CURRENT STATUS AND FUTURE DEVELOPMENTS IN NUCLEAR-POWER INDUSTRY OF THE WORLD

Современное состояние мировой ядерной энергетики. Проблемы и перспективы

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http://nuclearengineering.asmedigitalcollection.asme.org/article.aspx?articleID=2718229

Sources for Electrical Energy Generation

It is well known that the electrical power generation is the key factor for advances in any other industries, agriculture and level of living.

In general, electrical energy can be produced by: 1) non-renewable sources such as coal, natural gas, oil, and nuclear; and 2) renewable sources such as hydro, wind, solar, biomass, geothermal and marine. However, the main sources for electrical-energy production are: 1) thermal - primary coal and secondary natural gas (also, in some countries oil is used); 2) hydro and 3) nuclear.

The rest of the sources might have visible impact just in some countries. In addition, the renewable sources such as wind and solar are not really reliable sources for industrial power generation, because they depend on Mother nature plus relative costs of electrical energy generated by these and some other renewable sources with exception of large hydro-electric power plants can be significantly higher than those generated by non-renewable sources.

Electrical Energy Consumption per Capita and HDI in Selected Countries

HDI* Rank (2017)	Country	HDI* (2017)	EEC** (2015 - 2017)		Population in millions (2018)
			W/Capita	GW·h	
Very High HDI					
1	Norway	0.953	2740	133,100	5.35
2	Switzerland	0.944	809	58,450	8.54
3	Australia	0.939	1112	223,600	24.77
5	Germany	0.936	753	514,600	82.29
6	Iceland	0.935	5777	17,980	0.34
8	Sweden	0.933	1467	125,400	9.98
12	Canada	0.926	1704	516,600	36.95
13	United States of America (USA)	0.924	1377	3,911,000	326.76
14	United Kingdom (UK)	0.922	547	301,600	66.57
19	Japan	0.909	841	933,600	127.18
23	South Korea	0.903	1109	497,000	51.16
24	France	0.901	736	436,100	65.23
34	United Arab Emirates (UAE)	0.863	1848	110,600	9.54
40	Saudi Arabia	0.853	1102	292,800	33.55
49	Russia	0.816	854	890,100	143.96
56	Kuwait	0.803	2176	54,110	4.19
High HDI					
79	Brazil	0.759	287	460,800	210.86
86	China	0.752	510	5,920,000	1,415.05
88	Ukraine	0.751	369	133,400	44.01
	World	0.728	370	24,816,000	7,658.82
Medium HDI					
130	India	0.640	128	1,048,000	1,354.05
Low HDI					
158	Rwanda	0.524	4	644	12.50
177	Guinea-Bissau	0.455	2	32	1.91
179	Eritrea	0.440	5	330	5.18
184	Sierra Leone	0.419	3	163	7.72
185	Burundi	0.417	4	304	11.21
186	Chad	0.404	1	200	15.35
187	South Sudan	0.388	6	694	12.91
188	Central African Republic (CAR)	0.367	4	162	4.73
189	Niger	0.354	7	1,072	22.31

* $EEC, \frac{W}{Capita} = \frac{EEC, \frac{TW\,h}{year} \times \frac{10^{12}}{365\ days \times 24\ h}}{Population,\ Millions \times 10^6}$.

** HDI – Human Development Index by United Nations (UN); HDI is a comparative measure of life expectancy, literacy, education and standards of living for countries worldwide. HDI is calculated by the following formula: HDI= $\sqrt[3]{LEI \times EI \times II}$, where LEI - Life Expectancy Index, EI - Education Index, and II - Income Index. It is used to distinguish whether the country is a developed, a developing or an under-developed country, and also to measure the impact of economic policies on quality of life. Countries fall into four broad human-development categories, each of which comprises ~42 countries: 1) Very high – 42 countries; 2) high – 43; 3) medium – 42; and 4) low – 42 (Wikipedia, 2014).

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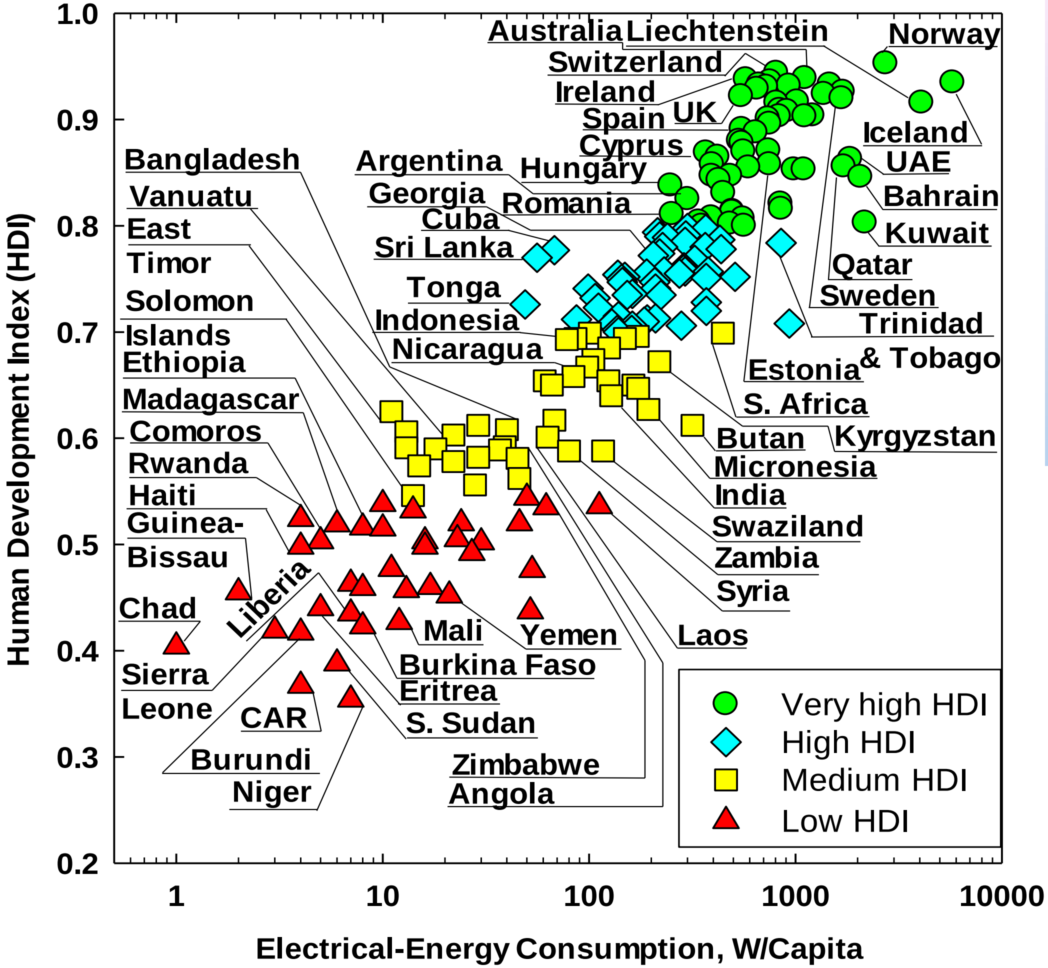
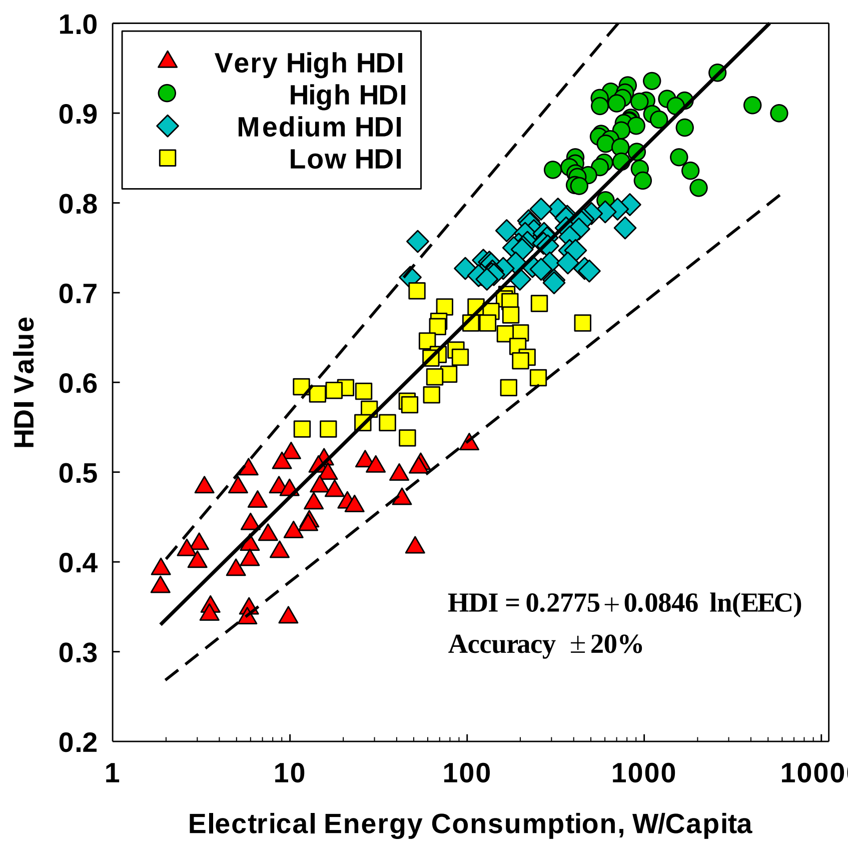


Human Development Index (HDI)
Electrical-Energy Consumption, W/Capita
Australia
Liechtenstein
Norway
Switzerland
Ireland
Spain
UK
Cyprus
Iceland
UAE
Bahrain
Kuwait
Qatar
Sweden
Trinidad & Tobago
Estonia
S. Africa
Kyrgyzstan
Bangladesh
Vanuatu
East Timor
Solomon Islands
Ethiopia
Madagascar
Comoros
Rwanda
Haiti
Guinea-Bissau
Chad
Sierra Leone
Liberia
CAR
Burundi
Niger
Argentina
Hungary
Georgia
Romania
Cuba
Sri Lanka
Tonga
Indonesia
Nicaragua
Butan
Micronesia
India
Swaziland
Zambia
Syria
Laos
Mali
Yemen
Burkina Faso
Eritrea
S. Sudan
Zimbabwe
Angola
Very high HDI
High HDI
Medium HDI
Low HDI



HDI Value
Electrical Energy Consumption, W/Capita
Very High HDI
High HDI
Medium HDI
Low HDI
HDI = 0.2775 + 0.0846 ln(EEC)
Accuracy ± 20%

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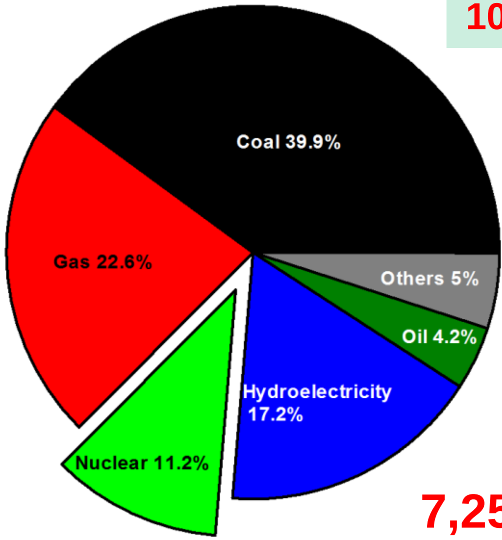
Electricity production by source in the world & selected countries

(upper row: all data from 2013–2014; lower row: data for diagrams from 2016, for HDI & Rank from 2015)

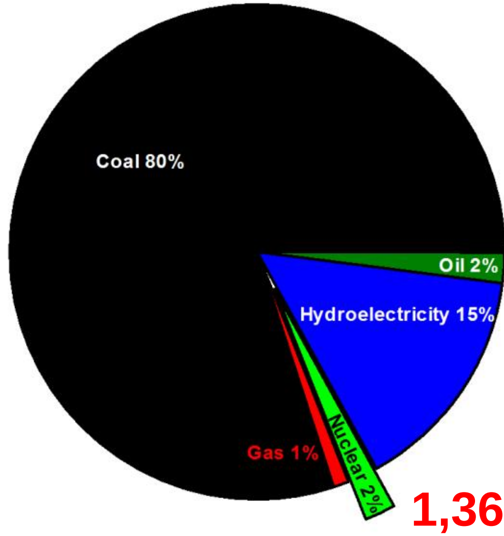
(population in millions: upper row from 2014; lower row from November 2018)

World, 310 W/capita, HDI Rank 103



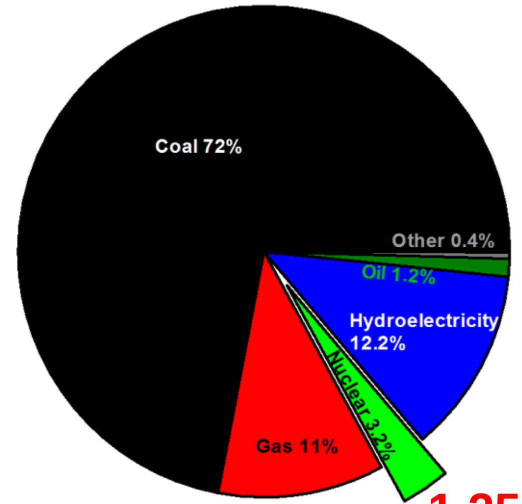
7,256

China, 461 W/capita, HDI Rank 90



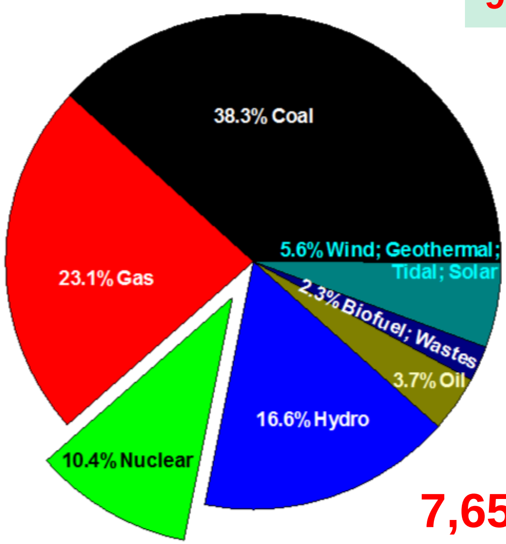
1,367

India, 79 W/capita, HDI Rank 130



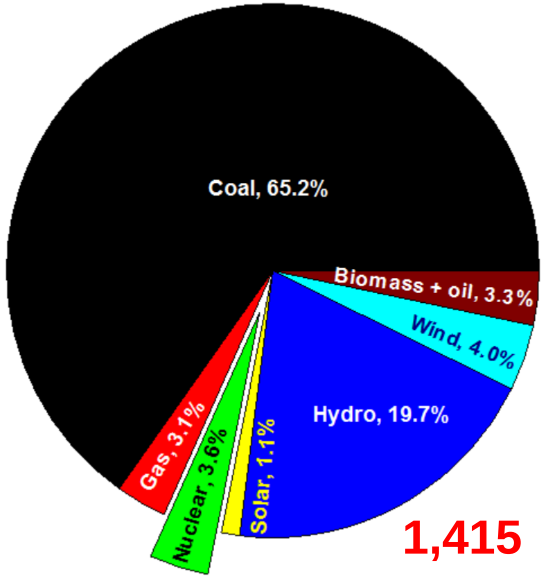
1,252

World, 372 W/capita, HDI Rank 98



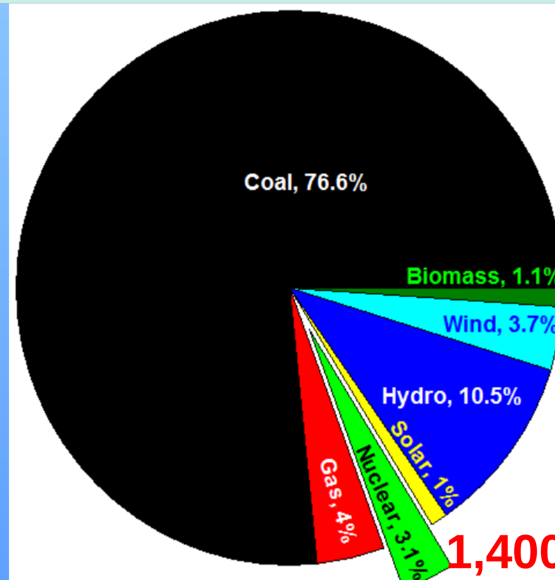
7,659

China, 510 W/capita, HDI Rank 86



1,415

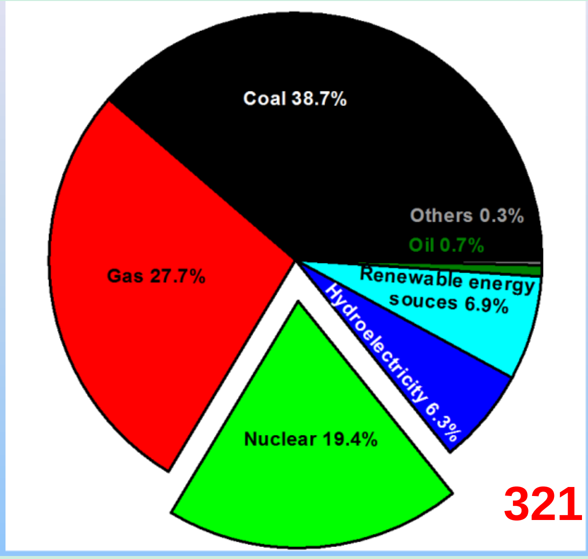
India, 114 W/capita, HDI Rank 130



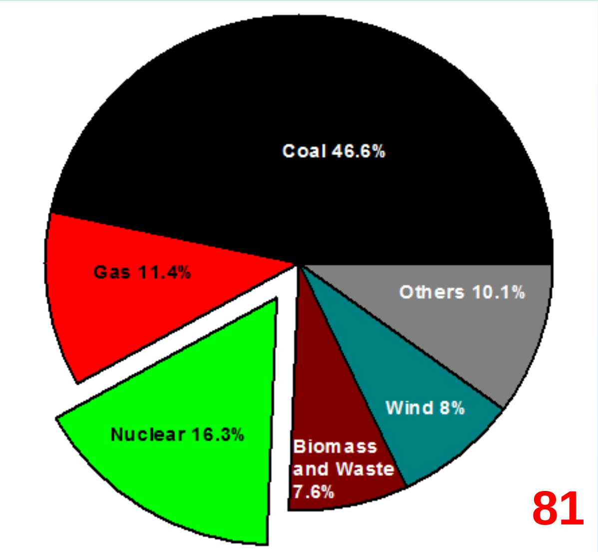
1,400

Electricity production by source in the world & selected countries
(upper row: all data from 2013–2014; lower row: data for diagrams from 2016, for HDI & Rank from 2015)
(population in millions: upper row from 2014; lower row from January 2018)

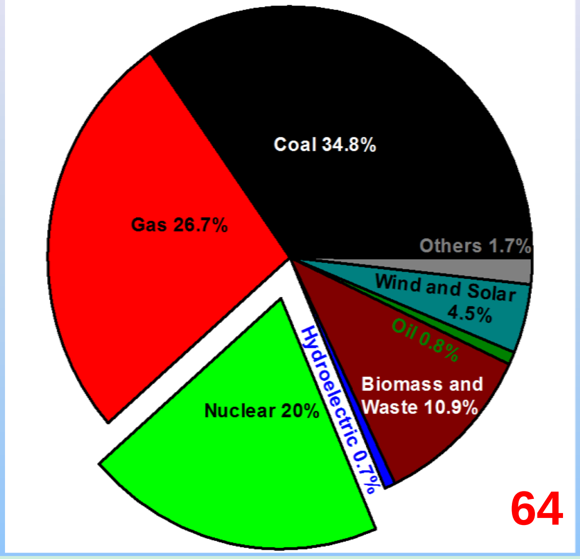
USA, 1360 W/capita, HDI Rank 8



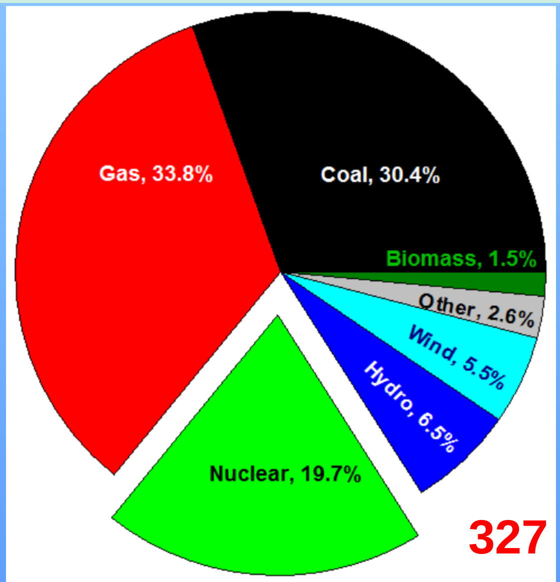
Germany, 762 W/capita, HDI Rank 6



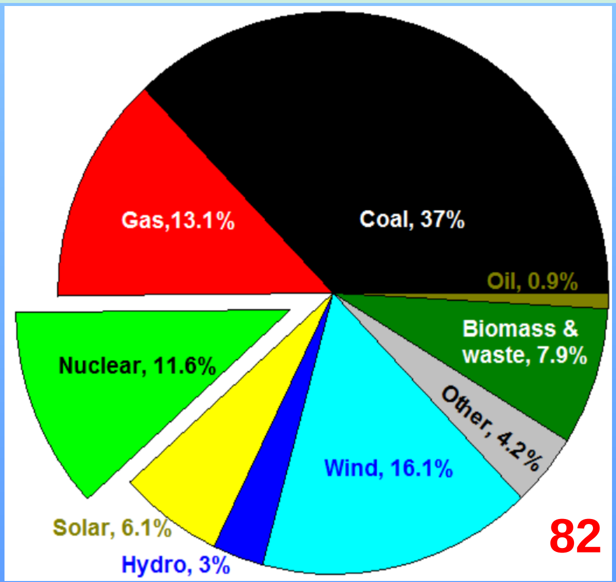
UK, 568 W/capita, HDI Rank 14



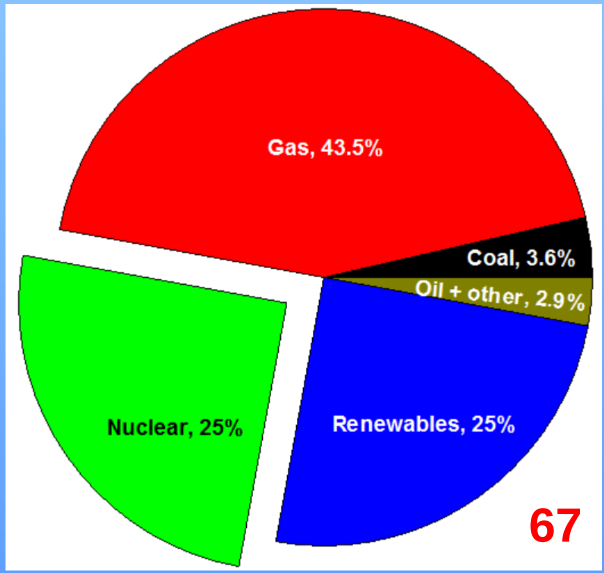
USA, 1377 W/capita, HDI Rank 13



Germany, 753 W/capita, HDI Rank 5



UK, 547 W/capita, HDI Rank 14

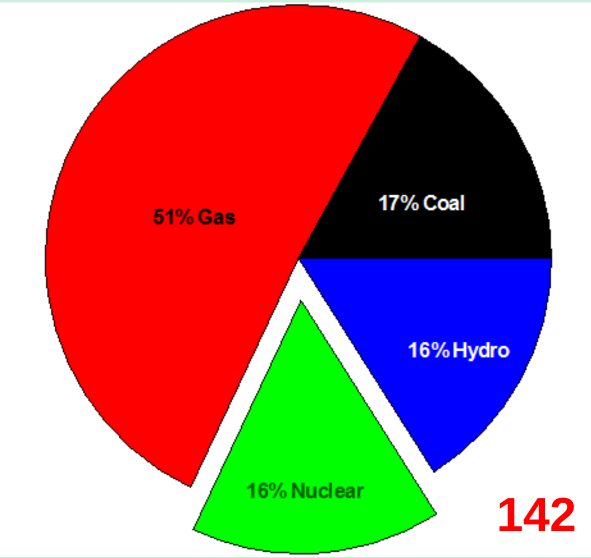


Electricity production by source in the world & selected countries

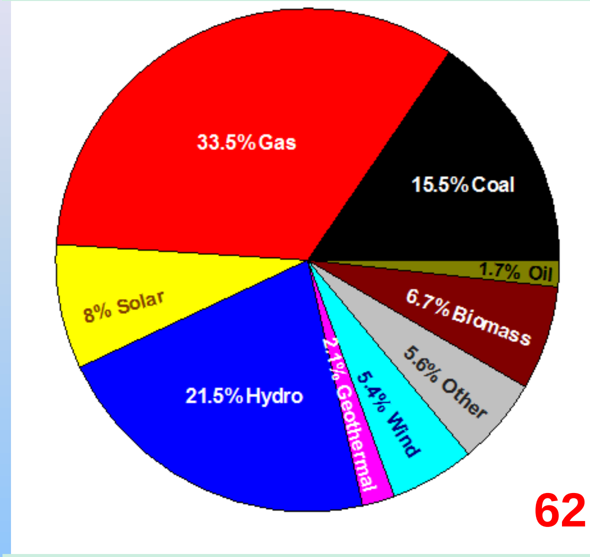
(upper row: all data from 2013–2014; lower row: data for diagrams from 2016, for HDI & Rank from 2015)

(population in millions: upper row from 2014; lower row from January 2018)

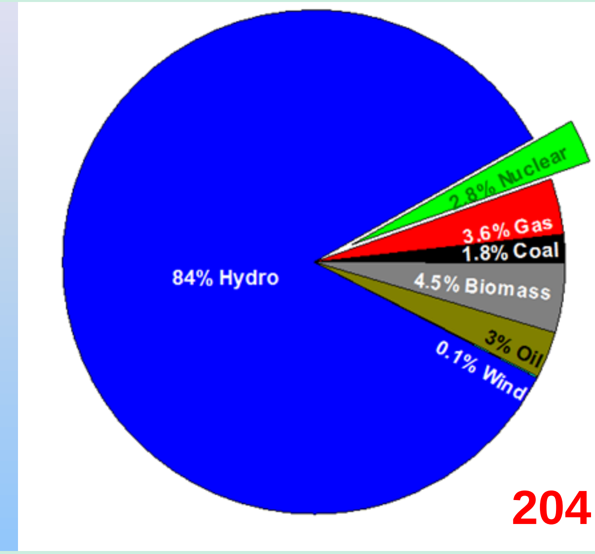
Russia, 831 W/capita, HDI Rank 50



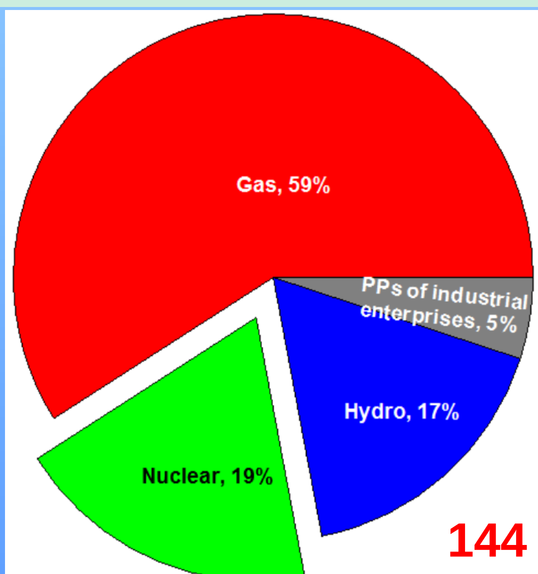
Italy, 559 W/capita, HDI Rank 27



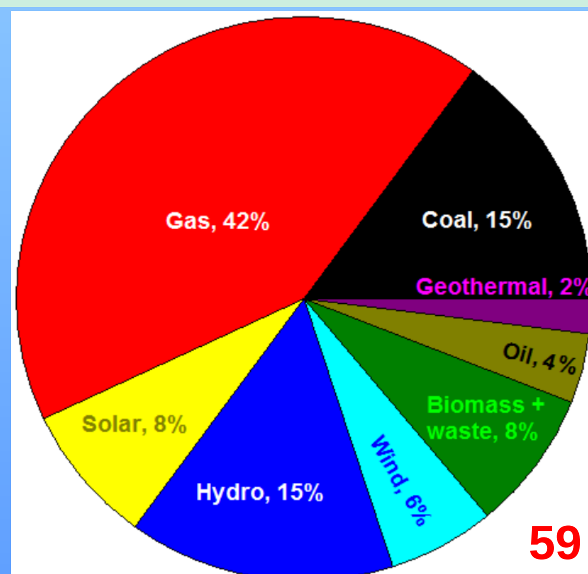
Brazil, 270 W/capita, HDI Rank 75



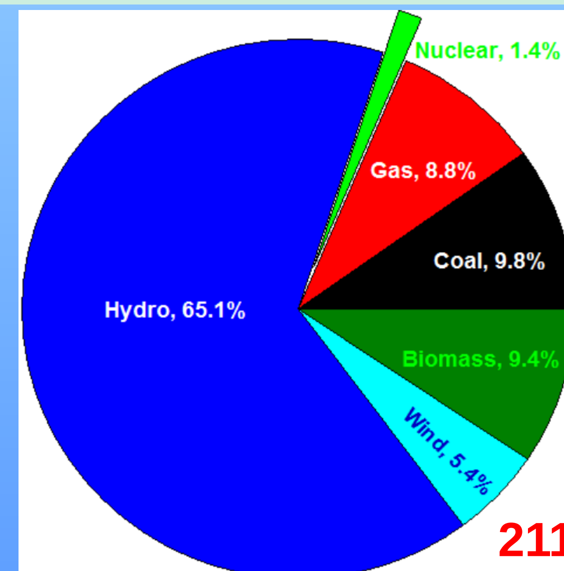
Russia, 854 W/capita, HDI Rank 49



Italy, 535 W/capita, HDI Rank 28



Brazil, 287 W/capita, HDI Rank 79

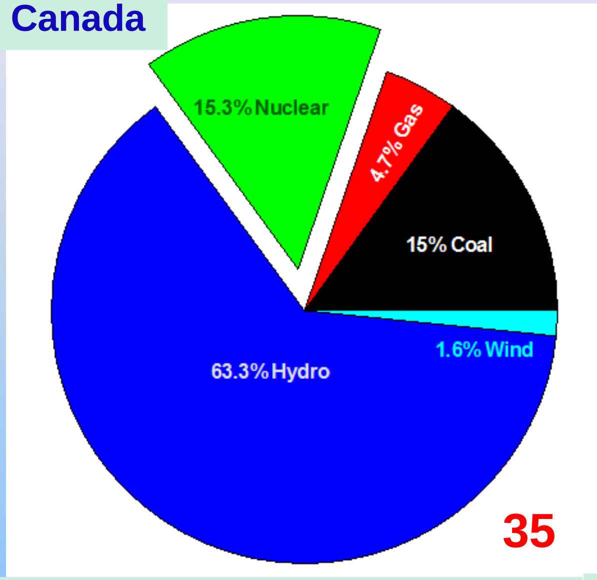


Electricity production by source in the world & selected countries

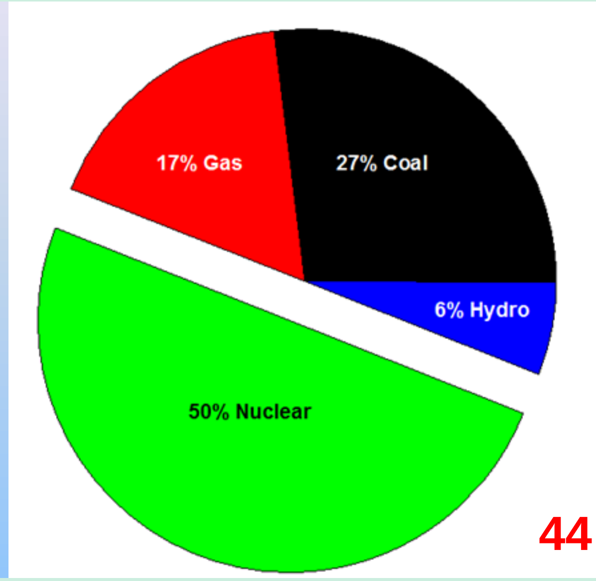
(upper row: all data from 2013–2014; lower row: data for diagrams from 2016, for HDI & Rank from 2015)

(population in millions: upper row from 2014; lower row from January 2018)

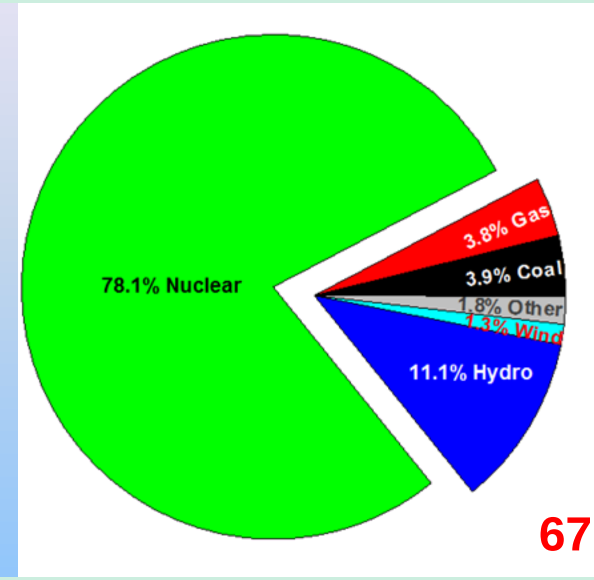
Canada, 1706 W/capita, HDI Rank 9



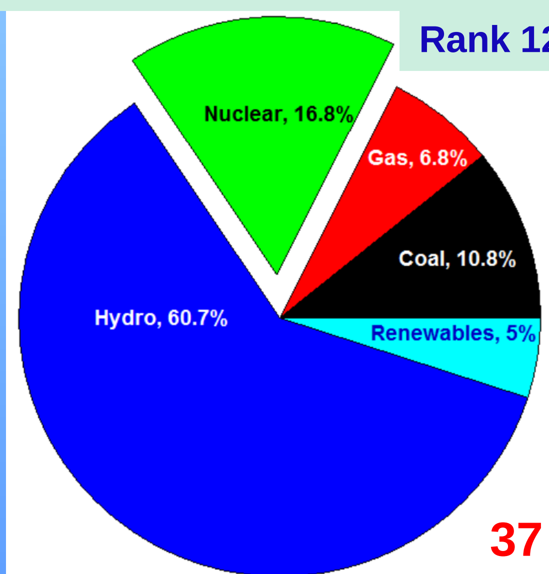
Ukraine, 410 W/capita, HDI Rank 81



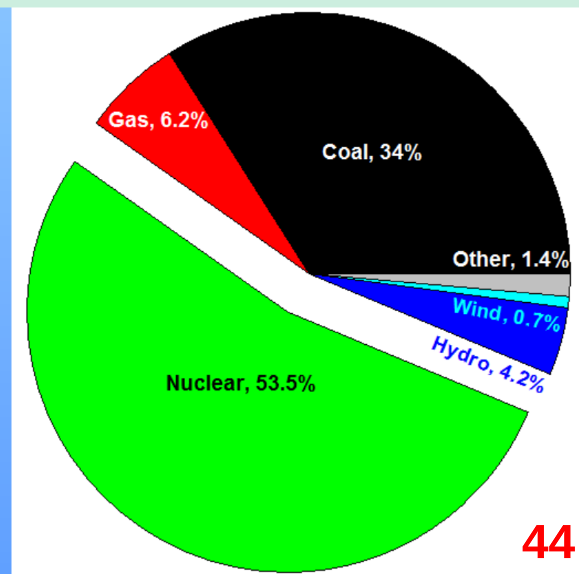
France, 773 W/capita, HDI Rank 22



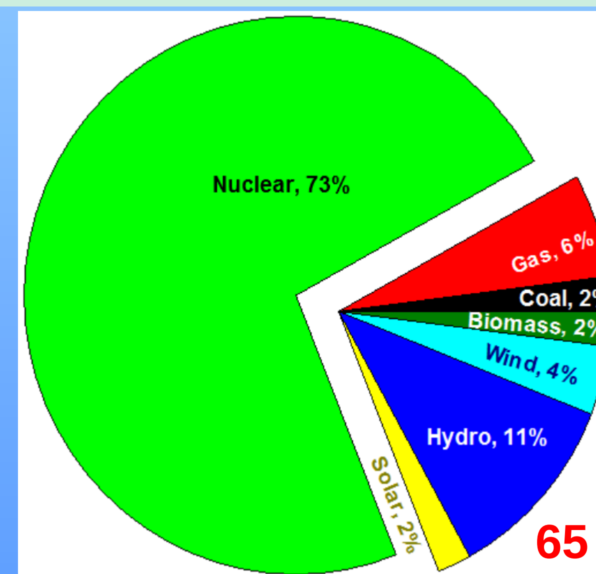
Canada, 1704 W/capita, HDI Rank 12



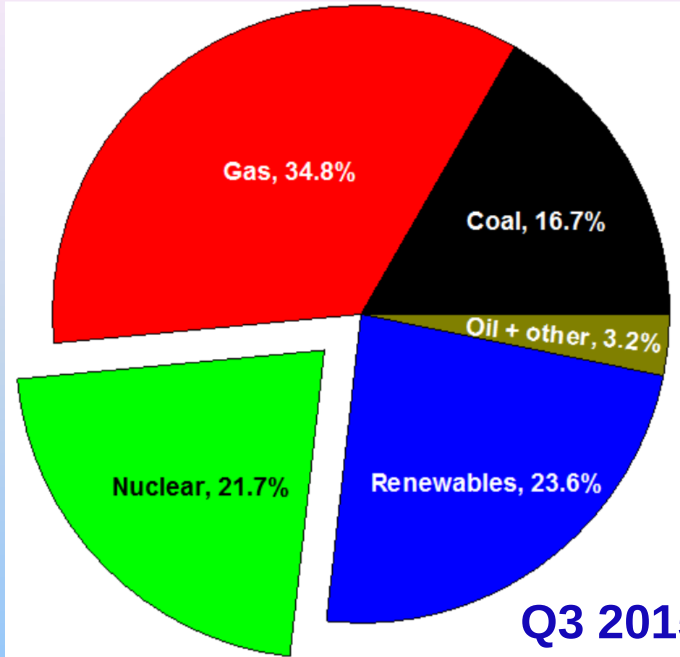
Ukraine, 369 W/capita, HDI Rank 88



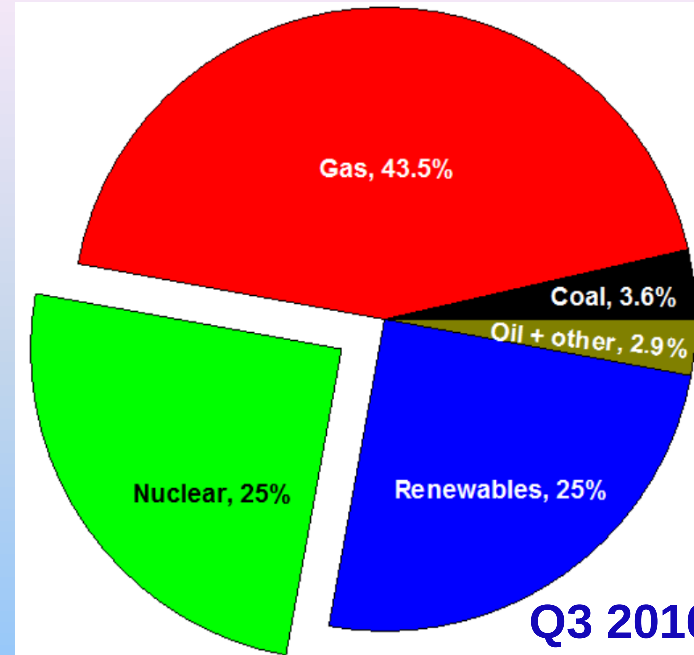
France, 736 W/capita, HDI Rank 24



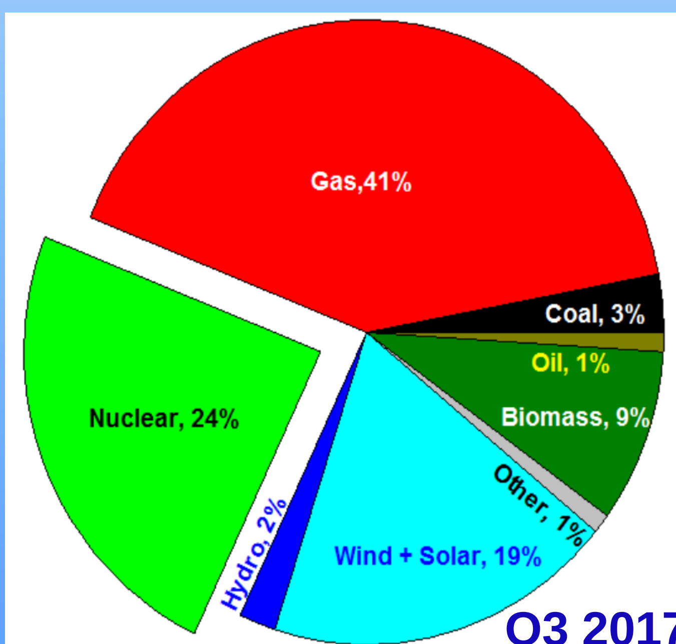
Changes in electricity generation in UK by source within 2015 - 2017



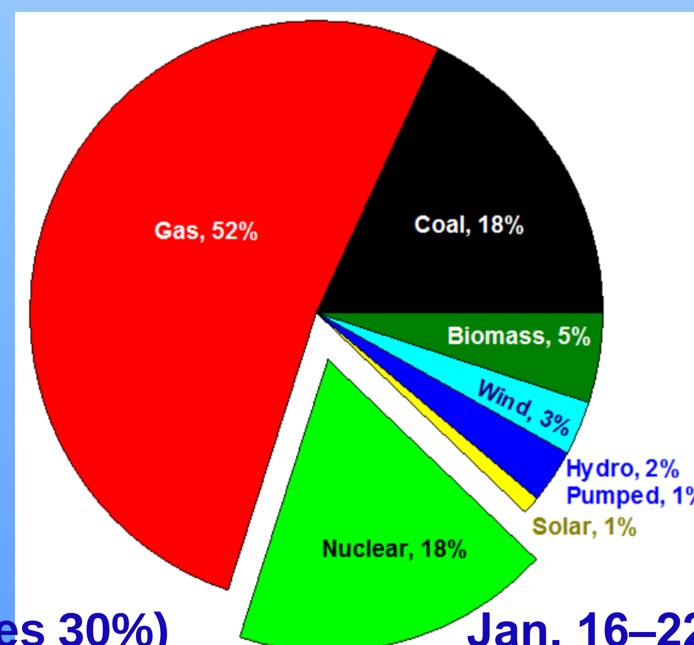
Q3 2015



Q3 2016



Q3 2017 (renewables 30%)



Jan. 16–22, 2017

Sources for data in previous slides with sector diagrams

Population – data for 2018: http://www.worldometers.info/world-population/population-by-country/

EEC in TW h – data for 2016: https://en.wikipedia.org/wiki/List_of_countries_by_electricity_production

HDI report 2017, but data for 2015:

https://en.wikipedia.org/wiki/List_of_countries_by_Human_Development_Index

https://www.cia.gov/library/publications/the-world-factbook/rankorder/2233rank.html

Data in diagrams for UK for 2015 – 2017:

http://euanmearns.com/uk-grid-january-2017-and-the-perfect-storm/

https://www.ofgem.gov.uk/data-portal/electricity-generation-mix-quarter-and-fuel-source-gb

https://utilityweek.co.uk/low-carbon-generation-supplies-half-britains-power/

Top 20 Largest Power Plants of the World

No	Plant	Country	Capacity MW_{el}	Ave. annual generation, TW h_{year}	Capacity factor, %	Plant type
1	Three Gorges Dam*	China	22,500	93.5_{2016}	47	Hydro
2	Itaipu Dam*	Brazil/Paraguay	14,000	103.1_{2016}	84	Hydro
3	Xiluodu*	China	13,860	55.2_{2015}	46	Hydro
4	Guri Dam	Venezuela	10,235	$47_{average}$	52	Hydro
5	Tucurui Dam	Brazil	8,370	21.4_{1999}	29	Hydro
6	Kashiwazaki-Kariwa (not in service)	Japan	7,965	(60.3_{1999})	(86)	Nuclear
7	Robert-Bourassa Dam	Canada	7,722	$26.5_{average}$	39	
8	Grand Coulee Dam	USA	6,809	$20.2_{average}$	34	Hydro
9	Xiangjiaba	China	6,448	30.7_{2015}	54	Hydro
10	Longtan Dam	China	6,426	17.3_{2015}	31	Hydro
11	Sayano-Shushenskaya	Russia	6,400	26.9_{2016}	48	Hydro
12	Bruce	Canada	6,384	47.6_{2015}	85	Nuclear
13	Kori	South Korea	6,040	39.3_{2015}	74	Hydro
14	Krasnoyarsk Dam	Russia	6,000	$18.4_{average}$	35	Hydro
15	Hanul	South Korea	5,928	48.2	93	Nuclear
16	Hanbit	South Korea	5,875	47.6	93	Nuclear
17	Nuozhadu Dam	China	5,850	$23.9_{estimate}$	47	Hydro
18	Zaporizhia	Ukraine	5,700	48.2	96	Nuclear
19	Kashima	Japan	5,660	–	–	Fuel oil, nat. gas
20	Shoaiba	Saudi Arabia	5,600	–	–	Fuel oil

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

Largest power plants by energy source

Rank	Plant	Country	Capacity, MW_{el}	Plant type
1	Three Gorges Dam	China	22 500	Hydro (dam)
2	Bruce NPP	Canada	6384	Nuclear
3	Taichung	Taiwan	5780	Coal
4	Shoaiba	S. Arabia	5600	Fuel oil
5	Surgut-2*	Russia	5597	Natural gas
6	Gansu	China	5160	Wind (onshore)
7	Jirau	Brazil	3,750	Hydro (run-of-the-river)
8	Bath County**	USA	3003	Hydro (pumped storage)
9	Eesti	Estonia	1615	Oil shale
10	Tengger Desert Solar Park	China	1547	Solar (flat panel Photo-Voltaic (PV))
11	The Geysers	USA	1517	Geothermal
12	Shatura*	Russia	1500	Peat*
13	Ironbridge	UK	740	Biofuel*
14	Walney	UK	659	Wind (offshore)
15	IPP3*	Jordan	573	Internal combustion engines
16	Ivanpah	USA	392	Solar (concentrated thermal)
17	Sihwa Lake	S. Korea	254	Tidal
18	Vasavi Basin Bridge	India	200	Diesel
19	Golmund 2	China	60	Concentrated Photo-Voltaic (CPV)
20	Sotenäs	Sweden	3	Marine (wave)

Thermal Efficiencies (Gross) of Thermal and Nuclear Power Plants

No	Plant	Eff., %
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}≈2.5 MPa, T_{in}≈1650°C) and Rankine steam-turbine cycle (steam parameters at turbine inlet: P_{in}≈12.5 MPa (P_{cr}=22.064 MPa), T_{in}≈620°C (T_{cr}=374°C))	Up to 62
2	Supercritical-pressure coal-fired power plant (Rankine-cycle steam inlet turbine parameters: P_{in}≈25–38 MPa (P_{cr}=22.064 MPa), T_{in}≈540-625°C (T_{cr}=374°C); and P_{reheat}≈4-6 MPa, T_{reheat}≈540-625°C)	Up to 55
3	Internal-combustion-engine generators (Diesel cycle and Otto cycle with natural gas as a fuel)	Up to 50
4	Subcritical-pressure coal-fired power plant (older plants; Rankine-cycle steam: P_{in} = 17 MPa, T_{in} = 540°C (T_{cr} = 374°C); and P_{reheat}≈3-5 MPa, T_{reheat} = 540°C)	Up to 43
5	Carbon-dioxide-cooled reactor NPP (Generation-III) (reactor coolant: P=4 MPa, T=290–650°C; and steam: P_{in}=17 MPa (T_{sat}=352°C) & T_{in}=560°C; and P_{reheat}≈4 MPa, T_{reheat} = 560°C)	Up to 42
6	Sodium-cooled Fast Reactor (BN-600 / BN-800) NPP (steam: P_{in}=14.2 MPa (T_{sat}=338°C), T_{in}=505°C; and P_{reheat}≈2.5 MPa, T_{reheat}=505°C)	Up to 40
7	Pressurized-Water-Reactor NPP (Generation-III+) (reactor coolant: P=15.5 MPa, T_{out}=327°C; steam: P_{in}=7.8 MPa, T_{in}=293°C; and P_{reheat}≈2 MPa, T_{reheat}≈265°C)	Up to 36-38
8	Pressurized-Water-Reactor NPP (Generation-III, current fleet) (reactor coolant: P=15.5 MPa, T_{out}=292–329°C; steam: P_{in}=6.9 MPa, T_{in}=285°C; and P_{reheat}≈1.5 MPa, T_{reheat}≈255°C)	Up to 34-36
9	Boiling-Water-Reactor NPP (Generation-III, current fleet) (P_{in}=7.2 MPa, T_{in}=288°C; and P_{reheat}≈1.7 MPa, T_{reheat}≈258°C)	Up to 34
10	Pressurized Heavy Water Reactor NPP (Generation-III, current fleet) (reactor coolant: P=11 MPa & T=260–310°C; steam: P_{in}=4.7 MPa, T_{in}=260°C; and P_{reheat}≈0.6 MPa, T_{reheat}≈250°C)	Up to 32

Gross thermal efficiency of a unit during a given period of time is the ratio of the gross electrical energy generated by a unit to the thermal energy of a fuel consumed during the same period by the same unit. The difference between gross and net thermal efficiencies includes internal needs for electrical energy of a power plant, which might be not so small; for example, for a medium gross capacity (~500 MW_{el}) supercritical-pressure coal-fired power plant the internal needs can be about 40 MW_{el} or 8% of the total electrical capacity.

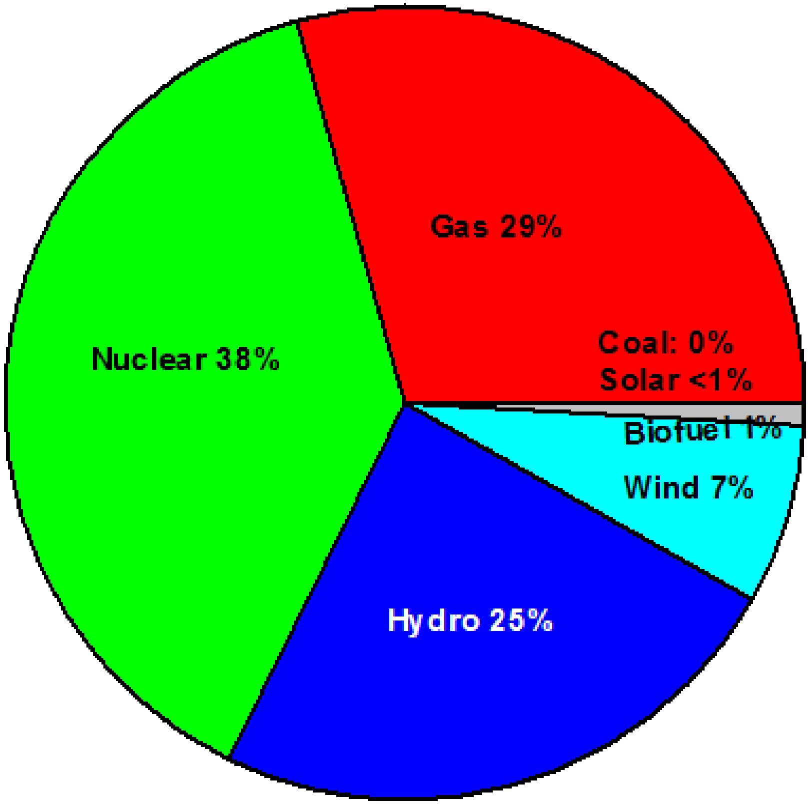
Average (typical) capacity factors[1] of various power plants (Wikipedia, 2018)

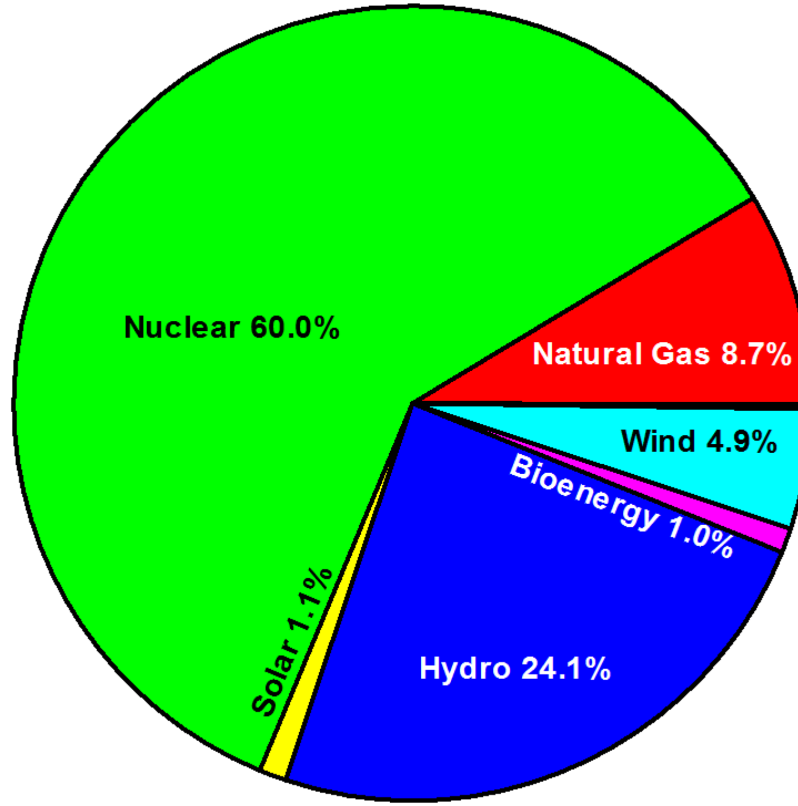
[1] The net capacity factor of a power plant (Wikipedia, 2012) is the ratio of the actual output of a power plant over a period of time and its potential output if it had operated at full nameplate capacity the entire time. To calculate the capacity factor, take the total amount of energy the plant produced during a period of time and divide by the amount of energy the plant would have produced at full capacity. Capacity factors vary significantly depending on the type of fuel that is used and the design of the plant.

No.	Power Plant type	Location	Year	Capacity factor, %
1	Nuclear	USA	2017	92
		Russia	2014	81
		UK	2015	75
		World	2017	81
2	Geothermal	USA	2017	76
3	Bioenergy	USA	2017	51-71
4	Combined-cycle	USA	2017	55
5	Coal-fired	USA	2017	54
6	Hydroelectric[1]	USA	2017	45
		World (average)	-	~45
		World (range)	-	10-99
7	Wind	USA	2017	37
		World	2011-2013	20-40
8	Concentrated-solar thermal	USA California	2017	22
		Spain (molten salt with storage)	2014	63
9	Photovoltaic (PV) solar	USA	2017	27
		UK	2015	12
10	Concentrated solar photovoltaic	Spain	-	12
11	Wave	UK	2015	3

[2] Capacity factors depend significantly on a design, size and location (water availability) of a hydroelectric power plant. Small plants built on large rivers will always have enough water to operate at a full capacity.

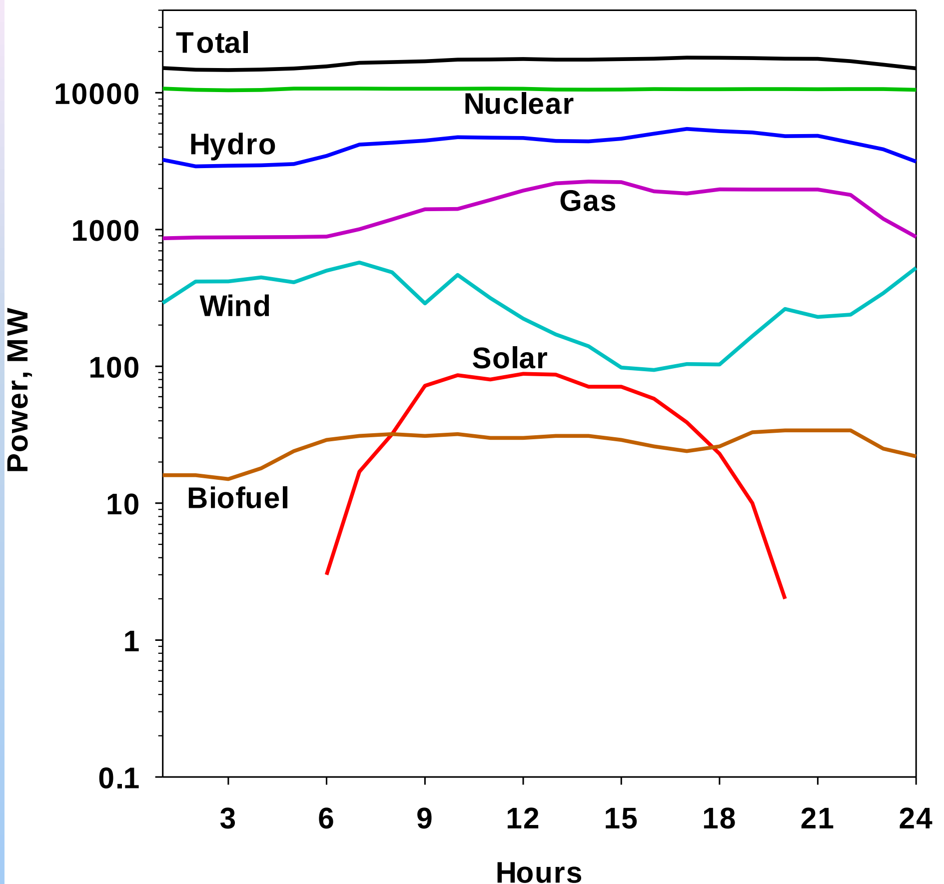
[3] Based on information from Torresol Energy (Spain) their Gemasolar a 19.9-MW_{el} concentrated solar power plant with a 140-m high tower, molten-salt heat-storage system and Rankine power cycle (Seville, Spain) has the capacity factor of 75%.

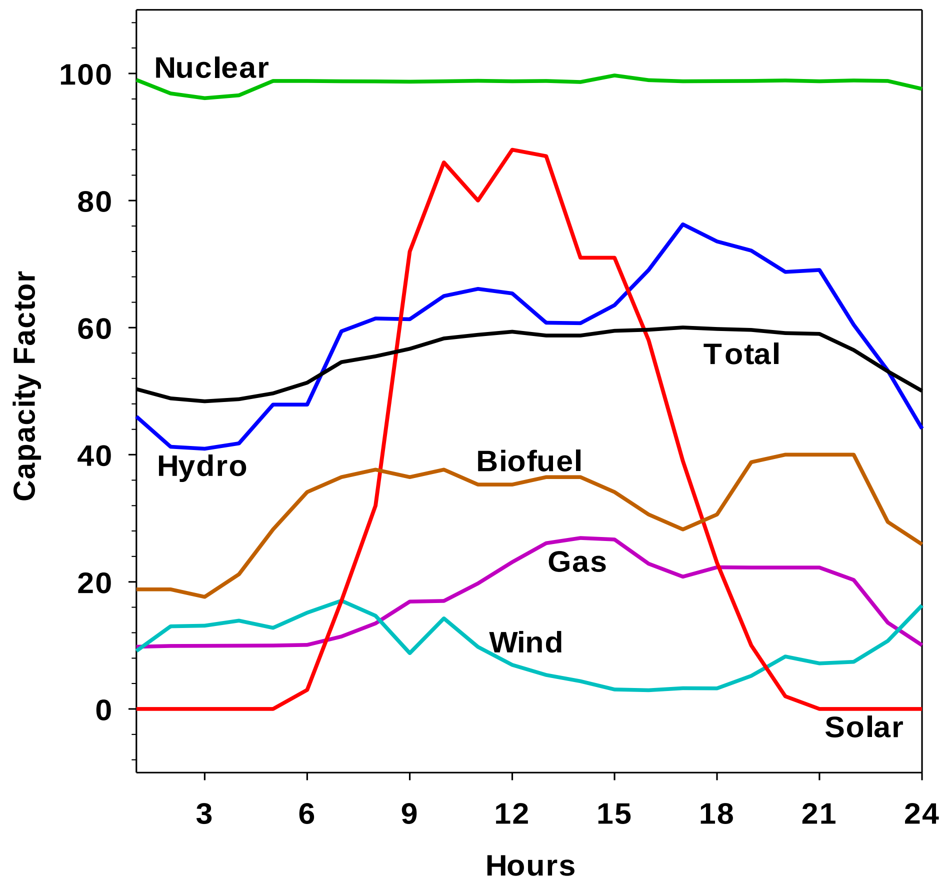




Installed capacity by energy source **Electricity generation by energy source**

Province of Ontario (Canada), 2014-2015 (population 14 million)
(based on data from Ontario Power Authority: http://www.powerauthority.on.ca and Ontario's Long-Term Energy Plan)





Power generated by various sources in Ontario on June 17 (Wednesday), 2015

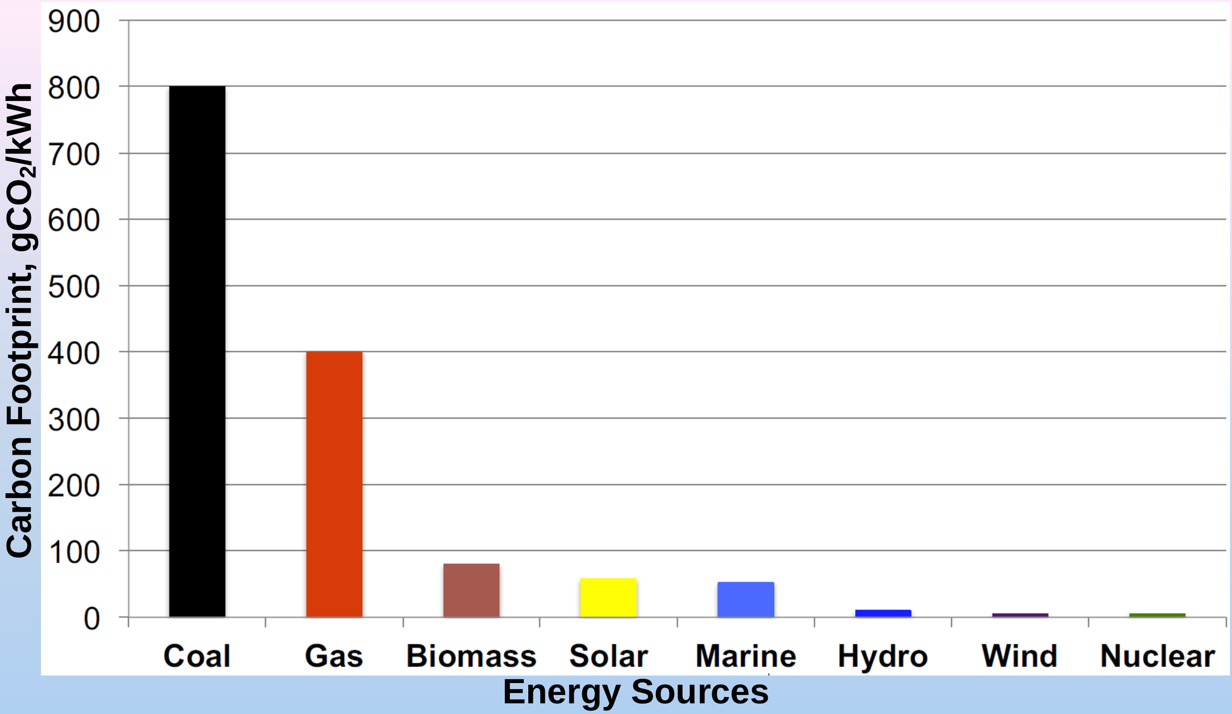
Capacity factors of various power sources in Ontario on June 17 (Wednesday), 2015

(based on data from: http://ieso.ca/imoweb/marketdata/genEnergy.asp)

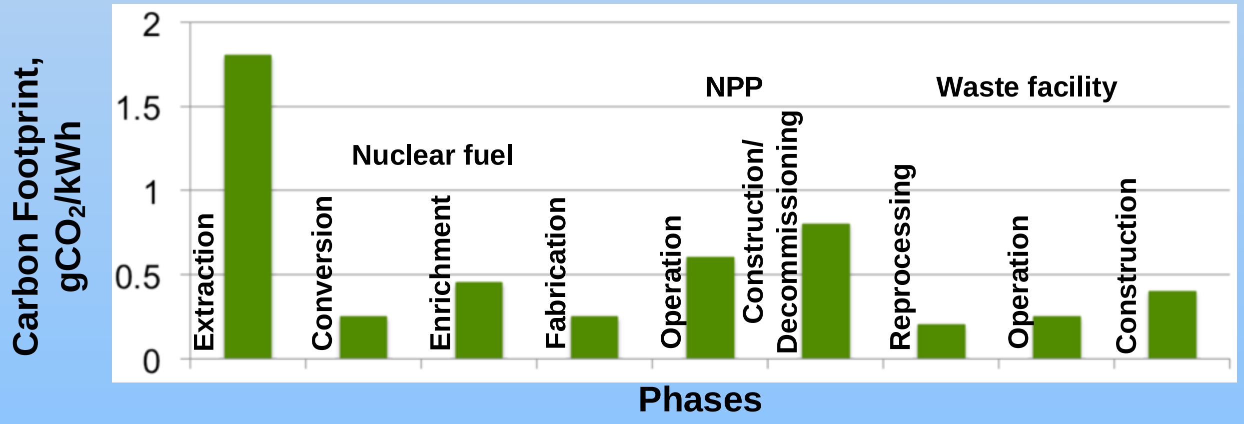
The major advantages of nuclear power are:

1. **Concentrated and reliable source of almost infinite energy, which is independent of weather conditions (however, it should be noted that in summer of 2018, which was very hot on a record due to fast climate changes, some reactors / NPPs were forced to decrease power load or even were shut down for some time, because of lower levels of water in rivers, etc. and/or of relatively high water temperatures including not only in-land water resources, but, also, sea / ocean waters);**
2. **High capacity factors are achievable, often in excess of 90% with long operating cycles, making units suitable for continuous base-load operation;**
3. **Essentially negligible operating emissions of carbon dioxide and relatively small amount of wastes generated compared to alternate fossil-fuel thermal power plants;**
4. **Relatively small amount of fuel required compared to that of fossil-fuel thermal power plants; and**
5. **NPPs can supply relatively cheap electricity for re-charging of electrical vehicles during night hours as they usually operate on full load (capacity) 24/7.**

As a result, nuclear power is considered as the most viable source for electricity generation within next 50 – 100 years. However, nuclear power must operate and compete in energy markets based on relative costs and strategic advantages of the available fuels and energy types.



Carbon footprint for various energy sources (courtesy of Dr. J. Roberts, University of Manchester, UK; based on data from [27]). If Carbon Capture and Storage (CCS) is used then the carbon footprint can be decreased for coal by about 6 fold and for gas about 6 fold.



Carbon footprint of nuclear power plant various phases (courtesy of Dr. J. Roberts, University of Manchester, UK; based on data from British Energy for Torness AGR NPP)

Approximate volumes of wastes per 1,000 MW_{el} power per year for nuclear and coal-fired power plants (courtesy of Dr. J. Roberts, University of Manchester, UK).

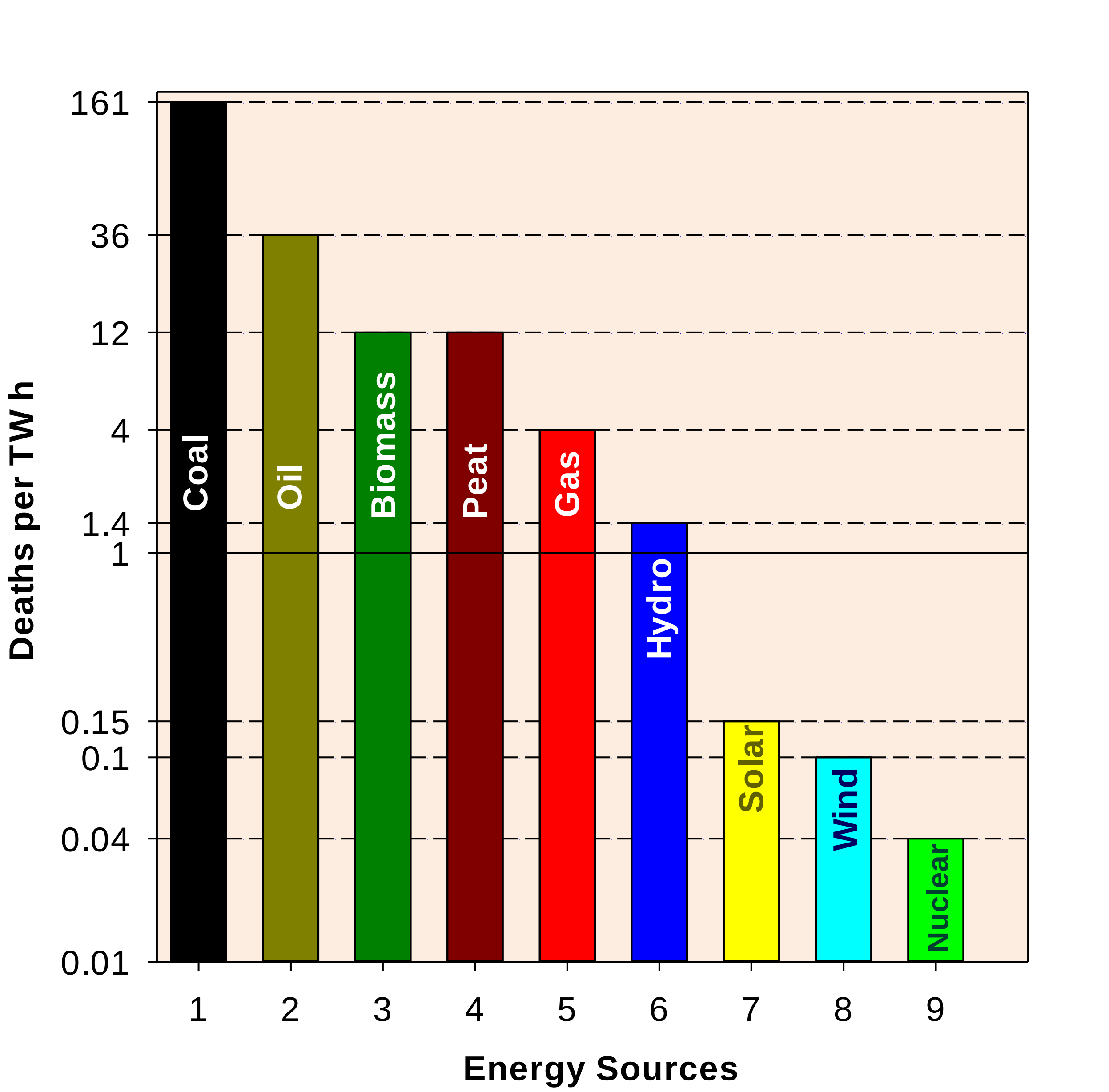
Nuclear Power Plant	Coal-fired Power Plant
Fuel	
25 t of UO_2	2.6 million t of coal (5 × 1400 t trains a day)
Wastes	
35 t High Level Wastes (HLW) 310 t Intermediate Level Wastes (ILW) 460 t Low Level Wastes (LLW)	6 500 000 t of CO_2 900 t of SO_2 4 500 t of NO_x 320 000 t of ash 400 t of toxic heavy metals

Table. Per cent of various wastes in total amount (courtesy of Dr. J. Roberts, University of Manchester, UK; partially based on data from: https://publications.parliament.uk/pa/cm200405/cmselect/cmenvfru/130/130we13.htm).

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

Comparison of selected nuclear-power-plant parameters to those of onshore wind farm (courtesy of Dr. J. Roberts, University of Manchester, UK).

Parameters	NPP	Onshore Wind Farm
Carbon saved	86/100	90/100
Energy density	75/100	10/100
Reliability	90/100	20/100



Deaths per TWh for various energy sources (based on data from https://www.nextbigfuture.com/2011/03/deaths-per-twh-by-energy-source.html).

Casualties due to various accidents in power and chemical industries, transportation and from firearms (source: Wikipedia, 2018)

No.	Accidents / Causes of death	Year	Region	No of deaths
1	Fukushima NPP accident (deaths due to earthquake, not radiation)	2011	Japan	Few workers
2	Chernobyl NPP accident	1986[1]	Ukraine	56
		1986-now[2]		>4,000
3	Kyshtym radiation-release accident (Chelyabinsk region)	1957[3]	Russia	>>200
4	Sayano-Shushenskaya hydro-plant accident (6,000 MW_{el})	2009	Russia	75
5	Banqiao Dam[4]	1975	China	>26,000
6	Vajont Dam	1963	Italy	~2,000
7	Bhopal Union Carbide India Ltd. accident	1984	India	
	Immediate deaths (official data) / By Government of Madhya Pradesh			2,259 / 3,787
	Other estimations (since the disaster)			8,000
	No. of people exposed to methyl iso-cyanate gas and other chemicals			500,000
8	Car accidents[5] (in (…) population in millions)	Annually / daily	World (7,660)	~1,300,000 / ~3560
		2013	USA (316)	33,808
		2013	EU (503)	26,000
9	Shipwreck accidents	2011	World	3,335
10	Railway accidents	2009	EU	1,428
11	Air accidents[6]	2017 (9 accidents)	World	67
		2016 (16 accidents)		303
		2014		~990
		1972		3,344
		11.09.2001	USA New York	>4,500
12	Firearms casualties(~70% suicides and ~30% homicides)	2017	USA	~40,000

[1] 56 direct deaths (47 NPP and emergency workers and 9 children with thyroid cancer), i.e., deaths due to the explosion and initial radiation release.

[2] Deaths from cancer, heart disease, birth defects (in victims' children) and other causes, which may result from exposure to radiation. Various sources provide significantly different estimations starting from 30,000-60,000 casualties and up to 200,000 and even up to 985,000 casualties. However, these deaths may also result from other causes not related to the accident, for example, pollution from non-nuclear sources - industry, transportation; etc. In general, accurate estimation of all deaths related to the Chernobyl NPP accident is impossible.

[3] It is impossible to estimate accurately all casualties. Other sources estimate casualties from cancer within 30 years after the accident up to 8,000.

[4] Also, 145,000 died during subsequent epidemics & famine. Other sources estimate casualties as high as 230,000. About 11 million residents were affected.

[5] In addition to car fatalities ~50 million people become invalid annually in the world. Therefore, driving a car is a quite dangerous mode of travel!

[6] In 2000, commercial air carriers transported about 1.1 billion people on 18 million flights, while suffering only 20 fatal accidents. Therefore, air transportation remains among the safest modes of travel.

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

Number of nuclear-power reactors in operation and forthcoming as per June 2019 and before the Japan earthquake and tsunami disaster (March 2011) (Nuclear News, ANS)

No	Reactor type (Some details on reactors)	No. of units		Installed capacity, GW_{el}		Forthcoming units	
		As of June 2019	Before March 2011	As of June 2019	Before March 2011	No. of units	GW_{el}
1	Pressurized Water Reactors (PWRs) (largest group of nuclear reactors in the world – 65%)	303 ↑	268	288 ↑	248	75	82
2	Boiling Water Reactors (BWRs) or Advanced BWRs (2nd largest group of reactors in the world – 17%; ABWRs – the only ones Generation-III+ operating reactors)	69 ↓	92	69 ↓	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	6
4	Advanced Gas-cooled Reactors (AGRs) (UK, 14 reactors); (all these CO_2-cooled reactors will be shut down in the nearest future and will not be built again) (3%)	14 ↓	18	8 ↓	9	1*	0.2
5	Light-water, Graphite-moderated Reactors (LGRs) (Russia, 11 RBMKs and 3 EGPs; these pressure-channel boiling-water-cooled reactors will be shut down in the nearest future and will not be built again) (3%)	13 ↓	15	9 ↓	10	0	0
6	Liquid-Metal Fast-Breeder Reactors (LMFBRs) (Russia, SFR – BN-600; only one Generation-IV operating reactor)	2 ↑	1	1.3 ↑	0.6	3	0.6
	In total	449 ↑	444	398 ↑	378	93	97

Data in Table include 38 reactors in Japan, 29 of which are not in service as per June of 2019.
Arrows mean decrease or increase in a number of reactors.
*Forthcoming reactor is a helium-cooled reactor – High Temperature Reactor Pebble-bed Modular (HTR-PM) (China).
In 1990 we had 416 reactors.

Number of nuclear-power reactors by nation (11 nations with the largest number of reactors ranked by installed capacity) as per June of 2019 (Nuclear News, ANS and data from World Nuclear Association (WNA) (http://www.world-nuclear.org/) and before the Japan earthquake and tsunami disaster (March of 2011) (Nuclear News, ANS)

No	Nation	No. of units (PWRs/BWRs)		Installed capacity, GW_{el}		Changes in number of reactors from March 2011
		As of June 2019	Before Mar. 2011	As of June 2019	Before Mar. 2011	
1	USA	97 (65/32)	104	99	103	↓ Decreased by 7 reactors
2	France	58 (58/-)	58	63	63	No changes
3	China	46 (44/-/2[3])	13	43	10	↑ Increased by 33 reactors
4	Japan*	38 (16/22)	54	36	47	↓ Decreased by 16 reactors
5	Russia	36 (21/-/13[1]/2[2])	32	28	23	↑ Increased by 4 reactors
6	S. Korea	24 (21/-/3[3])	20	23	18	↑ Increased by 4 reactors
7	Canada	19 (-/-/19[3])	22	13	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	363 (252/58/13[1]/2[2]/24[3]/14[4])	364	341	331	↓ Decreased by 1 reactor, but installed capacity increased by 10 GW_{el}

[1] Number of LGRs; [2] LMFBRs; [3] PHWRs; [4] AGRs.
Arrows mean decrease or increase in a number of reactors.

*As per June of 2019, only nine PWRs are in operation. In general, 38 reactors are operable and potentially able to restart, and 24 of these reactors are in the process of restart approvals.

Number of nuclear-power reactors by nation (11 nations with the largest number of reactors ranked by installed capacity) as per June of 2019 (Nuclear News, ANS and data from World Nuclear Association (WNA) (http://www.world-nuclear.org/) and in 1990 (based on data from IAEA)

No	Nation	No. of units (PWRs / BWRS)		Installed capacity, GW_{el}		Changes in number of reactors from 1990
		As of June 2019	As of 1990	As of June 2019	As of 1990	
1	USA	97 (65/32)	108	99	96	↓ Decreased by 11 reactors
2	France	58 (58/-)	56	63	56	↑ Increased by 2 reactors
3	China	46 (44/-/2[3])	0	43	0	↑ Increased by 46 reactors
4	Japan*	38 (16/22)	41	36	31	↓ Decreased by 3 reactors
5	Russia	36 (21/-/13[1]/2[2])	29	28	19	↑ Increased by 7 reactors
6	S. Korea	24 (21/-/3[3])	9	23	7	↑ Increased by 15 reactors
7	Canada	19 (-/-/19[3])	20	13	14	↓ Decreased by 1 reactor
8	Ukraine	15 (15/-)	15	13	13	No changes
9	Germany	7 (6/1)	21	10	21	↓ Decreased by 14 reactors
10	Sweden	8 (5/3)	12	9	10	↓ Decreased by 4 reactors
11	UK	15 (1/-/14[4])	37	9	12	↓ Decreased by 22 reactors
	In total	363 (252/58/13[1]/2[2]/24[3]/14[4])	348	341	279	↑ Increased by 15 reactors, and installed capacity increased by 62 GW_{el}

[1] Number of LGRs; [2] LMFBRs; [3] PHWRs; [4] AGRs.
Arrows mean decrease or increase in a number of reactors.

*As per June of 2019, only nine PWRs are in operation. In general, 38 reactors are operable and potentially able to restart, and 24 of these reactors are in the process of restart approvals.

Nuclear-Power Reactors by Nation (as per March of 2019)
(Data based on Nuclear News (ANS), WNA, and IAEA)

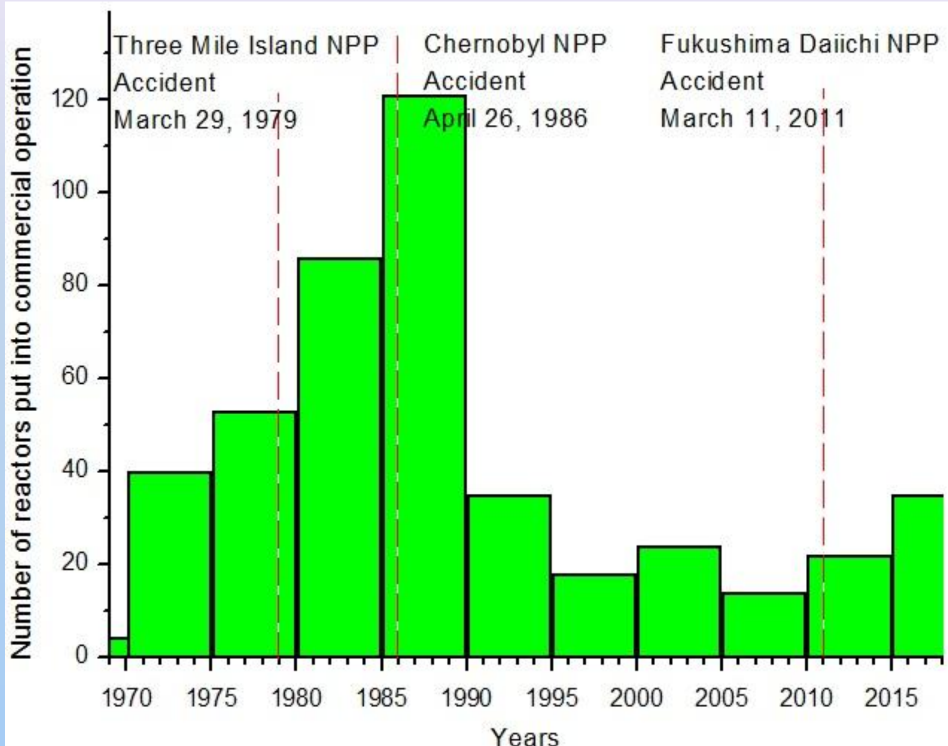
No	Nation	# Units (in operation)	Net MW_{el} (in operation)	# Units (forthcoming)	Net MW_{el} (forthcoming)
1	Argentina	3 (PHWRs)	1,632	1	25
2	Armenia	1 (PWR)	375	0	0
3	Bangladesh	2 (PWRs) (planned)	-	2	2,400
4	Belarus	2 (PWRs) (planned)	-	2	2,218
5	Belgium	7 (PWRs)	5,913	0	0
6	Brazil	2 (PWRs)	1,884	1	1,245
7	Bulgaria	2 (PWRs)	1,926	0	0
8	Canada	19 (PHWRs)	13,554	0	0
9	China	46 (44 PWRs; 2 PHWRs)	42,858	21	22,576
10	Czech Republic	6 (PWRs)	3,930	0	0
11	Egypt	4 (PWRs) (planned)	-	4	4,760
12	Finland	4 (2 PWRs; 2 BWRs)	2,764	2	2,800
13	France	58 (PWRs)	63,130	1	1,600
14	Germany	7 (6 PWRs; 1 BWRs)	9,515	0	0
15	Hungary	4 (PWRs)	1,889	2	2,400
16	India	22 (18 PHWRs; 2 BWRs; 2 PWR)	6,225	8	5,187
17	Iran	1 (PWR)	915	2	2,000
18	Japan	38 (16 PWRs; 18 BWRs; 4 ABWRs)	36,445	2	2,650
19	Mexico	2 (BWRs)	1,552	0	0
20	Netherlands	1 (PWR)	482	0	0
21	Pakistan	5 (4 PWRs; 1 PHWR)	1,320	3	3,028
22	Romania	2 (PHWRs)	1,300	2	1,440

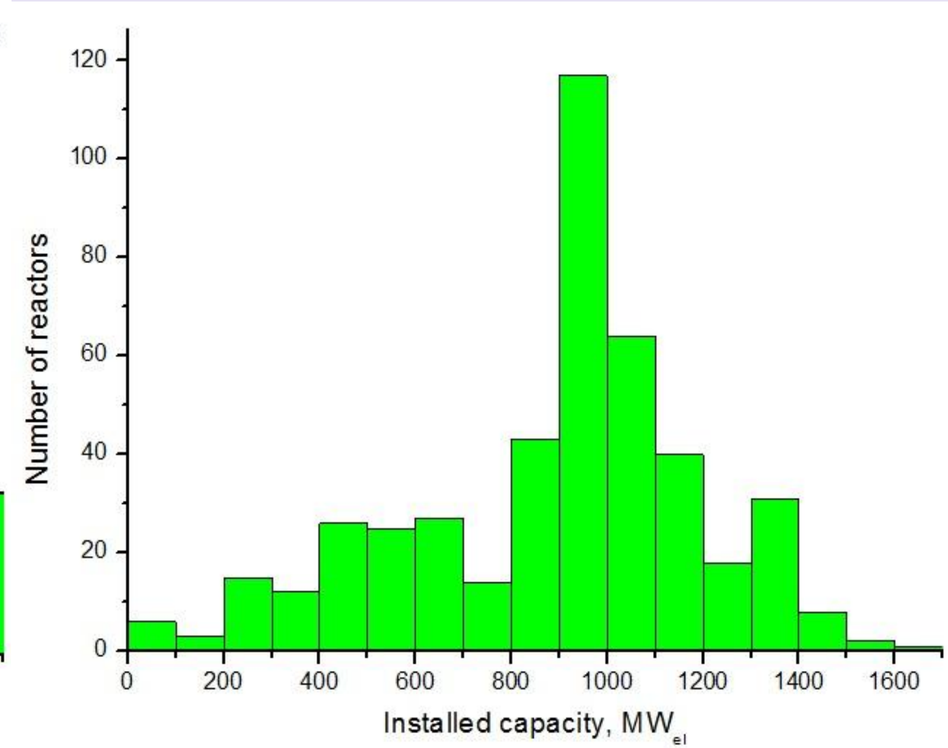
Nuclear-Power Reactors by Nation (as per March of 2019)
(Data based on Nuclear News (ANS), WNA, and IAEA)

No	Nation	# Units (in operation)	Net MW_{el} (in operation)	# Units (forthcoming)	Net MW_{el} (forthcoming)
23	Russia	36 (21 PWRs; 13 LGRs; 2 LMFBRs)	28,355	7	4,802
24	Slovakia	4 (PWRs)	1,814	2	880
25	Slovenia	1 (PWR)	688	0	0
26	South Africa	2 (PWRs)	1,860	0	0
27	South Korea	24 (21 PWRs; 3 PHWRs)	23,123	5	6,760
28	Spain	7 (6 PWRs; 1 BWR)	7,121	0	0
29	Sweden	8 (3 PWRs; 5 BWRs)	8,629	0	0
30	Switzerland	5 (3 PWRs; 2 BWRs)	3,333	0	0
31	Taiwan	4 (2 PWRs; 2 BWRs)	3,844	2	2,600
32	Turkey	4 (PWRs) (planned)	-	4	4,800
33	Ukraine	15 (PWRs)	13,107	3	2,850
34	UAE	4 (PWRs) (planned)	-	4	5,380
35	United Kingdom	15 (1 PWR; 14 AGRs)	8,883	2	3,200
36	USA	97 (65 PWRs; 32 BWRs)	98,656	6	7,100
	Total	449 reactors connected to grid	397,789	97	100,931

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

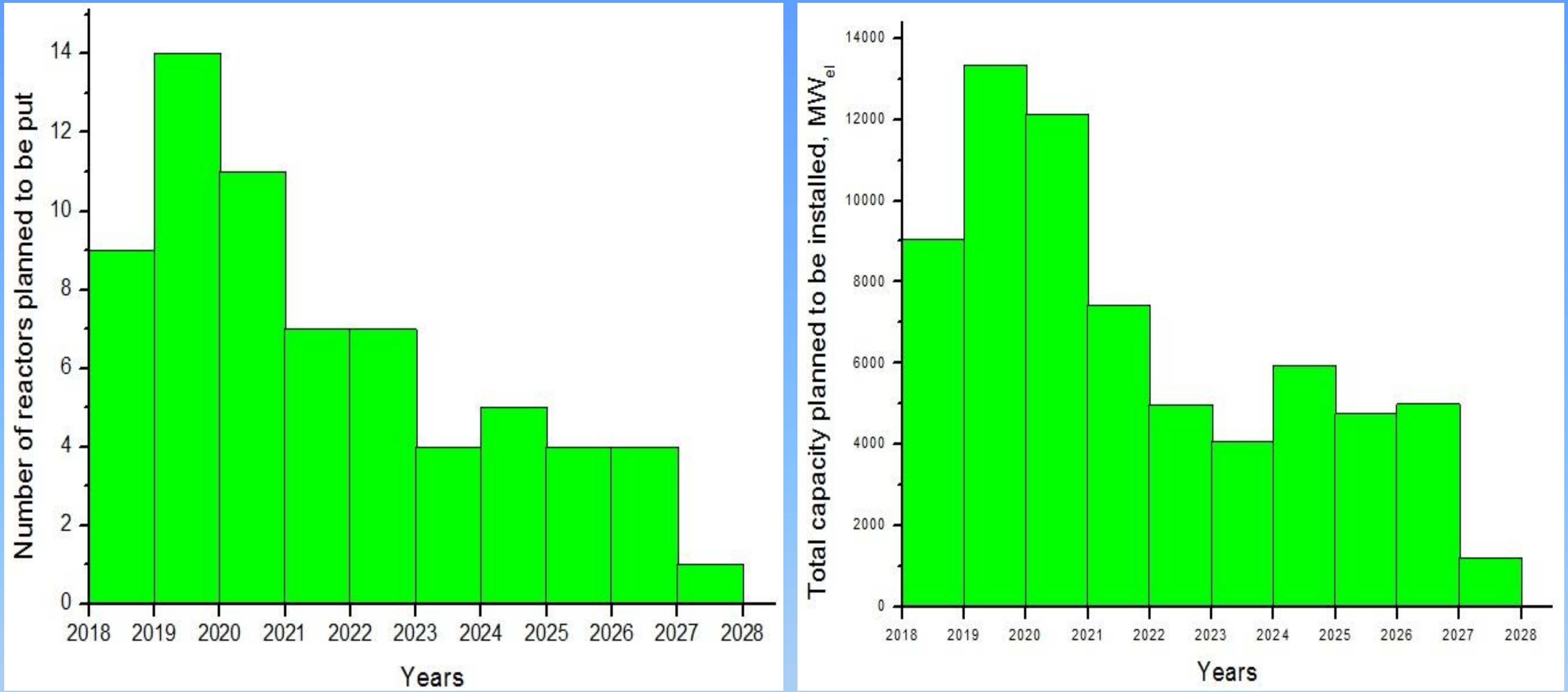
Number of nuclear power reactors in the world by installed capacity (based on data from Nuclear News (ANS), WNA and IAEA, Dec. 2018)





Number of nuclear-power reactors of the world put into commercial operation vs. years as per December, 2018 (Four 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. It is clear from this diagram that the Chernobyl NPP accident has tremendous negative impact on nuclear-power industry, which is lasting for decades, and, currently, we have additional negative impact of the Fukushima Daiichi NPP accident.

Number of nuclear-power reactors in the world by installed capacity as per December, 2018. For better understanding of this diagram, the largest number of reactors have installed capacities within the range of 900–999 MW_{el}.

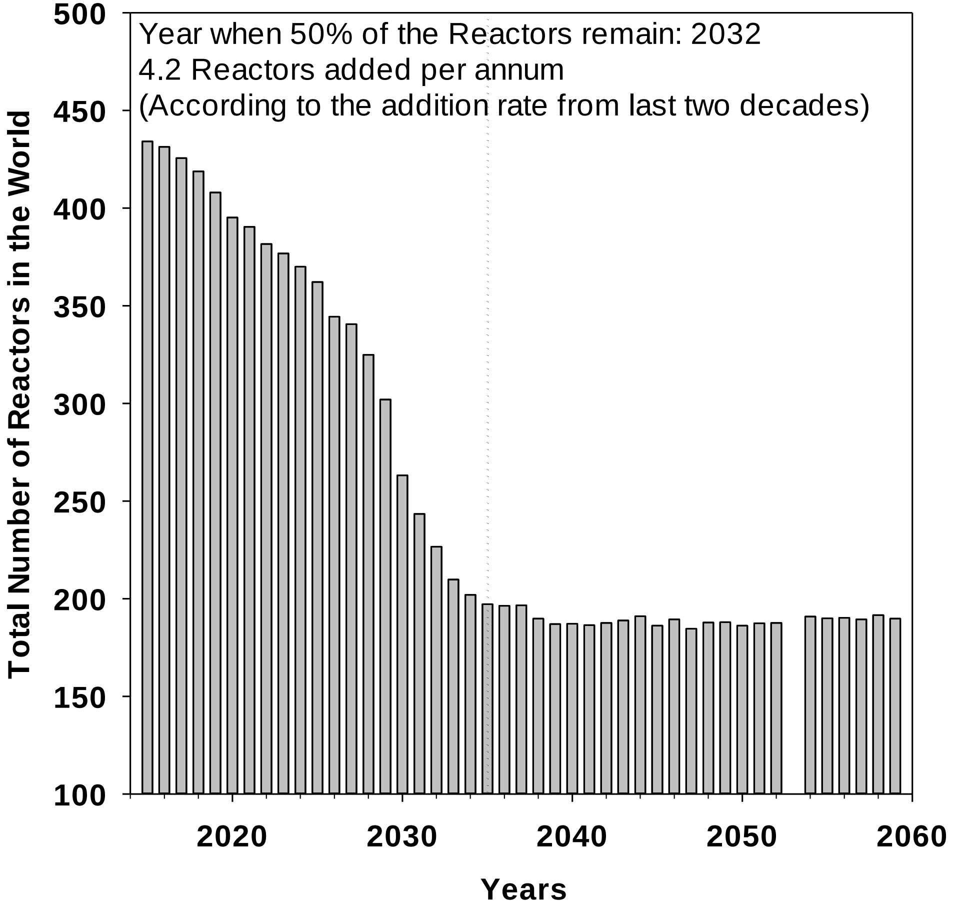


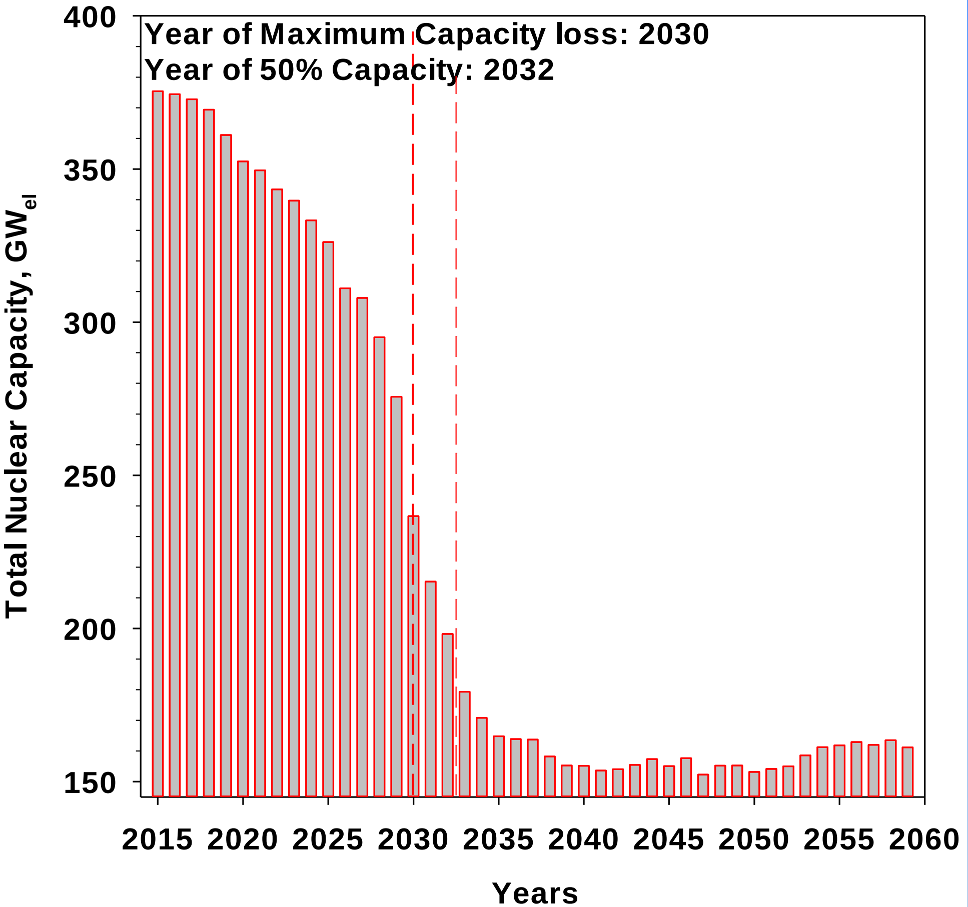
(a) (b)

Number of reactors planned to be built (a) and their planned installed capacities (b) from 2018 till 2028

Current activities worldwide on new nuclear-power-reactors build

No	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
7	Japan / Hitachi, Toshiba	Japan (1+1?), USA (2) In total: 3+1?
8	Slovakia / Skoda	Slovakia (2) In total: 2
9	Canada / AECL (Candu Energy, Inc.)	Romania (2) In total: 2
10	Germany / KWU (KraftWerk Union AG)	Brazil (1?) In total: 1?
11	Argentina / CNEA (Comisión Nacional de Energía Atómica)	Argentina (1?) In total: 1?



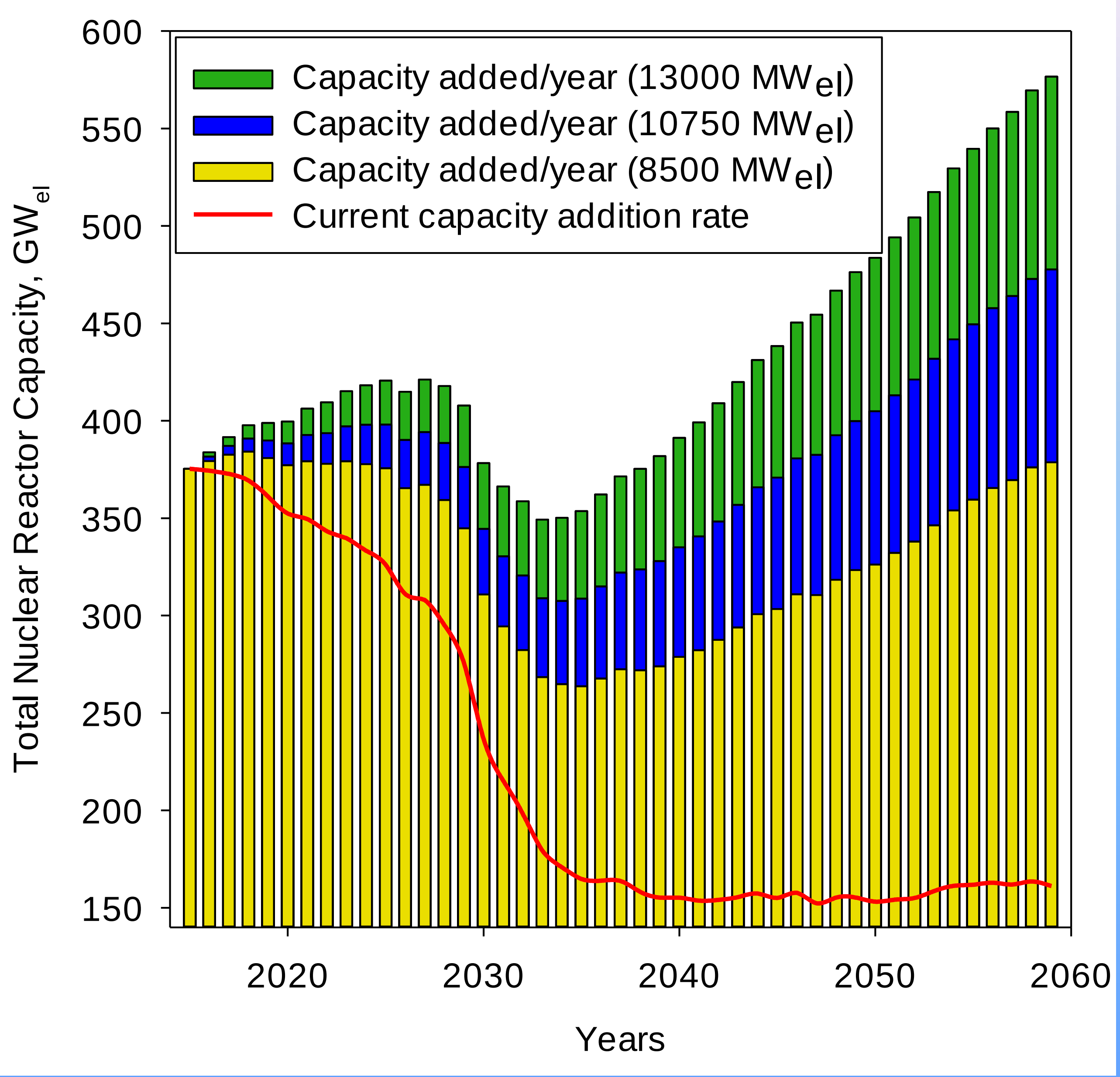


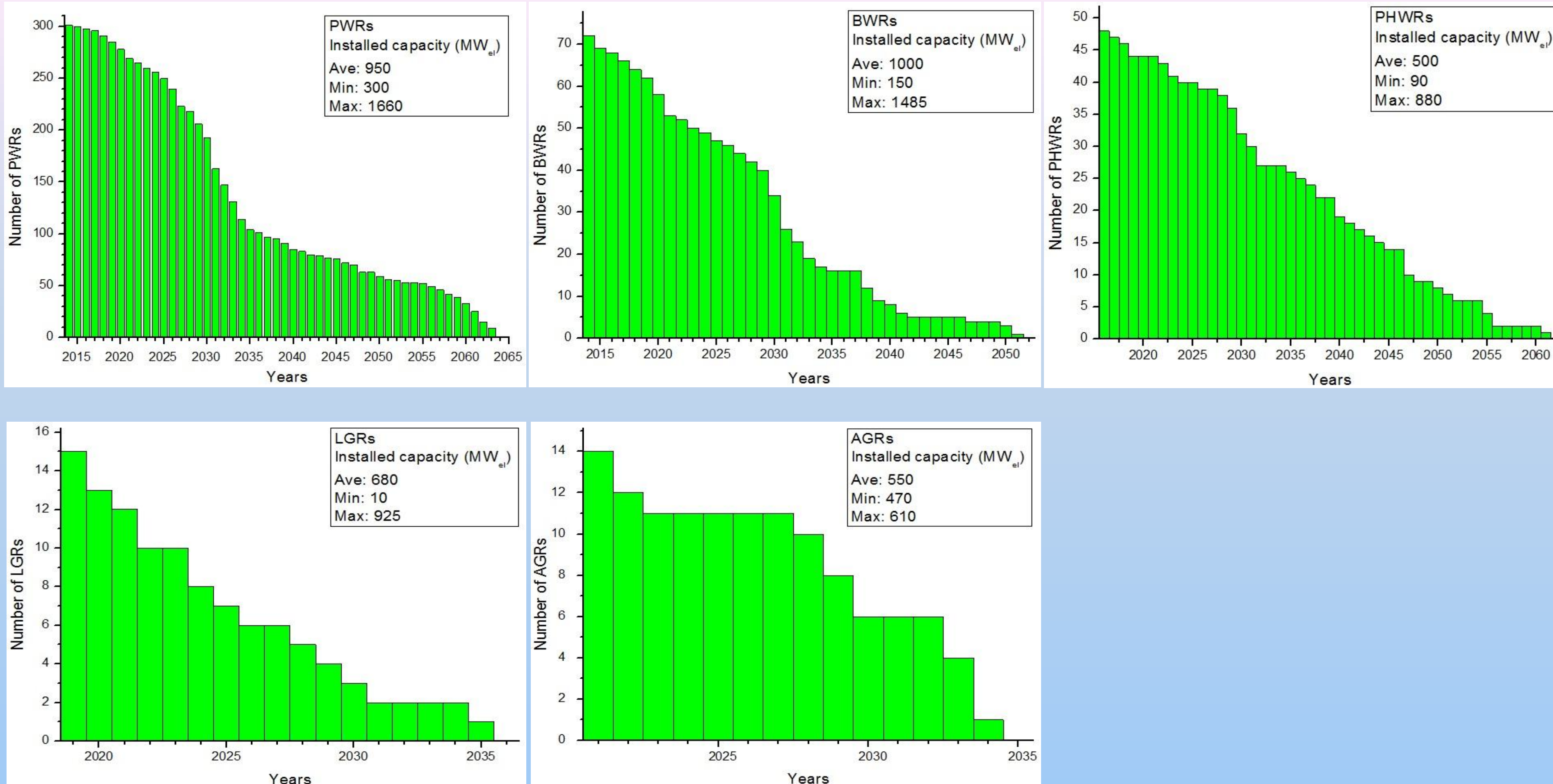
Projections of a number of nuclear-power reactors / nuclear capacities of the world within next 45 years. Assumptions:

1) **Maximum operating term of a unit – 45 years;**
2) **Average number of units put into operation per year – 4 units (in 5 years – 20 units).**

To avoid this significant decrease in a number of units – we need to put into operation about 10 units per year, i.e., to have more than twice higher rates for building and putting into operation new reactors.

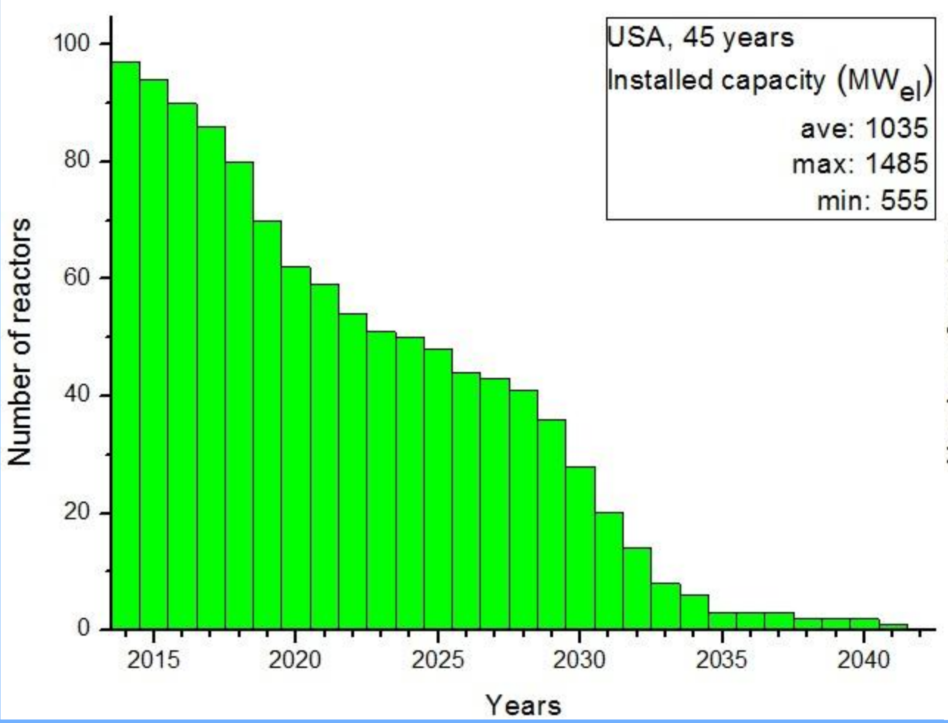
Possible Scenarios of Nuclear-Power Development in the World



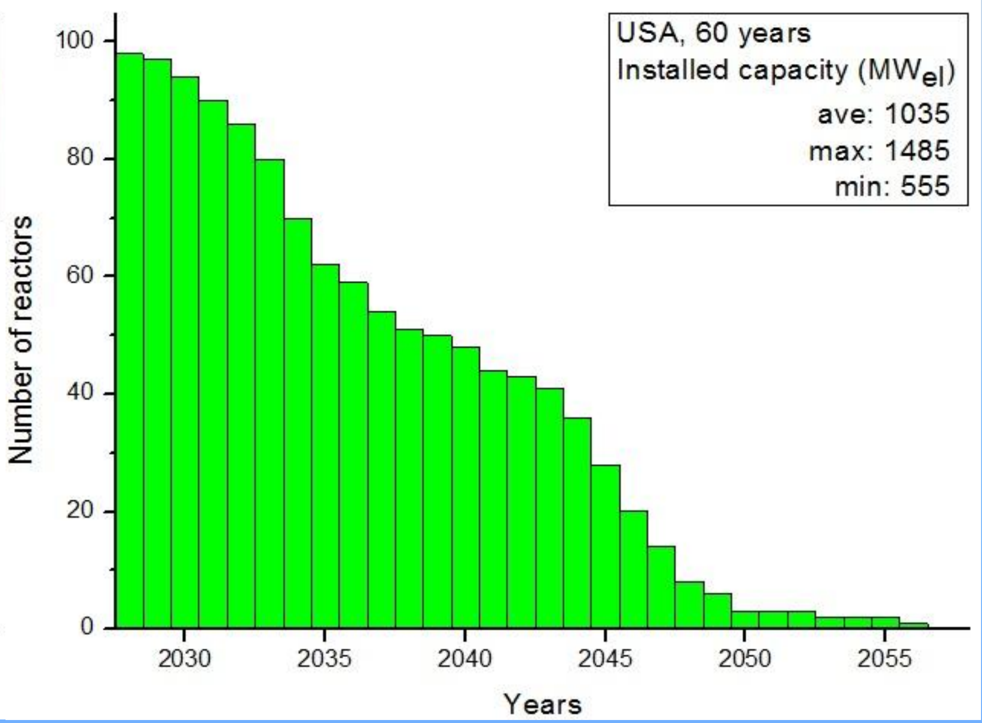


Possible conservative scenarios for future of nuclear-power reactors of various types, if no additional reactors are built, based on 45 years in service of current reactors

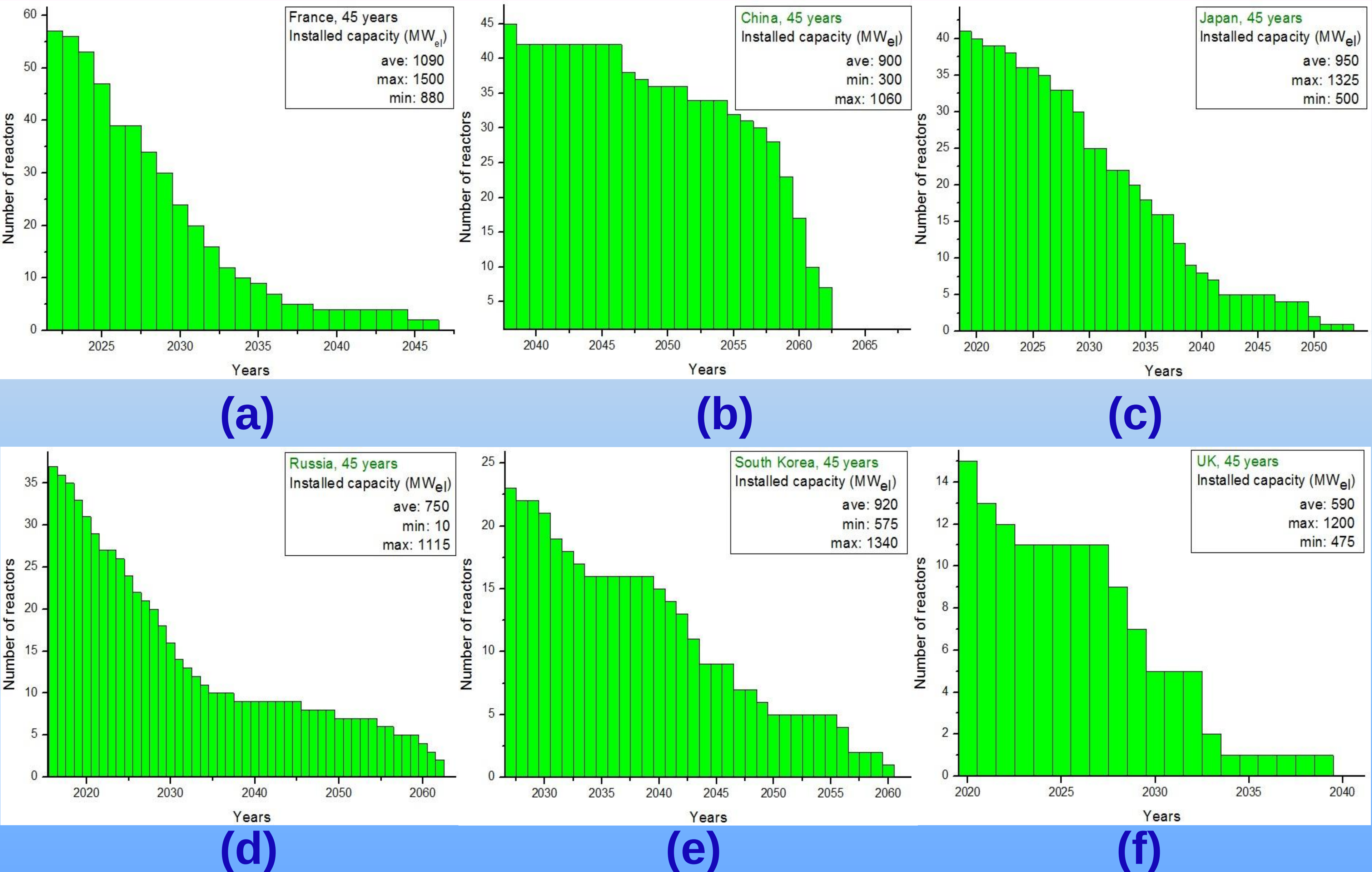
Possible scenarios for future of nuclear power in USA, if no additional reactors are built; based on 45 years (a) and 60 years (b) in service of current reactors



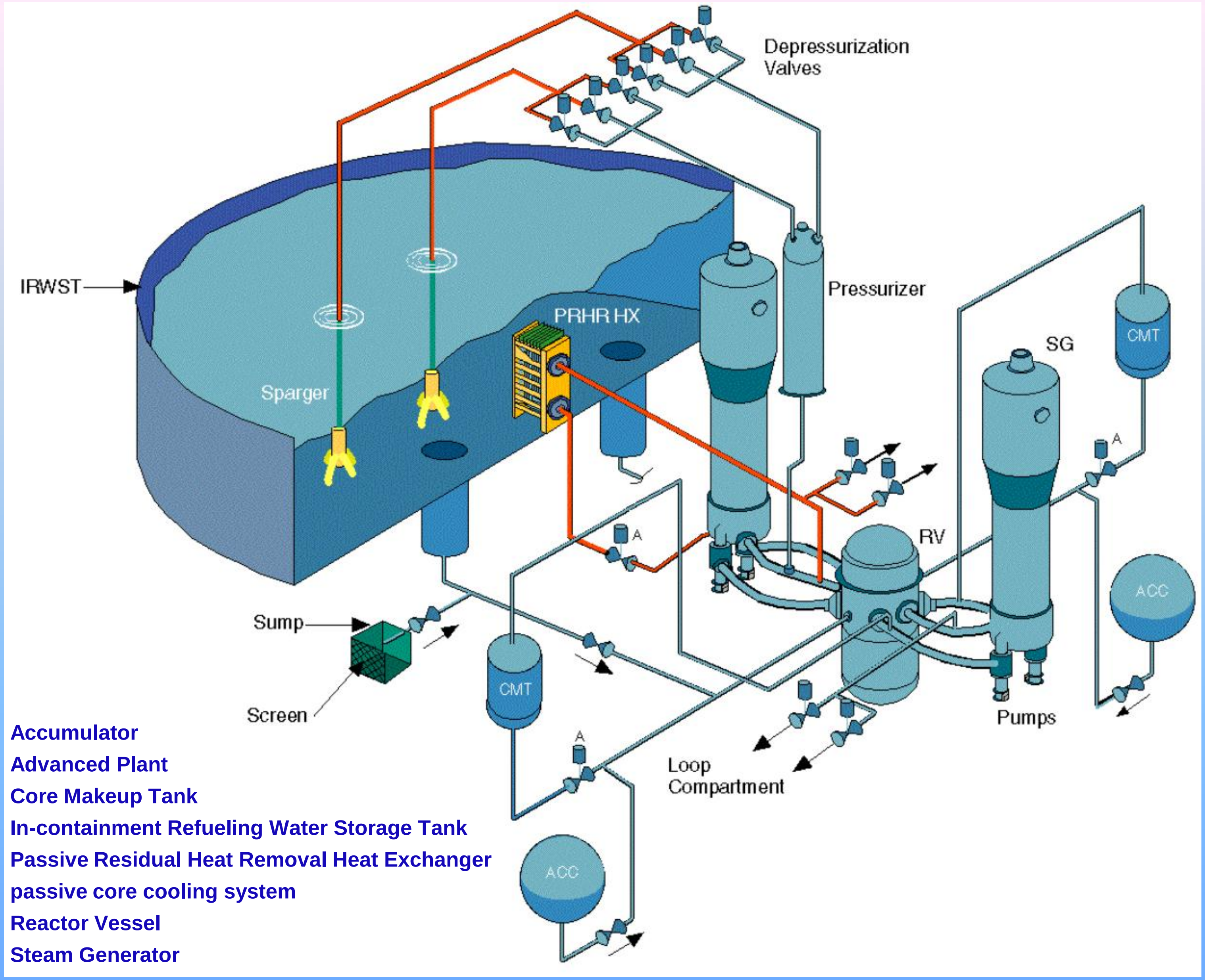
(a)



(b)



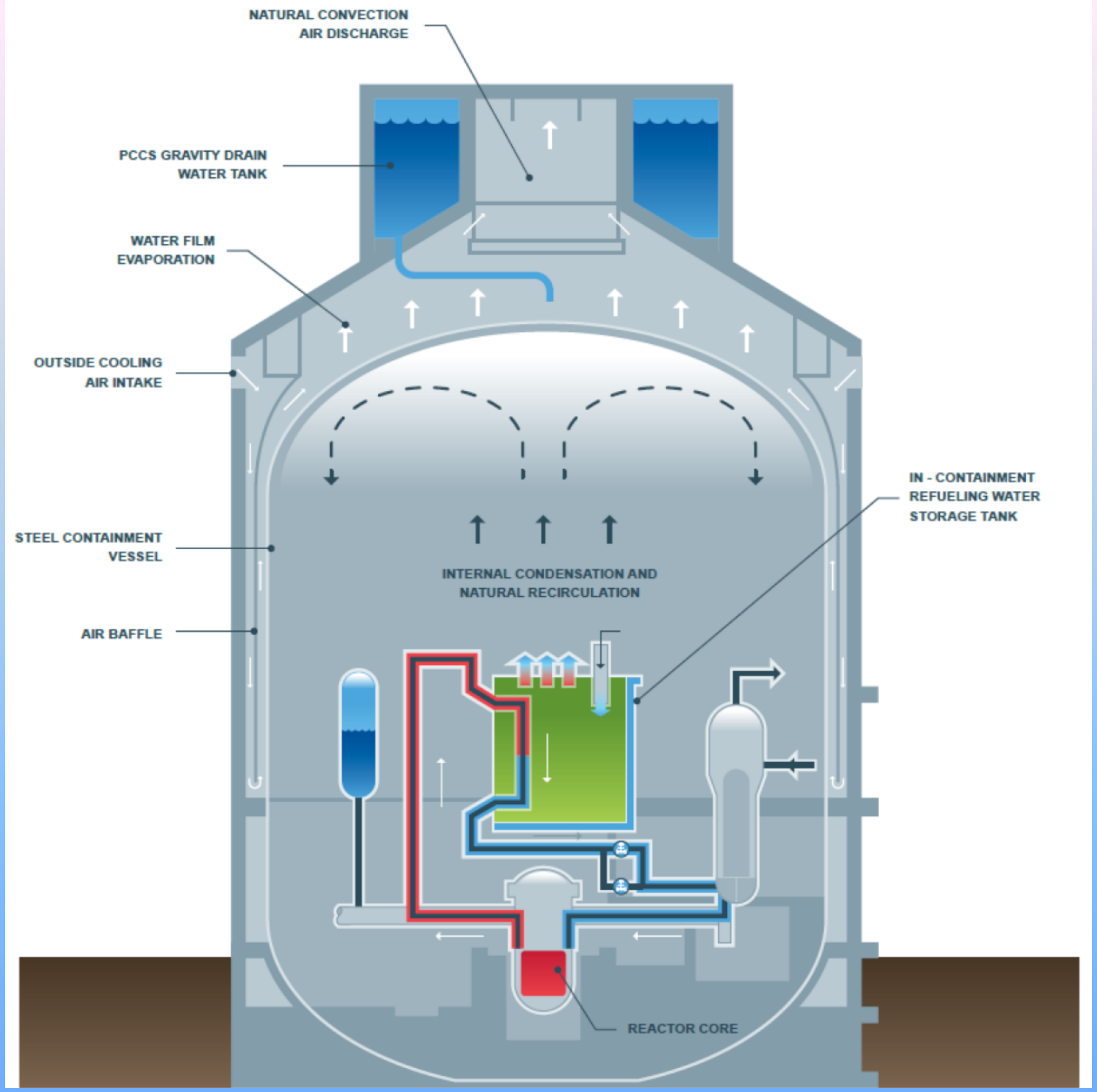
Possible scenarios for future of nuclear power in France (a), China (b), Japan (c), Russia (d), South Korea (e), and UK (f), if no additional reactors are built; based on 45 years in service of current reactors



ACC	**Accumulator**
AP	**Advanced Plant**
CMT	**Core Makeup Tank**
IRWST	**In-containment Refueling Water Storage Tank**
PRHR HX	**Passive Residual Heat Removal Heat Exchanger**
PXS	**passive core cooling system**
RV	**Reactor Vessel**
SG	**Steam Generator**

AP1000 Plant Passive Core Cooling System (PXS)

Showcasing Major Design Features and Parameters of the AP1000® Plant (Courtesy of Westinghouse Electric Company LLC) (ASME J. of NERS, Jan. 2019, Vol. 5 No. 1; by B.N. Friedman)



AP1000 Plant Passive Containment Cooling System (PCS) Operation)

Showcasing Major Design Features and Parameters of the AP1000® Plant (Courtesy of Westinghouse Electric Company LLC) (ASME J. of NERS, Jan. 2019, Vol. 5 No. 1; by B.N. Friedman)

Haiyang Nuclear Power Plant (Courtesy of Shandong Nuclear Power Company, Ltd.)

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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

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

http://www.epr-reactor.co.uk/ssmod/liblocal/docs/EPR%20Interactive/Brochures/300709_EPR_52pages.pdf

Small Modular Reactors (SMRs)

Small Modular Reactors (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 only two KLT-40S reactors have been constructed, installed on a barge, and should be put into operation in 2019; CAREM (Central ARgentina de Elementos Modulares) SMR (PWR-type; 25 (32) MW_{el}; CNEA (Comisión Nacional de Energía Atómica), Argentina) is under construction now, and FUJI (200 MW_{el}, MSR International Thorium Molten-Salt Forum (ITMSF), Japan) is possibly within an experimental phase.

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

Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2018. IAEA, 250 pages. Free download from: https://aris.iaea.org/Publications/SMR-Book_2018.pdf.

Handbook of Small Modular Nuclear Reactors, 2014. Editors: Carelli, M.D. and Ingersoll, D.T., 1st edition, Elsevier – Woodhead Publishing (WP), Duxford, UK, 536 pages.

Main parameters of Russian SMRs: KLT-40S and RITM-200M

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, %	~26	~31
Expected capacity factor, %	60 – 70	65
Maximum output thermal power, Gcal/h	73	-
Production of desalinated water, m^3/day	40,000 – 100,000*	-
Operating range of power, %	10 – 100	-
Normal-mode power variation, % / s	0.1	-
Primary circuit pressure, MPa	12.7	15.7
Primary circuit T_{in}/T_{out},°C	280 / 316	277 / 313
Reactor coolant massflow rate, t/h	680	3250
Primary circuit circulation mode	Forced	
Power cycle	Indirect Rankine cycle	
P_{steam} at SG outlet, MPa	3.72	3.82
T_{sat} at P_{steam}, °C	246.1	247.4
Overheated T_{steam} at SG outlet,°C	290	295
Steam massflow rate, t/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, t	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, years	~3**	Up to 10
Refueling outage, days	30 – 36	-
Fuel enrichment, %	18.6	Up to 20%
Fuel burnup, GWd/t	45.4	-
Predicted core damage frequency, event / reactor year	$0.5 \cdot 10^{-7}$	-
Seismic design	9 point on MSK scale	0.3g

Defficiencies of Modern Nuclear Power Plants

In spite of all current advances into nuclear power, modern Nuclear Power Plants (NPPs) have the following deficiencies:

1) **Generate radioactive wastes;**
2) **Have relatively low thermal efficiencies, especially, water-cooled NPPs (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.

Generation IV Nuclear Reactors

Currently, there are six Generation IV nuclear-reactor concepts under development worldwide

Generation IV nuclear reactors (deployment between 2010-2030)

1. Gas-cooled Fast Reactors (GFRs) (helium, 9 MPa, 485-850^{o}C)
2. Very High-Temperature gas-cooled Reactors (VHTRs) (helium, 7 MPa, 500-1000^{o}C)
3. Sodium-cooled Fast Reactors (SFRs) (520-550^{o}C)
4. Lead-cooled Fast Reactors (LFRs) (up to 550-800^{o}C)
5. Molten Salt-cooled Reactors (MSRs) (sodium fluoride salt with dissolved uranium fuel, up to 700-800^{o}C)
6. SuperCritical Water-cooled Reactors (SCWRs) (25 MPa, up to 625^{o}C)

Figure 1-3: Status of the GIF System Arrangements and Memoranda of Understanding
(as of 1 January 2014)

System	CA	CN	EU	FR	JP	KR	RU	CH	US	ZA
SFR		✓	✓	✓	✓	✓	✓		✓	
VHTR		✓	✓	✓	✓	✓		✓	✓	
SCWR	✓		✓		✓		✓			
GFR			✓	✓	✓			✓		
LFR			P		P		P			
MSR			P	P			P			

✓= Signatory to the System Arrangement; P = signatory to the Memorandum of Understanding; Argentina, Brazil, and the United Kingdom are inactive.

Thermal Efficiencies (Gross) of Generation-IV NPP Concepts

No	Nuclear Power Plant	Thermal Eff., %
1	Very High Temperature Reactor (VHTR) NPP (reactor coolant – helium: P=7 MPa and T_{in}/T_{out}=640/1000°C; primary power cycle – direct Brayton gas-turbine cycle; possible back-up – indirect Rankine steam cycle).	≥55
2	Gas-cooled Fast Reactor (GFR) or High Temperature Reactor (HTR) NPP (reactor coolant – helium: P=9 MPa and T_{in}/T_{out}=490/850°C; primary power cycle – direct Brayton gas-turbine cycle; possible back-up – indirect Rankine steam cycle).	≥50
3	SuperCritical Water-cooled Reactor (SCWR) NPP (one of Canadian concepts; reactor coolant – light water: P=25 MPa and T_{in}/T_{out}=350/625°C (T_{cr}=374°C); direct cycle; high-temperature steam superheat: T_{out}=625°C; possible back-up - indirect supercritical-pressure Rankine steam cycle with high-temperature steam superheat).	45-50
4	Molten Salt Reactor (MSR) NPP (reactor coolant – sodium-fluoride salt with dissolved uranium fuel: T_{out}=700/800°C; primary power cycle – indirect supercritical-pressure carbon-dioxide Brayton gas-turbine cycle; possible back-up – indirect Rankine steam cycle).	~50
5	Lead-cooled Fast Reactor (LFR) NPP (Russian design BREST-OD-300*: reactor coolant – liquid lead: P≈0.1 MPa and T_{in}/T_{out}=420/540°C; primary power cycle – indirect subcritical-pressure Rankine steam cycle: P_{in}≈17 MPa (P_{cr}=22.064 MPa) and T_{in}/T_{out}=340/505°C (T_{cr}=374°C); high-temperature steam superheat; (or indirect supercritical-pressure Rankine steam cycle: P_{in}≈24.5 MPa (P_{cr}=22.064 MPa) and T_{in}/T_{out}=340/520°C (T_{cr}=374°C); also, note that power-conversion cycle in different LFR designs from other countries is based on a supercritical-pressure CO_2 Brayton gas-turbine cycle.	~41-43
6	Sodium-cooled Fast Reactor (SFR) NPP (Russian design BN-600: reactor coolant – liquid sodium (primary circuit): P≈0.1 MPa and T_{in}/T_{out}=380/550°C; liquid sodium (secondary circuit): T_{in}/T_{out}=320/520°C; primary power cycle – indirect Rankine steam cycle: P_{in}≈14.2 MPa (T_{sat}≈337°C) and $T_{in\ max}$=505°C (T_{cr}=374°C); steam superheat: P≈2.45 MPa and T_{in}/T_{out}=246/505°C; possible back-up in some other countries - indirect supercritical-pressure carbon-dioxide Brayton gas-turbine cycle).	~40

References

Handbook

1. **Handbook of Generation IV Nuclear Reactors, 2016. Editor: I.L. Pioro, Elsevier, Duxford, UK, 940 pages.**

Technical Reference Book

1. **Pioro, I. & Duffey, R., 2007. Heat Transfer and Hydraulic Resistance at Supercritical Pressures in Power Engineering Applications, ASME Press, New York, NY, USA, 334 pages.**

Chapters

1. **Pioro, I. & Kirillov, P., 2013. Current Status of Electricity Generation in the World, Chapter in book: Materials and Processes for Energy: Communicating Current Research and Technological Developments, Energy Book Series #1, Editor: A. Méndez-Vilas, Formatex Research Center, Spain, pp. 783-795.** Free download from: http://www.formatex.info/energymaterialsbook/book/783-795.pdf.
2. **Pioro, I. & Kirillov, P., 2013. Current Status of Electricity Generation at Thermal Power Plants, Chapter in book: Materials and Processes for Energy: Communicating Current Research and Technological Developments, Energy Book Series #1, Editor: A. Méndez-Vilas, Formatex Research Center, Spain, pp. 796-805.** Free download from: http://www.formatex.info/energymaterialsbook/book/796-805.pdf.
3. **Pioro, I. & Kirillov, P., 2013. Current Status of Electricity Generation at Nuclear Power Plants, Chapter in book: Materials and Processes for Energy: Communicating Current Research and Technological Developments, Energy Book Series #1, Editor: A. Méndez-Vilas, Publisher: Formatex Research Center, Spain, pp. 806-817.** Free download from: http://www.formatex.info/energymaterialsbook/book/806-817.pdf.
4. **Pioro, I. & Kirillov, P., 2013. Generation IV Nuclear Reactors as a Basis for Future Electricity Production in the World, Chapter in book: Materials and Processes for Energy: Communicating Current Research and Technological Developments, Energy Book Series #1, Editor: A. Méndez-Vilas, Publisher: Formatex Research Center, Spain, pp. 818-830.** Free download from: http://www.formatex.info/energymaterialsbook/book/818-830.pdf.
5. **Peiman, W., Pioro, I. & Gabriel, K., 2012. Thermal Aspects of Conventional and Alternative Fuels in SuperCritical Water-Cooled Reactor (SCWR) Applications, Chapter in book "Nuclear Reactors", Editor A.Z. Mesquita, INTECH, Rijeka, Croatia, pp. 123-156.** Free download from: http://www.intechopen.com/books/nuclear-reactors/-thermal-aspects-of-conventional-and-alternative-fuels-in-supercritical-water-cooled-reactor-scwr-ap.
6. **Saltanov, Eu. & Pioro, I., 2011. World Experience in Nuclear Steam Reheat, Chapter in book "Nuclear Power: Operation, Safety and Environment", Editor: P.V. Tsvetkov, INTECH, Rijeka, Croatia, pp. 3-28.** Free download from: http://www.intechopen.com/books/nuclear-power-operation-safety-and-environment/world-experience-in-nuclear-steam-reheat.

References

Chapters

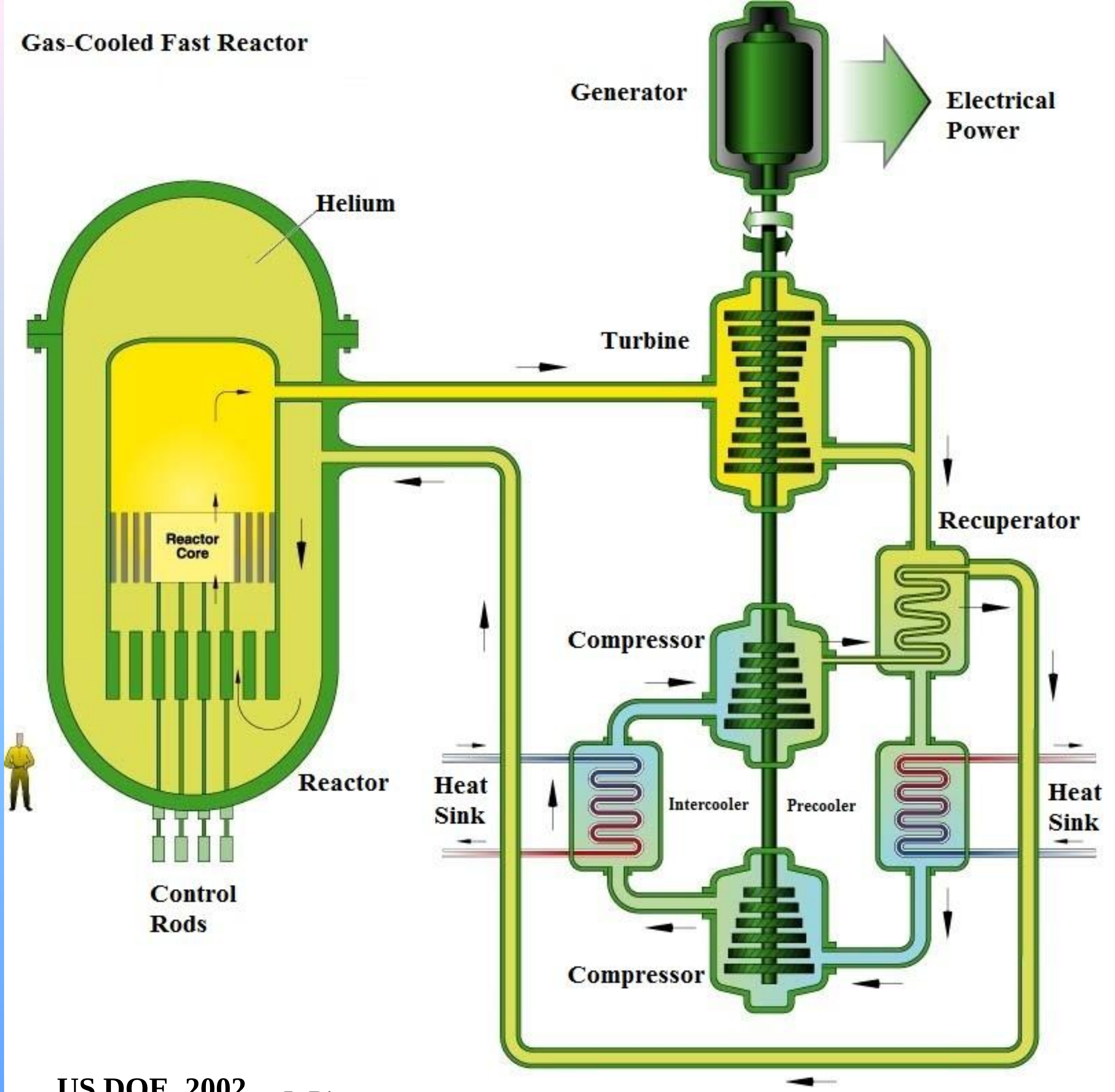
7. **Pioro, I., 2011. The Potential Use of Supercritical Water-Cooling in Nuclear Reactors. Chapter in Nuclear Energy Encyclopedia: Science, Technology, and Applications, Editors: S.B. Krivit, J.H. Lehr and Th.B. Kingery, J. Wiley & Sons, Hoboken, NJ, USA, pp. 309-347.**
8. **Pioro, I. & Mokry, S., 2011. Thermophysical Properties at Critical and Supercritical Conditions, Chapter in book "Heat Transfer. Theoretical Analysis, Experimental Investigations and Industrial Systems", Editor: A. Belmiloudi, INTECH, Rijeka, Croatia, pp. 573-592.** Free download from: http://www.intechopen.com/books/heat-transfer-theoretical-analysis-experimental-investigations-and-industrial-systems/thermophysical-properties-at-critical-and-supercritical-pressures.
9. **Pioro, I. & Mokry, S., 2011. Heat Transfer to Fluids at Supercritical Pressures, Chapter in book "Heat Transfer. Theoretical Analysis, Experimental Investigations and Industrial Systems", Editor: A. Belmiloudi, INTECH, Rijeka, Croatia, pp. 481-504.** Free download from: http://www.intechopen.com/books/heat-transfer-theoretical-analysis-experimental-investigations-and-industrial-systems/heat-transfer-to-supercritical-fluids.

Papers

1. **Pioro, I., Duffey, R.B., Kirillov, P.L., Pioro, R., Zvorykin, A., and Machrafi, R., 2019. Current Status and Future Developments in Nuclear-Power Industry of the World, ASME Journal of Nuclear Engineering and Radiation Science, Vol. 5, No. 2, 27 pages.** Free download from: http://nuclearengineering.asmedigitalcollection.asme.org/article.aspx?articleID=2718229.
2. **Pioro, I. and Duffey, R., 2015. Nuclear Power as a Basis for Future Electricity Generation, ASME Journal of Nuclear Engineering and Radiation Science, No. 1.**
3. **Dragunov, A., Saltanov, Eu., Pioro, I., Kirillov, P., and Duffey, R., 2015. Power Cycles of Generation III and III^{+} Nuclear Power Plants, ASME Journal of Nuclear Engineering and Radiation Science, No. 1.**
4. **Dragunov, A., Saltanov, Eu., Pioro, I., Ikeda, B., Miletic, M., and Zvorykina, A., 2013. Investigation of Thermophysical and Nuclear Properties of Prospective Coolants for Generation-IV Nuclear Reactors, Proceedings of the 21st International Conference on Nuclear Engineering (ICONE-21), July 29-August 2, Chengdu, China, Paper #16020, 11 pages.**

Thank you for your attention!

1. **Gas-cooled Fast Reactors (GFRs) or High Temperature Reactors (HTRs): a fast-neutron spectrum, closed fuel cycle, reactor coolant − helium, pressure of 9 MPa, temperatures of 485−850ºC, primary thermodynamic cycle – a direct cycle based on the Brayton cycle (gas-turbine cycle), back-up cycle – an indirect cycle based on the Rankine steam cycle through heat exchangers**



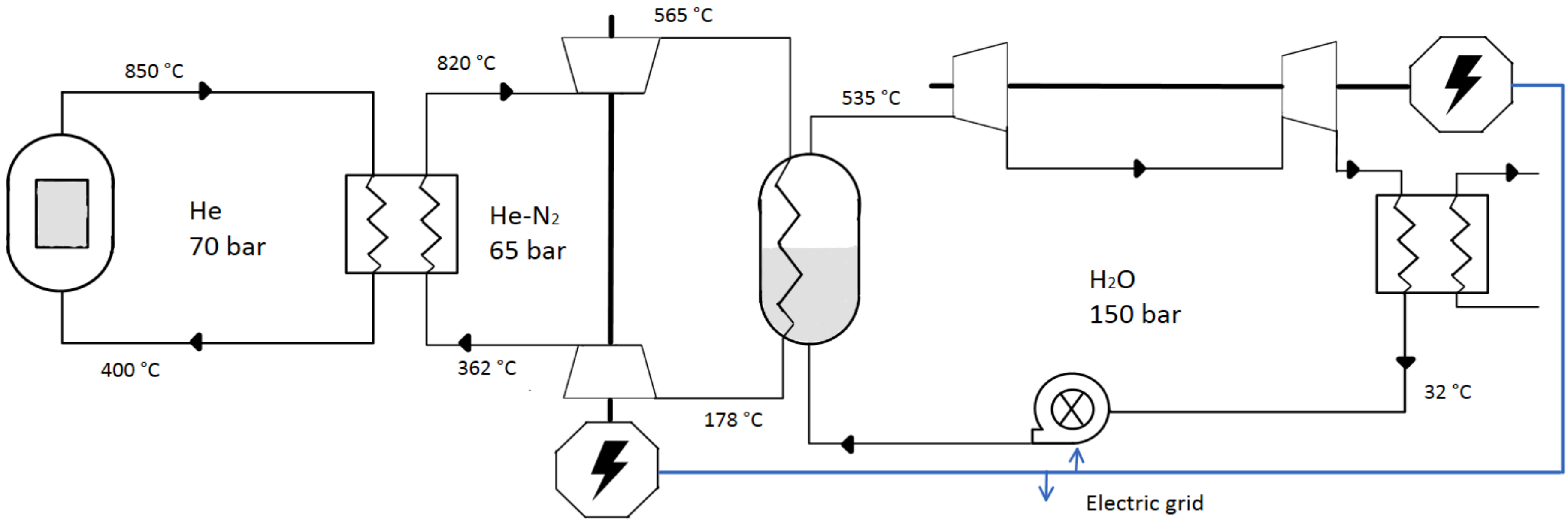
US DOE, 2002

I. Pioro

1. Gas-cooled Fast Reactors (GFRs)

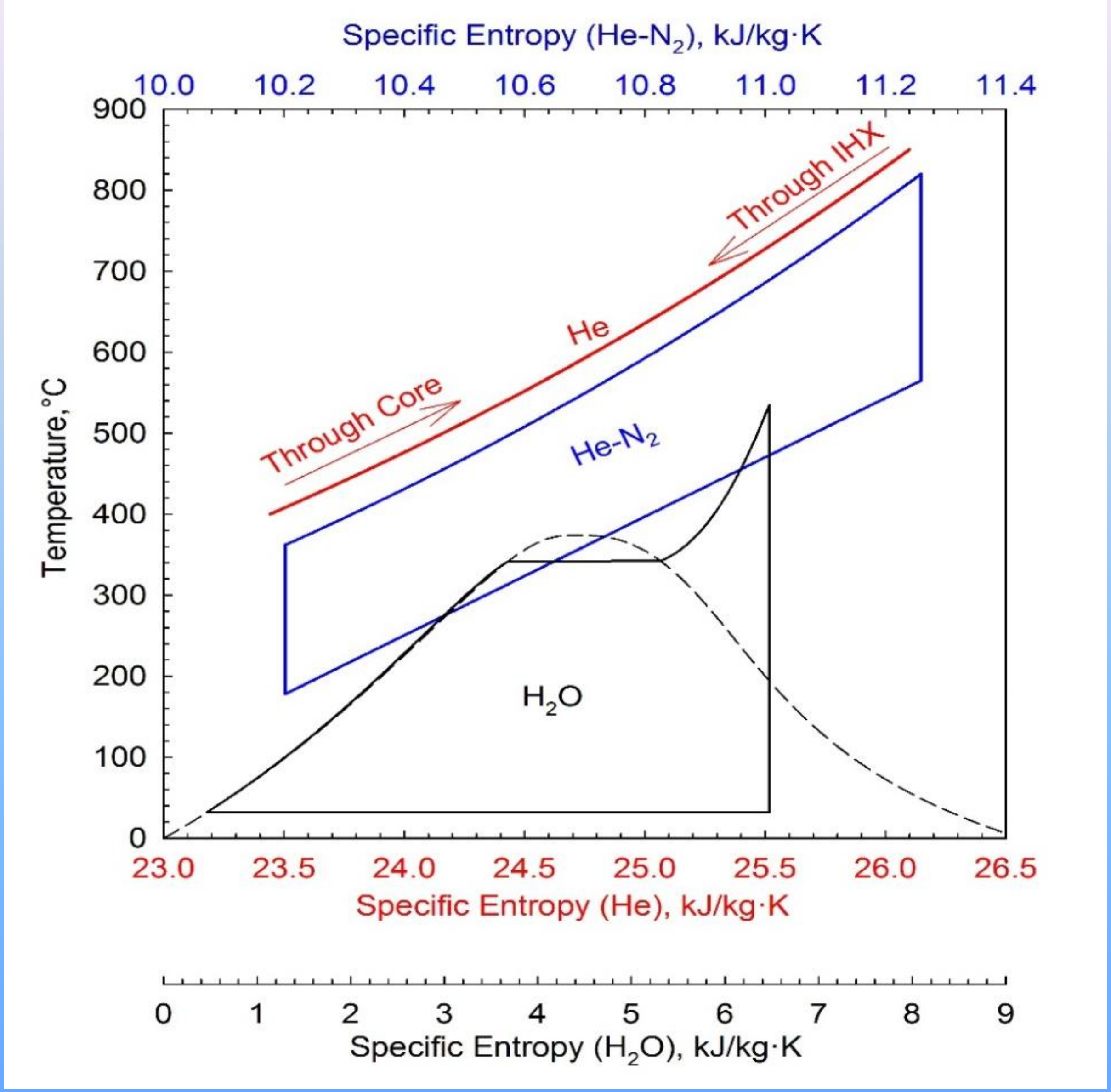
Key-design parameters of Gas-cooled Fast Reactor (GFR) concept (based on https://www.gen-4.org/gif/jcms/c_9357/gfr and Pioro and Kirillov, 2013).

Reactor Parameters	Unit	Reference Value
Reactor power	MW_{th}	600
Coolant inlet/outlet temperatures	°C	490/850
Pressure	MPa	9
Coolant massflow rate	kg/s	320
Average power density	MW_{th}/m^3	100
Reference fuel compound	–	UPuC/SiC (70/30%) with about 20% Pu
Net-plant efficiency	%	48

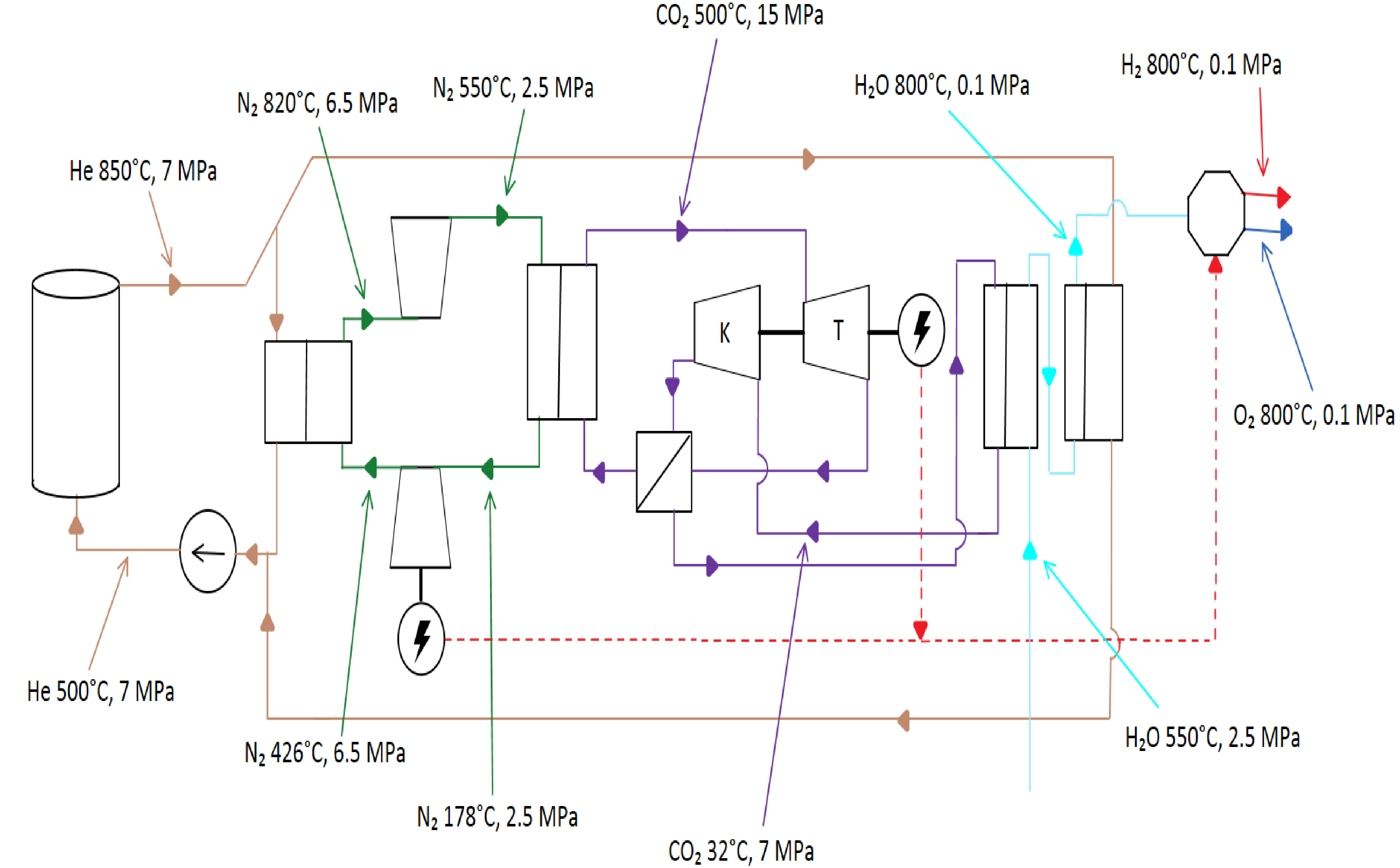


Simplified schematic of GFR (reactor coolant – helium at 7 MPa) with indirect combined cycle (Primary – SCP Brayton gas-turbine cycle (working fluid – mixture of nitrogen and helium at 6.5 MPa) and Secondary – Rankine steam-turbine cycle (at 15 MPa)) (based on Poette et al. (2013))

1. Gas-cooled Fast Reactors (GFRs)

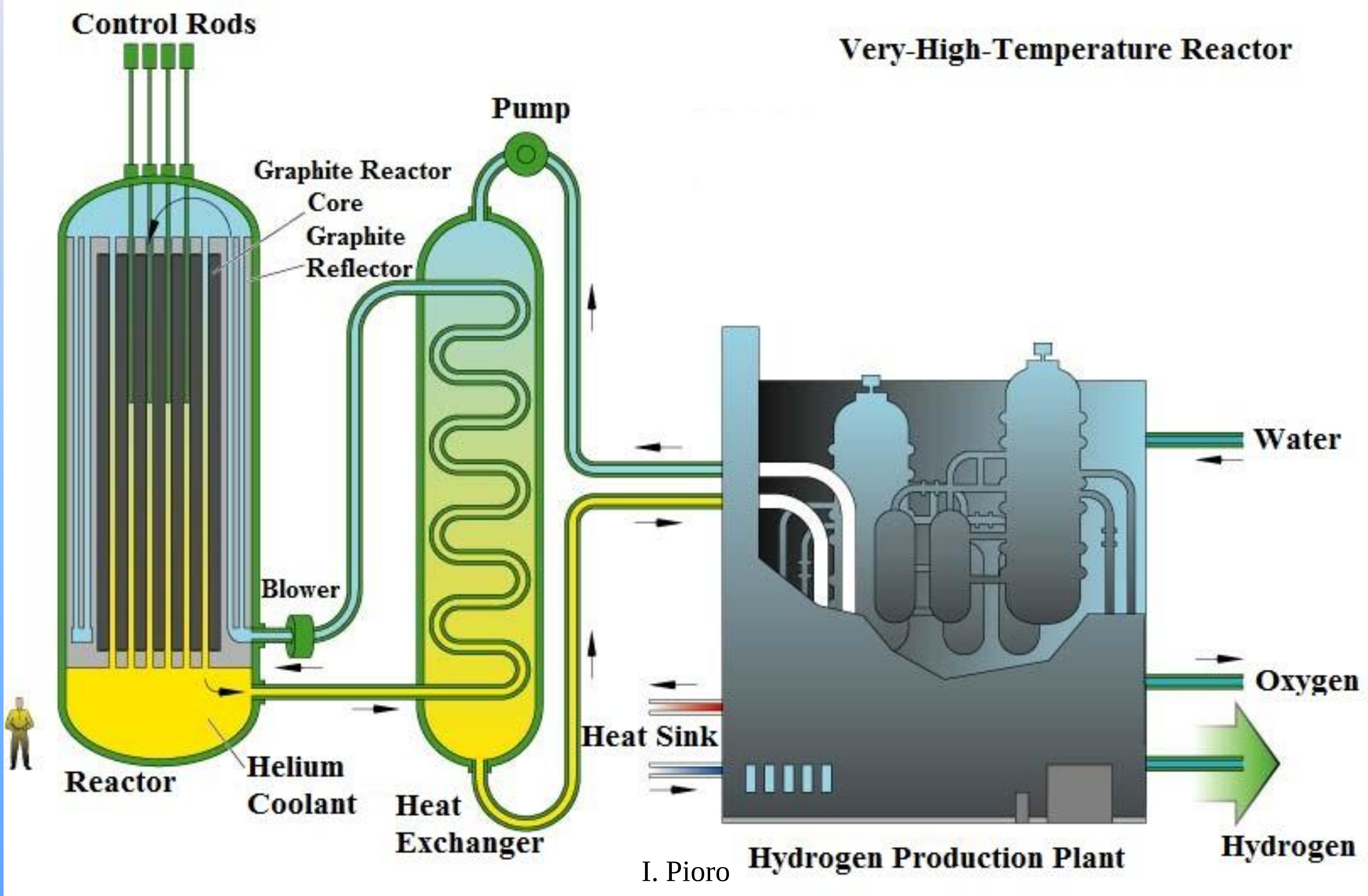


T–s diagram of GFR indirect combined power cycle with SCP nitrogen-helium mixture in Brayton cycle and Rankine steam cycle (based on data from Poette et al. (2013))



Simplified schematic of GFR (reactor coolant helium at 7 MPa) with indirect Brayton cycles (Primary – SCP Brayton gas-turbine cycle (working fluid – nitrogen at 6.5 MPa) and Secondary – SCP Brayton cycle (working fluid – carbon dioxide at 15 MPa)) and hydrogen co-generation (based on schematic from Hajek and Doucek (2014))

2. **Very High-Temperature gas-cooled Reactors (VHTRs): a graphite-moderated thermal cycle, once-through uranium-fuel cycle, reactor coolant − helium, 7 MPa, temperatures 500−1000ºC, primary thermodynamic cycle – a direct cycle based on the Brayton cycle (gas-turbine cycle), back-up cycle – an indirect cycle based on the Rankine steam cycle through heat exchangers. Also, proposed to be used for hydrogen co-generation through high-temperature electrolysis.**

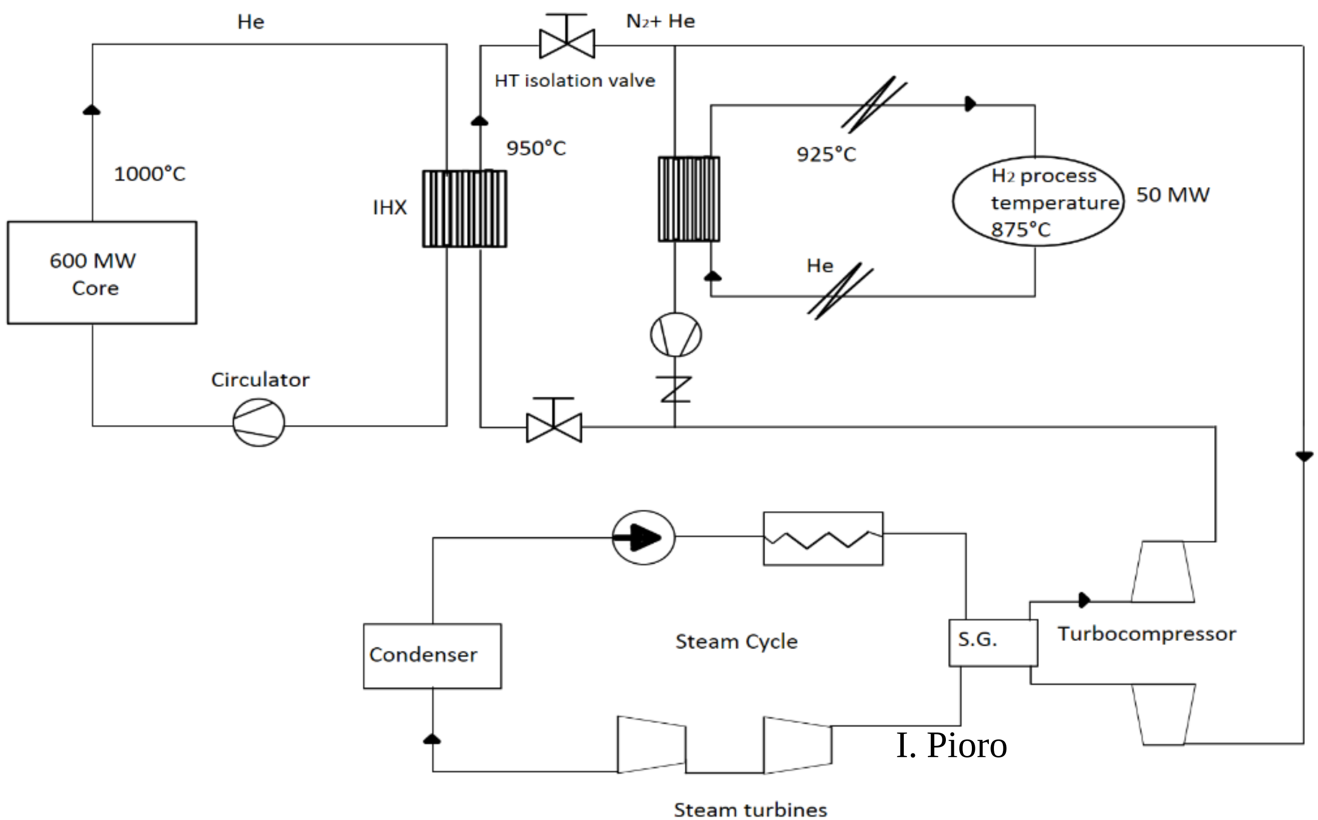


US DOE, 2002

2. Very High-Temperature gas-cooled Reactors (VHTRs)

Key-design parameters of Very High Temperature Reactor (VHTR) concept (based on https://www.gen-4.org/gif/jcms/c_42153/very-high-temperature-reactor-vhtr; Pioro and Kirillov, 2013)

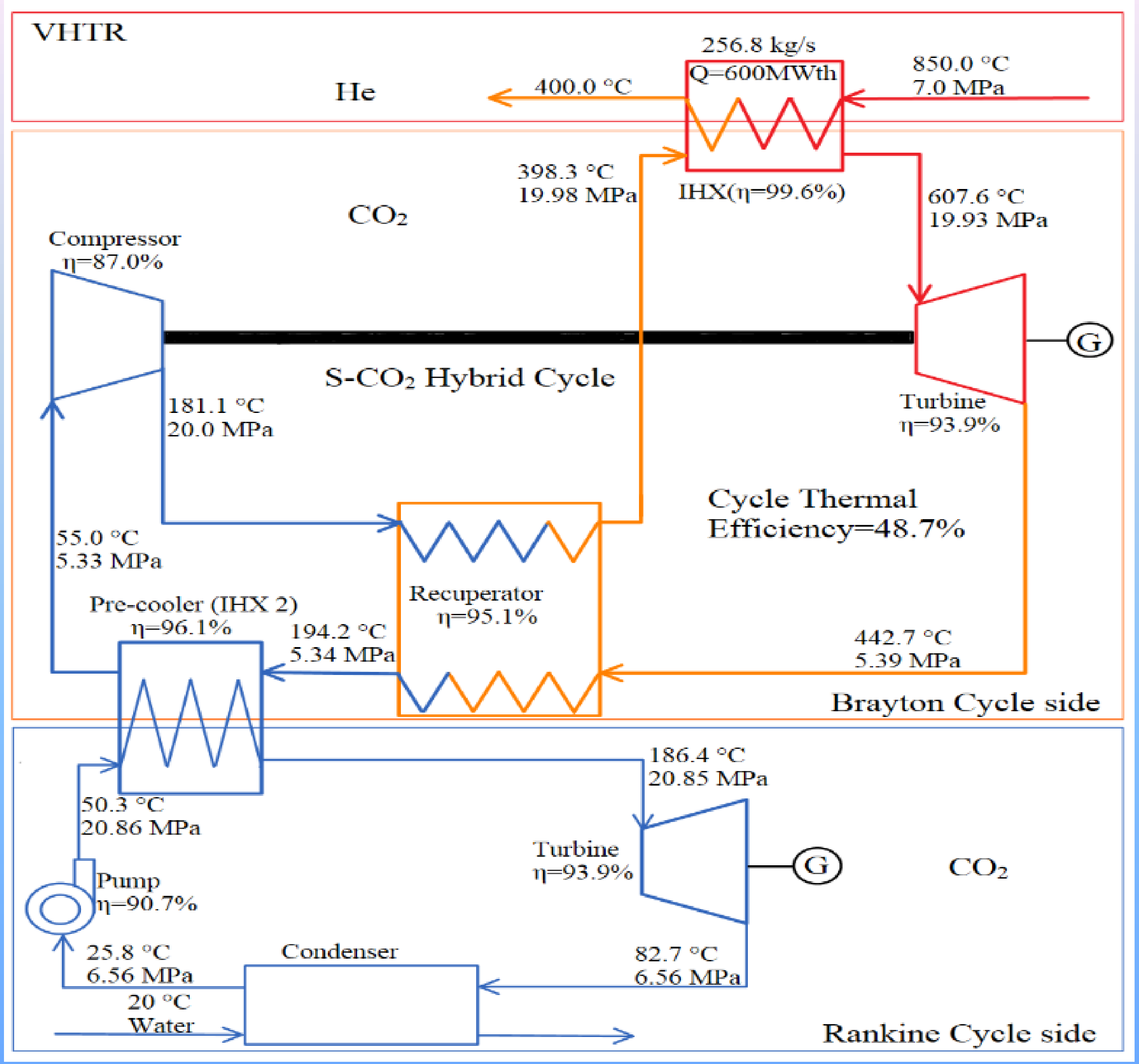
Reactor Parameter	Unit	Reference Value
Reactor power	MW_{th}	600
Average power density	MW_{th}/m^3	6–10
Coolant inlet/outlet temperatures	°C	640/1000
Coolant/Massflow rate	kg/s	Helium/320
Reference fuel compound	–	ZrC-coated particles in pins or pebbles
Net-plant efficiency	%	>50



I. Pioro

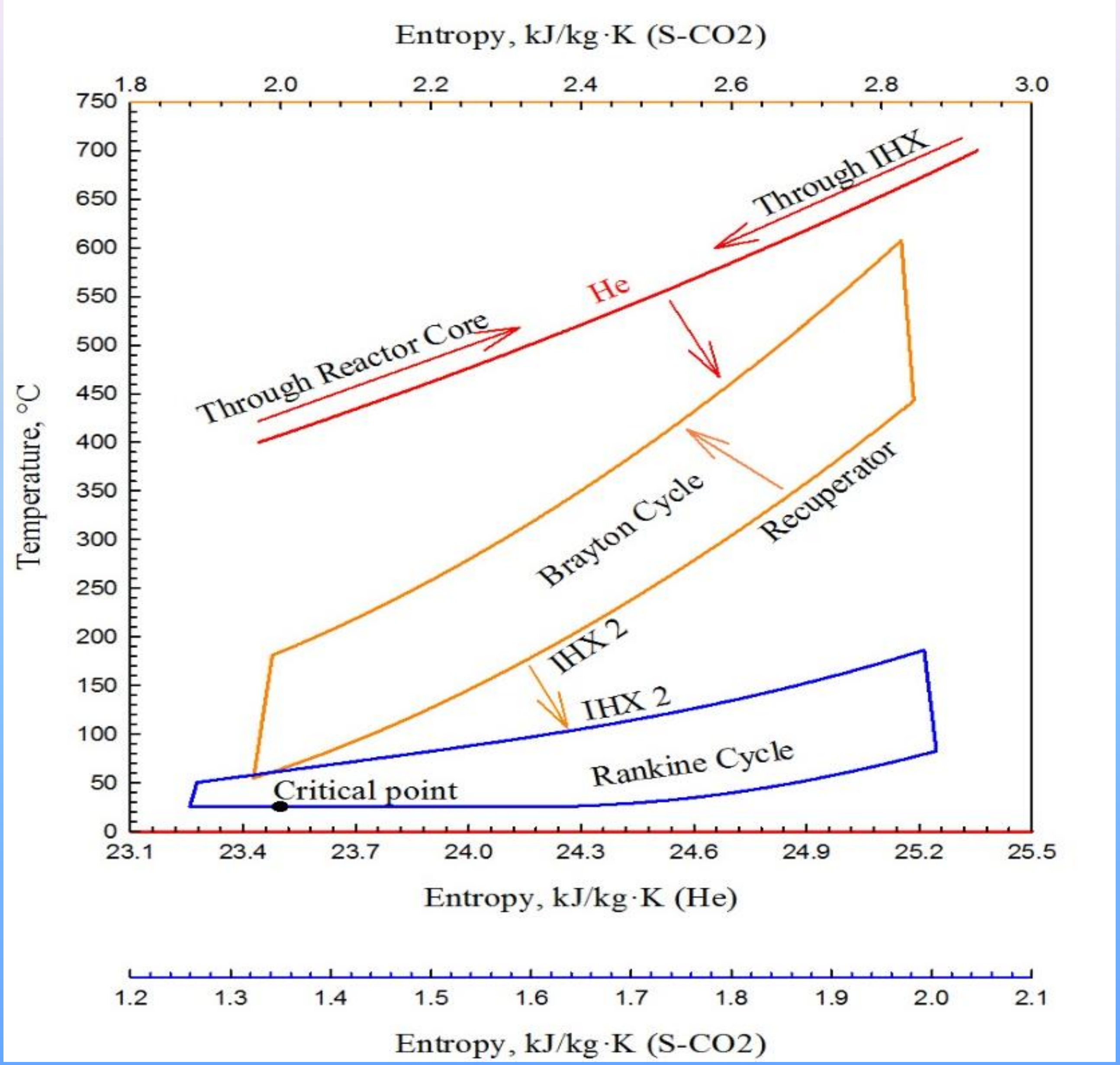
Simplified schematic of VHTR NPP (reactor coolant – helium at 5 MPa) with indirect combined cycle (Primary – Brayton gas-turbine cycle (working fluid – mixture of nitrogen and helium at 5 MPa) and Secondary – Rankine steam-turbine cycle) and hydrogen co-generation (based on schematic from Gauthier et al. (2004))

2. Very High-Temperature gas-cooled Reactors (VHTRs)



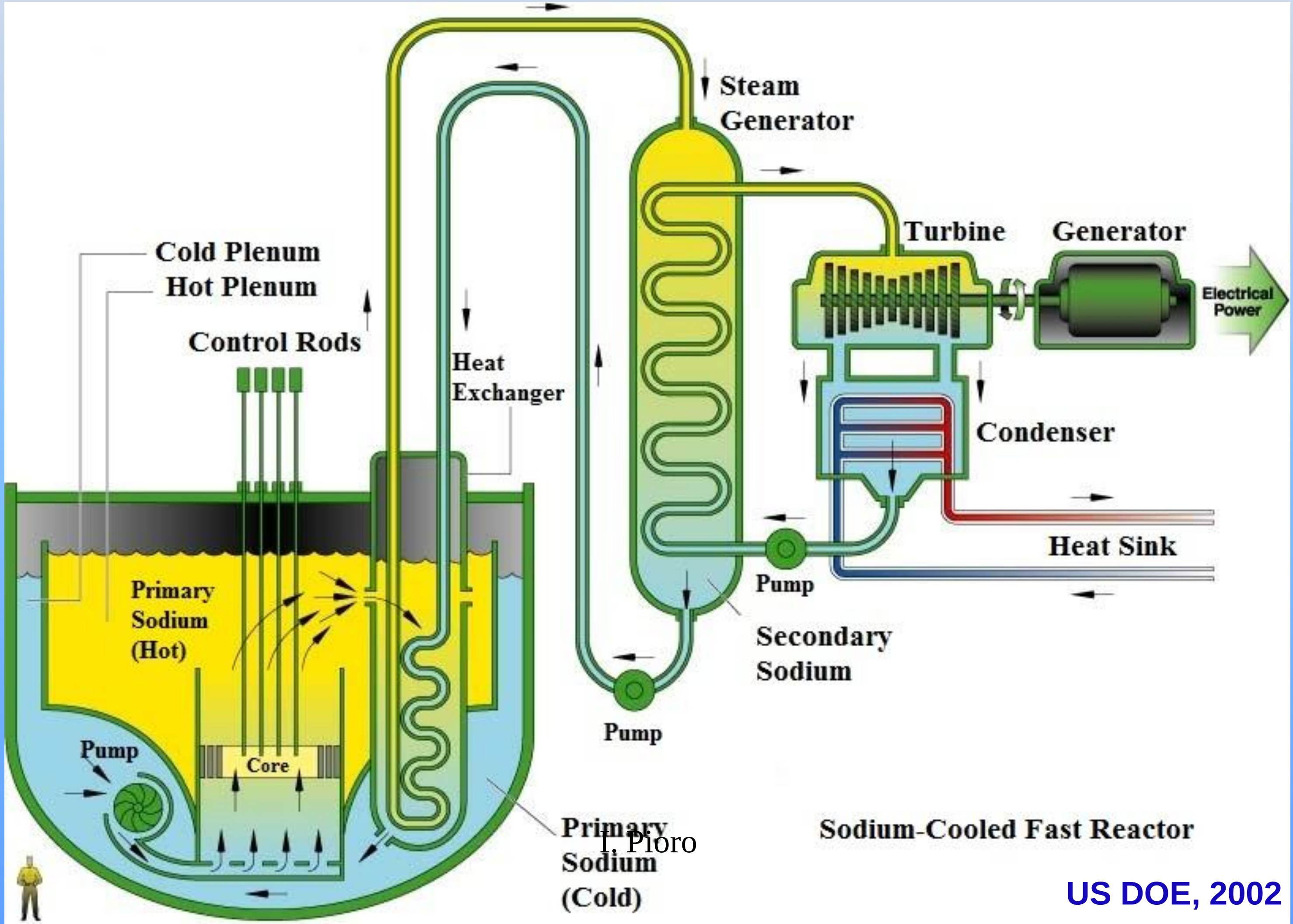
Simplified schematic of VHTR NPP (reactor coolant – helium at 7 MPa) with indirect combined cycle (Primary – SCP Brayton gas-turbine cycle (working fluid – carbon dioxide at ~20 MPa) and Secondary – SCP Rankine cycle (working fluid – carbon dioxide at ~21 MPa)) (based on Bae et al. (2014)).

2. Very High-Temperature gas-cooled Reactors (VHTRs)



T–s diagram of VHTR NPP indirect combined power cycle with SCP carbon dioxide in Brayton and Rankine cycles (based on diagram from Bae et al. (2014))

3. **Sodium-cooled Fast Reactors (SFRs): a fast-spectrum, closed fuel cycle for efficient management of actinides and conversion of fertile uranium, primary coolant – sodium, temperatures 520−550ºC, primary thermodynamic cycles – an indirect cycle based on the Rankine steam cycle through heat exchangers (current Russian design) or an indirect cycle based on the Brayton cycle (SC carbon-dioxide gas-turbine cycle)**



US DOE, 2002

3. Sodium-cooled Fast Reactors (SFRs)

Key-design parameters of generic SFR concept (based on https://www.gen-4.org/gif/jcms/c_9361/sfr and Pioro and Kirillov, 2013)

Reactor Parameter	Unit	Reference Value
Reactor power	MW_{th}	1000–5000
Thermal efficiency	%	40–42%
Coolant	–	Sodium
Coolant melting/boiling temperatures	°C	98/883
Coolant density at 450°C	kg/m^3	844
Pressure inside reactor	MPa	~0.1
Coolant maximum outlet temperature	°C	530–550
Average power density	MW_{th}/m^3	350
Reference fuel compound	–	Oxide or metal alloy
Cladding	–	Ferritic or ODS* ferritic
Average burnup	GWD**/MTHM***	~150–200

* ODS – Oxide Dispersion Strengthened
** GWD is GigaWatt-Days (1 GWd = 8.64 × 1013 J)
*** MTHM – Metric Tonne of Heavy Metal

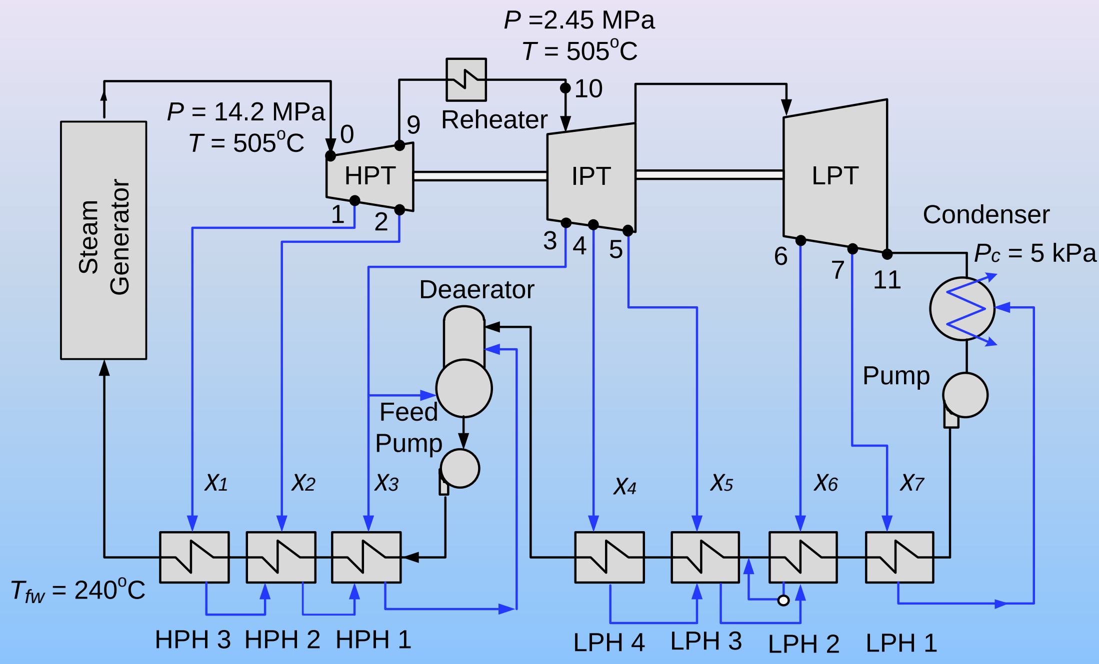
3. Sodium-cooled Fast Reactors (SFRs)

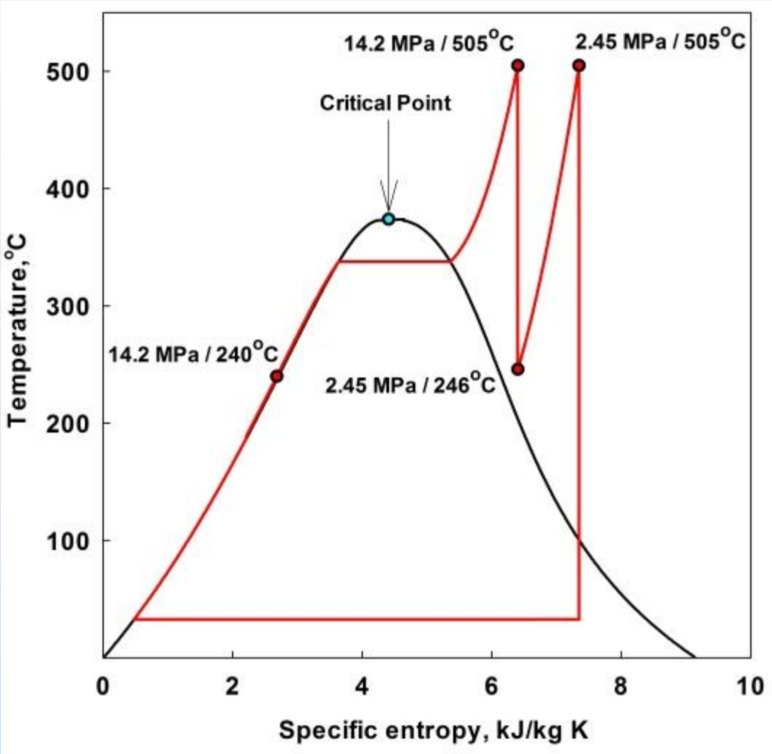
Key-design parameters of Russian SFRs (Pioro and Kirillov, 2013)

#	Parameter	BN-600*	BN-800**	BN-1200***
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 × ТЗВ-800-2	 1 × K-1200-160 1 × ТЗВ-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

* BN-600 – the only one long-term operating SFR in the world (Beloyarsk NPP); commercial start – 1981.
** BN-800 – the only second operating SFR in the world (Beloyarsk NPP), commercial start – 2016.
*** BN-1200 – concept of future SFR.

3. Sodium-cooled Fast Reactors (SFRs)





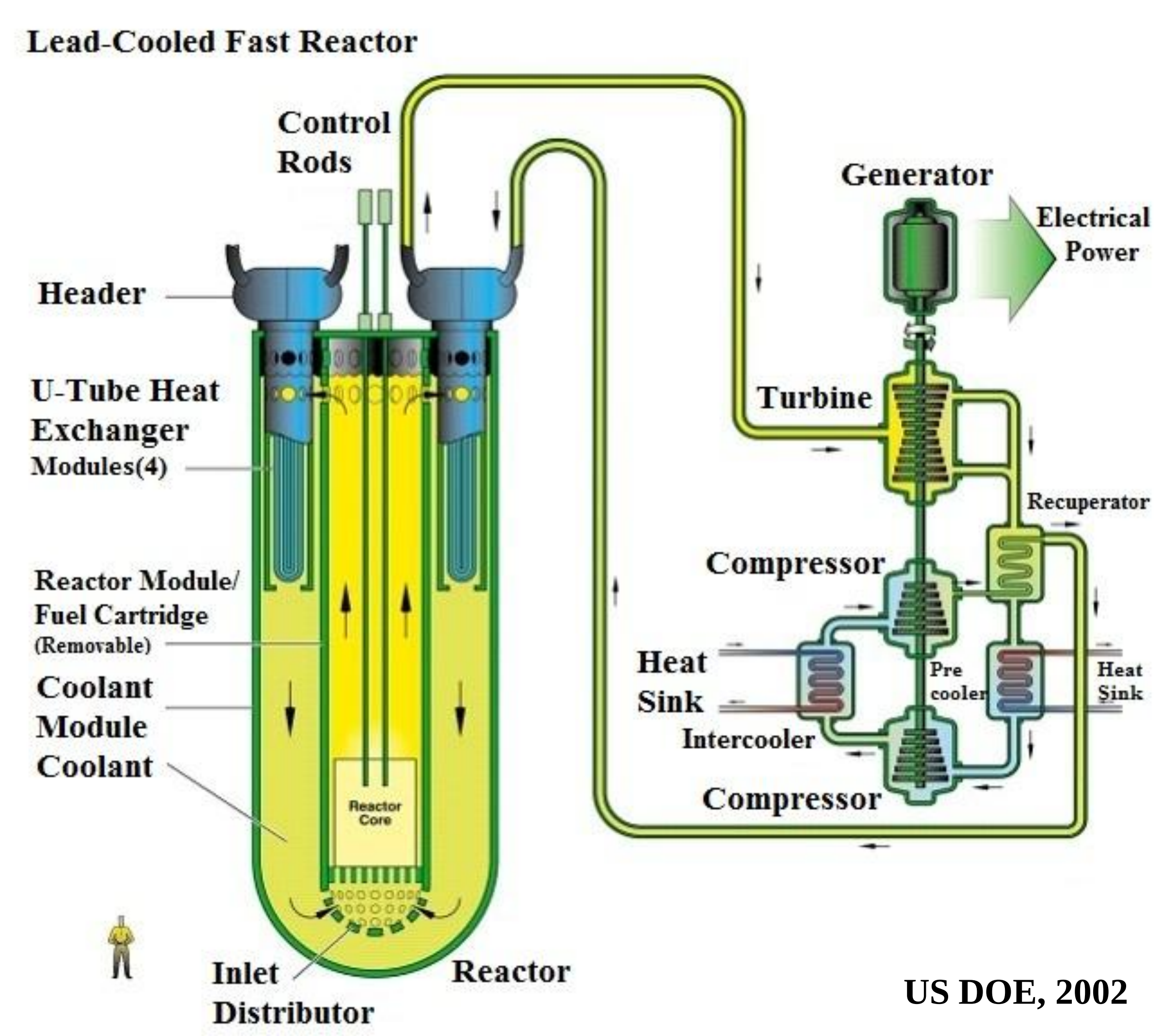
Thermodynamic layout of 600-MW_{el} BN-600 SFR NPP

T–s diagram for the 600-MW_{el} BN-600 SFR NPP turbine cycle

Grigor'ev, V.A. and Zorin, V.M., Editors, 1988. Thermal and Nuclear Power Plants. Handbook, (In Russian), 2nd edition, Energoatomizdat Publishing House, Moscow, Russia, 625 pages.

Margulova, T.Ch., 1995. Nuclear Power Plants, (in Russian), Izdat Publishing House, Moscow, Russia, 289 pages.

4. **Lead-cooled Fast Reactors (LFRs): a fast-spectrum, closed fuel cycle for efficient conversion of fertile uranium and management of actinides, coolant − lead or lead/bismuth eutectic, temperatures up to 550−800ºC, primary thermodynamic cycles – an indirect cycle based on the Rankine steam cycle through heat exchangers (current Russian design) or an indirect cycle based on the Brayton cycle (SC carbon-dioxide gas-turbine cycle);**

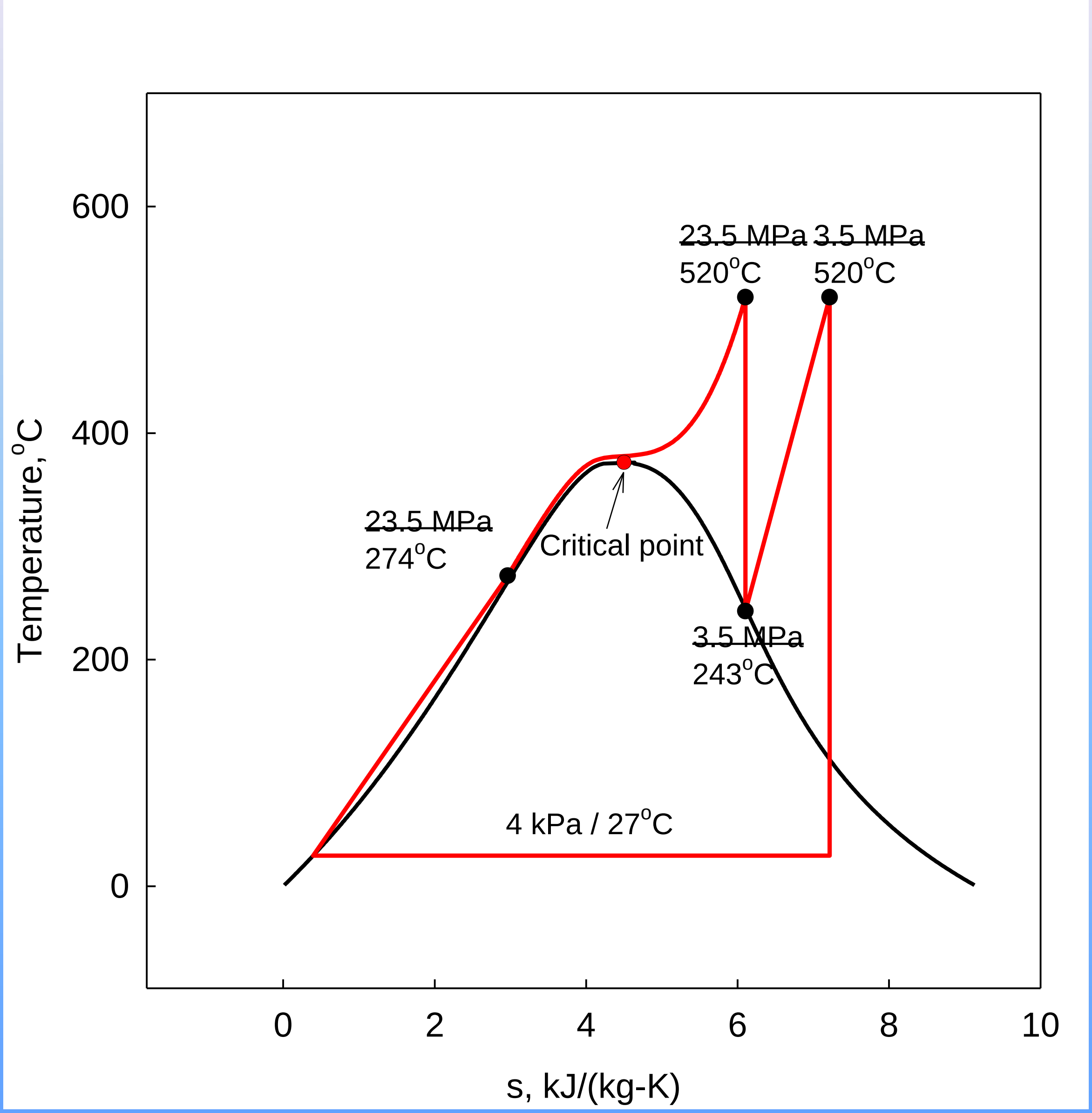


US DOE, 2002

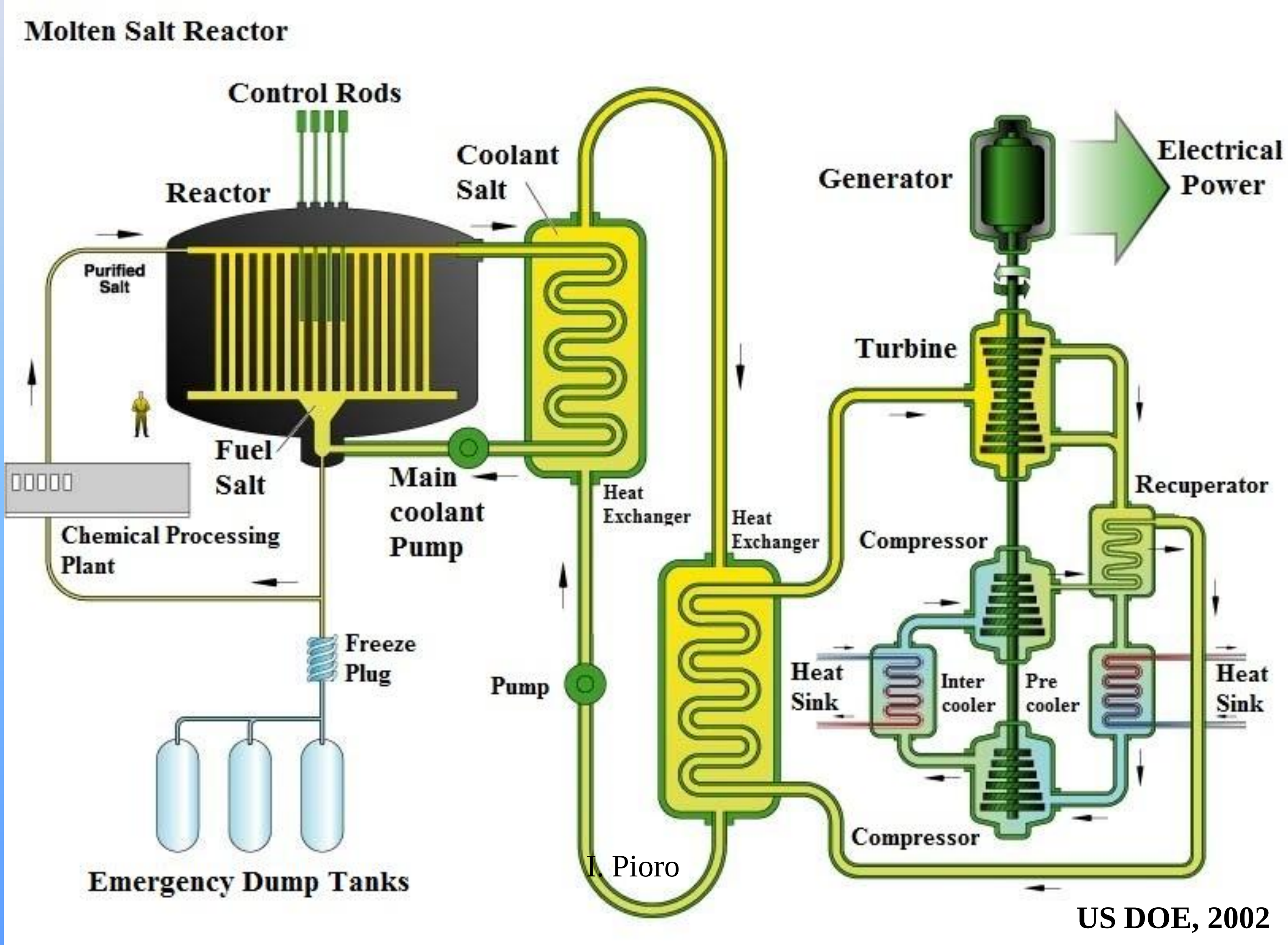
4. Key-design parameters of LFRs planned to be built in Russia (based on NIKIET)

Reactor Parameter	Unit	Brest-300	Brest-1200
Reactor power (thermal/electrical)	MW	700/300	2800/1200
Thermal efficiency	%	43	
Primary coolant	-	Lead	
Coolant melting/boiling temperatures	°C	328/1743	
Coolant density at 450°C	kg/m^3	10,520	
Pressure inside reactor	MPa	~0.1	
Coolant inlet/outlet temperatures	°C	420/540	
Coolant massflow rate	t/s	40	158
Maximum coolant velocity	m/s	1.8	1.7
Fuel	-	UN+PuN	
Fuel loading	t	16	64
Term of fuel inside reactor	years	5	5–6
Fuel reloading per year	-	1	
Core diameter/height	m / m	2.3/1.1	4.8/1.1
Number of fuel bundles	-	185	332
Fuel-rod diameter	mm	9.1; 9.6; 10.4	
Fuel-rod pitch	mm	13.6	
Maximum cladding temperature	°C	650	
Steam-generator pressure	MPa	24.5	
Steam-generator inlet/outlet temperatures	°C	340/520	
Steam-generator capacity	t/s	0.43	1.72
Term of reactor	years	30	60

Simplified T-s diagram for Brest-1200 with supercritical-pressure Rankine "steam"-turbine cycle



5. **Molten Salt-cooled Reactors (MSRs): Fast or epithermal-spectrum reactor, full actinide-recycle fuel cycle, reactor coolant − sodium-fluoride salt with dissolved uranium fuel, temperatures up to 700−800ºC, primary thermodynamic cycles – an indirect cycle based on the Rankine steam cycle through heat exchangers or an indirect cycle based on the Brayton cycle (SC carbon-dioxide gas-turbine cycle);**



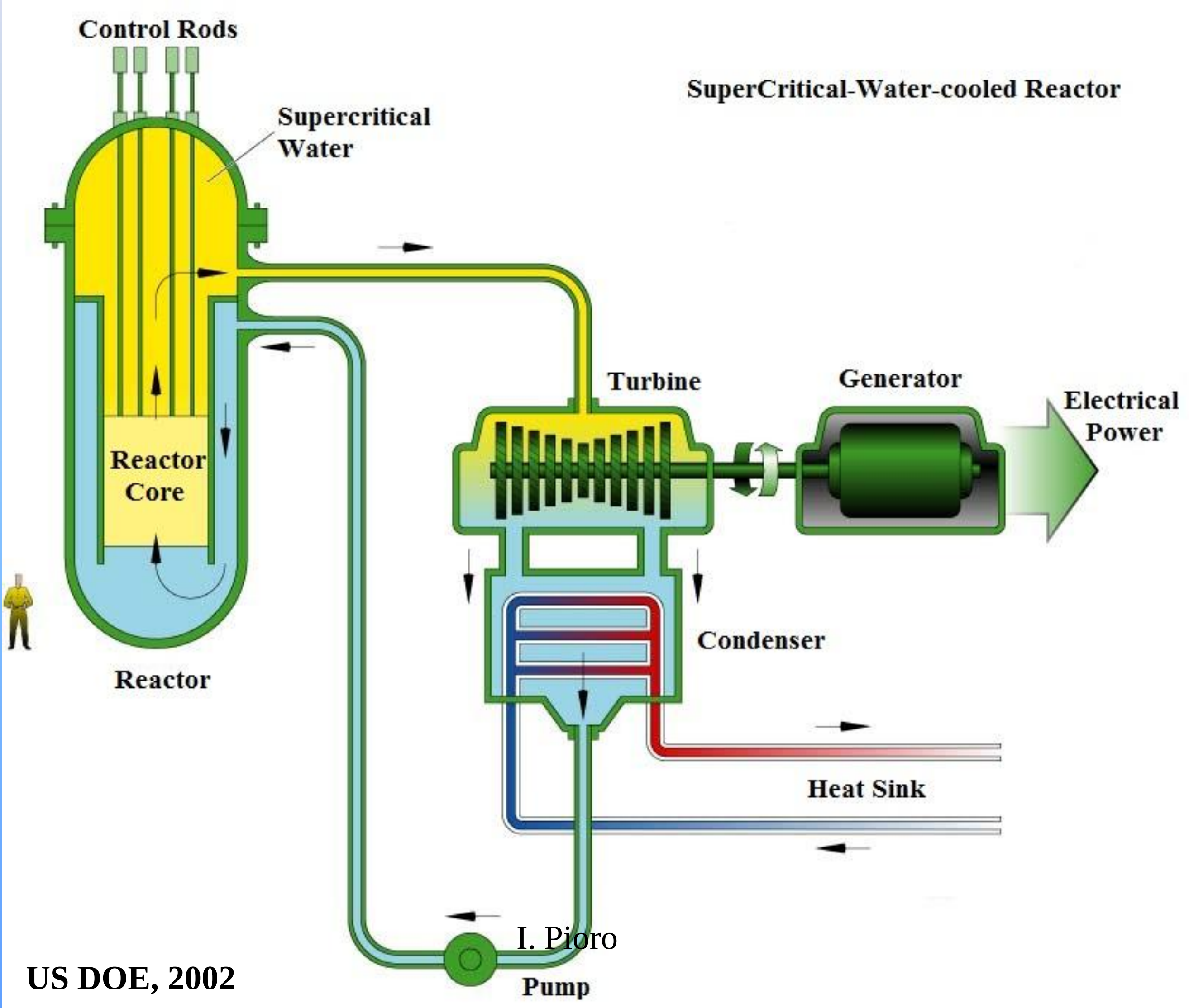
US DOE, 2002

5. Molten Salt-cooled Reactors (MSRs)

Key-design parameters of MSR concept (https://www.gen-4.org/gif/jcms/c_9359/msr Pioro and Kirillov, 2013).

Reactor Parameters	Unit	Reference Value
Reactor power	MW_{el}	1000
Net thermal efficiency	%	44–50
Average power density	MW_{th}/m^3	22
Fuel-salt inlet/outlet temperatures	°C	565/700 (800)
Moderator	–	Graphite
Neutron-spectrum burner	–	Thermal-Actinide

6. **SuperCritical Water-cooled Reactors (SCWRs): thermal spectrum (fast spectrum is possible), reactor coolant − SCW, pressure of 25 MPa, temperatures up to 625°C, primary thermodynamic cycle – a direct cycle based on the SC Rankine "steam" cycle, back-up cycle − indirect cycle based on the SC Rankine "steam" cycle through heat exchangers).**



US DOE, 2002

6. SuperCritical Water-cooled Reactors (SCWRs)

Selected concepts of Pressure-Vessel SuperCritical Water-cooled Reactors (PV SCWRs) (Pioro and Duffey, 2007).

Parameters	Unit	Pressure-Vessel SCWR Concepts		
Country	–	Russia		USA
Spectrum	–	Thermal	Fast	Thermal
Power electrical	MW	1500	1700	1600
Thermal efficiency	%	34	44	45
Pressure	MPa	25	25	25
Coolant inlet/outlet temperatures	ºC	280/550	280/530	280/500
Massflow rate	kg/s	1600	1860	1840
Core height/diameter	m/m	3.5/2.9	4.1/3.4	4.9/3.9
Fuel	–	UO_2	MOX	UO_2
Enrichment	$\%_{wt}$	–	–	5
Maximum cladding temperature	ºC	630	630	–
Moderator	–	H_2O	–	H_2O

Possible Applications of Supercritical-Pressure Technologies in Generation IV Nuclear-Reactor Concepts

I. Supercritical Fluids as Reactor Coolants

1. **SCWRs will use SuperCritical Water (SCW) (P_{cr}=22.064 MPa; T_{cr}=373.95°C)**
2. **Both HTRs (GFRs) and VHTRs will use SuperCritical Helium (P_{cr}=0.2276 MPa; T_{cr}=-267.95°C)**

II. Supercritical-Pressure Power Cycles

1. **SCWRs with direct or in-direct cycles will use SuperCritical-Pressure-Steam Rankine Cycle;**
2. **LFR (Russian design) will use SuperCritical-Pressure-Steam Rankine Cycle;**
3. **Both HTRs (GFRs) and VHTRs might use SuperCritical-Pressure-Helium Brayton Gas-Turbine Cycle (there is a possibility that HTRs (GFRs) will use SuperCritical-Pressure-Carbon-Dioxide Brayton Gas-Turbine Cycle (P_{cr}=7.3773 MPa; T_{cr}=30.978°C))**
4. **SFRs (USA concept) and MSRs will use SuperCritical-Pressure-Carbon-Dioxide Brayton Gas-Turbine Cycle.**

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