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

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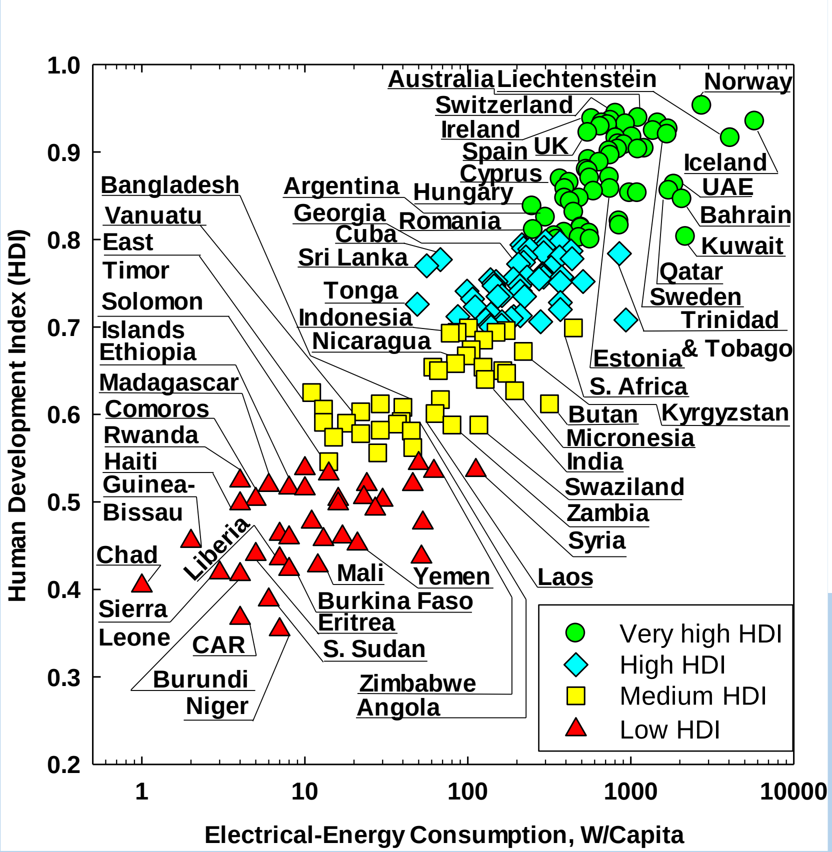
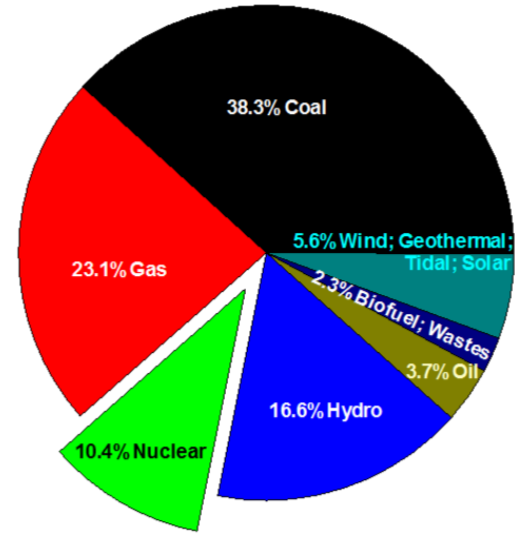
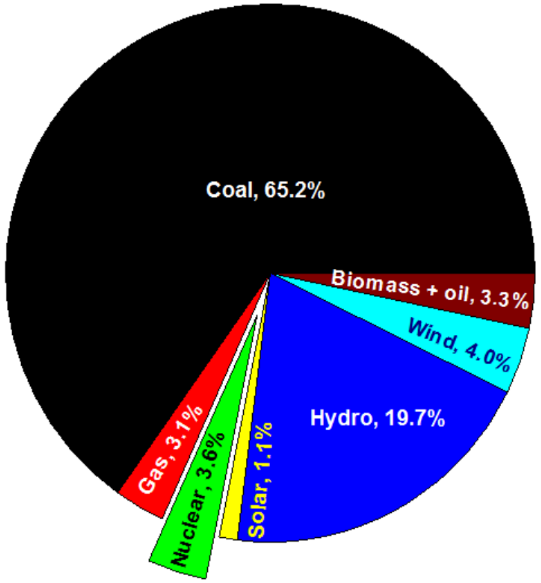
1. Electricity generation in the world

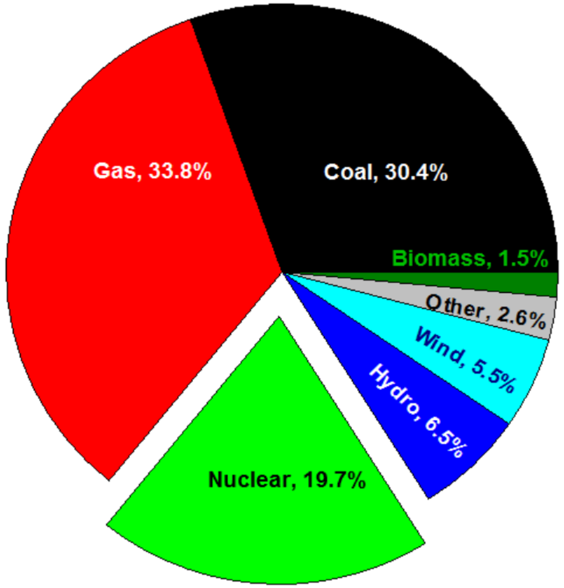
It is well known that electrical-power generation plays the key role in advances in industry, agriculture, technology, and the standard of living. Also, strong power industry with diverse energy sources is very important for a country independence.



Impact of Electrical-Energy Consumption (EEC) on Human Development Index (HDI) for all countries of the world







World: Population 7,659 million (Oct. 19, 2018); EEC 24,816 TW h per year or 372 W/Capita; HDI 0.728 or HDI Rank 98

Usage of coal decreased by ~2%

China: Population 1,415 million; EEC 5,920 TW h per year or 510 W/Capita; HDI 0.738 or HDI Rank 86

Usage of coal decreased by ~15%

USA: Population 327 million; EEC 3,911 TW h per year or 1377 W/Capita; HDI 0.924 or HDI Rank 13

Usage of coal decreased by ~9%

2. Current status of nuclear power

Number of nuclear-power reactors connected to electrical grid and forthcoming units as per October 2018 and before the Japan earthquake and tsunami disaster

No	Reactor type (Some details on reactors)	No. of units		Installed capacity, GW_{el}		Forthcoming units	
		As of Oct. 2018	Before Mar. 2011	As of Oct. 2018	Before Mar. 2011	No. of units	GW_{el}
1	Pressurized Water Reactors (PWRs) (largest group of nuclear reactors in the world – 66%)	300 ↑	268	285 ↑	248	77	84
2	Boiling Water Reactors (BWRs) or Advanced BWRs (2nd largest group of reactors in the world – 16%; ABWRs – the only ones Generation-III+ operating reactors)	72 ↓	92	72 ↓	84	6	8
3	Pressurized Heavy Water Reactors (PHWRs) (3rd largest group of reactors in the world – 11%; mainly CANDU-reactor type)	48 ↓	50	23 ↓	25	8	5
4	Advanced Gas-cooled Reactors (AGRs) (3%) (UK, 14 reactors); (all these CO_2-cooled reactors will be shut down in the nearest future and will not be built again)	14 ↓	18	8 ↓	9	1*	0.2*
5	Light-water-cooled, Graphite-moderated Reactors (LGRs) (3%) (Russia, 11 RBMKs and 4 EGPs; these pressure-channel boiling-water-cooled reactors will be shut down in the nearest future and will not be built again)	15	15	10	10	0	0
6	Liquid-Metal Fast-Breeder Reactors (LMFBRs) (Russia, SFRs – BN-600 and BN-800 (see Figure 11))	2 ↑	1	1.3 ↑	0.6	3	0.6
	In total	451 ↑	444	401↑	378	97	101

2. Current status of nuclear power

Number of nuclear-power reactors connected to electrical grid (11 nations ranked by nuclear-reactor installed capacities)and forthcoming units as per October 2018 and before the Japan earthquake and tsunami disaster

#	Nation	No. of units (PWRs/BWRs)		Installed capacity, GW_{el}		Changes in number of reactors from March 2011
		As of October 2018	Before March 2011	As of October 2018	Before March 2011	
1	USA	98 (65/33)	104	102	103	↓ Decreased by 6 reactors
2	France	58 (58/-)	58	63	63	No changes
3	China	43 (41/-/2[3])	13	40	10	↑ Increased by 30 reactors
4	Japan	42 (19/23)	54	40	47	↓ Decreased by 12 reactors
5	Russia	37 (20/-/15[1]/2[2])	32	29	23	↑ Increased by 5 reactors
6	S. Korea	24 (21/-/3[3])	20	23	18	↑ Increased by 4 reactors
7	Canada	19 (-/-/19[3])	22	14	15	↓ Decreased by 3 reactors
8	Ukraine	15 (15/-)	15	13	13	No changes
9	Germany	7 (6/1)	17	10	20	↓ Decreased by 10 reactors
10	Sweden	8 (5/3)	10	9	9	↓ Decreased by 2 reactors
11	UK	15 (1/-/14[4])	19	9	10	↓ Decreased by 4 reactors
	In total	366 (251/60/15[1]/2[2]/22[3]/14[4])	364	352	331	↑ Increased by 1 reactor and installed capacity increased by 21 GW_{el}

2. Current status of nuclear power

Summary for all countries of the world: 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 don't plan to build nuclear-power reactors. Moreover, such countries as Taiwan, Switzerland and some others might not proceed with new builds.

Current activities worldwide on new nuclear-power-reactors build

#	Country / Nuclear vendor	Countries, which looking forward for new builds (No of possible units)
1	China / Various vendors (Nuclear-power activities are supported by the Chinese government)	China (21+1?*), Pakistan (3), Romania (2), UK (2); In total: 28+1?
2	Russia / Rosatom (outside Russia - ASE (AtomStroyExport) is the Russian Federation's nuclear-power equipment and service exporter. It is a fully-owned subsidiary of Rosatom. Nuclear-power activities are financially supported by the Russian government.)	Russia (4+3?), Belarus (2), Finland (1), Iran (2), Hungary (2), India (1), China (2), Turkey (4), Egypt (4?), Bangladesh (2), India (1); In Total: 21+7?
3	USA / Westinghouse, GE	China (2), USA (4+2?), Taiwan (2?); In total: 6+4?
4	S. Korea / Various vendors	UAE (4), S. Korea (3); In total: 7
5	India / Various vendors	India (6); In total: 6
6	France / Areva	China (1), Finland (1), France (1), UK (2); In total: 5

2. Current status of nuclear power

Milestones Achieved

Last several years and, especially, year of 2018, were very important for the nuclear-power industry of the world. As such, Russia put into operation a number of Generation III+ VVERs (PWRs) and the SFR – BN-800 reactor in 2016 and continue to lead the SFR technologies in the world.

China put into operation many reactors / NPPs including the largest in the world Generation III+ PWR – EPR (Areva design) with amazing installed capacity of 1660 MW_{el}. In addition, several AP-1000 reactors (Westinghouse design), also, a Generation III+ design, were put into operation in China first time in the world

Milestones Planned for Next Years

Year of 2019 and following years will be also very important ones, because a unique GCR - a helium-cooled reactor (SMR) – High Temperature Reactor Pebble-bed Modular (HTR-PM) should be put into operation China. Also, a number of Generation III+ reactors around the world are expected to be put into operation as well, plus, at least one, or a number of SFR(s) can be added to the fleet of nuclear-power reactors.

2. Current status of nuclear power

Key-design parameters of Russian SFRs – BN reactors

#	Parameters	BN-600	BN-800	BN-1200 (future design)
1	Thermal power, MW_{th}	1470	2100	2800
2	Electrical power, MW_{el}	600	880	1220
3	Basic components: No of turbines × type No of generators × type	 3 × K-200-130 3 × ТГВ-200-М	 1 × K-800-130 1 × T3B-800-2	 1 × K-1200-160 1 × T3B-1200-2
4	Pressure vessel Diameter, m Height, m	 12.86 12.60	 12.96 14.82	 16.9 20.72
5	No of heat-transfer loops	3	3	4
6	*T* of reactor coolant: sodium, primary loop - T_{in} - T_{out}, °C	377/550	354 - 547	410/550
7	*T* of intermediate coolant: sodium, secondary loop - T_{in} - T_{out}, °C	328/518	309 - 505	355/527
8	*T* of power-cycle working fluid: water/steam - T_{in} - T_{out}, °C	240/505	210 - 490	275/510
9	*P* at Steam Generator outlet, MPa	13.7	14.0	17.0
10	Scheme of steam reheat with	Sodium	Steam	Steam
11	Basic unchangeable components service term, years	30	40	60
12	NPP thermal efficiency (gross), %	42.5	41.9	43.6
13	NPP thermal efficiency (net), %	40.0	38.8	40.5

2. Current status of nuclear power

Key specifications of ABWR (Generation III+) and BWR (Generation III) NPPs (courtesy of Hitachi-GE Nuclear Energy)

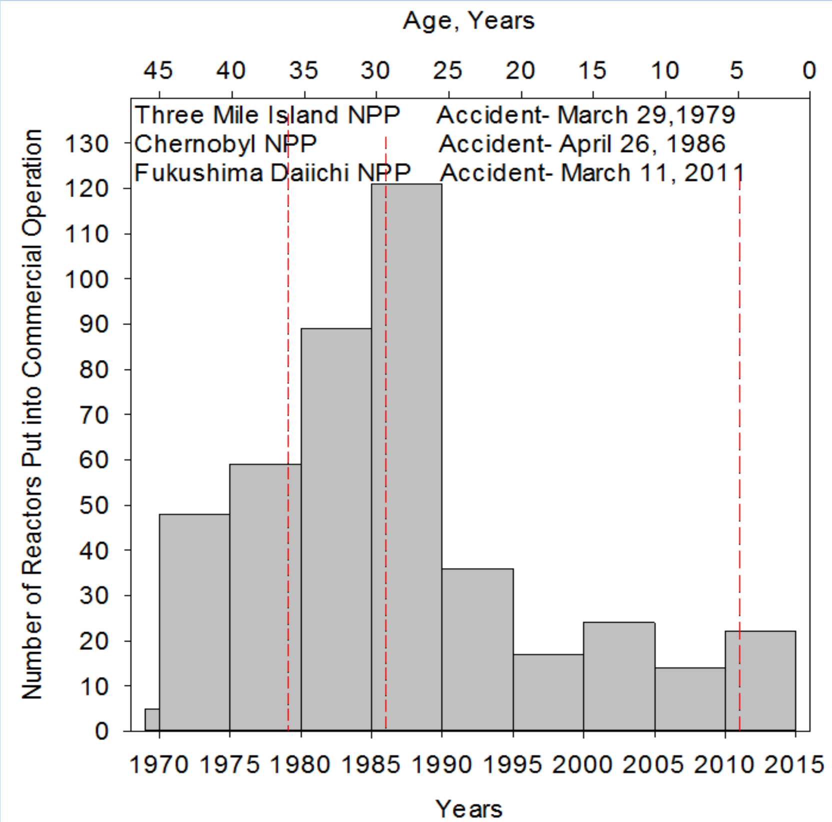
Parameters	Item	ABWR	BWR-5
Output	Plant Output	1,350 MW_{el}	1,100 MW_{el}
	Reactor Thermal Output	3,926 MW_{th}	3,293 MW_{th}
Thermal efficiency (gross)	%	34	33.4
Reactor Core	Fuel Assemblies	872	764
	Control Rods	205 rods	185 rods
Reactor Equipment	Recirculation System	Internal pump method	External recirculation type
	Control Rod Drive	Hydraulic / electric motor drive methods	Hydraulic drive
Reactor Containment Vessel		Reinforced concrete with built-in liner	Free-standing vessel
Residual Heat Removal System		3 systems	2 systems
Turbine Systems	Thermal Cycle	Two-stage reheat	Non-reheat
	Turbine (blade length)	1.32 m (52")	1.09 m (43")
	Moisture Separation Method	Reheat type	Non-reheat type
	Heater Drain	Drain up type	Cascade type

2. Current status of nuclear power

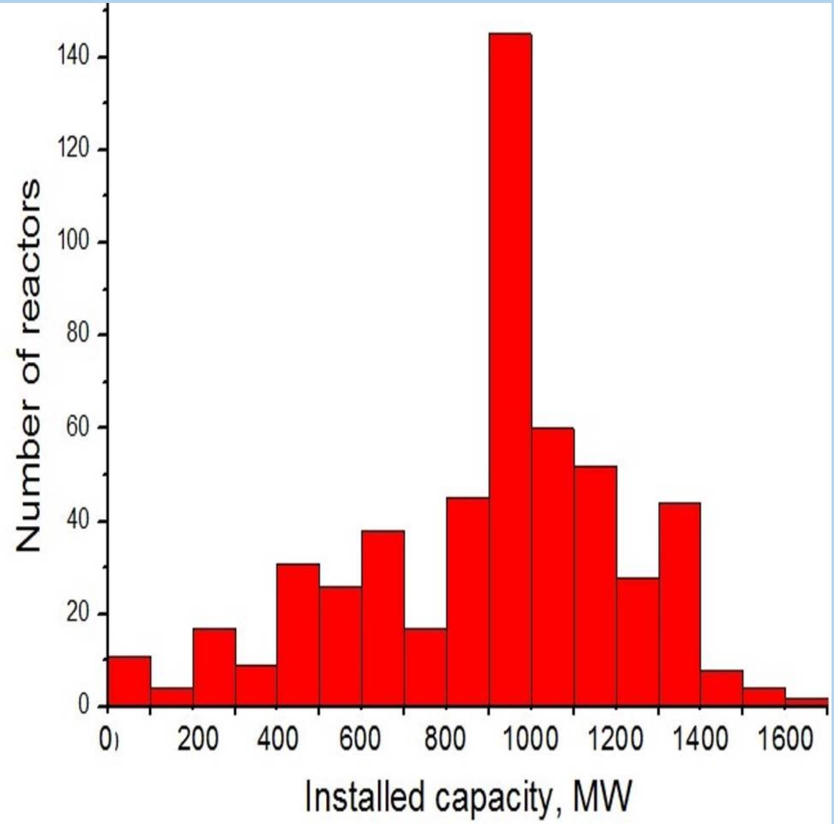
Basic data on AREVA’s Generation III+ PWR – EPR

Characteristics	Data
Reactor core	
Thermal power	4,590 MW_{th}
Electric power	1,600+ MW_{el}
Gross thermal efficiency	36–37%
Active fuel length	4.2 m
No of fuel assemblies	241
No of fuel rods	63,865
Fuel assembly array	17 × 17
No of RCCAs (Rod Cluster Control Assemblies)	89
Average linear power	166.7 W/cm
Operation cycle length up to	24 months
Reactor coolant system	
No of loops	4
Nominal flow	28,315 m^3/h
Reactor-pressure-vessel inlet temperature	295.2°C
Reactor-pressure-vessel outlet temperature (T_{sat} =344.8°C at 15.5 MPa)	330°C
Primary side operating pressure	15.5 MPa
Secondary side saturation pressure at nominal conditions (SG outlet) (T_{sat}=292.5°C)	7.72 MPa
Service life	60 years

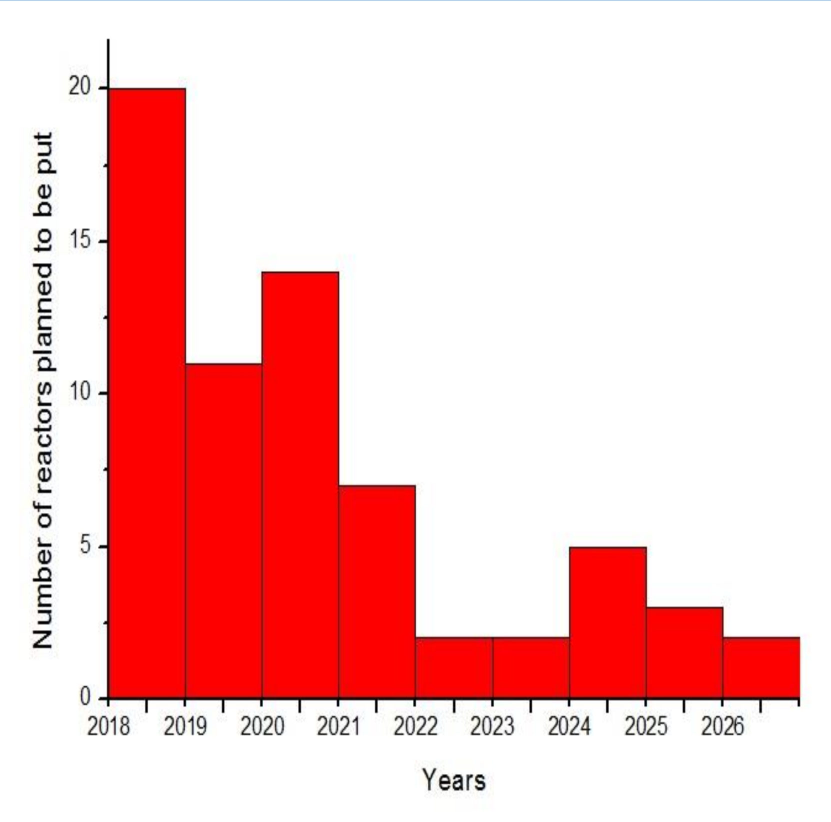
2; 3. Current status of nuclear power & Future trends



Number of nuclear-power reactors in the world put into commercial operation vs. years as per March of 2015; 4 reactors (India 2×150 MW_{el}; Switzerland 1×365 MW_{el}; and USA 1×613 MW_{el} and 1×650 MW_{el}) have been put into operation in 1969, i.e., they operate for almost 50 years.

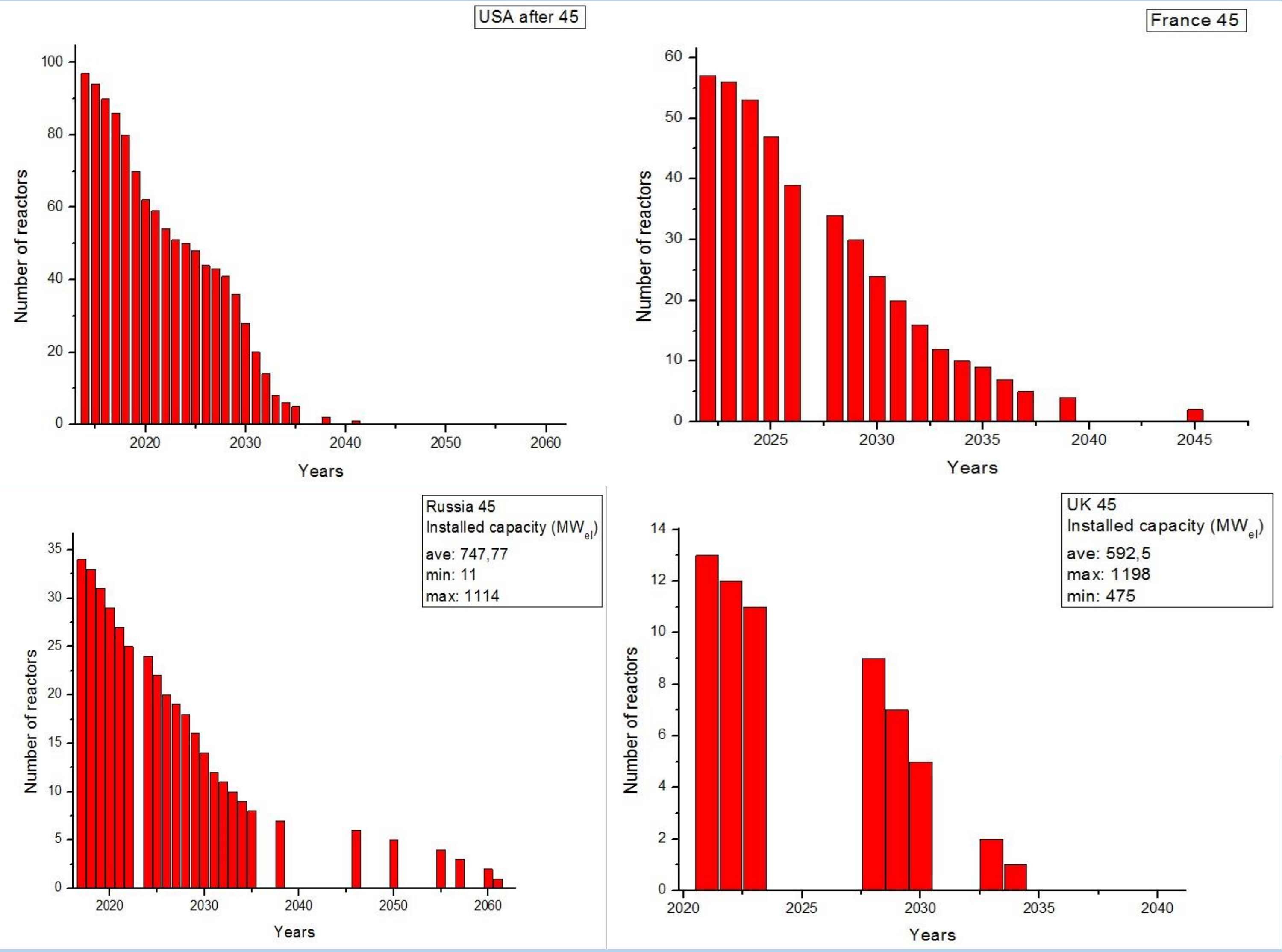


Number of nuclear-power reactors in the world by installed capacity as per March, 2017.

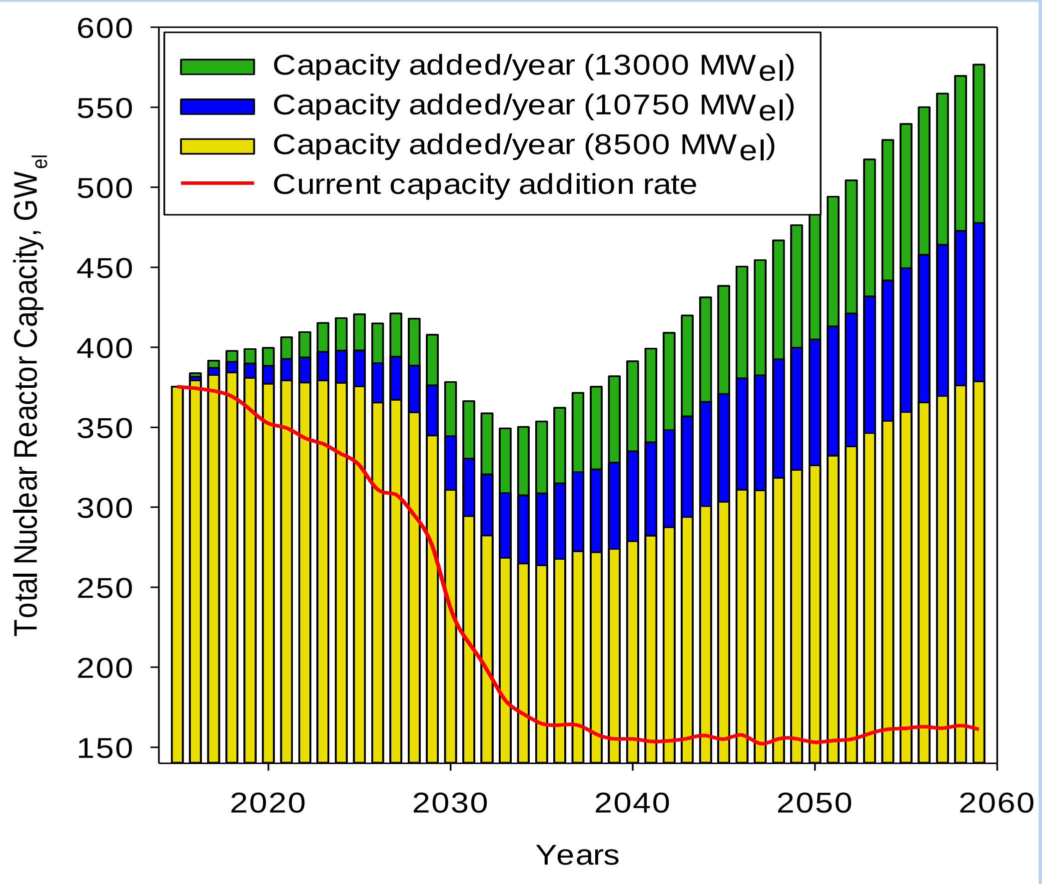


Number of reactors planned to be built from 2018 till 2027.

3. Future trends in nuclear power



Possible scenarios for future of nuclear power in USA, France, Russia and UK, if no additional reactors are built; based on 45 years in service of current reactors



Possible scenarios for future of nuclear power; based on 45 years in service of current reactors and adding new reactors with rate of ~21 reactor per 5 years (red line)

4. Small Modular Reactors (SMRs)

If we have currently operating small nuclear-power reactors? – Yes!

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

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

4. Small Modular Reactors (SMRs)

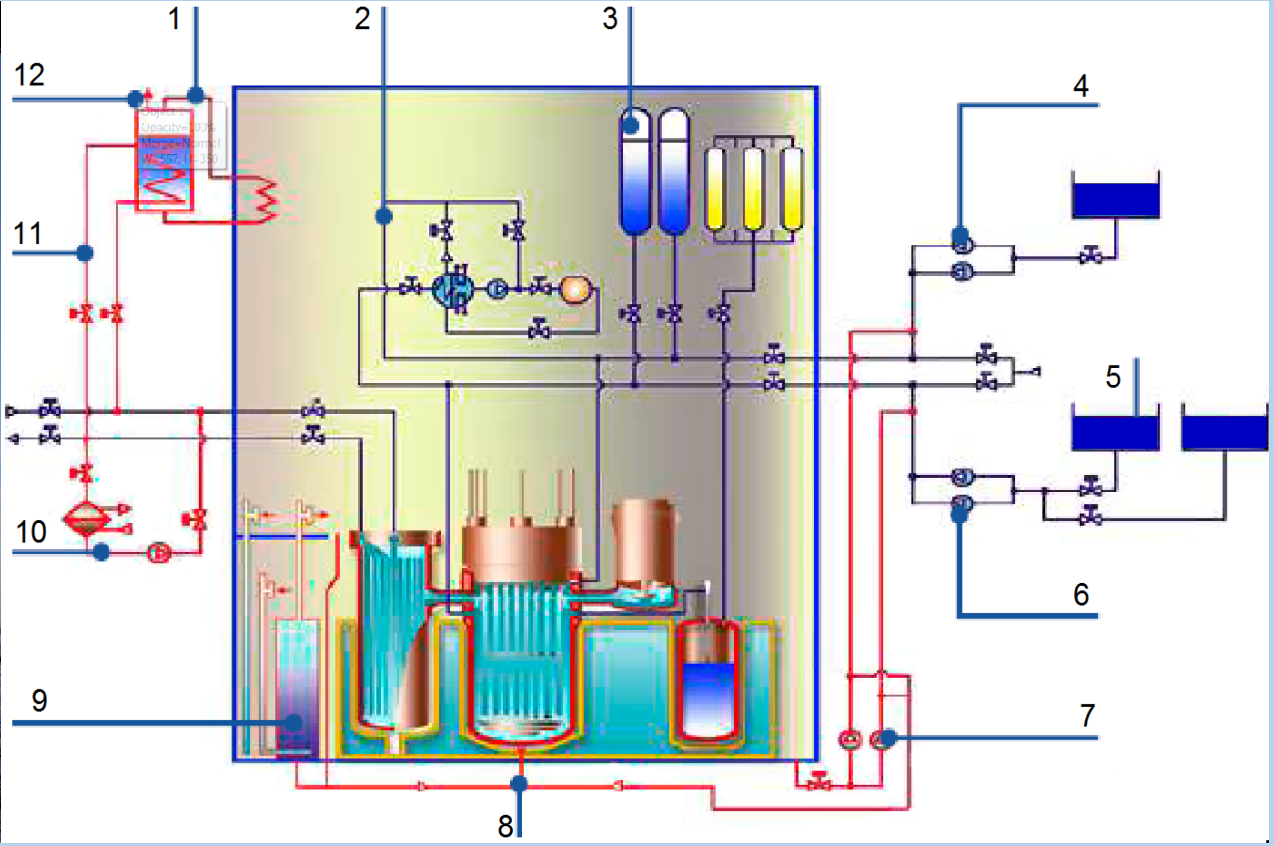
SMRs are today's a very "hot" topic in nuclear engineering worldwide.

According to the IAEA ARIS (Advanced Reactors Information System) data, there are about 55 SMRs designs / concepts, which can be classified as:

1) **Water-cooled SMRs (land based) – 19;**
2) **Water-cooled SMRs (marine based) – 6;**
3) **High-temperature gas-cooled SMRs – 10;**
4) **Molten-salt SMRs – 9;**
5) **Fast-neutron-spectrum SMRs – 10; and**
6) **Other SMRs – 1.**

From all these 55 SMRs: Two KLT-40S reactors (Russia) have been constructed, installed on a barge, and should be put into operation in 2019 (moreover, on Nov. 4, 2018, first KLT-40S reached the minimum controlled power level); and one SMR – 200-MW$_{el}$ HTR-PM is, also, constructed and should be put into operation in China in 2019; CAREM (Central ARgentina de Elementos Modulares) SMR (PWR-type; 25 (32) MW$_{el}$; CNEA (Comisión Nacional de Energía Atómica), Argentina) is under construction now, and FUJI (200 MW$_{el}$, MSR International Thorium Molten-Salt Forum (ITMSF), Japan) is possibly within an experimental phase.

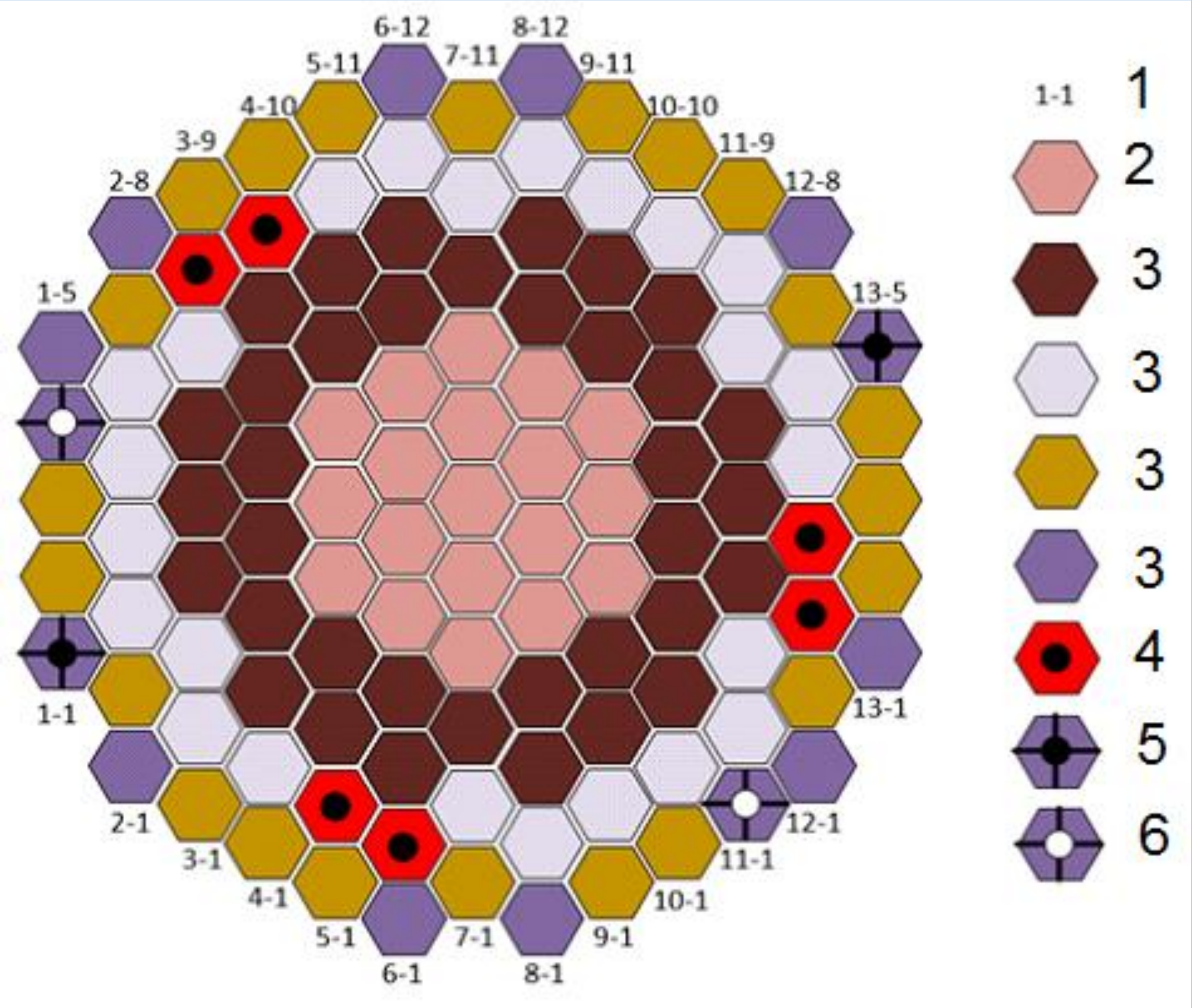
4. Small Modular Reactors (SMRs) - KLT-40S



Schematic of KLT-40S reactor and its systems (based on original figures from AO OKBM by the name of I.I. Afrikantov, Brochure on KLT-40S): 1 – Passive system of containment emergency pressure decrease (condensing system); 2 – Active emergency cooling system through heat exchangers of loops I - III; 3 - Passive emergency core cooling system (hydraulic accumulators); 4 – Active emergency core cooling system from feedwater pumps; 5 – Active system for injecting liquid absorber; 6 – Active emergency core cooling system from feedwater pumps; 7 – Active emergency core cooling system through recirculation pumps; 8 – System of reactor caisson filling with water; 9 – Containment passive emergency pressure decrease system (bubbling); 10 – Active emergency shutdown cooling system (through process condensers); 11 – Passive emergency shutdown cooling system; 12 – To atmosphere.

4. Small Modular Reactors (SMRs) - KLT-40S

Reactor KLT-40S (in the center) with four steam generators (larger cylinders) and four reactor-coolant circulation pumps (smaller cylinders)



KLT-40S reactor-core cross section: 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

4. Small Modular Reactors (SMRs) - KLT-40S

Parameters	KLT–40S
Reactor type; Reactor coolant / moderator	PWR; Light water
Thermal power / Electric power / Thermal efficiency	150 MW_{th} / 35 MW_{el} (net) (38.5 MW_{el} gross) / ~26%
Expected capacity factor	60 – 70%
Maximum output thermal power	73 Gcal/h
Production of desalinated water	40,000 – 100,000 m^3/day
Operating range of power	10 – 100%
Normal-mode power variation	0.1% per second
Primary circuit pressure (T_{sat}) / Primary circuit T_{in} - T_{out}	12.7 MPa (329°C) / 280°C - 316°C
Reactor coolant massflow rate	680 ton/h
Primary circuit circulation mode	Forced
Power cycle	Indirect Rankine cycle
P_{steam} at Steam Generator (SG) outlet (T_{sat} at P_{steam}) / Overheated T_{steam} at SG outlet	3.72 MPa (246.1°C) / 290°C
Steam massflow rate,	240 ton/h
Temperature of feed-water in – out	70 – 130°C (170°C)
Reactor-Pressure Vessel Height / diameter	4.8 m / 2.0 m
Maximum mass of reactor pressure vessel	46.5 ton
Fuel type / Assembly array	UO_2 pellets in silumin matrix
Fuel assembly active length	1.2 m
Number of fuel assemblies	121
Core service life	21,000 hours
Refueling interval / Refueling outage	~3 years / 30 – 36 days
Fuel enrichment / Fuel burnup	18.6% / 45.4 GWd/t
Predicted core damage frequency, event / reactor year	$0.5 \cdot 10^{-7}$
Seismic design	9 point on MSK scale

5. Conclusions

1. It is well known that electrical-power generation is the key factor for advances in industry, agriculture, technology, and level of living. Also, strong power industry with diverse energy sources is very important for a country's independence. Major sources for electrical-energy generation in the world today are: 1) thermal - primary coal (38.3%) and secondary natural gas (23.1%); 2) "large" hydro (16.6%); and 3) nuclear (10.4%). The remaining 11.6% of the electrical energy is generated using oil (3.7%) and renewable sources (biomass, wind, geothermal, and solar energy) (7.9%) in selected countries. Other energy sources such as renewable wind-, solar-, marine-power have a visible impact just in some countries, especially, where there are government incentives with electricity prices guaranteed by legislation and power-purchase contracts. However, these apparently attractive renewable-energy sources (wind, solar, tidal, etc.) are not reliable as full-time energy sources for industrial-power generation. To overcome this problem, an electrical grid must also include "fast-response" power plants such as gas- (coal-) fired and/or large hydro-power plants.
2. In general, the major driving force for all advances in thermal and nuclear power plants is thermal efficiency and generating costs. Ranges of gross thermal efficiencies of modern power plants are as the following: 1) Combined-cycle thermal power plants – up to 62%; 2) Supercritical-pressure coal-fired thermal power plants – up to 55%; 3) Carbon-dioxide-cooled reactor NPPs – up to 42%; 4) Sodium-cooled Fast Reactor (SFR) NPP – up to 40%; 5) Subcritical-pressure coal-fired thermal power plants – up to 43%; and 6) Modern water-cooled-reactor NPPs – 30–36% (38%).
3. Nuclear power is, in general, a non-renewable source unless fuel recycling, thoria fuel, and/or fast-neutron-spectrum reactors are adopted, which means that nuclear resources can be used significantly longer than some fossil fuels. Currently, this source of energy is considered as the most viable one for base-load electrical generation for the next 50 – 100 years.
4. However, all current Generation-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).
5. The major advantages of nuclear power are well known, including cheap reliable base-load power, high capacity factor, low carbon-dioxide emissions, and minor environmental impact. However, these factors are offset today by a competitive disadvantage with natural gas and the occurrence of three significant nuclear accidents (Fukushima, Chernobyl, and Three Mile Island NPPs). The latter have caused significant social disruption together with high capital costs.

5. Conclusions

6. 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 don't plan to build new nuclear-power reactors. Moreover, such countries as Taiwan, Switzerland and some others might not proceed with new builds.
7. In October of 2018, 451 nuclear-power reactors operated around the world. This number includes 300 PWRS, 72 BWRs, 48 PHWRs, 14 AGRs, 15 LGRs, and 2 LMFBRs. Considering the number of forthcoming reactors, the number of BWRs / ABWRs and PHWRs will possibly decrease within next 20 – 25 years. Furthermore, within next 10 – 15 years or so, all AGRs (carbon-dioxide-cooled) and LGRs will be shut down forever. However, instead of carbon-dioxide-cooled AGRs helium-cooled reactors will be built and put into operation.
8. In 2018, several very important milestones have been achieved – first EPR and AP-1000 NPPs have been put into operation in China. In 2019, it is expected that China will put into operation first in the world nuclear-power helium-cooled pebble-bed reactor. Also, in 2016, second SFR – BN-800 was put into operation in Russia.
9. Analysis of the current statistics on nuclear-power reactors of the world shows that we might face a very significant drop (up to 3 times) in a number of operating nuclear-power reactors somewhere between 2030 – 2040; if we assume that current operating term of reactors is on average 45 years, and the rate of building and putting into operation new reactors is ~21 reactors per 5 years. Even with higher rates of new nuclear-capacities additions, we will have a tangible decrease in a number of operating reactors. If this forecast(s) is correct, the nuclear-power industry will face very difficult times ahead.
10. SMRs are today's a very "hot" topic in nuclear engineering worldwide [1, 42]. According to the IAEA, there are about 55 SMRs designs / concepts proposed in the world. There is a possibility that in 2019, Russia will put into operation first two SMRs – KLT-40S reactors barge-based as a floating NPP for the Northern regions.
11. In spite of all current advances in nuclear power, NPPs have the following deficiencies: 1) Generate radioactive wastes; 2) Have relatively low thermal efficiencies, especially, NPPs equipped with water-cooled reactors (up to 1.6 times lower than that for modern advanced thermal power plants; 3) Risk of radiation release during severe accidents; and 4) Production of nuclear fuel is not an environment-friendly process. Therefore, all these deficiencies should be addressed in next generation – Generation IV reactors and NPPs.

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