactors or 68% of the total number), and quite a significant number of PWRs are planned to be built (about 45 + 22?) (for details, see Table 1 and Fig. 2, which shows the data from Table 1 in the form of sector diagrams for a number of reactors by type and by installed capacities). The second largest group of reactors is BWRs/Advanced BWRs (ABWRs) (65 reactors or 15% of the total number). The third group is pressurized heavy water reactors (PHWRs) (48 reactors or 11% of the total number). Considering the number of forthcoming reactors, the number of BWRs/ABWRs and PHWRs will decrease globally within next 20–25 years. Furthermore, within next 10–15 (20) years or so, all LGRs and advanced gas-cooled reactors (AGRs) (carbon-dioxide-cooled) will be shut down forever.

For our opinion, the Chernobyl NPP accident (April of 1986), which had happened with the RBMK-1000—LGR, has forced Ukraine to shut down this NPP and Russia to cancel any further R&D and construction of new LGRs. In the same way, a small

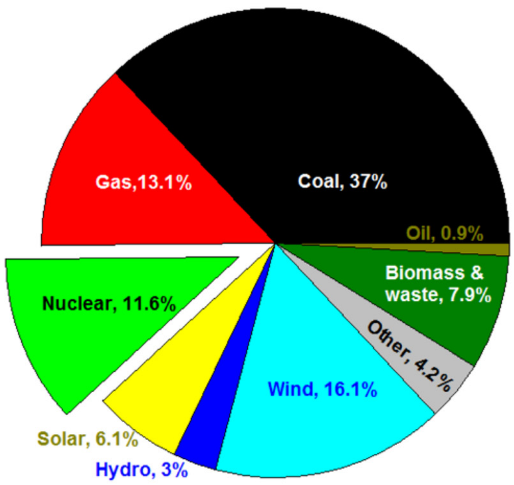
[1]https://www.statista.com/
[2]https://www.worldometers.info/world-population/population-by-country/
[3]https://www.eia.gov/international/data/world
[4]http://hdr.undp.org/en/content/2019-human-development-index-ranking
[5]http://hdr.undp.org/sites/default/files/hdr2019.pdf?



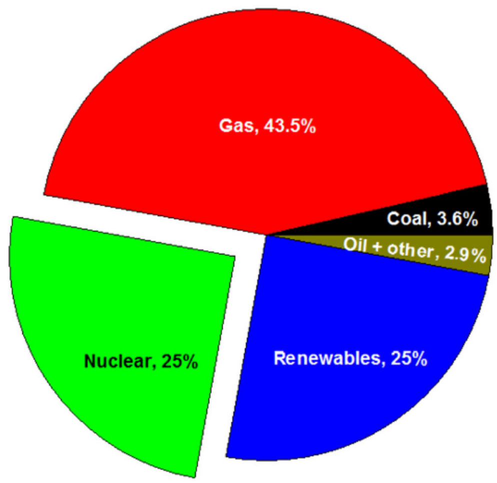

**(*e*) Russia: Population 144 million; EEC 890 TW h per year or 919 W per Capita; HDI 0.824 or HDI Rank 49 (PPs – Power Plants).**




**(*f*) Japan: Population 126 million; EEC 946 TW h per year or 857 W per Capita; HDI 0.915 or HDI Rank 19.**




**(*g*) Germany: Population 84 million; EEC 539 TW h per year or 732 W per Capita; HDI 0.939 or HDI Rank 4.**




**(*h*) UK: Population 68 million; EEC 307 TW h per year or 515 W per Capita; HDI 0.920 or HDI Rank 15.**

**Fig. 1** **Continued**

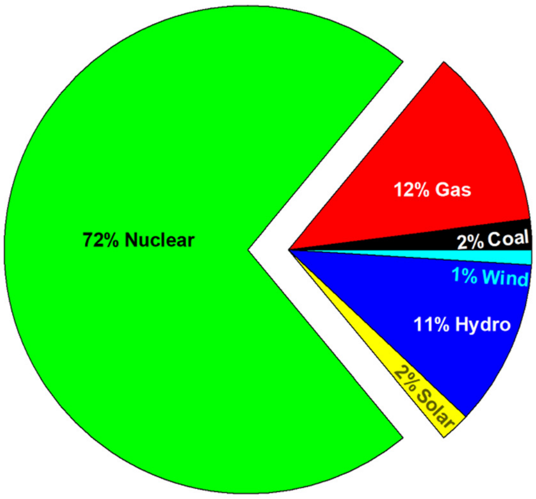
number of BWRs/ABWRs planned to be built is possibly due to the Fukushima-Daiichi NPP severe accident, which had happened with older design BWRs in March of 2011. However, it should be mentioned that all nuclear vendors, of course, including BWR/ABWR ones, have updated their designs with additional features/systems to enhance safety based on lessons learned from the all nuclear accidents (for example, see Table 17 in Ref. [2], which lists differences/improvements between BWR-5 and ABWR designs).

Table 2 lists average, maximum, and minimum installed capacities of nuclear-power reactors of the world of various types. Analysis of these data shows that using only number of reactors as a characteristic parameter for nuclear-power industry is not the best option due to very significant differences in reactors' installed capacities, which can vary from 10 and up to 1660 $MW_{el}$.

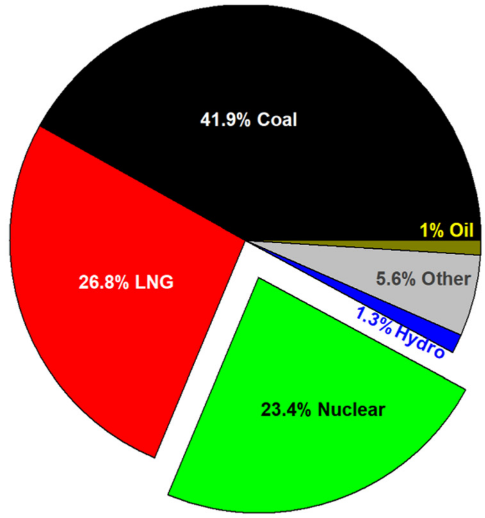
Table 3 lists a number of nuclear-power reactors connected to grid by 13 nations/countries with the largest number of reactors/installed capacities as per July 2020 and before the Japan earthquake and tsunami disaster. Sources of electricity generation in these 13 countries are shown in Fig. 1. Data for all countries with nuclear-power reactors and countries, which work to introduce nuclear power on their soil, are listed in Table 4.

Analysis of the current statistical data on nuclear-power reactors/NPPs (see Table 4) 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 soil.

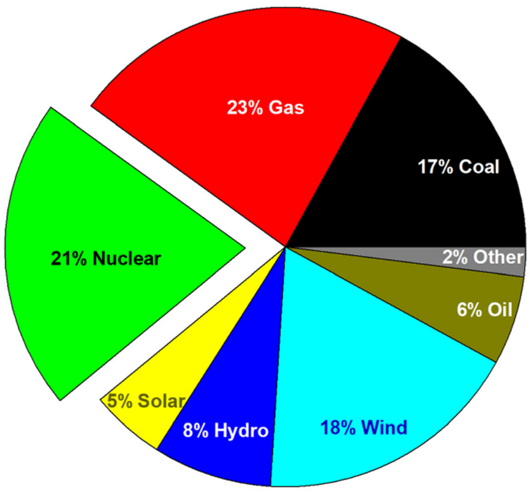
Analysis of the data in Tables 3 and 4 shows that real nuclear "renaissance" is in China (34 reactors built and put into operation within past 9 years!), in Russia (addition of six reactors), in South Korea (addition of four reactors), and in India (addition of three reactors). Meanwhile, the most significant drop in a number of reactors is in Japan (21 reactors were shut down) (only about 9 reactors out of 33 are currently in operation), in Germany (11



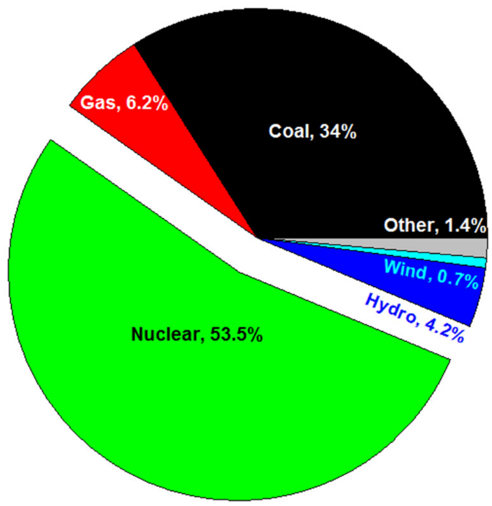

(*i*) **France: Population 65 million; EEC 455 TW h per year or 799 W per Capita; HDI 0.891 or HDI Rank 26.**




(*j*) **S. Korea: Population 51 million; EEC 512 TW h per year or 1146 W per Capita; HDI 0.906 or HDI Rank 22.**




(*k*) **Spain: Population 47 million; EEC 242 TW h per year or 588 W per Capita; HDI 0.893 or HDI Rank 25.**




(*l*) **Ukraine: Population 40 million; EEC 124 TW h per year or 354 W per Capita; HDI 0.750 or HDI Rank 88.**

**Fig. 1 Continued**

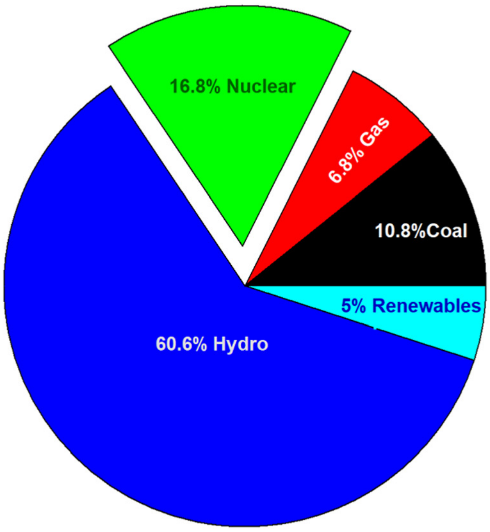
reactors), in USA (9 reactors), in UK (4 reactors), in Canada (3 reactors), and in Sweden (3 reactors). In addition, Canada, Germany, and Sweden have no plans to build new reactors.

It should be noted that in spite of outstanding achievements in nuclear-power industry, especially, in China, and, partially, in India, electricity share by nuclear power is very small (see Figs. 1(*b*) and 1(*c*)), i.e., in China—only 4.8%, and in India—2.7%!

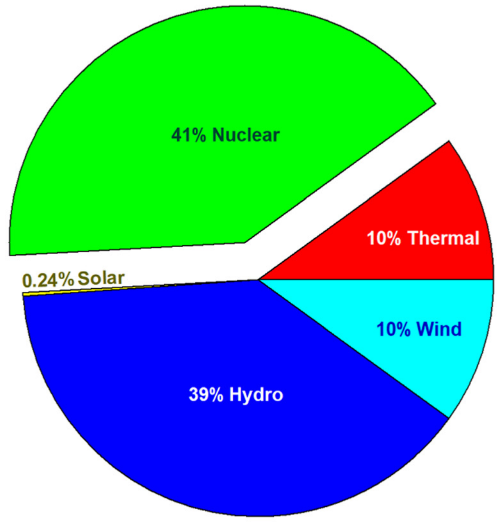
Table 5 lists latest years when various types of reactors have been built and connected to grid. The latest AGR (carbon-dioxide-cooled) in UK was connected to grid in 1989, i.e., no new AGRs have been built for last 31 years. Therefore, unfortunately, these reactors/NPPs, which are actually the most efficient NPPs in the world (~42% thermal efficiency) (see Table 10), will never build again! Possible reasons for stopping AGRs in the UK were the cost, build difficulty (problems with intermediate heat exchanger and thermal insulation), and issues with full-power refueling.

Table 6 lists latest years when reactors have been built and connected to grid in various countries. These data are also quite important, because if a country/company has not built any reactors within 10–15 years, they, usually, lose important experience in this particular area, and might not be able, at least, to meet the promised new-reactor-construction timeframe and budget, e.g., new EPRs in Finland and France, AP-1000 in USA, etc.

Table 7 lists smallest in the world operating nuclear-power reactors within the range of installed capacities from 10 to 300 $MW_{el}$. These reactors belong to a group of small- and medium-size reactors or S&MRs (do not mix up with SMRs). Analysis of the data in Table 7 shows that the smallest nuclear-power reactors with the installed capacities below 50 $MW_{el}$ are in




(*m*) **Canada: Population 38 million; EEC 509 TW h per year or 1529 W per Capita; HDI 0.922 or HDI Rank 13.**




(*n*) **Sweden: Population 10 million; EEC 133 TW h per year or 1518 W per Capita; HDI 0.937 or HDI Rank 8.**

**Fig. 1 Continued**

**Table 1 Number of nuclear-power reactors connected to electrical grid and forthcoming units as per July 2020 (based on data from Ref. [8][6,7]) and prior to Japan earthquake and tsunami disaster (based on data from Ref. [9])**

| | | No. of units | | Installed capacity, $GW_{el}$ | | Forthcoming units | |
|---|---|---|---|---|---|---|---|
| Rank by no. | Reactor type (% total reactors/average installed capacity) | As of July 2020 | Before Mar. 2011 | As of July 2020 | Before Mar. 2011 | No. of units | $GW_{el}$ |
| 1 | PWRs (68%/950 $MW_{el}$) | 297 ↑ | 268 | 282 ↑ | 248 | 45 + 22?[a] | 52 + 21?[a] |
| 2 | BWRs or advanced BWRs (15%/1025 $MW_{el}$) | 65 ↓ | 92 | 67 ↓ | 84 | 1 + 3? | 1.3 + 3.9? |
| 3 | PHWRs (11%/500 $MW_{el}$) | 48 ↓ | 50 | 24 ↓ | 25 | 6 + 2? | 3.8 + 1.4? |
| 4 | AGRs ($CO_2$-cooled) (3%/550 $MW_{el}$) | 14 ↓ | 18 | 8 ↓ | 9 | 1?[b] | 0.2?[b] |
| 5 | LGRs (3%/715 $MW_{el}$) | 13 ↓ | 15 | 9 ↓ | 10 | 0 | 0 |
| 6 | Liquid-metal fast-breeder reactors (LMFBRs—SFRs) (0.5%/690 $MW_{el}$) | 2 ↑ | 1 | 1.4 ↑ | 0.6 | 1 + 1? | 0.6 + 0.5? |
| In total | | 439 ↓ | 444 | 391↑ | 377 | 53 + 29? | 58 + 27? |

(Technical parameters of various reactors are listed in Tables 8 and 9 and in details are shown in Ref. [3]). (For graphical representation of current data, see Fig. 2). Note: Arrows mean decrease or increase in a number of reactors and installed capacities. Data in Table 1 include 33 reactors in Japan, 24 of which were not in service as of December 2019.

[a]?—Means "Commercial start date—indefinitely" (Nuclear News, 2020 [8]).

[b]Forthcoming reactor is a helium-cooled reactor—high temperature reactor pebble-bed modular (HTR-PM) (China).

Russia. Currently, three EGP-6 reactors are still in operation (one was shut down in 2019), but all of them will be shut down and electricity generated by them will be replaced with two KLT-40S reactors, which are the first in the world SMRs put into operation in December of 2019. Also, it should be noted that many of S&MRs are PHWRs of older designs.

Table 11 lists current activities in various countries worldwide on new nuclear-power-reactors build. Analysis of the data in Table 11 clearly shows that China and Russia are the front runners in new nuclear builds in their countries and abroad, largely, because both governments provide significant political and long-term support with various funds for nuclear-power R&D and for their government-controlled nuclear vendors, as, also, do South Korea and France, especially, to build NPPs abroad plus credits and other incentives for foreign buyers, to introduce nuclear power.

[6]http://www.world-nuclear.org/

[7]https://pris.iaea.org/pris/

The last several years were very important for the nuclear-power industry of the world. Russia put into operation a number of Generation-III$^{+}$ VVERs (PWRs) and the SFR—BN-800 reactor in 2016 and continue to lead the SFR technologies in the world [2,3].

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 $MW_{el}$. In addition, several AP-1000 reactors (Westinghouse design), also, a Generation-III$^{+}$ design, were put into operation in China first time in the world [8]. In general, Generation-III$^{+}$ water-cooled reactors/NPPs have installed capacities from 1100 to 1660 $MW_{el}$, enhanced safety, and can reach slightly higher thermal efficiencies up to 36–37% (38%) compared to those of Generation-III water-cooled reactors/NPPs (see Table 10). In addition, South Korea put into operation several their Generation-III$^{+}$ APR-1400 (Doosan design) on their soil, and plans to put seven more these reactors into operation soon: 3 inside country and 4 in UAE [8].

Year 2020 and the following years will be also very important ones, because a unique GCR—a helium-cooled reactor—high

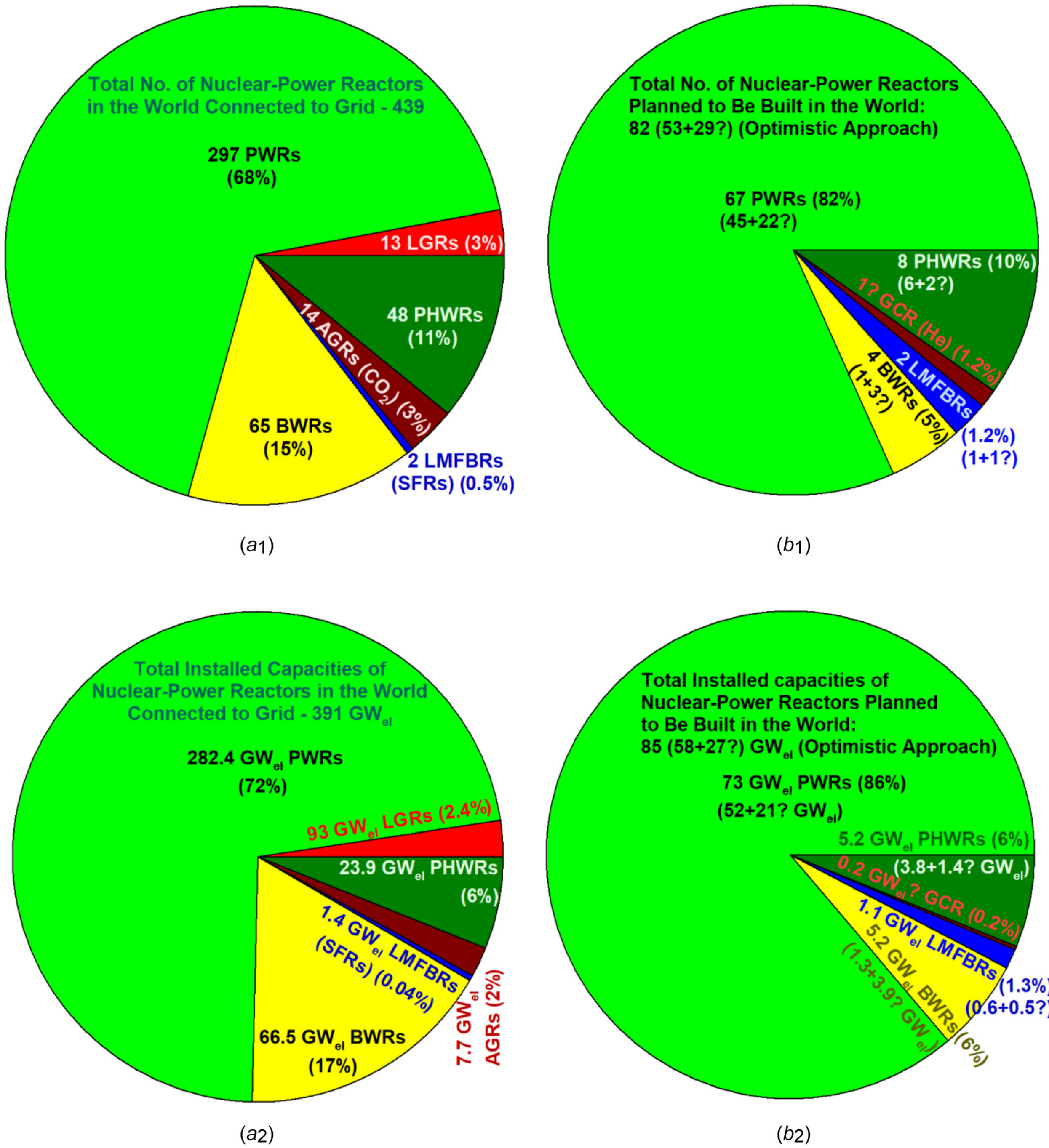



**Fig. 2 Nuclear-power reactors of the world (based on data from Table 1 and Ref. [8][6,7]): (*a*) connected to grid—($a_1$) by type and ($a_2$) by installed capacities; and (*b*) planned to be built (optimistic approach, i.e., including those under ?)—($b_1$) by type and ($b_2$) by installed capacities**

temperature reactor pebble-bed modular (HTR-PM) should be put into operation in 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 Tables 1 and 4 or the latest March issue of Nuclear News).

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.

## 3 Economics of Existing Units and New Builds

Since existing units sell into the electricity marketplace, they must compete on the basis of generating price, which for fully amortized or older plants means solely reclaiming the operating costs plus some profit. Hence, life extensions, refurbishments, and/or license renewals have been popular if, when and where the units can still generate at a competitive price, as it is simply cheaper than building new and there are no technical “show stoppers” [10,11]. Such methods have been adopted in Canada (for 10 CANDU units) and in the USA (for approximately 20 Light Water-cooled Reactors (LWRs) units) for extended

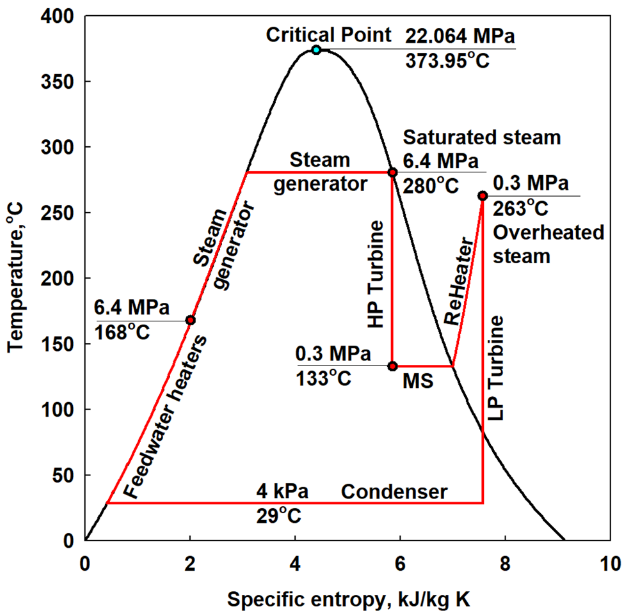



**Fig. 3 Simplified *T–s* diagram for typical PWR, BWR, or LGR NPP turbine cycle (Rankine cycle is based on that of RBMK-1000, winter operation) [3]**

lifetimes from a few to up to 80 years (two BWRs at the Peach Bottom NPP and two PWRs at the Turkey Point NPP have received extension to operate for 80 years). In other power markets, some profit margins are too small to justify continued operation and plant closure is possible. Appeals have been made to allow "carbon offsets" or zero emissions environmental offsets, as there is growing international realization of the value of NPPs in reducing $CO_2$ emissions [12].

It is key to know the likely investment, capital, and generating costs (levelized unit energy cost (LUEC)) for new builds of existing and/or known designs. Because of its commercial nature and the resulting strictures of competitive secrecy, there is often a scarcity or nondisclosure of the full financial details, and there is no single source for such potentially sensitive information. For estimation purposes, we have to rely on data openly published or reported for builds underway in multiple countries and locations, from 2016 up to late 2019. Where necessary we have back-calculated the generating costs if, say, only the overall capital cost and project schedule were given.

To provide a common basis for intercomparison except, where explicitly stated, we adopted a typical uniform weighted average cost of credit (WACC) plus return-on-investment (ROI) of 12% prevalent in global commercial markets [13], which then also includes an added 6% risk premium. Using such a common interest rate, which can easily be varied/removes the effects of any artificial subsidies, hidden licensing support, preferential taxes rates or relief, artificially low interest rates, or low-cost noncommercial or government backed overseas loans and contracts. Some interested parties may challenge this rate or assumptions, which

**Table 2 Average, maximum, and minimum installed capacities of nuclear-power reactors of the world of various types (values rounded to nearest 0 or 5) (based on data from Ref. [8][6,7]).**

| Type of reactor Parameter | PWRs | BWRs | PHWRs | AGRs ($CO_2$-cooled) Installed capacities, $MW_{el}$ | LGRs | LMFBRs (SFRs) |
|---|---|---|---|---|---|---|
| Average | 950 | 1025 | 500 | 550 | 715 | 690 |
| Maximum | 1660 | 1435 | 880 | 620 | 925 | 820 |
| Minimum | 30 | 150 | 90 | 480 | 10 | 560 |

**Table 3 Number of nuclear-power reactors connected to grid by nation (13 nations ranked by nuclear-reactor installed capacities) as per July 2020 (based on data from Ref. [8][6,7]) and before the Japan earthquake and tsunami disaster (based on data from Ref. [9])**

| | | No. of units (PWRs/BWRs/other types) | | Installed capacity, $GW_{el}$ | | | |
|---|---|---|---|---|---|---|---|
| No. | Nation | As of July 2020 | Before Mar. 2011 | As of July 2020 | Before Mar. 2011 | Changes in No. of reactors from March 2011 | % of electricity generated by nuclear |
| 1 | USA | 95 (63/32) | 104 | 98 | 103 | ↓ 9 | 19.7 |
| 2 | France | 56 (56/-) | 58 | 61 | 63 | ↓ 2 | 72.0 |
| 3 | China | 47 (45/-/2[a]) | 13 | 45 | 10 | ↑ 34 | 4.8 |
| 4 | Russia | 38 (23/-/13[b]/2[c]) | 32 | 28 | 23 | ↑ 6 | 19.0 |
| 5 | Japan[d] | 33 (16/17) | 54 | 32 | 47 | ↓ 21 | 4.7 |
| 6 | South Korea | 24 (21/-/3[a]) | 20 | 23 | 18 | ↑ 4 | 23.4 |
| 7 | Canada | 19 (-/-/19[a]) | 22 | 14 | 15 | ↓ 3 | 16.8 |
| 8 | Ukraine | 15 (15/-) | 15 | 13 | 13 | N/A | 53.5 |
| 9 | UK | 15 (1/-/14[e]) | 19 | 9 | 10 | ↓ 4 | 25.0 |
| 10 | Germany | 6 (5/1) | 17 | 8 | 20 | ↓ 11 | 11.6 |
| 11 | Sweden | 7 (5/2) | 10 | 8 | 9 | ↓ 3 | 41.0 |
| 12 | Spain | 7 (6/1) | 8 | 7 | 8 | ↓ 1 | 20.4 |
| 13 | India | 22 (2/2/18[a]) | 19 | 6 | 4 | ↑ 3 | 2.7 |
| In total | | 384 (258/55/13[b]/2[c]/42[a]/14[e]) | 391 | 352 | 343 | ↓ 7, but installed capacity ↑by 9 $GW_{el}$ | |

Note: Data for all countries with nuclear-power reactors are listed in Table 4. Arrows mean decrease or increase in a number of reactors.
[a]No. of PHWRs.
[b]No. of LGRs.
[c]No. of LMFBRs.
[d]As per December of 2019, only nine reactors were in operation.
[e]No. of AGRs.

**Table 4 Number of nuclear-power reactors connected to electrical grid and forthcoming units as per July 2020 (based on data from Ref. [8][6,7]) (countries planning to build new reactors are in bold color)**

| No. | Nation | # Units (type) (connected to grid) | Net $MW_{el}$ | # Units | Net $MW_{el}$ (forthcoming) | Type |
|---|---|---|---|---|---|---|
| 1 | **Argentina** | **3 (PHWRs)** | **1,633** | **1?[a]** | **25?** | **PWR** |
| 2 | Armenia | 1 (PWR) | 375 | 0 | 0 | — |
| 3 | **Bangladesh** | **—** | **—** | **2** | **2160** | **PWR** |
| 4 | **Belarus** | **—** | **—** | **2** | **2218** | **PWR** |
| 5 | Belgium | 7 (PWRs) | 5,918 | 0 | 0 | — |
| 6 | **Brazil** | **2 (PWRs)** | **1,889** | **1?** | **1245?** | **PWR** |
| 7 | Bulgaria | 2 (PWRs) | 1,966 | 0 | 0 | — |
| 8 | Canada | 19 (PHWRs) | 13,554 | 0 | 0 | — |
| 9 | **China** | **47 (45 PWRs; 2 PHWRs)** | **45,498** | **10 + 8?** | **10,922+ 8,000?** | **18 PWRs 1 GCR[b]** |
| | | | | **1?** | **200?** | **1 LMFBR** |
| | | | | **1** | **600** | |
| 10 | Czech Rep. | 6 (PWRs) | 3932 | 0 | 0 | — |
| 11 | **Egypt** | **—** | **—** | **4?** | **4760?** | **PWR** |
| 12 | **Finland** | **4 (2 PWRs; 2 BWRs)** | **2794** | **2** | **2800** | **PWR** |
| 13 | **France** | **56 (PWRs)** | **61,370** | **1?** | **1600?** | **PWR** |
| 14 | Germany | 6 (5 PWRs; 1 BWR) | 8113 | 0 | 0 | — |
| 15 | **Hungary** | **4 (PWRs)** | **1902** | **2?** | **2400?** | **PWR** |
| 16 | **India** | **22 (18 PHWRs; 2 BWRs; 2 PWRs)** | **6255** | **6** | **3780** | **6 PHWRs** |
| | | | | **4** | **3368** | **4 PWRs** |
| | | | | **1?** | **470?** | **1 LFMBR** |
| 17 | **Iran** | **1 (PWR)** | **915** | **2** | **1830** | **PWR** |
| 18 | **Japan[c]** | **33 (16 PWRs; 13 BWRs; 4 ABWRs)** | **31,679** | **1 + 1?** | **2650** | **BWR** |
| 19 | Mexico | 2 (BWRs) | 1552 | 0 | 0 | — |
| 20 | Netherlands | 1 (PWR) | 482 | 0 | 0 | — |
| 21 | **Pakistan** | **5 (4 PWRs; 1 PHWR)** | **1318** | **3?** | **3028?** | **PWR** |
| 22 | **Romania** | **2 (PHWRs)** | **1300** | **2?** | **1440?** | **PHWR** |
| 23 | **Russia** | **38 (23 PWRs; 13 LGRs; 2 LMFBRs)** | **28,419** | **3 + 2?** | **5533** | **PWR** |
| 24 | **Slovakia** | **4 (PWRs)** | **1814** | **2?** | **880** | **PWR** |
| 25 | Slovenia | 1 (PWR) | 696 | 0 | 0 | — |
| 26 | S. Africa | 2 (PWRs) | 1860 | 0 | 0 | — |
| 27 | **S. Korea** | **24 (21 PWRs; 3 PHWRs)** | **23,137** | **4** | **5360** | **PWR** |
| 28 | Spain | 7 (6 PWRs; 1 BWR) | 7121 | 0 | 0 | — |
| 29 | Sweden | 7 (2 PWRs; 5 BWRs) | 7710 | 0 | 0 | — |
| 30 | Switzerland | 4 (3 PWRs; 1 BWRs) | 2960 | 0 | 0 | — |
| 31 | **Taiwan** | **4 (2 PWRs; 2 BWRs)** | **3844** | **2?** | **2600?** | **BWR** |
| 32 | **Turkey** | **—** | **—** | **4** | **4456** | **PWR** |
| 33 | **Ukraine** | **15 (PWRs)** | **13,107** | **2?** | **2070?** | **PWR** |
| 34 | **UAE** | **—** | **—** | **4** | **5380** | **PWR** |
| 35 | **UK** | **15 (1 PWR; 14 AGRs)** | **8923** | **2** | **3260** | **PWR** |
| 36 | **USA** | **95 (63 PWRs; 32 BWRs)** | **99,091** | **2** | **2200** | **2 PWRs** |
| **In total** | | **439 (297 PWRs; 65 BWRs; 48 PHWRs; 14 AGRs; 13 LGRs; 2 LMFBRs)** | **391,127** | **53 + 29?** | **57,734+ 26,831?** | **—** |

Summary: 31 countries have operating nuclear-power reactors, and 5 countries plan to build nuclear-power reactors (in bold 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. (Countries planning to build new reactors are in bold).

[a]?—Means "Commercial start date – indefinitely" (Nuclear News, 2020 [8]).

[b]GCR is a helium-cooled reactor—high temperature reactor pebble-bed modular (HTR-PM) (China).

[c]As per December of 2019, only nine reactors were in operation.

**Table 5 Latest years when various types of reactors have been built and connected to grid [8]**

| No. | Type of reactor | Model | Reactor supplier | Country | Installed capacity, $MW_{el}$ | Year | Reactor age, years |
|---|---|---|---|---|---|---|---|
| 1 | **PWR** | EPR | Areva | China | 1660 | **2019** | **1** |
| | | ACPR-1000 | CNNC | | 1000 | | |
| | | AES-2006 | AEP | Russia | 1114 | **2019** | **1** |
| | | KLT-40S (2 SMRs) | OKBM | | 32 | | |
| | | APR-1400 | Doosan | S. Korea | 1383 | **2019** | **1** |
| 2 | **BWR** | ABWR | Hitachi | Japan | 1108 | **2006** | **14** |
| 3 | **PHWR** | Two-loop | Siemens | Argentina | 693 | **2016** | **4** |
| 4 | **AGR** | AGR | NNC | UK | 605 | ***1989*** | ***31*** |
| 5 | **LGR** | RBMK-1000 | MTM | Russia | 925 | ***1990*** | ***30*** |
| 6 | **LMFBR** | BN-800 | OKBM | Russia | 820 | **2016** | **4** |

Note: Reactors built before 1995, i.e., 25 and more years old are in italic style.

Table 6 Latest years when reactors have been built and connected to grid in various countries [8]

| No. | Country | Reactor type | Model (No. of units if more than 1) | Reactor supplier | Installed capacity, $MW_{el}$ | Year | Reactor age |
|---|---|---|---|---|---|---|---|
| 1 | Argentina | PHWR | Two-loop | Siemens | 693 | **2016** | **4** |
| 2 | Armenia | PWR | VVER-440/V270 | MTM | 375 | ***1980*** | ***40*** |
| 3 | Belgium | PWR | Three-loop (2) | ACECOWEN | 1038 | ***1985*** | ***35*** |
| 4 | Brazil | PWR | Four-loop | KWU | 1280 | **2001** | **19** |
| 5 | Bulgaria | PWR | VVER-1000/V320 | AEE/OKBG | 1003 | ***1993*** | ***27*** |
| 6 | Canada | PHWR | CANDU (2) | AECL | 878 | ***1993*** | ***27*** |
| 7 | China | PWR | EPR ACPR-1000 | Areva | 1660 | **2019** | **1** |
| | | | | CNNC | 1000 | | |
| 8 | Czech Rep. | PWR | VVER-1000/V320 | Skoda | 1027 | **2004** | **16** |
| 9 | Finland | BWR | BWR 75 | ASEA-Atom | 890 | ***1982*** | ***38*** |
| 10 | France | PWR | N4 (2) | Framatome | 1495 | **2002** | **18** |
| 11 | Germany | PWR | Konvoi | KWU | 1310 | ***1989*** | ***31*** |
| 12 | Hungary | PWR | VVER-440/V213 | AEE/Skoda | 473 | ***1987*** | ***33*** |
| 13 | India | PWR | AES-92 | ASE | 932 | **2017** | **3** |
| 14 | Iran | PWR | VVER-1000 | ASE | 915 | **2013** | **7** |
| 15 | Japan | PWR | Three-loop | MHI | 866 | **2009** | **11** |
| 16 | Mexico | BWR | BWR-5 | GE | 1552 | ***1995*** | ***25*** |
| 17 | Netherlands | PWR | Two-loop | KWU/RDM | 482 | ***1973*** | ***47*** |
| 18 | Pakistan | PWR | CNP-300 | CNNC | 313 | **2017** | **3** |
| 19 | Romania | PHWR | CANDU®-6 | AECL/Vickers | 650 | **2007** | **13** |
| 20 | Russia | PWR | AES-2006 | AEP | 1114 | **2019** | **1** |
| | | | KLT-40S (2) | OKBM | 32 | | |
| 21 | Slovakia | PWR | VVER-440/V213 | Skoda | 436 | **2000** | **20** |
| 22 | Slovenia | PWR | Two-loop | Westinghouse | 696 | ***1983*** | ***37*** |
| 23 | S. Africa | PWR | Two-loop | Framatome | 930 | ***1985*** | ***35*** |
| 24 | S. Korea | PWR | APR-1400 | Doosan | 1383 | **2019** | **1** |
| 25 | Spain | PWR | Three-loop | Westinghouse | 1045 | ***1988*** | ***32*** |
| | | | | KWU/ENSA | 1003 | | |
| 26 | Sweden | BWR | BWR-75 | ABB-Atom | 1159 | ***1985*** | ***35*** |
| | | | | | 1400 | | |
| 27 | Switzerland | BWR | BWR-6 | GETSCO | 1220 | ***1984*** | ***36*** |
| 28 | Taiwan | PWR | Three-loop | Westinghouse | 938 | ***1985*** | ***35*** |
| 29 | Ukraine | PWR | VVER-1000/V320 | MTM | 950 | **2006** | **14** |
| 30 | UK | PWR | Four-loop | PPP | 1198 | ***1995*** | ***25*** |
| 31 | USA | PWR | Four-loop | Westinghouse | 1170 | **2016** | **4** |

Reactors built before 1995, i.e., 25 and more years old are in italic style.

are solely aimed at evaluating any relative competitive advantage; and we welcome receiving and access to any other cost and price data.

Table 12 lists the calculated capital, overnight, generating, and investment costs all in 2019 US$, using the currency-conversion rates shown. To retain comparability, included are nominal operating, fuel and decommissioning costs; while excluded are all utility, licensing, and environmental assessment costs. For comparative market purposes, we also show the published costs for conventional USA hydropower; typical natural gas 350-$MW_{el}$ CCGT in the USA and EU; and a proposed build of a $12 \times 60\,MW_{el}$ SMR concept in the USA. It is important to note

Table 7 Smallest in the world operating nuclear-power reactors (10–300 $MW_{el}$) (based on data from Ref. [8])

| | | | Reactor | | | | |
|---|---|---|---|---|---|---|---|
| NPP | No. of units | Net $MW_{el}$ | Type | Model | Commercial start | Location | Reactor supplier |
| <50 $MW_{el}$ | | | | | | | |
| Bilibino | 3 | 11 | LGR | EGP-6 | 1975; 1976; 1977 | Russia, Chukotka | MTM |
| Acad. Lomonosov | 2 | 32 | PWR | KLT-40S | 2019 | Russia, Chukotka | OKBM Afrikantov |
| $50-99\,MW_{el}$ | | | | | | | |
| 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 |
| In total | | | | | 27 | | |

Table 8 Basic parameters of all current reactors' types (Part 1) (based on data from Ref. [3])[8]

| No. | Reactor type | | Bundle orientation | Sheath material[a] | Neutron spectrum | Reactor: Coolant | Reactor: Moderator | Reactor coolant: P (MPa) | Reactor coolant: T (°C) | Refueling | Fuel[b] | Fuel enrichment, % | Heat transfer coefficient[c] ($kW/m^2K$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | PWR | PV | Vert. | Zr | Th. | $H_2O$ | | 15-16.2 | 295 → 330 | Batch | $UO_2$ | 3-5 | ~30 |
| | SMR KLT-40S | PV | Vert. | Zr | Th. | $H_2O$ | | 12.7 | 280 → 316 | Batch | $UO_2$ | 18.6 | - |
| 2 | BWR | PV | Vert. | Zr | Th. | $H_2O$ | | 7.2 | ~288 | Batch | $UO_2$ | ~2 | ~60 |
| 3 | PHWR (CANDU®) | PCh | Hor. | Zr | Th. | $D_2O$ | $D_2O$[d] | 11 → 10 | 260 → 310 | On-line | $UO_2$ | 0.7 | ~50 |
| 4 | AGR | PV[e] | Vert. | SS | Th. | $CO_2$ | C | ~4 | 290 → 650 | Batch[f] | $UO_2$ | 2.5-3.5 | ~2-5 |
| 5 | LGR (RBMK) | PCh | Vert. | Zr | Th. | $H_2O$ | C | 6.9 | 284.9 | On-line | $UO_2$ | 2-2.4 | ~60 |
| 6 | LMFBR (BN-800) | V | Vert. | SS | Fast | Na | — | ~0.1 | 354 → 547 | Batch | MOX | 17/20/24 | 55-85 |

[a]Zr, zirconium alloys; SS, stainless steel.
[b]Commonly used fuel.
[c]Heat transfer coefficients are approximate values, shown just for reference purposes.
[d]CANDU®-reactor moderator has $P = \sim 0.1$ MPa at the top of calandria vessel and $T = \sim 70\,°C$. (CANDU®—Trademark of Atomic Energy of Canada Ltd. (AECL), used under license by Candu Energy, Inc., Member of the SNC-Lavalin Nuclear Group).
[e]Concrete PV.
[f]AGRs were designed to be refueled on-line. However, it was found that during refueling at full power fuel assemblies can vibrate, due to that on-line refueling was suspended from 1988 till the mid-1990 s. Nowadays, only refueling at part load or in shut-down state is now undertaken at AGRs.

Table 9 Basic parameters of all current reactors' types power cycles (Part 2) (based on data from Ref. [3]). (For more details, see Ref. [3])

| No. | Reactor type | Cycle[a] | No of loops | Primary-steam: $P_{in}$, MPa | Primary-steam: $T_{in}$, °C | Primary-steam: Steam | Secondary-steam reheat: $P_{in}$, MPa | Secondary-steam reheat: $T_{in}$, °C | Secondary-steam reheat: Steam | Thermal efficiencies (gross), % |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | PWR | Indirect | 2 | 7.72 | 295.2 | Saturated | 2 | 265 | Overheated | Up to 36-38 |
| | SMR KLT-40S | Indirect | 2 | 3.72 | 290 | Overheated | | N/A | | Up to 26 |
| **2** | BWR | Direct | 1 | 7.2 | 287.7 | Saturated | 1.7 | 258 | Overheated | Up to 34 |
| **3** | PHWR (CANDU®) | Indirect | 2 | 4.7 | 260.1 | Saturated | ~1.2 | 240 | Overheated | Up to 34 |
| **4** | AGR | Indirect | 2 | 17 | 560 | Superheated | 4 | 560 | Superheated | Up to 42 |
| **5** | LGR (RBMK) | Direct | 1 | 6.9 | 284.9 | Saturated | ~0.3 | ~263 | Overheated | Up to 34 |
| **6** | LMFBR (BN-800) | Indirect | 3[b] | 14.2 | 505 | Superheated | 2.5 | 505 | Superheated | Up to 40 |

Rankine-cycle parameters.

[a]All current reactors connected to Rankine steam cycle (light-water working fluid).
[b]BN-800 has 3 loops: (1) liquid sodium circulating inside reactor; (2) intermediate loop with liquid sodium; and (3) water-steam in Rankine cycle.
Note: In addition, see Table 10 and Fig. 3.

the current over supply of U.S. and global natural gas and the continuing concomitant and significant reduction in price since 2017.

By comparison, the present average generating cost for the existing and mainly full-amortized NPPs in 2019 in the USA was stated as 3.2 ¢/kWh with a capacity factor of just over 92%.[9] The data imply a significant new build cost disadvantage and that going forward "the main problem with the nuclear option is that it is not economically viable".[10]

The significant range of build schedules (being from first concrete to demonstration power run) and in estimated LUEC show the vital importance of effective project management and of avoiding delays and overruns. One potentially important observation is the reduced construction schedule and costs achieved for the last of the UAE Barakah $4 \times 1400\,MW_{el}$ multiple-build units, illustrating the impact of repetitive production and the agreement with learning theory shown in Fig. 4 [14]. The example $\sim 1000^{+}$-$MW_{el}$ units now building in China show a similarly shortened schedule and reduced cost compared to ongoing large single unit projects in the USA, UK, and Europe. More details on the Levelized cost of energy can be found in the LAZARD'S Levelized Cost of Energy Analysis [15].

## 4 Small-/Medium-Size and Modular Reactors

Before a general discussion on small-/medium-size and modular reactors, which are currently go under a single acronym—SMRs, we have to separate these two groups of reactors, because they are not the same. Therefore, new acronym(s) should be introduced:

(1) Small modular reactors, i.e., modular-type reactors with installed capacities $\leq 300\,MW_{el}$, with claimed features of "modularity" in design, production, and/or construction. Currently, only two SMRs: Russian PWRs—KLT-40S; are in operation as a floating NPP. Also, a new acronym started to be used—advanced modular reactors, i.e., reactors based on some new or so far not deployed technology or concept, but having similar claimed features of "modularity" in design, production, and/or construction as SMRs.
(2) Small- and medium-size reactors, which have installed capacities $\leq 300\,MW_{el}$ (in total 27 reactors in the world, for details see Table 7) and 300–700 $MW_{el}$ (in total 85 reactors), respectively, many with claimed features of "modularity" in design, production, and/or construction.

[8]http://www.okbm.nnov.ru/upload/iblock/525/525fc6c42d8d70f418de75555d609a23.pdf
[9]https://www.nei.org/CorporateSite/media/filefolder/resources/fact-sheets/nuclear-by-the-numbers.pdf
[10]https://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx

**Table 10 Typical ranges of thermal efficiencies (gross) of modern thermal and nuclear power plants [2,3][8]**

| No. | Power plant | Gross thermal efficiency |
|---|---|---|
| 1 | Combined-cycle power plant (combination of Brayton gas-turbine cycle (fuel—natural gas or LNG; combustion-products parameters at gas-turbine inlet: $P_{in} \approx 2.5$ MPa, $T_{in} \approx 1650\,°C$) and Rankine steam-turbine cycle (steam parameters at turbine inlet: $P_{in} \approx 12.5$ MPa ($T_{sat} = 327.8\,°C$), $T_{in} \approx 620\,°C$ ($T_{cr} = 374\,°C$)) | Up to 62% |
| 2 | Supercritical-pressure coal-fired power plant (Rankine-cycle steam inlet turbine parameters: $P_{in} \approx 23.5$–38 MPa ($P_{cr} = 22.064$ MPa), $T_{in} \approx 540$-$625\,°C$ ($T_{cr} = 374\,°C$); and $P_{reheat} \approx 4$-6 MPa, $T_{reheat} \approx 540$-$625\,°C$) | Up to 55% |
| 3 | Internal-combustion-engine generators (diesel cycle and Otto cycle with natural gas as fuel) | Up to 50% |
| 4 | Subcritical-pressure coal-fired power plant (older plants; Rankine-cycle steam: $P_{in} = 17$ MPa ($T_{sat} = 352.3\,°C$), $T_{in} = 540\,°C$ ($T_{cr} = 374\,°C$); and $P_{reheat} \approx 3$-5 MPa, $T_{reheat} = 540\,°C$) | Up to 43% |
| 5 | Carbon-dioxide-cooled reactor (AGR) NPP (generation-III) (reactor coolant: $P = 4$ MPa, $T = 290$–$650\,°C$; and steam: $P_{in} = 17$ MPa ($T_{sat} = 352.3\,°C$) and $T_{in} = 560\,°C$ ($T_{cr} = 374\,°C$); and $P_{reheat} \approx 4$ MPa, $T_{reheat} = 560\,°C$) | Up to 42% |
| 6 | Sodium-cooled fast reactor (SFR) (BN-600 & BN-800) NPP (steam: $P_{in} = 14.2$ MPa ($T_{sat} = 337.8\,°C$), $T_{in} = 505\,°C$ ($T_{cr} = 374\,°C$); and $P_{reheat} \approx 2.5$ MPa, $T_{reheat} = 505\,°C$) | Up to 40% |
| 7 | PWR NPP (Generation-III$^{+}$) (reactor coolant: $P = 15.5$ MPa ($T_{sat} = 344.8\,°C$), $T_{out} = 327\,°C$; steam: $P_{in} = 7.8$ MPa, $T_{in} = T_{sat} = 293.3\,°C$; and $P_{reheat} \approx 2$ MPa ($T_{sat} = 212.4\,°C$), $T_{reheat} \approx 265\,°C$) (for details, see Fig. 3) | Up to 36-38% |
| 8 | PWR NPP (Generation-III, current fleet) (reactor coolant: $P = 15.5$ MPa ($T_{sat} = 344.8\,°C$), $T = 292$–$329\,°C$; steam: $P_{in} = 6.9$ MPa, $T_{in} = T_{sat} = 284.9\,°C$; and $P_{reheat} \approx 1.5$ MPa ($T_{sat} = 198.3\,°C$), $T_{reheat} \approx 255\,°C$) (for details, see Fig. 3) | Up to 34-36% |
| 9 | BWR NPP (Generation-III, current fleet) (reactor coolant: $P = 7.2$ MPa, $T_{out} = T_{sat} = 287.7\,°C$; steam: $P = 7.2$ MPa, $T_{in} = T_{sat} = 287.7\,°C$ and $P_{reheat} \approx 1.7$ MPa ($T_{sat} = 204.3\,°C$), $T_{reheat} \approx 258\,°C$) (for details, see Fig. 3) | Up to 34% |
| 10 | PHWR NPP (Generation-III, CANDU®-6, current fleet) (reactor coolant: $P_{in} = 11$ MPa/ $P_{out} = 9.9$ MPa ($T_{sat} = 310.3\,°C$) and $T = 260$–$310\,°C$; steam: $P_{in} = 4.7$ MPa, $T_{in} = T_{sat} = 260.1\,°C$; and $P_{reheat} \approx 1.2$ MPa ($T_{sat} = 188.0\,°C$), $T_{reheat} \approx 240\,°C$) | Up to 32% (34%[a]) |
| 11 | PWR SMR NPP (RITM-200M, Russia) (Generation-III$^{+}$) (not yet in operation as an SMR NPP) (reactor coolant: $P = 15.7$ MPa ($T_{sat} = 345.8\,°C$), $T = 277$–$313\,°C$; steam: $P_{in} = 3.82$ MPa, $T_{in} = 295\,°C$ ($T_{sat} = 247.6\,°C$) (for details, see Fig. 10) | Up to ~31% |
| 12 | PWR SMR NPP (KLT-40S, Russia) (Generation-III, current fleet) (reactor coolant: $P = 12.7$ MPa ($T_{sat} = 329.0\,°C$), $T = 280$–$316\,°C$; steam: $P_{in} = 3.72$ MPa, $T_{in} = 290\,°C$ ($T_{sat} = 246.1\,°C$) (for details, see Fig. 9) | Up to ~26% |

[a]Darlington NPP with four 878 $MW_{el\ net}$ reactors has gross thermal efficiency of 34.4% (net 32.3%), which is the highest one for CANDU®-reactors NPPs. Reactor coolant: $P_{in} = 11$ MPa/$P_{out} = 9.9$ MPa ($T_{sat} = 310.3\,°C$ ) and $T = 267$–$310\,°C$ ; steam: $P_{in} = 5.0$ MPa, $T_{in} = T_{sat} = 263.9\,°C$; and *preheat* $\approx 1.3$ MPa ($T_{sat} = 191.6\,°C$ ), $T_{reheat} \approx 245\,°C$ (steam-reheat parameters were estimated).

In this case, we must also define what is meant or implied by the widespread use of the terms "module," "modular design," and "modular construction." As adopted in building, modular design, and construction usually refers simply to the use of off-site prefabricated construction and the on-site assembly of multiple (identical or duplicate module) sections (or part submodules) including for different functions and uses. Since there is no restraint on the definition, degree, extent, or type of what constitutes a modular "module" (it could be the entire reactor core, the entire reactor, or the entire unit, or any such subunits), we have *not* distinguished between the differing SMR nomenclatures or claims. Therefore, to avoid any misunderstanding and ambiguity, it is proposed to use the following acronym—S&MRs. Currently, we have a relatively large number of S&MRs in operation in the world (in total 112). One exception is two KLT-40S actual SMRs installed on the floating NPP Akademik (Academician) Lomonosov. Also, it should be noted that actual SMRs can be included into S&MRs, but many S&MRs are not actual modular reactors.

The overarching requirements and objectives for any and all new nuclear reactors of any and all sizes are as the following [16]:

- safer than previous "generations";
- low financial risk exposure and capital cost;
- ease and speed of build;
- readily licensable—anywhere, anytime;
- simple to operate and secure;
- assured fuel supply and sustainability;
- providing social value and acceptance, and, of course;
- still be competitive.

We have examined the status of SMRs/S&MRs, which are today a very "hot" topic in nuclear engineering worldwide [2,3,17][11,12] and many variants exist in a plethora of potential design concepts using a wide variety of coolants, fuels, and core physics. According to the IAEA ARIS (Advanced Reactors Information System) data [16],[11] there are about 72 reactor designs/concepts, which can be classified as: (1) water-cooled reactors (land based)—24 (see Table 13); (2) water-cooled reactors (marine based)—6 (see Table 14); (3) high-temperature gas-cooled reactors—12 (see Table 15); (4) fast-neutron-spectrum reactors—17 (see Table 16); (5) molten-salt reactors—11 (see Table 17); and (6) other reactors—2 (see Table 18). However, an additional number of SMRs/S&MRs (in total 27) was added into Tables 13–18 from other sources. Below Table 18 SMRs and S&MRs are listed just by numbers per each country, which develops these reactors.

[11]https://aris.iaea.org/sites/overview.html

[12]http://www.okbm.nnov.ru/upload/iblock/456/45621ca6723f2345078c93b06b36c7e2.pdf

Table 11 **Current activities worldwide on new nuclear-power-reactors build (based on data from Ref. [8])**

| No. | Country/nuclear vendor | Countries, which are looking forward for new builds (no. of possible units) |
|---|---|---|
| **1** | China/various vendors (nuclear-power activities are supported by the Chinese government) | China (6 + 9?[a]), Pakistan (3?), Romania[b] (2? CANDU® reactors)<br>In total: 6 + 14? |
| **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 (3 + 2?), Bangladesh (2), Belarus (2), China (4), Egypt (4?), Finland (1), Hungary (2?), India (4), Iran (2), and Turkey (4)<br>In total: 22 + 8? |
| **3** | South Korea/Doosan and Kepco | South Korea (4) and UAE (4)<br>In total: 8 |
| **4** | India/various vendors | India (6 PHWRs)<br>In total: 6 |
| **5** | France/Framatome | Finland (1), France (1?), and UK (2)<br>In total: 3 + 1? |
| **6** | USA/GE and Westinghouse | Taiwan (2?), and USA (2),<br>In total: 2 + 2? |
| **7** | Czech Republic/Skoda | Slovakia (2?), Ukraine (2?)<br>In total: 4? |
| **8** | Japan/Toshiba + Hitachi | Japan (1 + 1?)<br>In total: 1 + 1? |
| **9** | Canada/AECL (Candu Energy, Inc.) together with CGNPC (China) | Romania[2] (2? CANDU® reactors)<br>In total: 2? |
| **10** | Germany/KWU (KraftWerk Union AG) | Brazil (1?)<br>In total: 1? |
| **11** | Argentina/CNEA (Comisión Nacional de Energía Atómica) | Argentina (1?)<br>In total: 1? |

[a]?—Means "Commercial start date—indefinitely" (Nuclear News, 2020 [8]).
[b]Two CANDU® reactors in Romania for the Cernavoda NPP are a joint venture proposal between China and Canada.

Table 12 **Current build comparative published or estimated costs at 12% (WACC + ROI) if not stated (1€ = US $1.12; 90% capacity factor; nuclear plant life 60 years; CCGT and ship 30 years)**

| $MW_{el}$ country/reactor TYPE | Capital (M$) | Overnight ($/kW) | LUEC (¢/kWh) | Investment (M$) | Schedule (months) | Sources |
|---|---|---|---|---|---|---|
| 1700 UK/EPR | 10,000 | 5900 | 12.5 | 13,300 | 72 | a,b |
| 1100 US/PWR | 3850 | 2750 | 5.4 | 4300 | 123 | c |
| 1100 US/PWR | 12,000 | 10,000 | 15.3 | 13,300 | 123 | d |
| 2 × 1000 Russia/VVER (PWR) | 8500 | 4250 | 9.2 | 11,200 | 69 | e |
| 700 China/PWR | 2000 | 2700 | 7.4 | 2600 | 69 | f |
| 4 × 1400 UAE/PWR | 7500 | 5400 | 9.9 | 8300 | 48 | g |
| 1400 UAE/PWR (7%) | 4000 | 2300 | 5.2 | 4400 | 48 | h |
| 12 × 60 SMR US | 2150 | 3000 | 5.5 | 2240 | 36 | i |
| 1000 China/PWR (Yangjiang) | 3100 | 3417 | 6.3 | 3436 | 66 | j |
| 1000 China/PWR (Xudabao) (7%) | 1650 | 1650 | 3.8 | 1800 | 48 | k |
| 2 × 35 Russia/ SMR (KLT-40S) | 10,000 | 10,600 | 24 | 770 | 48 | l |
| 350 CCGT US | – | 890 | 4.2 | 992 | 36 | m |
| Hydro US | – | – | 3.8 | — | — | i |
| 350 CCGT EU | – | – | 7.4 | — | — | n |

[a]https://world-nuclear-news.org/Articles/EDF-ratings-downgraded,-UK-arm-clarifies-Hinkley-c
[b]https://www.world-nuclear-news.org/Articles/Hinkley-gets-one-answer-but-more-questions
[c]https://dms.psc.sc.gov/Attachments/Order/9aaf3291-dd3a-4ac6-a4db-adda60c21158
[d]www.powermag.com/georgia-psc-backs-additional-costs-for-vogtle-nuclear-project
[e]https://op.europa.eu/en/publication-detail/-/publication/f9665d94-7c64-11e9-9f05-01aa75ed71a1/language-en/format-HTML/source-105828394
[f]https://www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report
[g]http://nuclearrc.sa.gov.au/app/uploads/2016/05/WSP-Parsons-Brinckerhoff-Report.pdf
[h]https://d2umxnkyjne36n.cloudfront.net/documents/D7.3-ETI-Nuclear-Cost-Drivers-Summary-Report_April-20.pdf
[i]https://www.postregister.com/news/government/idaho-falls-power-nuscale-reps-outline-reactor-project/article_8782c25a-f1ef-55e6-ba50-77d6ba30118d.html
[j]https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
[k]https://www.world-nuclear-news.org/NN-Contract-for-nuclear-islands-of-Xudabao-Phase-I-1410164.html
[l]https://wiseinternational.org/nuclear-monitor/872-873/smr-cost-estimates-and-costs-smrs-under-construction
[m]https://www.pjm.com/~/media/committees-groups/committees/mic/20180425-special/20180425-pjm-2018-cost-of-new-entry-study.ashx
[n]https://ec.europa.eu/transparency/regdoc/rep/10102/2019/EN/SWD-2019-1-F1-EN-MAIN-PART-1.PDF

Table 13 Land-based water-cooled SMRs and S&MRs (31 in total) (based on data from Refs. [3], [16], and [17])

| Country | Design | Output $MW_{el/th}$ = Th.Eff. (%) | Type | Designers | Phase | Fuel enrich./cycle (yr) | Fuel type |
|---|---|---|---|---|---|---|---|
| Argentina | CAREM | 30/100 = 30 | PWR | CNEA | Construction | 3.1%/1.2 | $UO_2$ |
| Brazil | FBNR | 70/134 = 52.2 | PWR | Fed. University of Rio Grande do Sul | Conceptual | N/A/N/A | TRISO |
| Canada | SSR | 300/667 = 45 | SCWR[a] | AECL | Conceptual | Enriched | U or Th |
| China (1) | ACP100 | 125/385 = 33 | PWR | CNNC | Basic | <5%/2 | $UO_2$ |
| China (2) | DHR400 | -/400 = N/A | LWR | CNNC | Basic | <5.0%/0.8 | $UO_2$ |
| China (3) | CAP200 | >200/600 = >30 | PWR | CGNPC | Conceptual | 4.2%/2 | $UO_2$ |
| China (4) | CNP-300 | 300-340/1000 = 30-34 | PWR | CNNC | Operational in China/Pakistan | <5%/1.25 | $UO_2$ |
| China (5) | SNP350 | 350/1035 = 33.8 | PWR | SNERDI | Conceptual | <5%/N/A | $UO_2$ |
| China (6) | NHR-200II | –/200 = N/A | PWR | INET | Final | <5%/N/A | $UO_2$ |
| China (7) | HAPPY200 | –/200 = N/A | PWR | SPIC | Final | N/A/N/A | N/A/N/A |
| # of Countries | IRIS | 335/1000 = 34 | PWR | IRIS Consortium | Conceptual | 5%/4 | $UO_2$/MOX |
| France | NUWARD | 300-400/- = N/A | PWR | CEA, EDF, Naval Gr., TechnicAtome | Preliminary | N/A/N/A | N/A |
| India (1) | AHWR-300-LEU | 304/920 = 33 | LHR (HWR) | BARC | Conceptual | <5% (MOX)/Cont. | Th–U or Th–Pu, MOX |
| India (2) | PHWR-220 | 235/755 = 31.2 | PHWR | NPCI Ltd. | 16 Units Operational | <5%/Cont. | $UO_2$ |
| Japan (1) | DMS | 300/840 = 36 | BWR | Hitachi-GE | Basic | <5%/2 | $UO_2$ |
| Japan (2) | IMR | 350/1000 = 35 | PWR | MHI | Conceptual | 4.8%/2.2 | $UO_2$ |
| Japan (3) | CCR | 423/1268 = 33.4 | BWR | Toshiba Corp. | Conceptual | N/A/2 | N/A |
| Japan (4) | MRX | 33.3/100 = 33.3 | PWR | JAERI | Final | 4.3%/3.5 | $UO_2$ |
| Korea S. | SMART | 100/330 = 30 | PWR | KAERI | Certified | <5%/3 | $UO_2$ |
| Russia (1) | ELENA | 0.068/3.3 = 2 | PWR | Kurchatov Institute | Conceptual | 15.2%/25 | $UO_2$ (MOX) |
| Russia (2) | UNITHERM | 6.6/30 = 22 | PWR | NIKIET | Conceptual | 19.8%/16.7 | $UO_2$ |
| Russia (3) | RUTA-70 | –/70 = N/A | PWR | NIKIET | Conceptual | 3%/3 | Cermet |
| Russia (4) | KARAT-45 | 45–50/180 = 25-28 | BWR | NIKIET | Conceptual | 4.5%/7 | $UO_2$ |
| Russia (4) | KARAT-100 | 100/360 = 28 | BWR | NIKIET | Conceptual | 4%/7.5 | $UO_2$ |
| Russia (5) | VK-300 | 250/750 = 33 | BWR | NIKIET | Final | 4%/6 | $UO_2$ |
| UK | UK-SMR | 443/1276 = 26 | PWR | Rolls-Royce | Final | <5%/1.5-2 | $UO_2$ |
| USA (1) | NuScale | 50/160 = 31 | PWR | NuScale Power | Preliminary | <5%/2 | $UO_2$ |
| USA (2) | SMR-160 | 160/525 = 31 | PWR | Holtec Int. | Preliminary | 5%/1.5-2 | $UO_2$ |
| USA (3) | mPower | 195/575 = 34 | PWR | BWX Techn. | Developmental | <5%/2 | $UO_2$ |
| USA (4) | W-SMR | >225/800 = >28 | PWR | Westinghouse | Conceptual | <5%/2 | $UO_2$ |
| USA (5) | BWRX-300 | 300/– = N/A | BWR | GE-Hitachi | Final | 3.4-4.95%/N/A | $UO_2$ |

[a]Generation-IV concept.

Much design data are considered or labeled "proprietary," and hence, not in the public domain. For the all-important status of the designs we must rely here on published statements and claims, which are subject to some interpretation. We classify according to the typical phases in the normal design and development evolution process, which assists in characterizing the relative "maturity" or potential technical "feasibility," recognizing that some may have had prior development, some may have a pause or hiatus between phases, and not all aspects in a phase may be at the same stage at the same time. We do not pass judgment regarding the viability, development potential, and probability of demonstration success of these alternatives, which will be ultimately determined in and by the evolving national and international marketplaces and any related enabling governmental policies.

Also, the phases may not be totally distinct in that they continually merge, transition, and may overlap as the design progresses. A priori we do not know if all developers even use the same terminology, so here we, at least, attempt to standardize and define the status as far as possible to allow or enable intercomparison.

In addition, the degree and extent of independent reviews, safety and risk-analysis requirements, and the national licensing process will vary. The terminology and status may vary according to whether the design is in the commercial or

Table 14 Marine-based water-cooled SMRs and S&MRs (seven in total) (based on data from Refs. [3], [16], and [17])

| Country | Design | Output $MW_{el/th}$ = Th.Eff., % | Type | Designers | Phase | Fuel enrich. /cycle (yr) | Fuel type |
|---|---|---|---|---|---|---|---|
| China | ACPR50S | 50/200 = 25 | PWR | CGNPC | Preliminary | <5%/2.5 | $UO_2$ |
| France | Flexblue | 160/600 = 26.7 | PWR | DCNS | Preliminary | <5%/3 | $UO_2$ |
| Russia (1) | SHELF | 6.6/28.4 = 23 | Immersed NPP | NIKIET | Preliminary | 19.7%/6 | $UO_2$ |
| Russia (2) | ABV-6E | 6-9/38 = 16-24 | Floating PWR | OKBM Afrikantov | Final | <20%/10-12 | $UO_2$ |
| Russia (3) | KLT-40S | 35/150 = 23 | Floating PWR | OKBM Afrikantov | Operating | 18.6%/2.5-3 | $UO_2$ |
| Russia (4) | RITM-200M | 50/175 = 29 | Floating PWR | OKBM Afrikantov | Manufactured | <20%/10 | $UO_2$ |
| Russia (5) | VBER-300 | 325/917 = 35 | Floating NPP | OKBM Afrikantov | Licensing | 4.95%/6 | $UO_2$ |

Table 15 High-temperature gas-cooled SMRs and S&MRs (18 in total) (Generation-IV concepts) (based on data from Refs. [3], [16], and [17])

| Country | Design | Output $MW_{el/th}$ = Th.Eff. (%) | Designers | Phase | Fuel enrichment/ cycle (yr) | Fuel type |
|---|---|---|---|---|---|---|
| Africa S. (1) | HTMR-100 | 35/100 = 35 | Steenkampskraal Thorium Ltd. | Conceptual | 10–93%/Online refueling | LEU, Th/LEU, Th/HEU, Th/Pu |
| Africa S. (2) | A-HTR-100 | 50/100 = 50 | Eskom Holdings SOC Ltd. | Conceptual | LEU or WPu/N/A | CPF |
| Africa S. (3) | PBMR-400 | 165/400 = 41.3 | PBMR SOC Ltd. | Preliminary | 9.6% LEU or WPu/N/A | CPF |
| Africa S. (4) | PBMR-100 | 100/250 = 40 | PBMR SOC Ltd. | Preliminary | N/A/Online | TRISO-coated $UP_2$ |
| Canada | Starcore SMR | 20/36 = 55.6 | Starcore | Preliminary | N/A/5 | TRISO |
| China | HTR-PM | 210/2 × 250 = 42 | INET, Tsinghua University | Construction | 8.5%/on-line refueling | Spherical El. with CPF |
| France (1) | Allegro | –/50-100 = N/A | CEA | Conceptual | N/A/N/A | MOX |
| France (2) | ANTARES | –/≥600 = N/A | AREVA | Conceptual | N/A/N/A | N/A |
| Japan | GTHTR300 | 100–300/ <600 = >17–50 | JAEA | Basic | 14%/4 | $UO_2$ |
| Russia (1) | MHR-100 | 25–87/215 = 12–41 | OKBM Afrikantov | Conceptual | LEU<20%/N/A | CPF |
| Russia (2) | GT-MHR | 288/600 = 48 | OKBM Afrikantov | Preliminary | LEU or WPu/2.08 | CPF |
| Russia (3) | MHR-T | 4 × 206/4 × 600 = 34 | OKBM Afrikantov | Conceptual | 20%/2.5 | CPF |
| UK | U-Battery | 4/10 = 40 | URENCO | Preliminary | 17-20%/5 | TRISO |
| USA (1) | Xe-100 | 75/200 = 37.5 | X-energy LLC | Conceptual | 15.5%/online refueling | UCO TRISO |
| USA (2) | SC-HTGR | 272/625 = 43.5 | FRAMATOME, Inc. | Conceptual | <20%/$^1/_2$ core replaced every 1.5 years | UCO TRISO particle fuel |
| USA (3) | Prismatic HTR | 150/350 = 42.8 | General Atomics | Developmental | 15.5%/1.5 | TRISO-coated UCO |
| USA (4) | MMR | 5/15 = 33.3 | USNC | Preliminary | N/A/Never | FCM |
| USA (5) | HOLOS | 3–13/22 = 13.6-59.0 | HolosGen | Preliminary | 15%/3.5-8 | TRISO |

governmental domain, or directly or indirectly subsidized, and whether the schedule and/or demonstration cost is known or even revealed.

The actual timing of the phases may also vary according to the market conditions, funding revenue, budget and incurred expenses, and R&D and licensing schedules.

**Preconceptual**

- Basic ideas, sketches, preliminary or scoping calculations, and possible parameter ranges, free-wheeling options in performance and costs, continual changes, objective evolution, evaluation of acceptable items or targets, competitive analyses, concept scrubbing.

**Conceptual**

- Firm outline, optional layouts, R&D needs, design "cartoons," range limits, performance goals and design targets set, initial physics and safety feasibility, economic and size requirements established, "show stoppers" identified, outline costing, project scope defined.

**Basic**

- Main layout, thermal limits and fuel requirements, commercial risk assessment, safety argument defined, R&D program initiated, initial CAD/CAE diagrams, system requirements specified, plant performance, and safety-analysis models, initial investment secured, documentation underway, initial independent reviews undertaken, preliminary business case made.

**Developmental**

- Design and layout in computer or CAD/CAE format, physics and core design semi-complete, engineering analyses underway, scoping costing, potential project schedule, safety analysis underway, confirmatory R&D in progress, performance and safety margins defined, fuel cycle and components definition, and refining of design optimization(s), commitments to proceed, milestones established.

**Preliminary**

- Transition to formal project management, design review, uncertainties defined, layout fixed, formal change control initiated, reference parameters established, costing reevaluated, fuel cycle, physics and thermal performance optimized, design changes subject to controls, R&D results incorporated, BOP and systems layout fixed, modules and manufacturing defined, supply chain established, bid estimate uncertainties defined, formal licensing basis established, desired build schedule established, project management structure and business controls, external independent review(s).

**Final/Certified**

- "Frozen" design, final safety analyses completed, R&D finished, engineering work nearly complete, final documentation of design, licensing basis, and/or "certification" review underway, commercial contracts and suppliers in place, systems for QA/QC/change controls, all major construction tasks and sequence established and proven, advanced or

Table 16 Fast-neutron-spectrum SMRs and S&MRs (25 in total) (Generation-IV concepts) (based on data from Refs. [3], [16], and [17])

| Country | Design | Output $MW_{el/th} = Th.Eff.$ (%) | Type | Designers | Phase | Fuel enrichment/ cycle (yr) | Fuel type |
|---|---|---|---|---|---|---|---|
| China | CFR-600 | 600/1500 = 40 | SFR | CIAE | Construction | N/A/N/A | $UO_2$/MOX |
| France | ASTRID | 600/1500 = 40 | SFR | CEA | Preliminary | N/A/N/A | MOX |
| Italy (1) | ALFRED | 125/300 = 41.7 | LFR | Ansaldo | Preliminary | N/A/5 | MOX |
| Italy / EU (2) | ELFR | 630/1500 = 42 | LFR | Ansaldo | Conceptual | N/A/2.5 | MOX |
| Japan (1) | 4S | 10/30 = 33 | SFR | Toshiba Corp. | Developmental | <20%/N/A | MF (U–Zr) |
| Japan (2) | LSPR | 53/150 = 35.3 | LMFR | Tokyo Tech. | Developmental | 10–12.5%/12 | U–Pu–N/U–Pu–Zr |
| Japan (3) | PBWFR-150 | 150/450 = 33.3 | LMFR | Tokyo Tech. | Developmental | N/A/10 | U–Pu nitride |
| Japan (4) | Rapid-L | 0.2/5 = 4 | LMFR | CRIEPI | Operating | 40%/10 | UN |
| Korea S. (1) | KALIMER-600 | 600/1523.4 = 39.4 | SFR | KAERI | Preliminary | N/A/1 | U–TRU–Zr |
| Korea S. (2) | PGSFR | 150/400 = 37.5 | SFR | KAERI | Preliminary | N/A/~1 | U–TRU–Zr |
| Korea S. (3) | PEACER | 300/850 = 35 | LMFR | Seoul Nat. Univ. | Conceptual | N/A/1 | U–TRU–Zr |
| Luxembourg (1) | LFR-TL-X | 5/15 = 33 10/30 = 33 20/60 = 33 | LFR | Hydromine Nuclear Energy | Conceptual | 19.8%/≥8.33 | LEU |
| Luxembourg (2) | LFR-AS-200 | 200/480 = 42 | LFR | Hydromine Nuclear Energy | Preliminary | 14.6–20.4–23.2% in Pu/6.7 years for 5 batches | MOX |
| Russia (1) | SVBR-100 | 100/280 = 37 | LFR | JSC AKME Engineering | Final | <19.3%/ 0.58–0.67 | $UO_2$ |
| Russia (2) | BREST-OD-300 | 300/700 = 43 | LFR | NIKIET (RDIPE) | Final | 13.5%/2.46–4.1 | Mixed U–Pu–N |
| Sweden | SEALER | 3/8 = 38 | Lead cooled | LeadCold | Conceptual | 19.75%/27 full power years | $UO_2$ |
| USA (1) | SUPERSTAR | 120/300 = 40 | LMFR | Argonne National Lab. | Conceptual | <12%/15 | Particulate-based U–Pu–Zr MF with weapons Pu |
| USA (2) | $EM^2$ | 265/500 = 53 | GMFR | General Atomics | Conceptual | 14.5% LEU/30 | UC |
| USA (3) | WLFR | >450(Net)/ 950 = >47 | LFR | Westinghouse | Conceptual | ≤19.75%/≥2 | Oxide |
| USA (4) | AFR-100 | 100/250 = 40 | SFR | Argonne National Lab. | Conceptual | 13.5%/N/A | U-Zr |
| USA (5) | ARC-100 | 100/260 = 38.5 | SFR | ARC | Final | N/A/20 | LEU |
| USA (6) | G4M (HYPERION) | 25/70 = 35.7 | LMFR | Gen4 Energy, Inc. | Conceptual | 19.75%/10 | UN |
| USA (7) | PRISM | 311/500 = 62 | SFR | GE-Hitachi | Preliminary | N/A/1.33 | U–Pu–Zr metal |
| USA (8) | ENHS | 50/125 = 40 | LMFR | UC Berkeley | Conceptual | 13% (U-Zr)/N/A | Pu–U/U–Zr |
| USA (9) | TWR-P | 600/1475 = 41% | SFR | TerraPower | Conceptual | N/A/1.5-2 | U–Zr10% MF |

long-lead components and manufacturing, interface agreements and integrated customer schedule in place, business model and financing established.

**Construction**

- Authorization to proceed, site preparation completed, project management assures product delivery, overall schedule and costs known, final work breakdown schedule, on-site work underway, prototype, FOAK or "demonstration" unit, manufacturing and component delivery in progress, interface agreements refined, building and system installation, staff training and assignments, licensing finalized or only subject to final review/verification, customer acceptance criteria, commissioning and operation planned, contingency refined.

It is evident from this still evolving listing that there are not only too many SMRs/S&MRs under development, but there are no accepted "acceptance criteria." Many of them are in the early stages, and there is a general lack of public data about many of the actual details of even the "final" designs. Therefore, sometimes it is not easy to separate SMRs from S&MRs, because at the final stages SMRs can be considered as S&MRs and vice versa. In reviewing the literature, the overall goals of safety, sustainability, competitiveness, and social acceptance are widely claimed, but not demonstrated. While there are many small 10–300 $MW_{el}$ units and power plants already in operation (see Table 7), there are just three new demonstration SMR units planned or actually underway:

(a) Carem, Argentina;
(b) HTR-PM, China; and
(c) CFR-600, China.

Modular-construction technology, per se, is not new, being widely used in oil rigs, military equipment, buildings, data centers, computers, and CCGT unit installations. For NPPs specifically, some of the many stated advantages of SMRs are that they offer the vision of:

(a) lowering total investment amounts and, hence, reduced project risks;
(b) providing the opportunity for mass-production in module "factories" thus reducing on-site costs and embody the "latest" manufacturing technology;
(c) potentially reduced construction times due to simpler or less design complexity;
(d) sharing expertise, facilities, and equipment at a multiple module site (e.g., staff, security, switchyard, operation and maintenance, etc.);
(e) adding power/units in stages as demand and market allow;
(f) "generic" licensing of some standard design; and
(g) applicability in smaller markets and remote deployment.

Table 17 Molten salt SMRs and S&MRs (14 in total) (Generation-IV concepts) (based on data from Refs. [3], [16], and [17])

| Country | Design | Output $MW_{el/th}$ = Th.Eff. (%) | Designers | Phase | Fuel enrichment/ cycle (yr) | Fuel type |
|---|---|---|---|---|---|---|
| Canada (1) | IMSR | 190/400 = 48 | Terrestrial Energy | Basic | <5%/7 years before core-unit replacement | MSF |
| China | TMSR-LF | 168/373 = 45 | SINAP | Conceptual | 19.75%/online | LiF–Be-$F_2$–$UF_4$–$ThF_4$, LiF-$BeF_2$–$PuF_3$–$ThF_4$ |
| Denmark (1) | CA Waste Burner | 20/50 = 40 | Copenhagen Atomics | Conceptual | N/A/N/A | LiF–$ThF_4$ |
| Denmark (2) | CMSR (MSTW) | 100–115/250 = 40-46 115/270 = 42.6 | Seaborg Technologies | Conceptual | Preprocessed SNF (U 1.1% fissile, Pu 69% fissile)/6 | Na–actinide fluoride (93% Th, 3.5% U, 3.5% Pu) |
| Int. Consortium | ThorCon | 250 (per module) / 557 = 45 | Martingale | Basic | 19.7%/8 | 12% HM in NaBe salt |
| Japan | FUJI | 200/450 = 44 | Int. Thorium Molten-Salt Forum | Pre conceptual | 2.0% Pu or LEU (continuous operation is possible) | MSF with Th & U |
| UK (1) | Stable Salt Reactor-Wasteburner | 300 (continuous as baseload)/750 = 40 | Moltex Energy | Conceptual | Reactor grade Pu/ 12.5 | MSF |
| UK (2) | Stable Salt Reactor—Th. Spectrum | 300 (baseload)/ 750 = 40 | Moltex Energy | Pre-Conceptual | 5%/2 | MSF |
| USA (1) & Canada (2) | MCSFR | 50/100 = 50 | Elysium Industries | Conceptual | 10–20%/online refueling | MSF |
| USA (2) | Mk1 PB-FHR | 100/236 = 42 | University of CA, Berkeley | Pre-Conceptual | 19.9%/2.1 months for fuel core residence time | TRISO particles |
| USA (3) | LFTR | 250/600 = 42 | Flibe Energy | Conceptual | N/A/continuous refueling | LiF–$BeF_2$–$UF_4$ |
| USA (4) | KP-FHR | 140/311 = 45 | Kairos Power | Pre-Licensing | 19.75%/online | TRISO particles |
| USA (5) | MCFR | N/A/N/A = N/A | TerraPower | Pre-Licensing | N/A/online | N/A |
| USA (6) | SmAHTR | 50/125 = 40 | Oak Ridge National Lab. | Conceptual | 19.75%/N/A | TRISO particles |

Building and operating smaller units is, of course, how the nuclear industry actually began and is not itself a novelty, and prior examples of standardization include the Standardized Nuclear Unit Power Plant System (SNUPPS) series of PWRs. 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 7). Moreover, some of them operate successfully for about 50 years, but, 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 ship's propulsion reactors. Therefore, many modern designs/concepts of SMRs are based on these achievements (see Tables 13 and 14). Also, it should be mentioned that a number of SMRs concepts are based on the six Generation-IV nuclear-power-reactor concepts (see Tables 13 (SSR by Canada), 14 (VEBR-300 by Russia), 15–17).

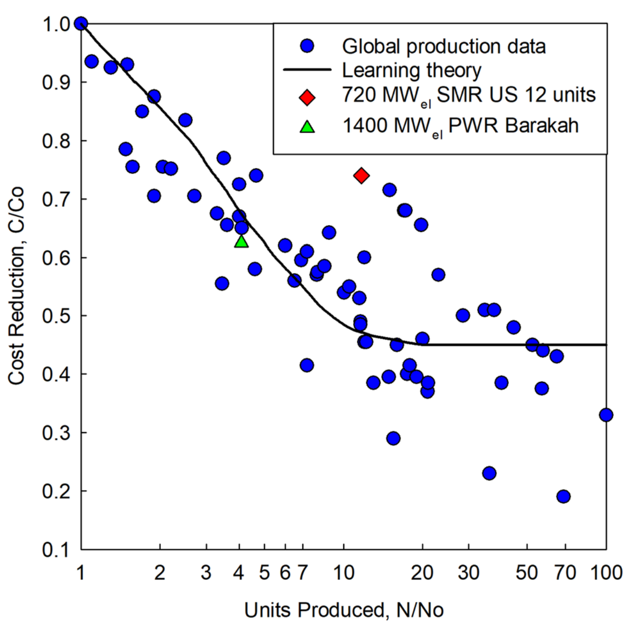



**Fig. 4 Updated cost reduction learning curve showing recent estimates and builds [14]**

Analysis of the data in Tables 13–18 shows that many SMRs usually require a higher level of fuel enrichment up to <20% (the maximum level for LEU limited by the IAEA) to operate with smaller amount of fuel and to have longer terms between refueling and, usually, lower NPP thermal efficiencies compared to those of large nuclear-power reactors NPPs of the same type (see Table 10 for RITM-200M and KLT-40S thermal efficiencies).

## 5 Russian KLT-40S and RITM-200M Small Modular Reactors

Russia is the first country in the world, which developed, designed, and put into operation two SMRs, and this success is not an accidental one, because 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).[8,12]

However, it should be mentioned that the idea to use a nuclear reactor as a floating NPP belongs to the USA.[13] The first in the world floating NPP was the 10-$MW_{el}$ MH-1A (Mobile High

[13]https://www.maritime-executive.com/article/floating-nuclear-plant-sturgis-dismantled

**Table 18 Other Types SMR (4 SMR) (based on data from Refs. [3], [16], and [17])**

| Country | Design | Output $MW_{el/th}$ = Th.Eff. (%) | Type | Designers | Phase | Fuel enrich./cycle (yr) | Fuel type |
|---|---|---|---|---|---|---|---|
| Canada | Leadir-PS100 | 36/100 = 36 | LMR | Northern Nuclear Industries | Conceptual | N/A/N/A | TRISO |
| Japan | MoveluX | N/A/10 = N/A | Heat Pipes | Toshiba | Preliminary | 4.99/N/A | LEU |
| USA (1) | Aurora | 1.5/N/A=N/A | Heat Pipes | Oklo | Preliminary | <20%/N/A | HALEU-U-Zr |
| USA (2) | eVinci | 0.2-15/0.6-40 = 33.3-37.5 | Heat Pipes | Westinghouse | Developmental | 19.5%/10 | $UO_2$ or UN |

Total number of SMRs and S&MRs by countries: S. Africa—4 HTGRs; Argentina—1 PWR; Brazil—1 PWR; Canada—5 (1 SCWR; 1 HTGR; 2 MSRs; 1 Other); China—11 (7 PWRs land-base; 1 PWR marine-based; 1 HTGR; 1 Fast Reactor; and 1 MSR); Denmark—2 MSRs; France—5 (2 PWRs; 2 HTGRs; and 1 SFR); India—2 (1 LHR, 1 PHWR); Italy—2 LFRs; Japan—11 (4 PWRs land-base; 1 HTGR; 4 fast reactors; 1 MSR; and 1 other type reactor); Luxemburg—2 LFRs; S. Korea—4 (1 PWR and 3 fast reactors); Russia—15 (5 PWRs land-base; 5 PWRs marine-based; 3 HTGRs; and 2 fast reactors); Sweden—1 LFR; UK—4 (PWR; HTGR; and 2 MSRs); USA—27 (5 PWRs land-base; 5 HTGRs; 9 fast reactors; 6 MSRs; and 2 other type reactors); International Consortiums—2 (PWR and MSR).

power) reactor (built in 1961) installed on the ship named "Sturgis" (built in 1945), which was towed to Panama Canal. The reactor has reached first criticality in 1967, and electricity was supplied from 1968 till 1975. The reactor has used LEU with enrichment from 4% to 7%. Containment vessel has weighted 350 tons. Also, similar projects have been developed in Germany and UK.

Figure 5 shows a schematic of KLT-40S reactor and its systems; Figure 6(*a*) photo of the reactor KLT-40S with four steam generators and reactor-coolant circulation pumps; Fig. 7—KLT-40S reactor-core cross section; Fig. 8—photo of the Floating Nuclear Thermal-Power Plant (FNThPP) with two KLT-40S reactors; and Table 19—main parameters of KLT–40S.

The barge with two KLT-40S SMRs was towed to port of Pevek, Russia's northernmost city in 2019, where it will gradually replace the Bilibino NPP (see Table 7) and the Chaunskaya combined heat and power plant, which are being retired. These two SMRs were connected to grid in December of 2019.

Moreover, Russia has developed and tested more advanced SMR—RITM-200M (see Fig. 6(*b*) and Table 19), which is an integral PWR of Generation-III+.[14,15]

Analysis of the data in Table 19 shows that KLT-40S and RITM-200M require LEU with enrichments of 18.6% and <20%, respectively, which are significantly higher than those in any modern light- or heavy-water reactors. Also, thermal efficiencies of these NPPs are lower than those of modern NPPs equipped with

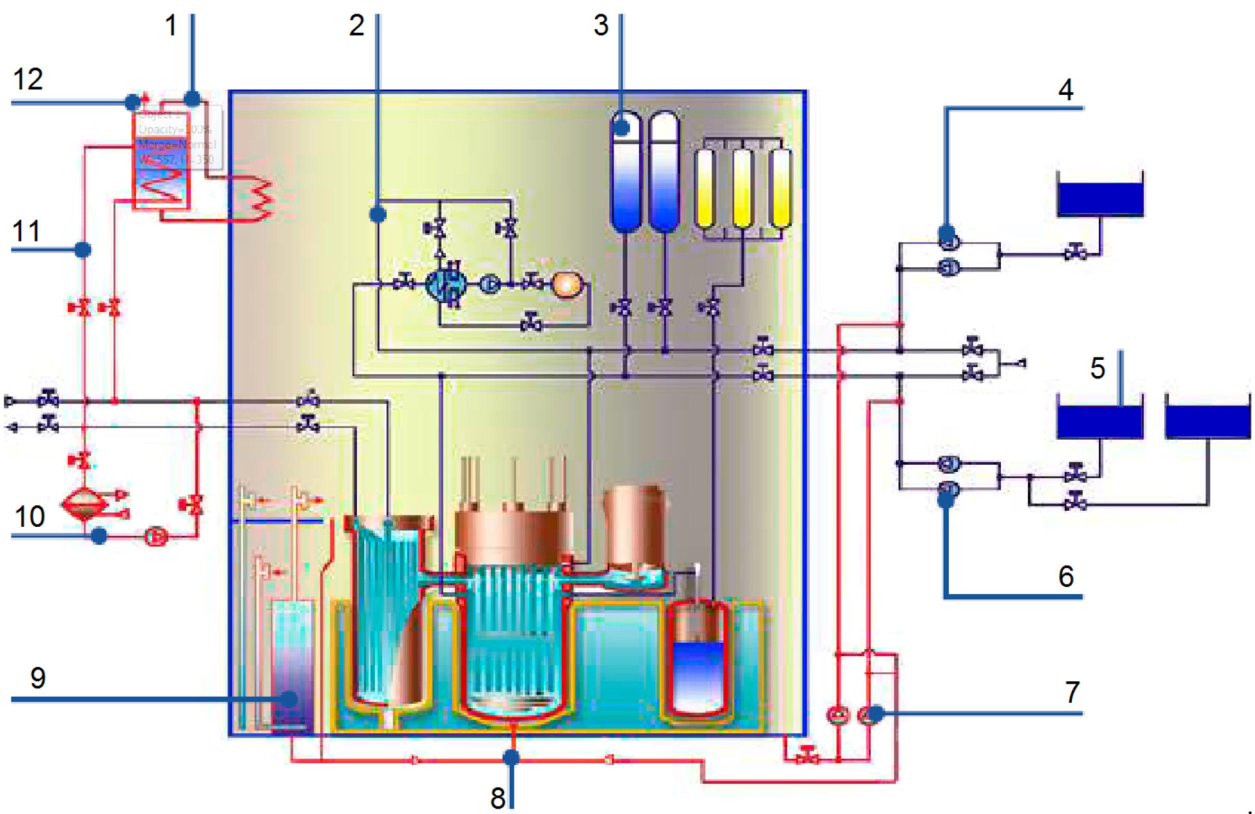
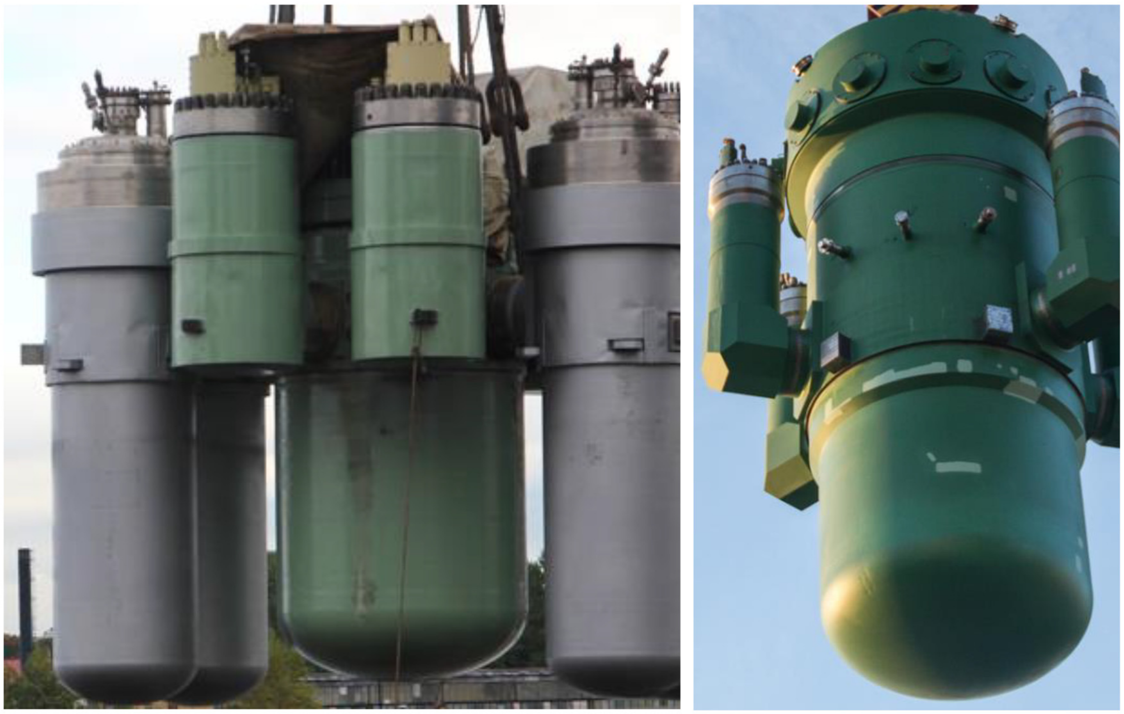



**Fig. 5 Schematic of KLT-40S reactor and its systems (based on original figures from AO OKBM by the name of I. I. Afrikantov, Brochures on KLT-40S [8,13] (in red—newly introduced safety systems): 1—passive system of containment emergency pressure decrease (condensing system); 2—active emergency cooling 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; and 12—to atmosphere.**



(a) (b)

**Fig. 6 Russian SMRs[8,12,14,15,16]: (*a*) KLT-40S (КЛТ-40С in Russian abbreviations) (in center) with four steam generators (larger cylinders) and four reactor-coolant circulation pumps (smaller cylinders) and (*b*) RITM-200M with steam generators integrated into pressure vessel (courtesy of ROSATOM)**

LWRs. Also, interesting fact is that both these SMRs NPPs have overheated steam at the outlet of steam generators compared to saturated steam at light- and heavy-water-cooled reactors NPPs. Also, based on the data from open literature, the Rankine power cycle does not have a reheat option, which is common for any other NPPs. In addition, it should be noted that development of these two SMRs took significantly longer time (13 yr) than it was expected from the beginning and original budget was overspent.

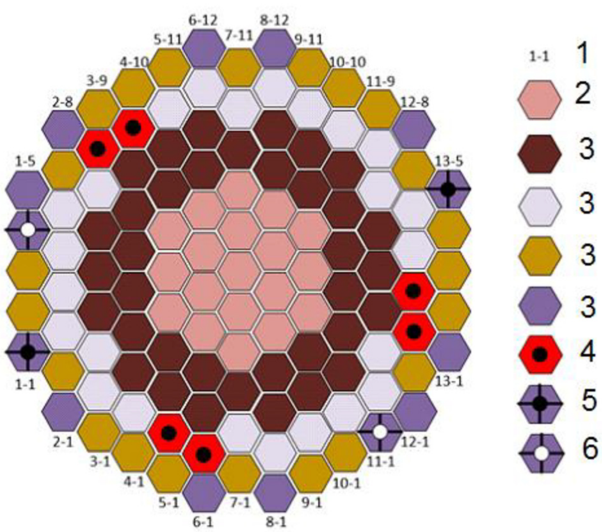



**Fig. 7 KLT-40S reactor-core cross section (prepared by UOIT student A. Khan; based on original figure from AO OKBM by the name of Afrikantov[8,13]): 1—cell number; 2—main assembly in central zone; 3—main assemblies; 4—assembly with emergency shut-down rod; 5—assembly for neutron-absorber location; and 6—assembly peripheral zone for location of extra sensors for neutron-flux control.**

Extra things, which should be known, are: (1) The KLT-40S reactors have been installed at the manufacturing plant and this operation has required a 300-ton crane; and (2) for operations inside the barge—a 40-ton crane just required.

## 6 Special Considerations on Small Modular Reactors and Future Development and Implementation

**6.1 Safety and Licensing Requirements.** The basic overarching and most important safety objective is to keep the reactor core cooled and the system controlled at all times [18,19]. Often confused, it is important to distinguish between:

(a) Improved safety and reduced risk in the sense of assuring event-free operation, "resilience" to unexpected happenings and challenges, market return on investment, reduced accident chances, and improved societal acceptance; for new builds, designs and concepts, it has been pointed out elsewhere that past safety-analysis practice and systems design really require updating and enhancement based on exploiting modern technological advances [20]; and

(b) traditional formal licensing processes and regulatory requirements, which are based on providing and issuing siting and operation permits, and focus on ensuring public safety based on accident frequency, activity release, and core damage estimates. The need to streamline or at least "harmonize" such past nationally different and cumbersome licensing processes is also being recognized, using a "risk-informed, performance-based, and technology-inclusive approach".[17]

[14]http://www.okbm.nnov.ru/upload/iblock/99a/99a99ac98bb4a29bc538d90b3d8be7dc.pdf

[15]http://www.okbm.nnov.ru/upload/iblock/75f/75f548d37f50a51cb99c338bf3122970.pdf

[16]https://www.flickr.com/photos/rosatom/albums/72157692330711570

[17]https://dailyenergyinsider.com/news/23528-nrc-proposes-new-rule-for-emergency-preparedness-for-reactors/


**Fig. 8 Photo of FNThPP (Плавающая Атомная Тепловая ЭлектроСтанция (ПАТЭС) (in Russian abbreviations)) on barge with two KLT-40S reactors on its way to port Pevek[17] (courtesy of ROSATOM, photo by A. Bashkirov). Barge: length—140 m; width—30 m; height of board—10 m; draft—5.6 m; displacement—$\sim$21,000 ton; underwater foundation pit in m—175 (*L*) × 45 (*W*) × 9 (*D*); operating term of FNThPP—40 years; number of servicing personal—$\sim$70; and construction term—4 years.**

In particular, it is not the responsibility of a regulator in any nation for actual plant operation, overall capacity factor, thermal efficiency, fuel-cycle sustainability, economic viability, project management, or energy market share. Obviously safe operation is vital, so is linked to safety "culture," reduced economic risks and public acceptance. Current data for actual severe reactor accidents (Three Mile Island, Chernobyl, and Fukushima) illustrate that the actual core damage frequency is higher than predicted by state-of-the-art probabilistic assessments, primarily due to the inadequate prevention against and control of extreme and unexpected events.

With multiple new concepts and many innovative designs, especially, those that claim long-term cooling due to natural

**Table 19 Main parameters of Russian SMRs: KLT-40S and RITM-200M[8,12,13,14,15]**

| Parameters | KLT–40S | RITM-200M |
|---|---|---|
| Reactor type | PWR | Integral PWR |
| Generation of SMRs | III | $III^+$ |
| Reactor coolant/moderator | Light water | |
| Thermal power ($MW_{th}$) | 150 | 175 |
| Electric power, gross/net ($MW_{el}$) | 38.5/35 | 55/50 |
| Thermal efficiency (%) | $\sim$26 | $\sim$31 |
| Expected capacity factor (%) | 60–70 | 65 |
| Maximum output thermal power, GJ/h (Gcal/h); MW | 305.6 (73); 84.9 | — |
| Production of desalinated water ($m^3$/day) | 40,000–100,000[a] | — |
| Operating range of power (%) | 10–100 | — |
| Normal-mode power variation (%/s) | 0.1 | — |
| Primary circuit pressure (MPa) | 12.7 | 15.7 |
| Primary circuit $T_{in}/T_{out}$ (°C) | 280/316 | 277/313 |
| Reactor coolant mass-flow rate (t/h) | 680 | 3250 |
| Primary circuit circulation mode | Forced | |
| Power cycle | Indirect Rankine cycle | |
| $P_{steam}$ at steam-generator outlet (MPa) | 3.72 | 3.82 |
| $T_{sat}$ at $P_{steam}$ (°C) | 246.1 | 247.4 |
| Overheated $T_{steam}$ at steam-generator outlet (°C) | 290 | 295 |
| Steam mass-flow rate (ton/h) | 240 | 261 (280) |
| $T$ feedwater in–out (°C) | 70–130 (170) | — |
| RPV height / diameter (m) | 4.8/2.0 | 9.2/3.5 |
| Maximum mass of reactor pressure vessel (ton) | 46.5 | — |
| Fuel type/assembly array | $UO_2$ pellets in silumin matrix | $UO_2$ pellet/hexagonal |
| Fuel assembly active length (m) | 1.2 | 2.0 |
| Number of fuel assemblies | 121 | 241 |
| Core service life (h) | 21,000 | 75,000 |
| Refueling interval (yr) | $\sim$3[b] | Up to 10 |
| Refueling outage (day) | 30–36 | — |
| Fuel enrichment (%) | 18.6 | Up to 20 |
| Fuel burnup (GWd/ton) | 45.4 | — |
| Predicted core-damage frequency (event/reactor year) | $0.5 \cdot \times 10^{-7}$ | — |
| Seismic design | 9 point on MSK scale | 0.3 g |

Note: For simplified *T-s* diagrams, see Figs. 9 and 10, respectively.
[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 tons of fuel oil per year. Every 12 years, the FNThPP will be towed back to the manufacturing plant and overhauled there.

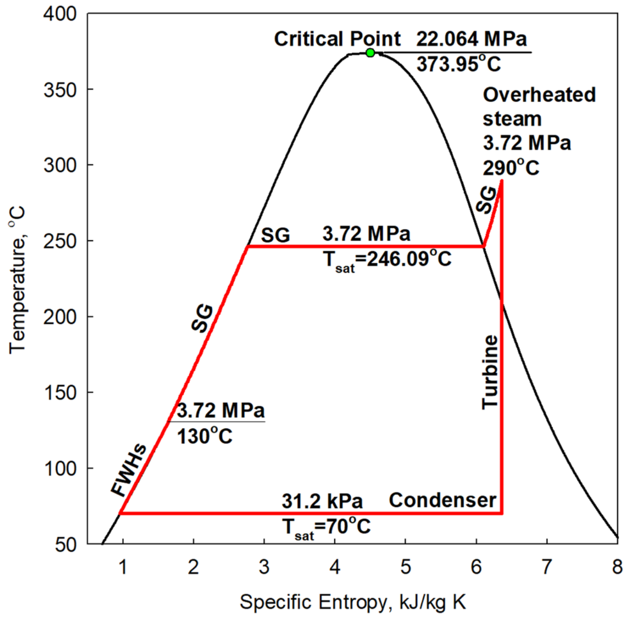



**Fig. 9 Simplified *T*–s diagram of 35-MW$_{el}$ SMR KLT-40S (Akademik Lomonosov floating NPP, Chukotka, Russia) Rankine cycle. The diagram was prepared based on data available in the open literature. FWHs—feedwater heaters; and SG—steam generator.**

circulation or almost complete avoidance of core damage, the safety focus is shifted from activity release consequences to verifying risk and safety margins with potentially limited experimental verification.

In addition, initial studies by the SMR Regulators Forum have focused making the distinction between examining multiple reactor units and the safety of multiple modules potentially sharing common facilities, safety systems, and sites.[11] The Forum notes

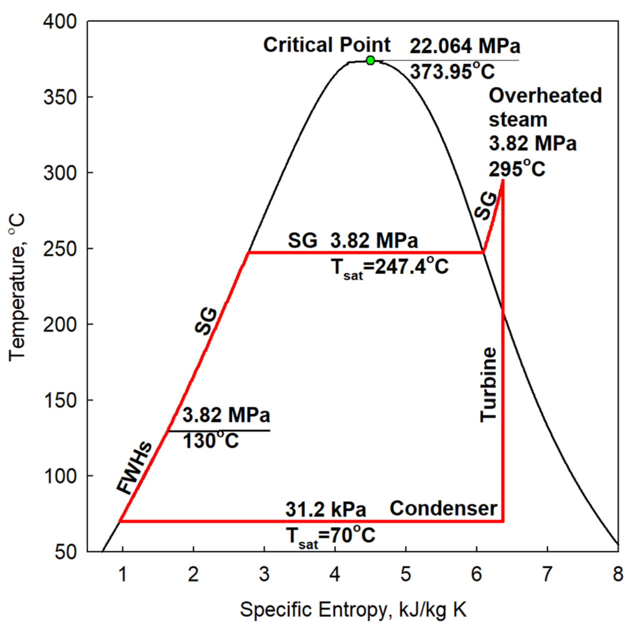



**Fig. 10 Simplified *T*–s diagram of 50-MW$_{el}$ SMR RITM-200M (Generation-III$^+$ SMR, Russia) Rankine cycle. Feedwater inlet and outlet temperatures were assumed to be the same as those in KLT-40S NPP. The diagram was prepared based on data available in the open literature. FWHs—feedwater heaters; and SG—steam generator.**

that multi-unit SMR plants "may impact among others, the selection of initiating events, internal and external hazards, the approach to shared systems, defense in depth, human factors engineering, and risk assessment."

Furthermore, the Forum has stated that the existing arrangements for regulating large NPPs are also suitable for regulating activities involving SMRs, implying the same lengthy and onerous level of paperwork, inspection, and review requirements *independent of the actual SMR concept or design*.

**6.2 Pathways to Success.** Development and design of any nuclear reactor require not only excellent ideas, but also excellence and special experience, qualifications, and dedication of the nuclear-engineering-company and plant-operating employees. Also, it should be a sort of a "critical mass" of a number of employees inside company to be able to deliver a complete design of a reactor. Of course, as additional factors, sophisticated test facilities, research reactor(s) for thermalhydraulics, fuels, and materials testing, and adequate funding are required for the success.

Other important considerations include:

(1) SMRs and SMR NPPs will be expensive during construction and operation (based on the example of KLT-40S);
(2) Operation of small NPPs will be more expensive per kW of installed capacity compared to that of large modern NPPs.

The only way to avoid these deficiencies is to build tens or even hundreds of SMRs. However, it will lead to the following problems:

(1) How to keep high level of safety and reliability?
(2) How to provide a proper operation of all these SMRs, continuous training, and high qualification of thousands of employees spread over a country?
(3) How to organize repairing services for a large number of SMRs scattering across a country including remote locations?
(4) Location of many "dangerous" objects as SMRs across a country will lead to more scare and opposition not only from a population, but also, from a government, because it will be more difficult to secure and supervise all these small NPPs!

The nuclear-power-industry history shows that even large and well-known world companies with tens of thousands of experienced, highly qualified and dedicated employees, sophisticated test facilities, research reactors, and adequate funding had failed to deliver their nuclear reactors on time and on budget.

Due to that they went through quite difficult times or even were split in parts and sold to other vendors and investors.

To the best of our belief, the SMR concepts will never directly replace or displace the role of large nuclear-power reactors, and very few of the listed SMRs/S&MRs in Tables 13–18 will reach the final design stage despite significant "enthusiasm." This includes worldwide efforts to develop various types of SMRs by well-known world nuclear vendors such as Areva, BARC, CEA/EDF, CNNC, General Atomics, Hitachi-GE, MHI, OKBM Afrikantov, ROSATOM, Toshiba, Westinghouse, and others, as well as by multiple start-up companies, research organizations, venture capitalists, entrepreneurs, universities, etc. This statement is partly based on the latest experience by the ROSATOM with the KLT-40S floating NPP (see Sec. 5), and the additional issues raised by Lankevich in "The main nonproliferation and safeguards challenges facing the small modular reactors".[18] These include requiring: Legal frameworks for widespread enriched-fuel utilization

[18] http://atominfo.ru/en/news4/d0530.htm

and its interstate transportation; elimination of potential for plutonium production; sabotage and terrorist-attacks prevention; accounting and remote monitoring of nuclear materials; assured cooling of spent nuclear fuel during transportation; and equipment operating without maintenance for a time commensurate with core lifetime.

However, SMRs will undoubtedly have their unique "niche" applications of being implemented in remote areas, small electrical grids, military facilities, and as floating NPPs.

## 7 Conclusions

(1) 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 follows: (1) combined-cycle thermal power plants—up to 62%; (2) supercritical-pressure coal-fired thermal power plants—up to 55%; (3) subcritical-pressure coal-fired thermal power plants—up to 43%; (4) carbon-dioxide-cooled reactor NPPs—up to 42%; (5) SFR NPP—up to 40%; (6) modern water-cooled-reactor NPPs—30–36% (up to 38%); and (7) Current PWR-SMRs NPPs—26–31%.

(2) 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).

(3) 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.

(4) The major advantages of nuclear power are well known, including cheap reliable base-load power, high capacity factors, 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.

(5) 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.

(6) In July of 2020, 439 nuclear-power reactors operated around the world, which is less by five reactors compared to that before the Fukushima NPP severe accident in March of 2011 (however, the total installed capacity increased by 14 $GW_{el}$). This number includes 297 $PWR_S$, 65 BWRs, 48 PHWRs, 14 AGRs, 13 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.

(7) In 2019, several very important milestones have been achieved—first EPR and AP-1000 NPPs have been put into operation in China. In 2020, it is expected that China will put into operation first in the world nuclear-power helium-cooled high-temperature pebble-bed reactor.

(8) SMRs are today a very "hot" topic in nuclear engineering worldwide. According to the IAEA, there are more than 55 SMRs designs/concepts proposed in the world. Russia is the first country in the world, which put into operation two SMRs—KLT-40S reactors barge-based as a floating NPP for the Northern regions. These first PWR-SMRs require LEU with enrichments of 18.6% and <20%, respectively, which are significantly higher than those in any modern light- or heavy-water reactors. Also, thermal efficiencies of these NPPs are lower than those of modern NPPs equipped with LWRs. In addition, it should be noted that development of these two KLT-40S SMRs took significantly longer time (13 years) than it was expected.

(9) Development and design of any nuclear reactor require not only excellent ideas, but also excellence and special experience, qualifications, and dedication of the nuclear-engineering-company and plant-operating employees. Also, it should be a sort of a "critical mass" of a number of employees inside company to be able to deliver a complete design of a reactor. Of course, as additional factors, sophisticated test facilities, research reactor(s) for thermalhydraulics, fuels, and materials testing, and adequate funding are required for the success.

(10) To the best of our belief, the SMR concepts will never directly replace or displace the role of large nuclear-power reactors, and very few of the developed SMRs/S&MRs in the world will reach the final design stage despite significant "enthusiasm." This includes worldwide efforts to develop various types of SMRs by well-known world nuclear vendors as well as by multiple start-up companies, research organizations, venture capitalists, entrepreneurs, universities, etc.

(11) Some issues, which have to be resolved before a widespread implementation of SMRs, include: Legal frameworks for widespread enriched-fuel utilization and its interstate transportation; elimination of potential for plutonium production; sabotage and terrorist-attacks prevention; accounting and remote monitoring of nuclear materials; assured cooling of spent nuclear fuel during transportation; and equipment operating without maintenance for a time commensurate with core lifetime. However, in spite of all difficulties in SMR development, they will undoubtedly have their unique "niche" applications of being implemented in remote areas, small electrical grids, military facilities, and as floating NPPs.

## Nomenclature

$P$ = pressure, MPa
$T$ = temperature, °C

## Subscripts

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

## Abbreviations

ABB = ASEA/Brown Boveri (Sweden, Switzerland)
ABV-6E = Nuclear Modular Water-cooled reactor 6-$MW_{el}$ (ABV-6E - Атомный Блочный Водяной (in Russian abbreviations) (Russia))
ABWR = advanced boiling water reactor

ACEC = Ateliers de Constructions Electriques de Charleroi
ACECOWEN = ACEC/COP/Westinghouse (Belgium)
ACP = advanced Chinese pressurized-water reactor
ACPR = advanced Chinese pressurized-water reactor
AECL = Atomic Energy of Canada Limited
AEE = AtomEnergoExport (Russia)
AEP = AtomEnergoProekt (Russia)
AES = atomic electrical station (NPP)
AFR = advanced sodium-cooled fast reactor (USA)
AGR = advanced gas-cooled reactor
AHTR-100 = advance high temperature reactor 100 $MW_{th}$ (South Africa)
AHWR = advanced heavy water reactor
ALFRED = Advanced Lead Fast Reactor European Demonstrator (Italy)
ANTARES = Areva's New Technology and advanced gas-cooled reactor for Energy Supply (France)
AO = Joint Stock Company
AP = Advanced Plant (Westinghouse Electric Company LLC, USA)
APR = Advanced Pressurized-Water Reactor (S. Korea)
ARC = Advanced Reactor Concepts (USA)
ARIS = Advanced Reactors Information System (IAEA)
ASE = AtomStroyExport (Russia)
ASEA = Allmänna Svenska Elektriska Aktiebolaget (General Swedish Electrical Limited Company)
ASME = American Society of Mechanical Engineers
ASTRID = Advanced Sodium Technological Reactor for Industrial Demonstration (France)
Ave. = average
B = billion
BARC = Bhabha Atomic Research Institute (India)
BN = Fast Sodium (reactor) (БН - Быстрый Натриевый (in Russian abbreviations) (Russia))
BNPP = Beloyarsk NPP (Russia)
BOP = balance of plant
BREST-OD = Fast Reactor with Inherent safety Lead Coolant - Experimental Demonstration (БРЕСТ-Од – Быстрый Реактор Естественной безопасности со Свинцовым Теплоносителем - Опытно-демонстрационный or Быстрый Реактор ЕСТественной безопасности - Опытно-демонстрационный (in Russian abbreviations) (Russia))
BWR = boiling water reactor
CA = Copenhagen Atomics (Denmark)
CAD = computer-aided design
CAE = computer-aided engineering
CANDU® = CANada Deuterium Uranium (reactor)
CAP = China Advanced Passive
CAREM = Central Argentina de Elementos Modulares (Argentina)
CCGT = combined-cycle gas-turbine
CCR = Compact Containment Boiling-Water Reactor (Japan)
CEA = Atomic Energy Commission (France)
CFR = China Fast Reactor
CGNPC = China General Nuclear Power Group
CIAE = China Institute of Atomic Energy
CMSR = Compact Molten Salt Reactor (Denmark)
CNEA = National Atomic Energy Commission (Argentina)
CNNC = China National Nuclear Corporation
CNP = china nuclear power
CPF = coated-particle fuel
COE = cost of energy
Commer. = commercial
Cont. = continuous
Corp. = corporation
CPV = concentrated photo-voltaic
CRIEPI = Central Research Institute of Electric Power Industry (Japan)
D = Depth
DAE = Department of Atomic Energy (India)
DCNS = Direction des Constructions Navales (France)
DHR = District Heating Reactor (China)
DMS = Double MS (Modular Simplified and Medium Small) (Japan)
EDF = Électricité de France
EEC = electrical-energy consumption
Eff. = efficiency
EGP = Power Heterogeneous Loop (reactor) (ЭГП - Энергетический Гетерогенный Петлевой (реактор с 6-ю петлями циркуляции теплоносителя) (in Russian abbreviations) (Russia))
El. = element(s)
ELFR = European Lead-cooled Fast Reactor (Italy/EU)
$EM^2$ = Energy Multiplier Module (USA)
ENHS = Encapsulated Nuclear Heat Source (USA)
EPR = European Pressurized-water Reactor (original acronym, later changed to Evolutionary Power Reactor) (France)
EU = European Union
FBNR = Fixed Bed Nuclear Reactor (Brazil)
FCM = Fully Ceramic Micro-encapsulated™ (fuel)
Fed. = Federal
FNThPP = floating nuclear thermal-power plant
FOAK = first-of-a-kind
GCR = gas-cooled reactor
GE = General Electric (USA)
Gr. = Group
GETSCO = General Electric Technical Services Co. (USA)
GT-MHR = Gas Turbine-Modular Helium Reactor (Russia/USA)
GTHTR300 = Gas Turbine High Temperature Reactor 300 $MW_{el}$ (Japan)
G4M = Gen4 Module (USA)
HALEU = high-assay low-enriched uranium
HAPPY200 = heating-reactor of advanced low-pressurized and passive safety system 200 $MW_{th}$
HDI = human development index
HEU = highly enriched uranium
HM = heavy metal
Hor. = Horizontal
HTMR-100 = High Temperature Modular Reactor 100 $MW_{th}$ (S. Africa)
HTR PM = High Temperature Reactor Pebble-bed Modular (China)
HWR = heavy water reactor (can be PHWR or light-water-cooled heavy-water-moderated reactor)
IAEA = International Atomic Energy Agency

IMR = Integrated Modular water Reactor (Japan)
IMSR = Integral Molten Salt Reactor (Canada)
Inc. = Incorporated
INET = Institute of Nuclear Energy and Technology (China)
Int. = International
IRIS = International Reactor Innovative and Secure
JAEA = Japan Atomic Energy Agency
JAERI = Japan Atomic Energy Institute
JSC = Joint Stock Company
KAERI = Korean Atomic Research Institute (S. Korea)
KALIMER = Korea Advanced LIquid MEtal Reactor (S. Korea)
KARAT = Boiling Nuclear Reactor of Autonomous Heat Supply (КАРАТ – Кипящий Атомный Реактор для Автономного Теплоснабжения (in Russian abbreviations) (Russia))
KLT = Container-carrier cargo-Lighter Transport (reactor) (КЛТ - Контейнеровоз Лихтеровоз Транспортный (реактор) (in Russia abbreviations) (Russia))
KP-FHR = Kairos Power Fluoride-salted-cooled High-temperature Reactor (USA)
KWU = KraftWerk Union (Germany)
L = length
Lab. = laboratory/laboratories
LBE = lead–bismuth–eutectic
LEADIR-PS100 = LEAD-cooled integral reactor-passively safe 100 $MW_{th}$
LEU = low enriched uranium
LFR = lead-cooled fast reactor
LFR-AS/TL-200/X = Lead-cooled Fast Reactor-Amphora-Shaped/Transportable Long-Lived-200 $MW_{el}$ (Luxembourg)
LFTR = Liquid-Fluoride Thorium Reactor (USA)
LGR = light-water-cooled graphite-moderated reactor
LHR = light-water-cooled heavy-water-moderated reactor
LLC = Limited Liability Company
LMFBR = liquid-metal fast-breeder reactor
LMFR = liquid-metal-cooled fast reactor
LMR = liquid-metal-cooled reactor
LNG = liquefied natural gas
LSPR = LBE-Cooled Long-Life Safe Simple Small Portable Proliferation-Resistant Reactor (Japan)
Ltd. = Limited
LUEC = levelized unit energy cost
LWR = light water reactor
Mar. = March
MCFR = Molten Chloride Fast Reactor (USA)
MCSFR = Molten Chloride Salt, Fast Reactor (Canada/USA)
MF = metallic fuel
MHI = Mitsubishi Heavy Industries (Japan)
MHR = Modular Thermal Reactor (MHR - Модульный Тепловой Реактор (in Russian abbreviations) (Russia))
MHR-T = Modular Helium Reactor-High Temperature (Russia)
Mk1 PB-FHR = Mark 1 Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (USA)
MMR = Micro Modular Reactor (USA)
MoveluX = Mobile-Very-Small Reactor for Local Utility in X-Mark (Japan)
MOX = mixed oxide (fuel)
MS = moisture separator
MSF = molten-salt fuel
MRX = Marine Reactor (Japan)
MSK = Medvedev–Sponheuer–Karnik scale
MSTW = Molten Salt Thermal Wasteburner reactor (Denmark)
MTM = Ministry of Heavy Machine Building (in Russian abbreviations) (Russia)
Nat. = National
N/A = not available/not applicable
NHR = Nuclear Heating Reactor (China)
NIKIET = Научно-Исследовательский и Конструкторский Институт ЭнергоТехники (in Russian abbreviations) (N.A. Dollezhal Research and Development Institute of Power Engineering (RDIPE)) (Russia)
NNC = National Nuclear Corporation (UK)
NPCI = Nuclear Power Corporation of India
NPP = Nuclear Power Plant
NUWARD = NUclear forWARD (France)
OKBM = Experimental Design Bureau of Mechanical-engineering (ОКБМ - Опытно-Конструкторское Бюро Машиностроения (in Russian abbreviations) (Russia))
OKBG = Experimental Design Bureau Gidropress (ОКБГ - Опытно-Конструкторское Бюро Гидропресс (in Russian abbreviations) (Russia))
PB-FHR = pebble-bed fluoride-salt high-temperature reactor
PBMR = pebble-bed modular reactor
PBWFR = Pb–Bi-cooled direct contact Boiling Water Fast Reactor (Japan)
PCh = pressure channel (reactor)
PEACER = Proliferation-Resistant Environment-friendly Accident-tolerant Continuable and Economical Reactor (S. Korea)
PGSFR = prototype gen-IV sodium-cooled fast reactor
PHWR = pressurized heavy-water reactor
PP = power plant
PPP = PWR Power Projects (UK)
PRISM = power reactor innovative small module
PV = photovoltaic or Pressure Vessel
PWR = pressurized water reactor
QA = quality assurance
QC = quality control
RAPID-L = Refueling by All Pins Integrated Design-Lunar-base (Japan)
RBMK = Reactor of Large Capacity Channel type (РБМК - Реактор Большой Мощности Канальный (in Russian abbreviations) (Russia))
R&D = Research and Development
RDIPE = Research and Development Institute of Power Engineering
RDM = Rotterdamse Drookdok Maatschappij (Netherlands)
Ref. = reference
Rep. = republic
RITM-200M = Reactor Integral Type Modular 200 $MW_{el}$ Modernized (РИТМ-200М - Реактор Интегрального Типа Модульный мощностью 200 МВт Модернизационный (in Russian abbreviations) (Russia))

ROI = return-on-investment
RPV = reactor pressure vessel
RUTA = Reactor Plant for Heat Supply with Atmospheric pressure in the first circuit (РУТА - Реакторная Установка для Теплоснабжения с Атмосферным давлением в первом контуре (in Russian abbreviations) (Russia))
SC-HTGR = Steam Cycle-High Temperature Gas-Cooled Reactor (USA)
SCWR = supercritical water-cooled reactor
SEALER = Swedish Advanced Lead Reactor
SFR = sodium fast reactor
SG = steam generator
SINAP = Shanghai Institute of Applied Physics (China)
SmAHTR = Small modular Advanced High-Temperature Reactor (USA)
SMART = System-Integrated Modular Advanced ReacTor (S. Korea)
SMR = small modular reactor
S&MRs = small- and medium-size reactors
SNERDI = Shanghai Nuclear Engineering and Design Institute (China)
SNF = spent nuclear fuel
SNP = State Nuclear Power (China)
SNUPPS = Standardized Nuclear Unit Power Plant System
SO = safety objective
SPIC = State Power Investment Corporation (China)
SSR = SuperSafe Reactor (Canada)
SUPERSTAR = Sustainable Proliferation-resistance Enhanced Refined Secure Transportable Autonomous Reactor (USA)
SVBR = Lead-Bismuth Fast Reactor (SVBR – Свинцово-Висмутовый Быстрый Реактор (in Russian abbreviations) (Russia))
Techn. = technologies
Th. = thermal
ThorCon = Thorium Converter (reactor)
TMSR-LF = Thorium Molten Salt Reactor-Liquid Fuel (China)
Tokyo Tech. = Tokyo Institute of Technology (Japan)
TRISO = tristructural isotropic
TRU = transuranic
TWR-P = Travelling Wave Reactor-Prototype (USA)
UAE = United Arab Emirates
UC = University of California
UCO = Uranium Oxycarbide (fuel)
UK = United Kingdom
UNITHERM = UNIversal THERMal reactor (Russia)
Univ. = University
UOIT = University of Ontario Institute of Technology
USA = United States of America
USNC = Ultra Safe Nuclear Corporation (USA)
V = vessel
VBER = Water Safe Power Reactor (ВБЭР - Водяной Безопасный Энергетический Реактор (in Russian abbreviations) (Russia))
Vert. = vertical
VK = Water-cooled Boiling (ВК - Водоохлаждаемый Кипящий (in Russian abbreviations) (Russia))
VVER = Water Water Power Reactor (ВВЭР - Водо-Водяной Энергетический Реактор (in Russian abbreviations) (Russia))
W = width
WACC = weighted average cost of credit
W-SMR = Westinghouse Small Modular Reactor (USA)
WLFR = Westinghouse Lead-Cooled Fast Reactor
WPu = weapons-grade plutonium
4S = Super Safe, Small and Simple (Japan)

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