

# **Current Status of Nuclear Power Including SMRs**

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# 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.**

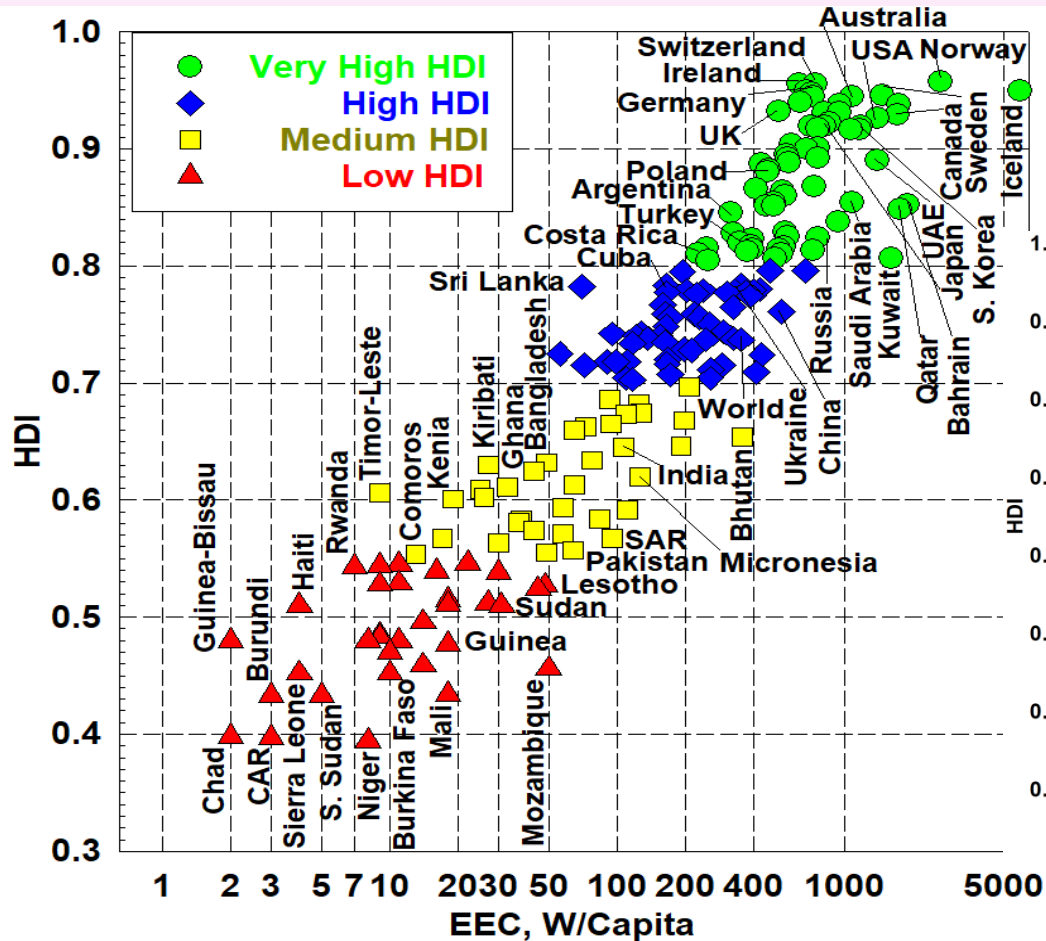
In general, electrical energy can be produced by: **1) non-renewable sources such as coal, natural gas, oil, and nuclear; and 2) renewable sources such as hydro, wind, solar, biomass, geothermal and marine.** However, the main sources for electrical-energy production are: **1) thermal - primary coal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

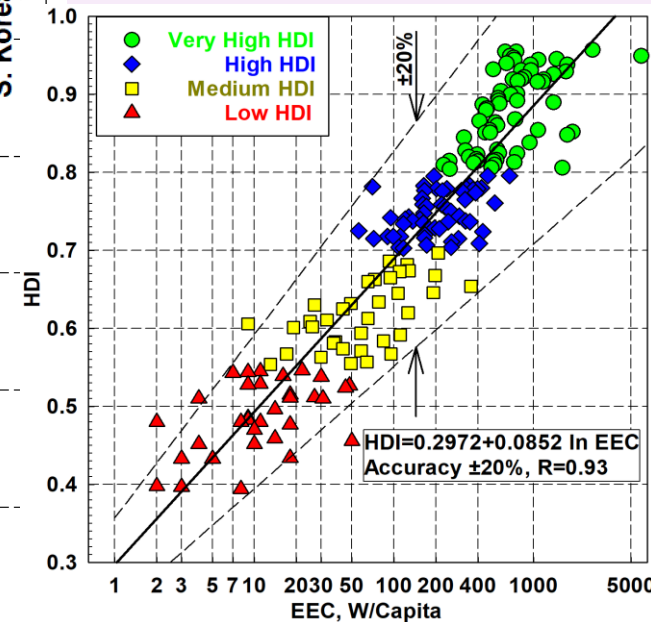
This presentation is mainly based on: Handbook of Generation IV Nuclear Reactors, 2023. 2<sup>nd</sup> edition, Editor: I.L. Pioro, Elsevier – Woodhead Publishing (WP), Kidlington, UK, 1079 pages (hard copy) and 197 pages (Appendices 3 – 9 on website: <https://www.elsevier.com/books-and-journals/book-companion/9780128205884>): <https://shop.elsevier.com/books/handbook-of-generation-iv-nuclear-reactors/pioro/978-0-12-820588-4>; <https://www.sciencedirect.com/book/9780128205884/handbook-of-generation-iv-nuclear-reactors#book-info> and <https://www.gen-4.org/resources/presentations/handbook-generation-iv-nuclear-reactors-second-edition>.

# Electrical Energy Consumption per Capita and HDI in Selected Countries

HDI* Rank (2022)	Country	HDI* (2022)	EEC** (2018 - 2019)		Population in millions (2023)
			W/Capita	GW-h	
<b>Very High HDI (0.8–1.0) (71 countries)</b>					
			<b>In red – highest values</b>		
1	Switzerland	0.967	750	56,350	8.80
2	Norway	0.957	2648	124,130	5.47
3	Iceland	0.959	5898	18,680	0.38
5	Sweden	0.952	1462	131,800	10.61
7	Germany	0.950	719	524,270	83.29
10	Australia	0.946	1084	241,020	26.44
15	UK	0.940	513	300,520	67.74
17	UAE	0.937	1395	119,460	9.52
18	Canada	0.935	1706	549,260	38.78
19	S. Korea	0.929	1163	527,040	51.78
20	USA	0.927	1387	3,989,570	340.00
23	Japan	0.919	816	902,840	123.29
28	France	0.910	765	449,420	64.76
40	Saudi Arabia	0.875	1073	322,370	36.95
49	Kuwait	0.847	1607	59,280	4.31
56	Russia	0.821	763	965,160	144.44
<b>High HDI (0.7–&lt;0.8) (49 countries)</b>					
75	China	0.788	527	7,225,500	1,425.67
89	Brazil	0.760	323	597,230	216.42
98	World	0.739	350	23,398,000	8,078.00
<b>Medium HDI (0.55–&lt;0.70) (42 countries)</b>					
134	India	0.644	107	1,547,000	1,428.63
<b>Low HDI (&lt;0.55) (34 countries)</b>					
179	Guinea-Bissau	0.483	2	40	2.15
184	Sierra Leone	0.458	4	240	8.79
187	Burundi	0.420	3	340	13.24
189	Chad	0.394	2	210	18.28
189	Niger	0.394	8	1,590	22.31
191	CAR	0.387	3	140	5.74
192	S. Sudan	0.381	5	530	11.09



**HDI – year 2019**  
**EEC – year 2018-2019**



Based on the correlation below:  
 To be in Very High HDI – ~400 W/Capita needed  
 High HDI – ~100 W/Capita needed  
 Medium HDI – ~20 W/Capita needed  
 However, in reality:  
 Very High HDI – 227 – 5,900 W/Capita  
 High HDI – 56 – 674 W/Capita  
 Medium HDI – 9 – 207 W/Capita  
 Low HDI – 2 – 50 W/Capita  
 What means 2 W ≈ 2 – 3 LED night light bulbs

\* 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: 1) Very high – 65 countries; 2) high – 53; 3) medium – 36; and 4) low – 33 (Wikipedia, 2019).

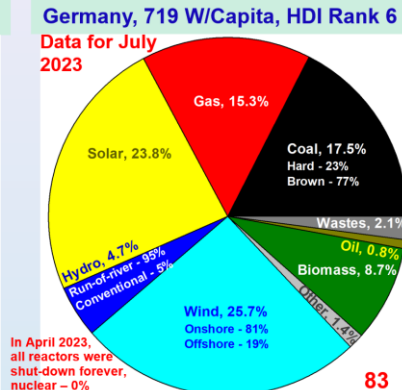
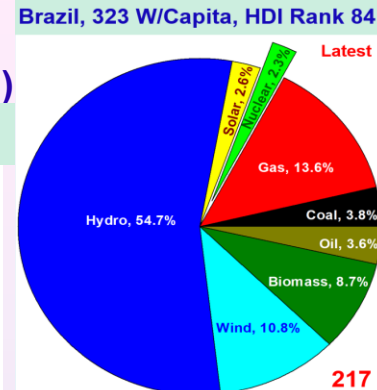
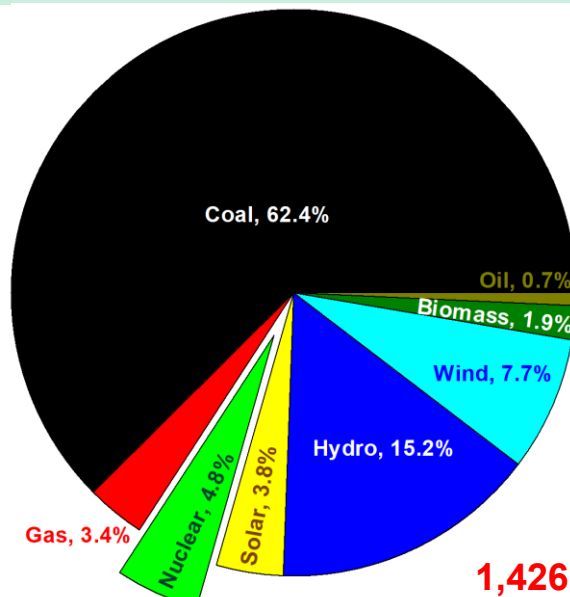
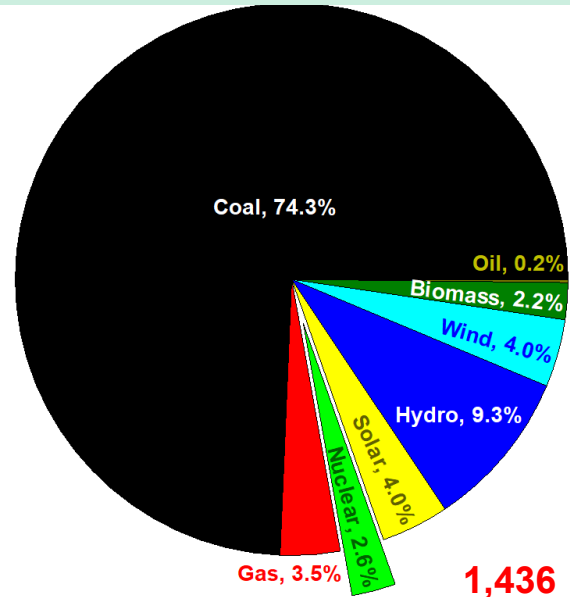
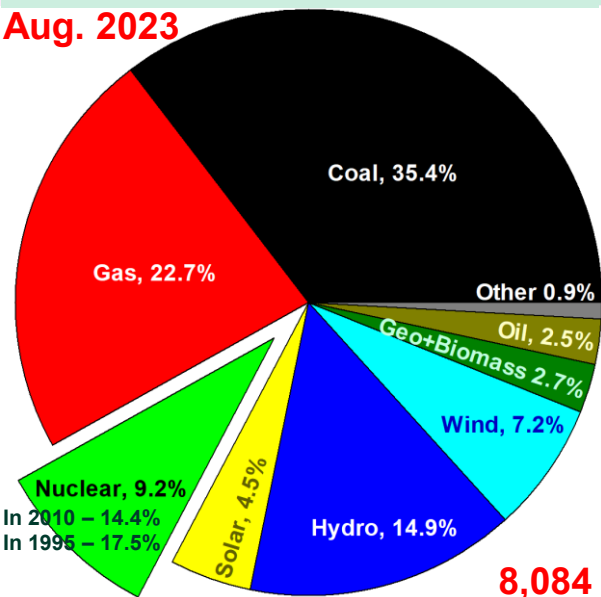
\*\* EEC,  $\frac{W}{Capita} = \frac{EEC, \frac{TW\ h}{year} \times \frac{10^{12}}{365\ days \times 24\ h}}{Population, Millions \times 10^6}$

# Electricity generation by source in the world & selected countries

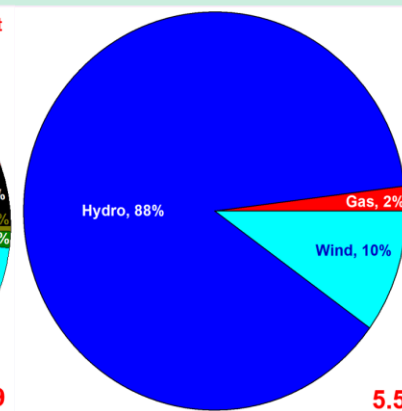
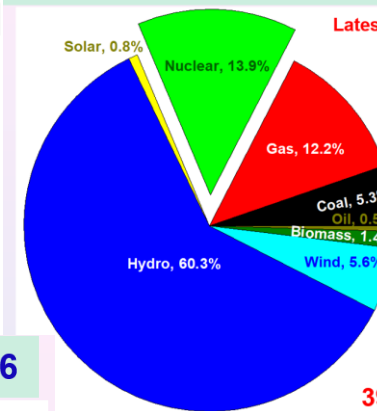
(HDI Rank - from 2019; EEC & data for diagrams – 2018–2019; **population in millions** from Dec. 2023)

**World, 350 W/Capita, HDI Rank 99**    **India, 107 W/Capita, HDI Rank 131**    **China, 527 W/Capita, HDI Rank 85**

**Aug. 2023**



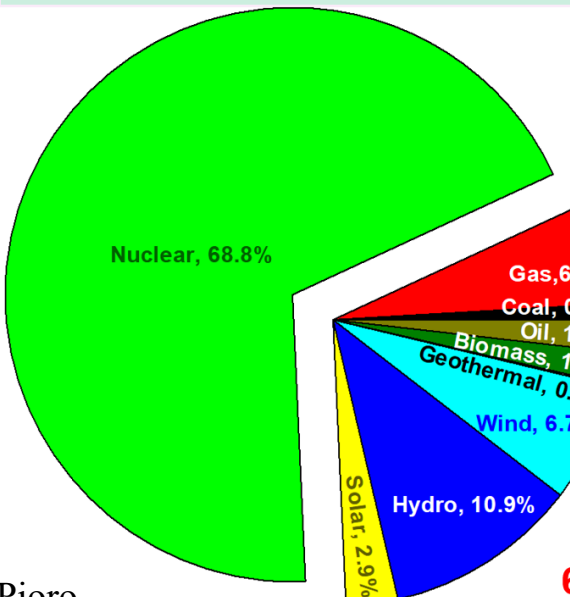
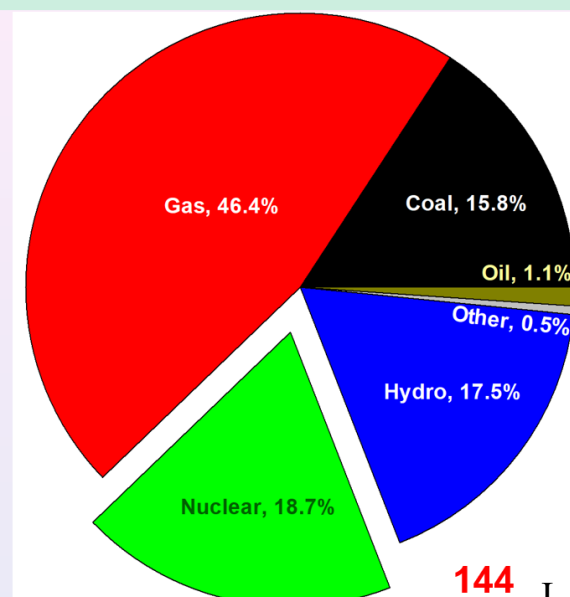
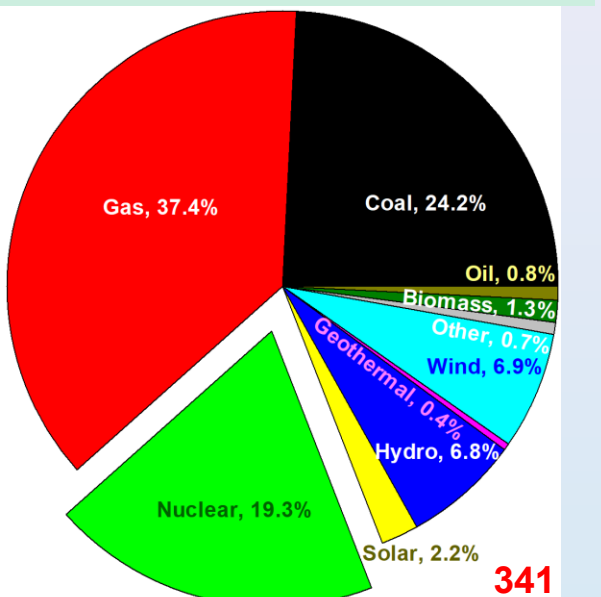
**Canada, 1706 W/Capita, HDI Rank 1**    **Norway, 2648 W/Capita, HDI Rank 1**



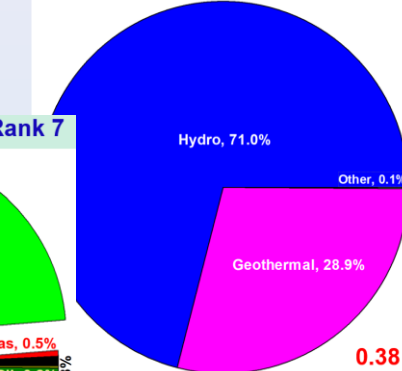
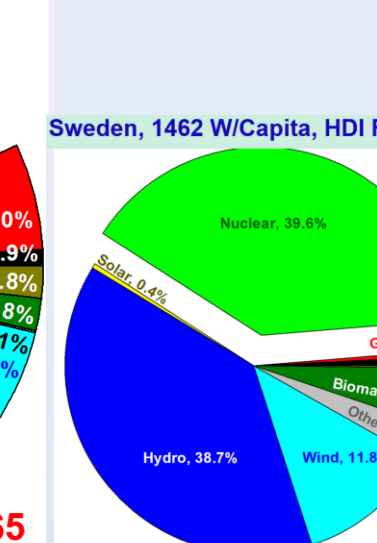
**USA, 1387 W/Capita, HDI Rank 17**

**Russia, 763 W/Capita, HDI Rank 52**

**France, 765 W/Capita, HDI Rank 26**



**Iceland, 5898 W/Capita, HDI Rank 4**



# 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.**
6. **High-temperature (~1000°C) He-cooled reactors can co-generate H<sub>2</sub> through high-temperature electrolysis (requires T=850°C).**

**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.**

## Number of nuclear-power reactors connected to electrical grids and forthcoming as per March 2025 and before the Japan earthquake and tsunami disaster

(March 2011) (Nuclear News (ANS), 2025 & 2011; <https://pris.iaea.org/pris/> and [wnn@world-nuclear-news.org](mailto:wnn@world-nuclear-news.org))

No	Reactor type (% of total reactors / average installed capacity)	No. of units		Installed capacity, GW <sub>el</sub>		Forthcoming units	
		As of March 2025	Before March 2011	As of March 2025	Before March 2011	No. of units	GW <sub>el</sub>
1	Pressurized Water Reactors (PWRs) (largest group of nuclear reactors in the world – 71% / 965 MW <sub>el</sub> )	313 ↑	268	302 ↑	248	38+38? <sup>1</sup> =76	35+44?=79
2	Boiling Water Reactors (BWRs) or Advanced BWRs (2 <sup>nd</sup> largest group of reactors in the world – 14% / 1030 MW <sub>el</sub> )	60 ↓	92	62 ↓	85	1+2? <sup>1</sup> +3	0.3+2.7?=3.0
1+2	Light Water-cooled Reactors (LWRs) – 84%	373 ↑	360	364 ↑	333	39+40?=79	35+47?=82
3	Pressurized Heavy Water Reactors (PHWRs) (3 <sup>rd</sup> largest group of reactors in the world – 11% / 515 MW <sub>el</sub> ; mainly CANDU-reactor type)	47 ↓	50	24	25	6+10?=16	4+6.3?=10
4	Advanced Gas-cooled Reactors (AGRs) (UK, 8 reactors); (all these CO <sub>2</sub> -cooled reactors will be shut down in the nearest future and will not be built again) (2% / 585 MW <sub>el</sub> )	8 ↓	18	4.7 ↓	9	0	0
5	Gas-Cooled Reactors* (GCRs) (China) (0.5% / 75 MW <sub>el</sub> )	2 ↑	-	0.2 ↑	-	-	-
6	Light-water, Graphite-moderated Reactors (LGRs) (Russia, 8 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) (2.5% / 650 MW <sub>el</sub> )	10 ↓	15	6.5 ↓	10	0	0
7	Liquid-Metal Fast-Breeder Reactors (LMFBRs) SFRs (Russia: BN-600 & 800 & China: 20 MW <sub>el</sub> ) (0.7% / 465 MW <sub>el</sub> ) LFR (Russia: BREST-OD-300)	3 ↑ - -	1 - -	1.4 ↑ - -	0.6 - -	3 1	1.7 0.3
	<b>In total</b>	<b>443 ↑</b>	<b>444</b>	<b>401 ↑</b>	<b>378</b>	<b>49+50?=99</b>	<b>41+55?=96</b>

Data in Table include 33 reactors (17 BWRs & 16 PWRs) in Japan from which only 10 PWRs and 2 BWRs were in commercial operation in March of 2025 (<http://www.genanshin.jp/db/fm/plantstatusN.php?x=d>) and 15 reactors in Ukraine, however, the Zaporizhzhia NPP (6 PWRs; 5.7 GW<sub>el</sub>) is currently occupied by Russian Federation and due to that these PWRs are not in service.

Arrows (↓ or ↑) mean decrease or increase in a number of reactors. <sup>1</sup> ? – Means “Commercial start date – indefinite”

\*Helium-cooled reactors – High Temperature Reactor Pebble-bed Module (HTB-PM) (China) (Generation-IV concept, one of VHTR options). Originally, the vast majority of GCRs were carbon-dioxide-cooled reactors of Generations I and II (about 29 Magnox reactors in UK; 8 GCRs in France, and some other countries), i.e., predecessors of current AGRs. However, several GCRs were helium-cooled. Nevertheless, all these early GCRs of Generations I and II were shut-down (operated within 1956 - 2012).

Number of nuclear-power reactors by nation (12 countries with the largest number of reactors ranked by installed capacity) as per March of 2025 (Nuclear News, March 2025; <https://pris.iaea.org/pris/> and [wnn@world-nuclear-news.org](mailto:wnn@world-nuclear-news.org)) and before the Japan earthquake and tsunami disaster (March of 2011) (Nuclear News, 2011)

No	Nation	No. of units (PWRs/BWRs/Other types)		Installed capacity, GW <sub>el</sub>		Changes in number of reactors from March 2011	% of electricity generated by nuclear (2023)
		As of March 2025	Before March 2011	As of March 2025	Before March 2011		
1	USA	94 (63/31)	104	99	103	↓ Decreased by 10 reactors	19.3
2	France	57 (57/-)	58	63	63	↓ Decreased by 1 reactor	68.8
3	China	60 (55/-/1 <sup>2</sup> /2 <sup>3</sup> /2 <sup>5</sup> )	13	57	10	↑ Increased by 47 reactors	4.8
4	Japan*	33 (16/17)	54	32	47	↓ Decreased by 21 reactors	6.4
5	Russia	36 (24/-/10 <sup>1</sup> /2 <sup>2</sup> )	32	27	23	↑ Increased by 4 reactors	18.7
6	S. Korea	27 (24/-/3 <sup>3</sup> )	20	27	18	↑ Increased by 7 reactors	24.7
7	Canada	17 (-/-/17 <sup>3</sup> )	22	13	15	↓ Decreased by 5 reactors	13.9
8	Ukraine**	15 (15/-)	15	13	13	No changes	54.9
9	India	24 (2/2/20 <sup>3</sup> )	19	8	4	↑ Increased by 5 reactors	2.6
10	Spain	7 (6/1)	8	7	8	↓ Decreased by 1 reactor	21.3
11	Sweden	6 (2/4)	10	7	9	↓ Decreased by 4 reactors	39.6
12	UK	9 (1/-/8 <sup>4</sup> )	19	6	10	↓ Decreased by 10 reactors	17.4
In total		385 (265/55/10 <sup>1</sup> /3 <sup>2</sup> /4 <sup>2</sup> /8 <sup>4</sup> /2 <sup>5</sup> )	374	359	323	↑ Increased by 11 reactors and installed capacity increased by 36 GW <sub>el</sub>	-

<sup>1</sup> Number of LGRs; <sup>2</sup> LMFBRs (Gen-IV concept); <sup>3</sup> PHWRs; <sup>4</sup> AGRs; <sup>5</sup> GCRs (He-cooled) (Gen-IV concept).

Arrows (↓ or ↑) mean decrease or increase in a number of reactors.

\*Data in Table include 33 reactors in Japan from which only 10 PWRs and 2 BWRs were in commercial operation in March of 2025 (<http://www.genanshin.jp/db/fm/plantstatusN.php?x=d>).

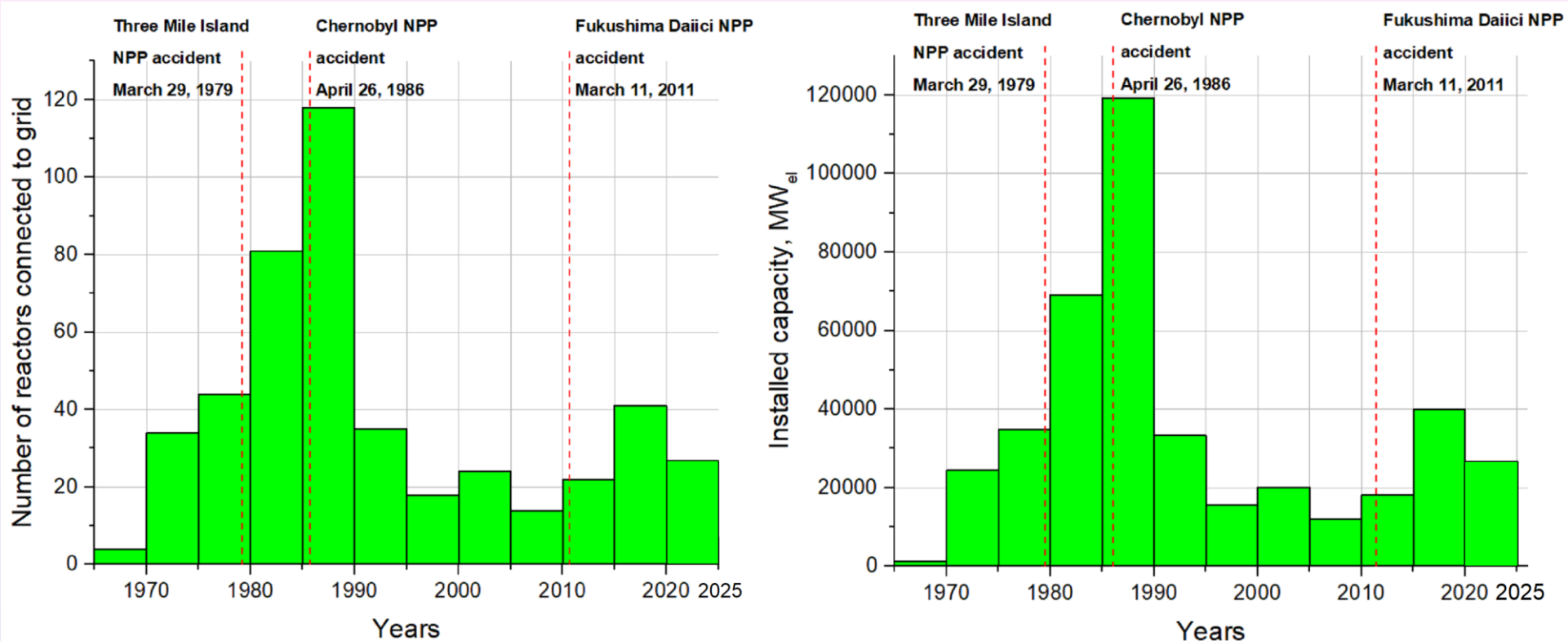
\*\* Data in Table include 15 reactors in Ukraine, however, the Zaporizhzhia NPP (6 PWRs; 5.7 GW<sub>el</sub>) is currently occupied by Russian Federation and due to that is not in service.

# Current activities worldwide on new nuclear-power-reactors build (based on Nuclear News, 2025, March)

No	Country / Nuclear Vendor	Countries, which looking forward for new builds (No. of possible units; ? - indefinite)
1	China / Various vendors (Nuclear-power activities are supported by the Chinese government)	Argentina (1?), China (21+27?), Pakistan (1?) <b>In total: 21+29?=50</b>
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 (9+1?), Bangladesh (1+1?), China (4), Egypt (4?), Hungary (2?), India (4?), Iran (2?), Turkey (4?) <b>In total: 15+15?=30</b>
3	India / Various vendors	India (4+15?) <b>In total: 19</b>
4	France / EDF (Framatome)	France (1+1?), <b>UK*</b> (1+1?) <b>In total: 2+2?=4</b>
5	S. Korea / Various vendors	S. Korea (1+2?) <b>In total: 3</b>
6	Czech Republic / Skoda	Slovakia (1), Ukraine (2?) <b>In total: 3</b>
7	Japan / Hitachi-GE Nuclear (USA), Toshiba, Hitachi,	Canada (1), Japan (2?) <b>In total: 3</b>
8	Canada / AECL (Candu Energy, Inc.)	Romania (2 CANDU reactors) <b>In total: 2</b>
9	USA / Westinghouse, GE together with Hitachi (Japan)	Canada (1) <b>In total: 1</b>
10	Germany / KWU (KraftWerk Union AG)	Brazil (1?) <b>In total: 1?</b>
11	Argentina / CNEA (Comisión Nacional de Energía Atómica)	Argentina (1?) <b>In total: 1?</b>
12	Iran / AEOI (Atomic Energy Organization of Iran)	Iran (1?) <b>In total: 1?</b>

\* Construction of Hinkley Point C - composed of two EPRs (1630 MW<sub>e</sub>, each) began in Dec. 2018, with Unit 1 scheduled to start originally at the end of 2025, based on revision in 2022 – in 2027 and will cost up to GBP26 billion (33 billion USD), is now unlikely to be operational before 2030, with the overall cost revised to be between GBP31 (39 USD) to GBP34 (43 USD) billion (in 2015 prices), EDF has said (Jan. 2024): <https://www.world-nuclear-news.org/Articles/EDF-announces-Hinkley-Point-C-delay-and-big-rise-i>.

# Number of nuclear power reactors in the world by installed capacity (based on data from Nuclear News (ANS), IAEA and WNA, Mach 2024)



Number of nuclear-power reactors of the world put into commercial operation vs. years as per March, 2024 (Four reactors (India 2 BWRs × 150 MW<sub>el</sub>; Switzerland 1 PWR × 365 MW<sub>el</sub>; and USA 1 BWR × 620 MW<sub>el</sub>) have been put into operation in 1969, i.e., they operate for about 55 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.

Their installed capacities as per March, 2024.

# Small Modular Reactors (SMRs)

**Small Modular Reactors (SMRs) (installed capacity  $\leq 300 \text{ MW}_{el}$ )** are today's a very "hot" topic in nuclear engineering worldwide. In general, there are about **108 concepts / designs of SMRs (S&MRs)**, which can be classified as: 1) **Water-cooled SMRs (land based) – 33**; 2) **Water-cooled SMRs (marine based) – 7**; 3) **High-temperature gas-cooled SMRs – 21**; 4) **Fast-neutron-spectrum SMRs – 26**; 5) **Molten-salt SMRs – 17**; and 6) **Other SMRs – 4**.

**From all these 108 SMRs only two KLT-40S reactors (PWRs) (OKBM Afrikantov, Russia) have been constructed, installed on a barge, and put into operation in December of 2019 in port of Pevek, Chukotka and RITM-200M was designed and manufactured; also, two HTR-PM SMRs (VHTR concept, He-cooled) were constructed and put into operation in March of 2022 in China; CAREM (Central ARgentina de Elementos Modulares) SMR (PWR-type; 25 (32)  $\text{MW}_{el}$ ), CNEA (Comisión Nacional de Energía Atómica), Argentina) is under construction.**

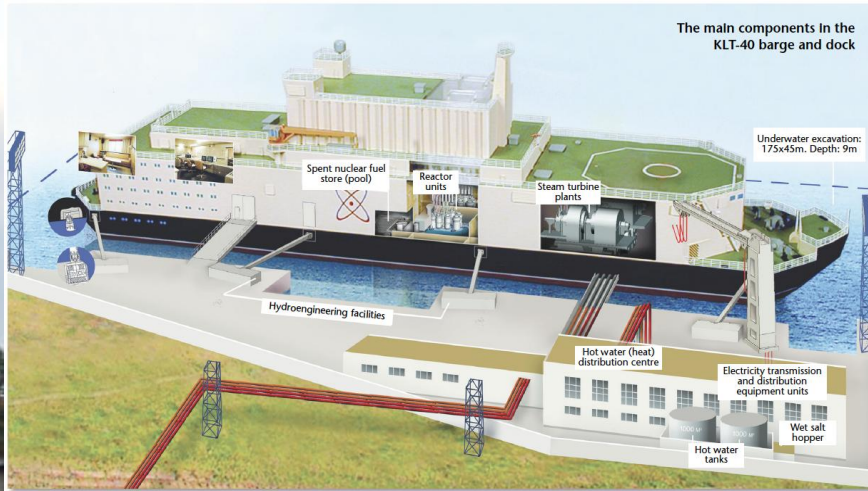
In general, as of today, a number of small nuclear-power reactors with installed capacities (10 – 300  $\text{MW}_{el}$ ) operate around the world. Moreover, some of them operate successfully for about 50 years! However, they cannot be named as SMRs. Also, France, Russia, UK, USA and other countries 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 is based on the Generation IV nuclear-power-reactors concepts.)

Small Modular Reactor Technology Catalogue. A Supplement to the non-serial publication: Small Modular Reactors: Advances in Developments 2024. IAEA Advanced Reactors Information System (ARIS), 2024. IAEA, 380 pages. Free download from: [https://aris.iaea.org/publications/SMR\\_Catalogue\\_2024.pdf](https://aris.iaea.org/publications/SMR_Catalogue_2024.pdf).

Handbook of Small Modular Nuclear Reactors, 2021. Editors: Ingersoll, D.T., and Carelli, M.D., 2<sup>nd</sup> edition, Elsevier – Woodhead Publishing (WP), Duxford, UK, 609 pages.

## Total number of SMRs and S&MRs by countries:

- 1 USA – 28 (5 PWRs land-base; 6 HTGRs; 9 Fast Reactors; 6 MSR; and 2 other type reactors)
- 2 Russia – 15 (5 PWRs land-base; 5 PWRs marine-based; 3 HTGRs; and 2 Fast Reactors)
- 3 China – 13 (7 PWRs land-base; 1 PWR marine-based; 2 HTGRs; 1 Fast Reactor; and 2 MSR)
- 4 Japan - 12 (4 PWRs land-base; 2 HTGR; 4 Fast Reactors; 1 MSR; and 1 other type reactor)
- 5 Canada – 6 (1 SCWR + 1 PHWR; 1 HTGR; 2 MSR; 1 Other)
- 6 France – 5 (2 PWRs; 2 HTGRs; and 1 SFR)
- 6 S. Korea – 5 (1 PWR and 4 Fast Reactors)
- 7 UK – 4 (PWR; HTGR; and 2 MSR)
- 7 S. Africa – 4 HTGRs
- 8 Denmark – 3 MSR
- 9 Czech Republic – 2 (1 HWR; and 1 MSR)
- 9 India – 2 PHWRs
- 9 Italy - 2 LFRs
- 9 Luxemburg – 2 (2 LFRs)
- 10 Sweden – 1 LFR
- 10 Argentina – 1 PWR



Reactor KLT-40S (КЛТ-40С in Russian abbreviations) (in center) with four steam generators (larger cylinders) and four reactor-coolant circulation pumps (smaller cylinders). KLT - Container-carrier cargo-Lighter Transport (reactor) (Контейнеровоз Лихтеровоз Транспортный (реактор) (in Russian abbreviations) (Courtesy of ROSATOM): Photo by N. Greidin, Baltzavod: <https://www.flickr.com/photos/rosatom/24835999197/in/album-72157671934046766/>.

Floating Nuclear Thermal-Power Plant with 2 KLT-40S SMRs has **thermal efficiency only 26%**.

Generation-III+ SMR - RITM-200M with **steam generators integrated into pressure vessel**; small cylinders – circulation pumps (courtesy of ROSATOM) : Photo by N. Greidin, Baltzavod: <https://www.flickr.com/photos/rosatom/24835999197/in/album-72157671934046766/>. NPP with 2 RITM-200M will have **thermal efficiency 31%**! These reactors currently used as propulsion reactors at 3 Russian icebreakers.

## Specifics of KLT-40S and RITM-200M SMRs

Analysis of the data on KLT-40S and RITM-200M shows that these 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 light-water reactors. 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. In addition, it should be noted that development of these two SMRs took significantly longer time than it was expected from the beginning and original budget was overspent.

## Special Considerations on SMRs Development and Implementation

Development and design of any nuclear reactor require special experience, qualifications, and dedication of nuclear-engineering-company 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 testing fuels and materials, and adequate funding are required for the success.

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, and due to that they went through quite difficult times or even were split in parts and sold to other vendors. Based on this experience it is very unlikely that the vast majority or even just a majority of the known 108 SMR design / concepts will be completed, manufactured, and put into operation. In the best way, we will see a small number of SMRs within 10-15 years ahead.

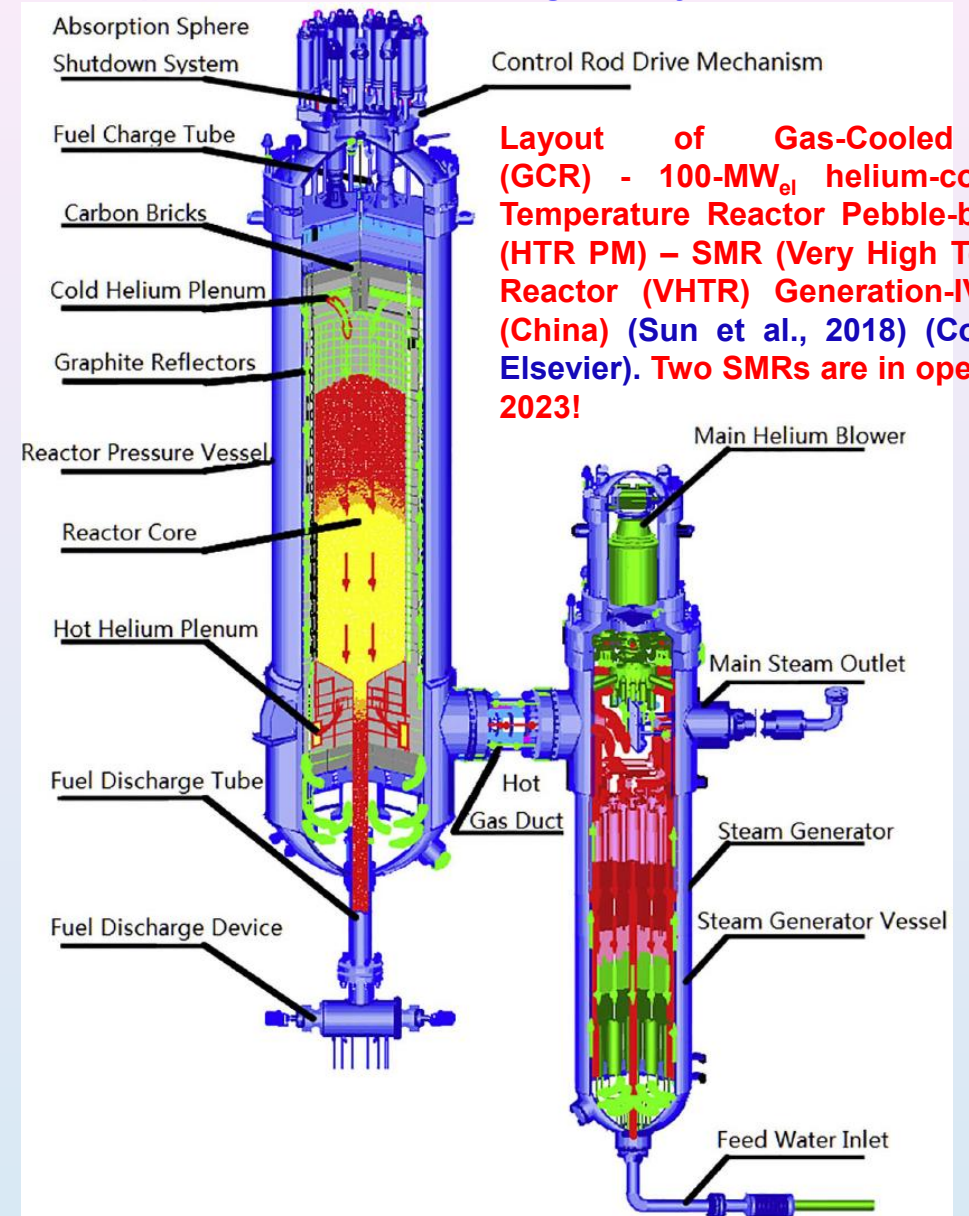
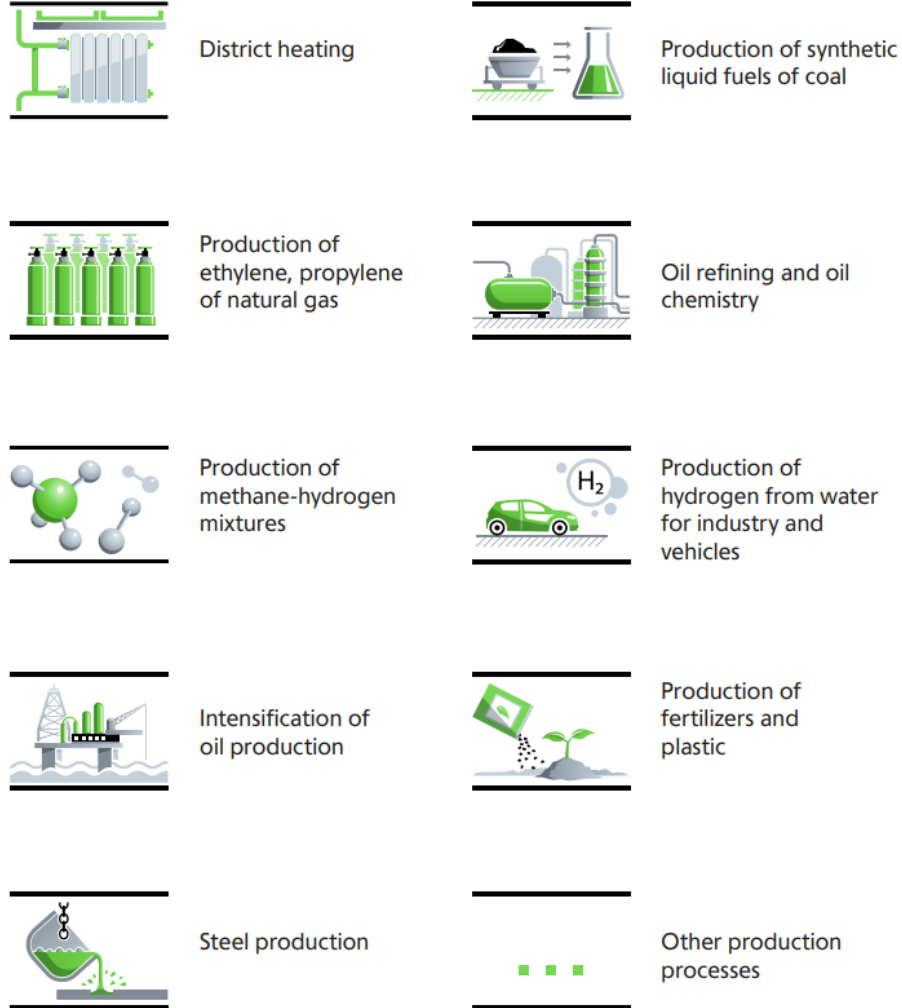
## SMRs under Construction

1. Lead-cooled Fast Reactor (LFR) (Russia) – BREST-OD-300 (to operate in breeding mode (**Core breeding ratio 1.05**)).
2. BWRX-300 (General Electric (USA) – Hitachi Nuclear Energy (Japan) (built in Canada).
3. PWR ACP-100 (China).
4. CAREM (CNEA) (Argentina) – indefinitely.
5. KP-FHR (USA) - Kairos Power’s Fluoride-salt-cooled High-temperature Reactor (Hermes Low-Power Demonstration Reactor project in Oak Ridge, Tennessee).

# Future-Oriented Technology of High-Temperature Gas-Cooled Reactors

High-Temperature Gas-cooled Reactors (HTGRs) are capable of generating heat at temperatures as high as 1000°C. Due to the high safety level HTGRs can be widely used to supply heat for industrial processes in different power-intensive branches of industry to generate electricity at high efficiency and to effectively produce hydrogen fuel. The HTGR is an ecologically-friendly universal nuclear power source with the high safety level.

## HTGR Application Options

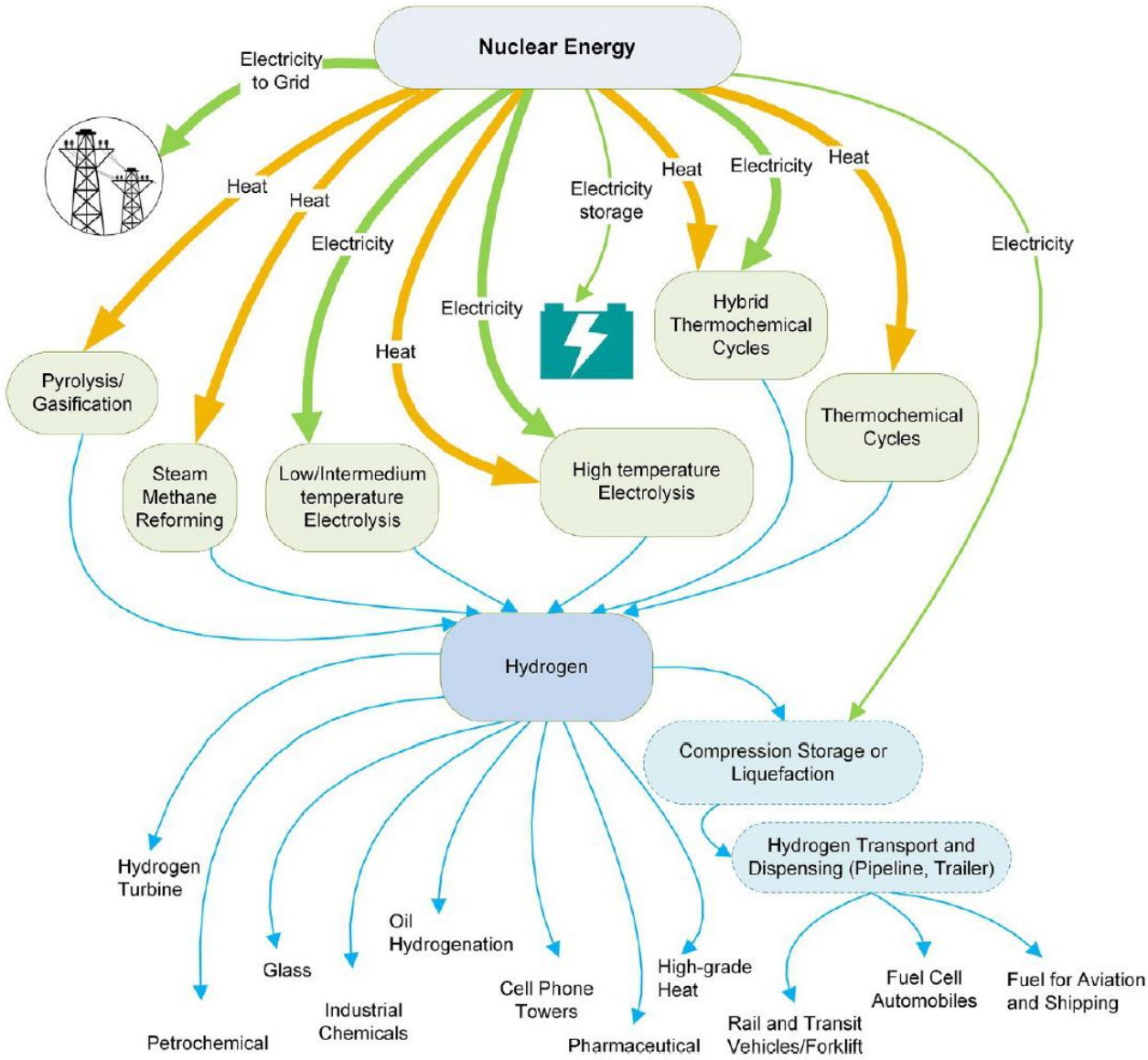


# Typical ranges of thermal efficiencies (gross) of modern thermal and nuclear power plants

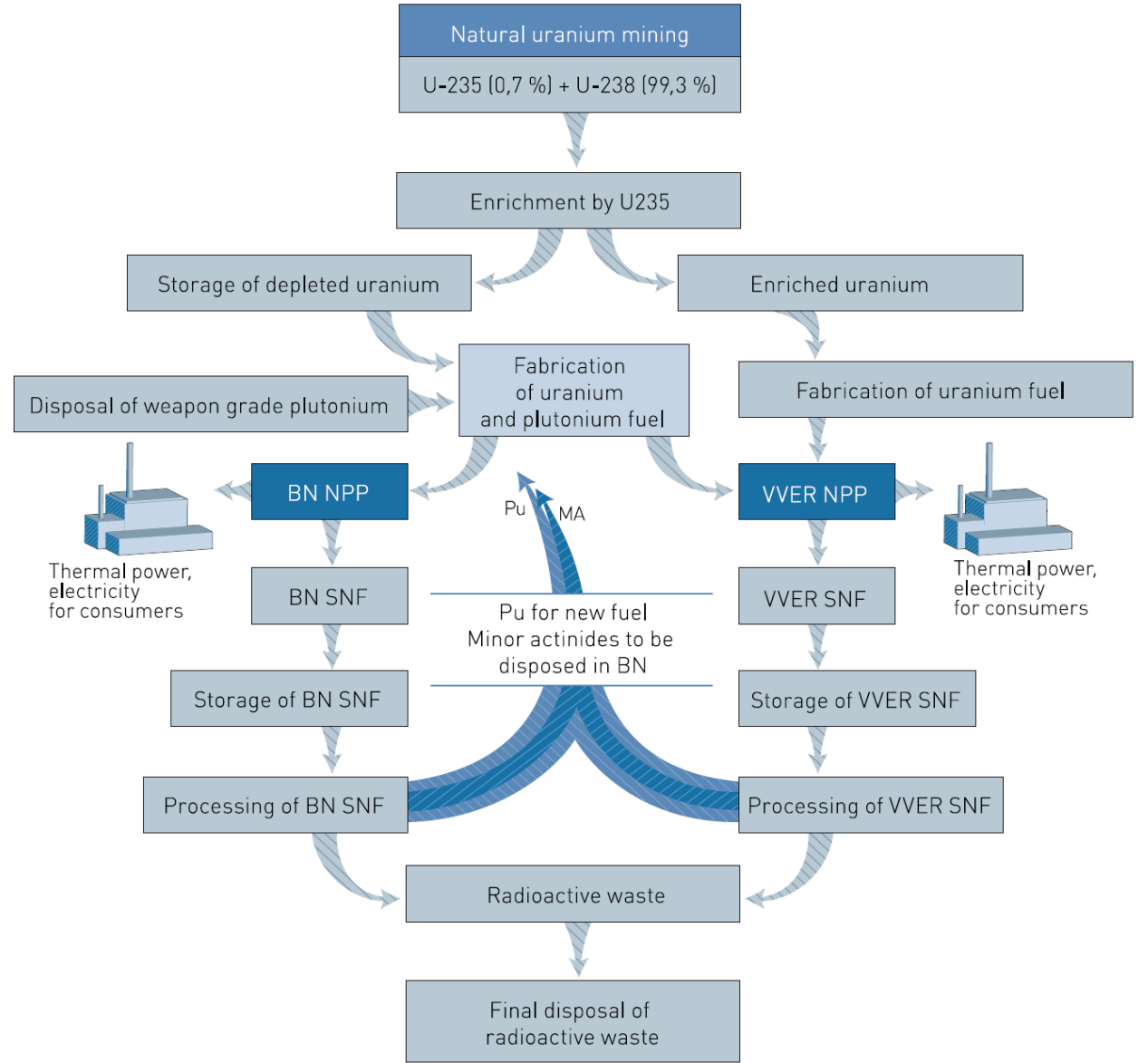
No	Power Plant	Gross Th. Eff.
1	Combined-cycle power plant (combination of Brayton gas-turbine cycle (fuel - natural gas or Liquefied Natural Gas (LNG)); combustion-products parameters at gas-turbine inlet: $P_{in} \approx 2.5$ MPa, $T_{in} \approx 1650^\circ\text{C}$ ) and subcritical-pressure Rankine steam-turbine cycle (steam parameters at turbine inlet: $P_{in} \approx 12.5$ MPa ( $T_{sat} = 327.8^\circ\text{C}$ ), $T_{in} \approx 620^\circ\text{C}$ ( $T_{cr} = 374^\circ\text{C}$ ))	Up to 62%
2	Supercritical-pressure coal-fired power plant (Rankine-cycle steam inlet turbine parameters: $P_{in} \approx 23.5\text{--}38$ MPa ( $P_{cr} = 22.064$ MPa), $T_{in} \approx 540\text{--}625^\circ\text{C}$ ( $T_{cr} = 374^\circ\text{C}$ ); and $P_{reheat} \approx 4\text{--}6$ MPa ( $T_{sat} = 250.4\text{--}275.6^\circ\text{C}$ ), $T_{reheat} \approx 540\text{--}625^\circ\text{C}$ )	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 ( $T_{sat} = 352.3^\circ\text{C}$ ), $T_{in} = 540^\circ\text{C}$ ( $T_{cr} = 374^\circ\text{C}$ ); and $P_{reheat} \approx 3\text{--}5$ MPa ( $T_{sat} = 233.9\text{--}263.9^\circ\text{C}$ ), $T_{reheat} = 540^\circ\text{C}$ )	Up to 43%
5	Carbon-dioxide-cooled-reactor (Advanced Gas-cooled Reactor (AGR)) NPP (Generation-III) (reactor coolant: $P = 4$ MPa, $T = 290\text{--}650^\circ\text{C}$ ; and Rankine-cycle steam: $P_{in} = 17$ MPa ( $T_{sat} = 352.3^\circ\text{C}$ ) and $T_{in} = 560^\circ\text{C}$ ( $T_{cr} = 374^\circ\text{C}$ ); and $P_{reheat} \approx 4$ MPa ( $T_{sat} = 250.4^\circ\text{C}$ ), $T_{reheat} = 560^\circ\text{C}$ )	Up to 43%
6	Gas-Cooled-Reactor (GCR) (High Temperature Reactor – Pebble-bed Module (HTR PM), helium cooled) NPP (reactor coolant: $P = 7$ MPa, $T = 250\text{--}750^\circ\text{C}$ ; and Rankine-cycle steam: $P_{in} = 14.1$ MPa ( $T_{sat} = 337.2^\circ\text{C}$ ), $T_{in} = 556^\circ\text{C}$ ( $T_{cr} = 374^\circ\text{C}$ ); and $P_{reheat} \approx 3.5$ MPa ( $T_{sat} = 242.6^\circ\text{C}$ ), $T_{reheat} = 560^\circ\text{C}$ ).	Up to 42%
7	Sodium-cooled-Fast-Reactor (SFR) (BN-600 & BN-800) NPP (reactor coolant: $P = 0.1$ MPa, $T = 377\text{--}550^\circ\text{C}$ ; and Rankine-cycle steam: $P_{in} = 14.2$ MPa ( $T_{sat} = 337.8^\circ\text{C}$ ), $T_{in} = 505^\circ\text{C}$ ( $T_{cr} = 374^\circ\text{C}$ ); and $P_{reheat} \approx 2.5$ MPa ( $T_{sat} = 224^\circ\text{C}$ ), $T_{reheat} = 505^\circ\text{C}$ )	Up to 40%
8	Pressurized-Water-Reactor (PWR) NPP (Generation-III*) (reactor coolant: $P = 15.5$ MPa ( $T_{sat} = 344.8^\circ\text{C}$ ), $T_{out} = 327^\circ\text{C}$ ; steam: $P_{in} = 7.8$ MPa, $T_{in} = T_{sat} = 293.3^\circ\text{C}$ ; and $P_{reheat} \approx 2$ MPa ( $T_{sat} = 212.4^\circ\text{C}$ ), $T_{reheat} \approx 265^\circ\text{C}$ )	Up to 36-38%
9	Pressurized-Water-Reactor (PWR) NPP (Generation-III, current fleet) (reactor coolant: $P = 15.5$ MPa ( $T_{sat} = 344.8^\circ\text{C}$ ), $T = 292\text{--}329^\circ\text{C}$ ; steam: $P_{in} = 6.9$ MPa, $T_{in} = T_{sat} = 284.9^\circ\text{C}$ ; and $P_{reheat} \approx 1.5$ MPa ( $T_{sat} = 198.3^\circ\text{C}$ ), $T_{reheat} \approx 255^\circ\text{C}$ )	Up to 34-36%
10	Boiling-Water-Reactor (BWR) NPP (Generation-III, current fleet) (reactor coolant: $P = 7.2$ MPa, $T_{out} = T_{sat} = 287.7^\circ\text{C}$ ; steam: $P = 7.2$ MPa, $T_{in} = T_{sat} = 287.7^\circ\text{C}$ and $P_{reheat} \approx 1.7$ MPa ( $T_{sat} = 204.3^\circ\text{C}$ ), $T_{reheat} \approx 258^\circ\text{C}$ )	Up to 34%
11	Light-water-cooled Graphite-moderated Reactor (LGR) (Russian RBMK-1000) NPP (Generation-III, current fleet) (reactor coolant: $P = 6.4$ MPa, $T_{out} = T_{sat} = 279.8^\circ\text{C}$ ; steam: $P = 6.4$ MPa, $T_{in} = T_{sat} = 279.8^\circ\text{C}$ and $P_{reheat} \approx 0.3$ MPa ( $T_{sat} = 133.5^\circ\text{C}$ ), $T_{reheat} \approx 263^\circ\text{C}$ )	Up to 34%
12	Pressurized-Heavy-Water-Reactor (PHWR) NPP (Generation-III, current fleet) (reactor coolant: $P_{in} = 11$ MPa / $P_{out} = 10$ MPa ( $T_{sat} = 311^\circ\text{C}$ ) & $T = 260\text{--}310^\circ\text{C}$ ; steam: $P_{in} = 4.7$ MPa, $T_{in} = T_{sat} = 260.1^\circ\text{C}$ ; and $P_{reheat} \approx 0.6$ MPa ( $T_{sat} = 158.8^\circ\text{C}$ ), $T_{reheat} \approx 250^\circ\text{C}$ )	Up to 32%
13	PWR-SMR NPP (RITM-200M, Russia) (Generation-III*) (not yet in operation as an SMR NPP) (reactor coolant: $P = 15.7$ MPa ( $T_{sat} = 345.8^\circ\text{C}$ ), $T = 277\text{--}313^\circ\text{C}$ ; steam: $P_{in} = 3.82$ MPa, $T_{in} = 295^\circ\text{C}$ ( $T_{sat} = 247.6^\circ\text{C}$ ); no reheat)	Up to 31%
14	PWR-SMR NPP (KLT-40S, Russia) (Generation-III, current fleet) (reactor coolant: $P = 12.7$ MPa ( $T_{sat} = 329^\circ\text{C}$ ), $T = 280\text{--}316^\circ\text{C}$ ; steam: $P_{in} = 3.72$ MPa, $T_{in} = 290^\circ\text{C}$ ( $T_{sat} = 246.1^\circ\text{C}$ ); no reheat)	Up to 26%

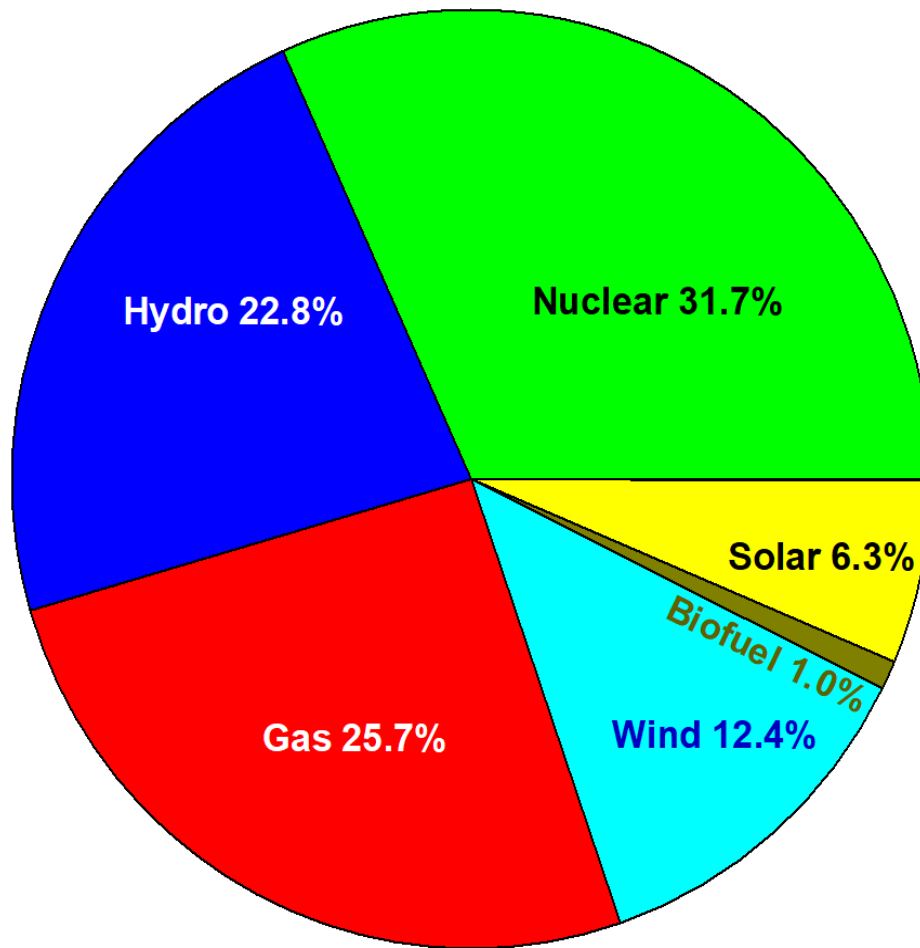
Sodium-cooled fast reactors are the main reactor type for implementing the closed fuel cycle.

With Fast Breeder Reactors (Sodium-; Lead-cooled and others in future nuclear power can become a renewable source of energy!

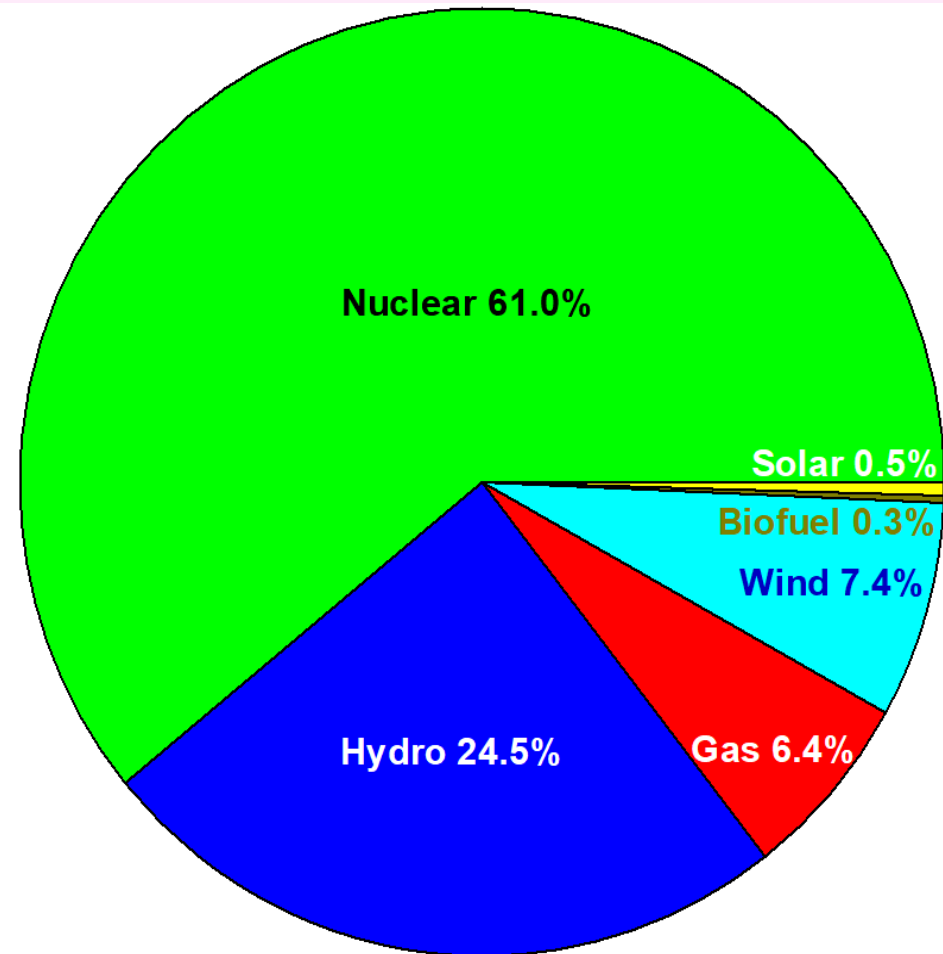


Alternative possible routes for nuclear co-generation plants for large-scale hydrogen production



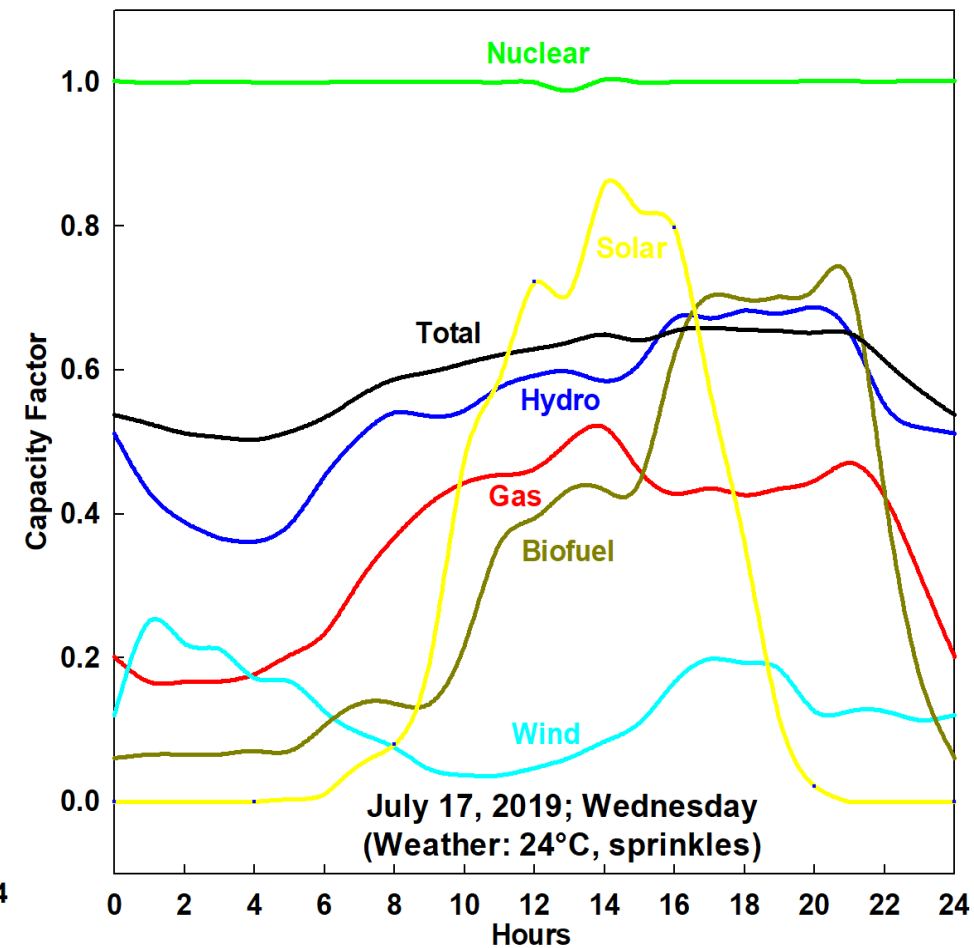
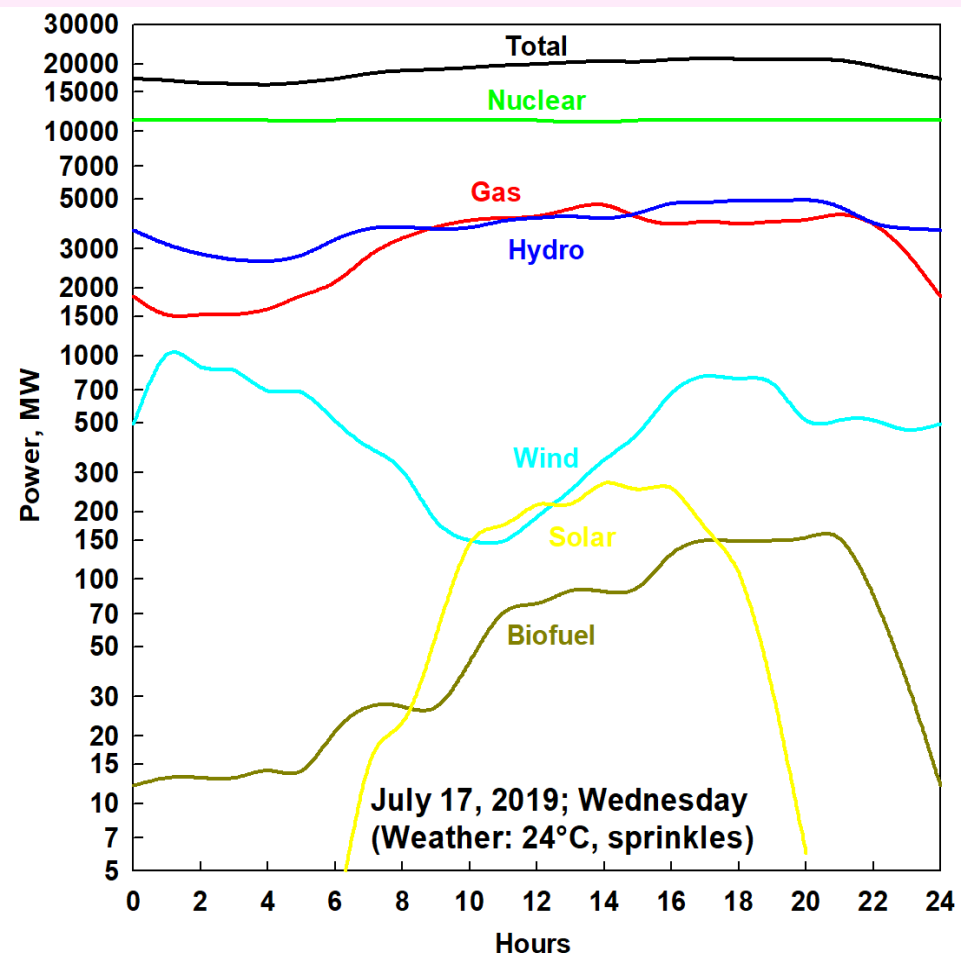


**Installed capacity by energy source**



**Electricity generation by energy source**

**Province of Ontario (Canada), 2022 (population 15 million)**  
 (based on data from Ontario Power Authority: <http://www.powerauthority.on.ca> and Ontario's Long-Term Energy Plan)



Power generated (a) and capacity factors (b) of various energy sources in Ontario (Canada) (population ~15 million people, year 2022) in hot summer working day (Wednesday) of 2019 (based on data from <http://ieso.ca/Power-Data/Data-Directory>). Weather data is related to Toronto (population 6.14 million) – capital of Ontario and the largest city in Canada. Three NPPs equipped with 18 CANDU reactors, including the largest operating one – Bruce NPP, are located nearby.

**What is the best solution for a country, a region, etc.???**

**Energy Mix is the best for a Sustainable and Bright Future**

## Electrical Energy Consumption (EEC) in the world & selected countries

(HDI Rank - from 2019; EEC & other data – 2018–2019; population in millions from June 2021)

No.	Country	Population in millions June 2021	EEC (2018-2019)		Coal				Gas				Hydro	Nuclear	Wind	Solar	Biomass	Other
			TWh	Country % World	%	TWh	CO <sub>2</sub> , Mt	Country % World	%	TWh	CO <sub>2</sub> , Mt	Country % World						
	World	7871	23,398	100	37	8587	6870	100	24	5499	2199	100	15.8	10.4	5.3	2.7	–	5.6
1	China	1439	7226	31	62	4494	3595	52	3	231	93	4	17.7	4.8	5.5	3.1	–	3.5
2	USA	331	3990	17	24	966	772	11	37	1492	597	27	6.8	19.3	6.9	2.2	1.3	1.9
3	India	1380	1547	7	71	1098	879	13	5	70	28	1	10.9	2.9	4.1	3.2	2.8	0.6
4	Russia	146	965	4	16	153	122	~0	46	448	179	8	17.5	18.7	–	–	–	1.6
5	Japan	126	903	4	32	285	228	3	34	306	122	6	8.8	6.4	0.8	7.4	1.8	9.3

EEC, TWh: China + USA = 48% of the world  
 EEC, TWh: All 5 countries = 63% of the world

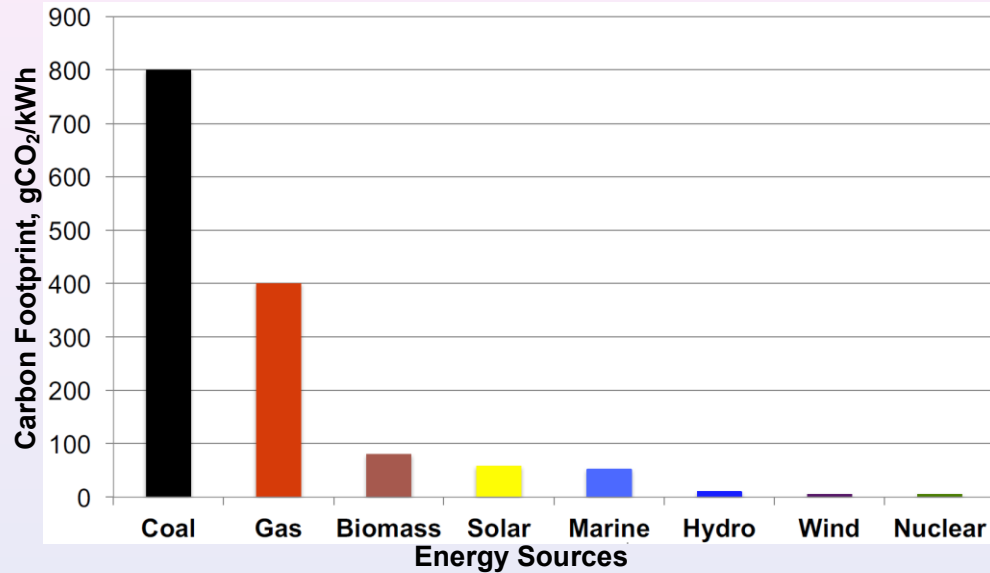
Coal-based CO<sub>2</sub> emissions  
 China + USA + India = 76%  
 All 5 countries = 79%

4 countries = 45% - Gas-based CO<sub>2</sub> emissions  
 without India

### Capturing emissions (WNA)

There are proposals for capturing the CO<sub>2</sub> emissions from burning fossil fuels in large power plants and then injecting them deep underground – so-called, Carbon Capture and Storage (CCS). Though geological disposal of CO<sub>2</sub> has been demonstrated, the effective capture of CO<sub>2</sub> from power stations is difficult and expensive. Despite the application of significant R&D funding for CCS, there has been little progress in demonstrating its technical feasibility. The UN Intergovernmental Panel on Climate Change (IPCC) estimated that it would increase the fuel needs of a power station by at least 25%, and likely double the price of electricity.

Carbon footprint for various energy sources (courtesy of Dr. J. Roberts, University of Manchester, UK: <http://researchbriefings.files.parliament.uk/documents/POST-PN-268/POST-PN-268.pdf>)

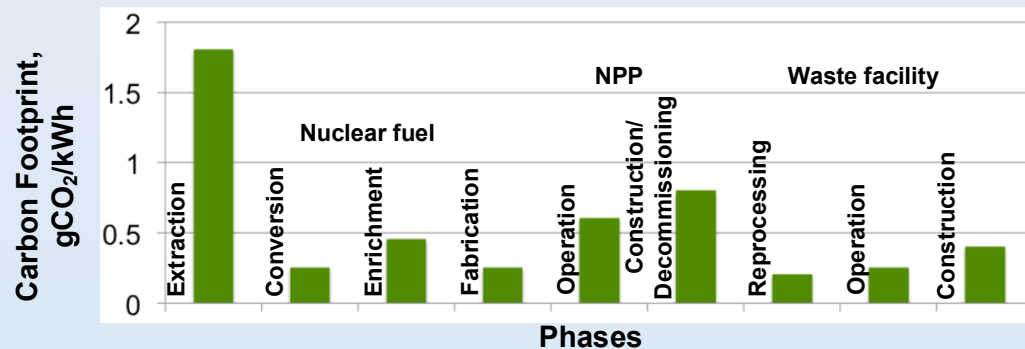


Carbon-dioxide emissions from various energy sources (based on data from Intergovernmental Panel on Climate Change (IPCC) and <https://world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx>)

#	Energy sources	gCO <sub>2</sub> equivalent / kW h
1	Coal	820
2	Biomass co-firing	740
3	Natural gas	490
4	Biomass	230
5	Solar PV - utility	48
6	Solar PV - roof	41
7	Geothermal	38
8	Solar - concentrated	27
9	Hydro-power	24
10	Wind offshore	12
11	Nuclear	12
12	Wind onshore	11

Yellow highlighted – new data or different data compared to those in left Fig.

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)



To reduce emissions sufficiently, all energy sectors will need to be decarbonized. However, much of the immediate focus is on the electricity sector for several reasons (WNA):

- The electricity sector is the most readily-decarbonized, as it provides the means to use non-fossil low-carbon energy (e.g., hydro, nuclear, wind and solar).
- Electricity is clean at the point of final use. This has two main advantages: improving air quality in urban areas; and centralizing energy-related emissions (i.e. at power stations), making emissions regulation more straightforward.
- Generating electricity is emissions intensive. About 20% of final energy consumption is in the form of electricity, but the generation of electricity is responsible for over 40% of all energy-related emissions.

Despite the focus on electricity, limited progress has been made to date. 50% more electricity is generated today from fossil fuels than 20 years ago.

# Top 20 Largest\* Power Plants of the World\*\*

No	Plant	Country	Capacity MW <sub>el</sub>	Ave. annual generation, TW h <sub>year</sub>	Capacity factor, %	Plant type
1	Three Gorges Dam	China	22,500	111.8 <sub>2020</sub>	57	Hydro
2	Itaipu Dam	Brazil/Paraguay	14,000	76.4 <sub>2020</sub>	62	Hydro
3	Gansu	China	14,000	49.3 <sub>2020</sub>	40	Wind
4	Xiluodu	China	13,860	57.1 <sub>average</sub>	47	Hydro
5	Baihetan	China	16,000	64.4 <sub>average</sub>	45	Hydro
6	Belo Monte	Brazil	11,233	39.5 <sub>expected</sub>	40	Hydro
7	Guri Dam	Venezuela	10,235	47.0 <sub>average</sub>	52	Hydro
8	Jebel Ali (power & water desalination)	UAE	9,547	–	–	Natural Gas
9	Tucuruí Dam	Brazil	8,370	21.4 <sub>average</sub>	29	Hydro
10	Kashiwazaki-Kariwa (not in service)	Japan	7,965	(60.3 <sub>1999</sub> )	(86)	Nuclear
11	Xiangjiaba	China	7,750	30.7 <sub>average</sub>	45	Hydro
12	Grand Coulee Dam	USA	6,809	20.2 <sub>average</sub>	34	Hydro
13	Tuoketuo	China	6,720	33.3	57	Coal
14	Bruce	Canada	6,578	49.0 <sub>2017</sub>	87	Nuclear
15	Longtan Dam	China	6,426	18.7 <sub>estimated</sub>	33	Hydro
16	Sayano-Shushenskaya	Russia	6,400	23.5 <sub>average</sub>	42	Hydro
17	Tae'an	South Korea	6,100	–	–	Coal
18	Dangjin	South Korea	6,040	–	–	Coal
19	Krasnoyarsk Dam	Russia	6,000	18.4 <sub>average</sub>	35	Hydro
20	Hongyanhe	China	6,366	48.0 <sub>average</sub>	90	Nuclear

\* It should be mentioned that the data listed in Table might be correct within a certain time frame, because there is a possibility that new largest in the world power plant(s) will be put into operation or new units will be added to the existing plant(s), or, on opposite, current largest power plant(s) can be temporary out of service, e.g., Kashiwazaki-Kariwa NPP, or even in shut-down state for some unit(s) or entirely.

I. Pioro

\*\* There are, at least, two known in the world proposals for possible future power plants: 1) Grand Inga Dam in DR of Congo with maximum installed capacity of 39,000 MW<sub>el</sub> and 2) Penzhin Tidal Power Plant Project in Russia with maximum installed capacity of 87,000 MW<sub>el</sub>.

## Largest power plants in the world by energy source

Rank	Plant	Country	Capacity, MW <sub>el</sub>	Plant type / Energy source
1	Three Gorges Dam	China	22,500	Hydroelectric (dam)
2	Gansu	China	14,000	Wind (onshore)
3	Jebel Ali	UAE	8,695	Natural Gas
4	Tuoketuo	China	6,720	Coal
5	Bruce NPP	Canada	6,578	Nuclear
6	Shoaiba	S. Arabia	5,600	Fuel Oil
7	Jirau	Brazil	3,750	Hydroelectric (run-of-the-river)
8	Bath County	USA	3,003	Hydroelectric (pump storage)
9	Drax	UK	2,595	Biomass
10	Bhadla	India	2,245	Solar (PV)
11	Eesti	Estonia	1,615	Oil Shale
12	Geysers	USA	1,517	Geothermal
13	Shatura	Russia	1,500	Peat
14	Hornsea 1	UK	1,218	Wind (offshore)
15	IPP3*	Jordan	573	Internal combustion engines
16	Ouarzazate	Morocco	510	Solar (concentrated solar)
17	Sihwa Lake	S. Korea	254	Tidal
18	Vasavi Basin Bridge	India	200	Diesel
19	Golmud 2	China	60	Concentrated Photo-Voltaic (CPV)
20	Veyo	USA (Yuta)	9	Recovered energy***
21	Sotenäs	Sweden	3	Marine (wave)

\*Some thermal power plants use multi-fuel options, for example, Surgut-2 (15% natural gas); Shatura (peat – 11.5%, natural gas – 78%, fuel oil – 6.8% and coal – 3.7%) power plants.

\*\* Pumped-Storage Hydro-electricity (PSH), or Pumped Hydro-electric Energy Storage (PHES), is a type of hydro-electric power plant used by electric grids for load balancing.

\*\*\* It is very difficult or just impossible to find the largest recovered-energy power plant in the world, therefore, just for reference purposes, one of the ORMAT recovered-energy power plants is shown here. Usually, their installed capacities can be within 2 – 9 MW<sub>el</sub>: <https://www.ormat.com/en/renewables/reg/view/?ContentID=231>.

# Average (typical) capacity factors of various power plants

Data for 2017 and earlier are taken from Wikipedia (2018);

Data for USA (year 2022) are taken from Nuclear News (May 2023 & 2024) and (year 2021) – from Statista:

<https://www.statista.com/statistics/183680/us-average-capacity-factors-by-selected-energy-source-since-1998/>

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	2023	93
		Romania (CANDU®-reactors)	2017	93
		Canada (CANDU®-reactors)	average lifetime	87
		China	2019	86
		Russia	2019	85
		World	2017	81
		France	2019	77
		UK	2015	75
		India (PHWRs)	2015-2017	69
2	Geothermal	USA	2021	71
3	Bioenergy	USA	2021	64
4	Combined-cycle	USA	2022	57
5	Coal-fired	USA	2022	48
6	Hydroelectric <sup>1</sup>	USA	2023	34
		World (average)	-	~45
		World (range)	-	10-99
7	Wind	USA	2023	34
		World (range)	2011-2013	20-40
8	Concentrated-solar thermal	USA California	2021	21
		Spain (molten salt with storage)	2014	63 <sup>2</sup>
9	Photovoltaic (PV) solar	USA	2023	23
		UK	2015	12
10	Concentrated solar photovoltaic	Spain	-	12
11	Wave	UK	2015	3

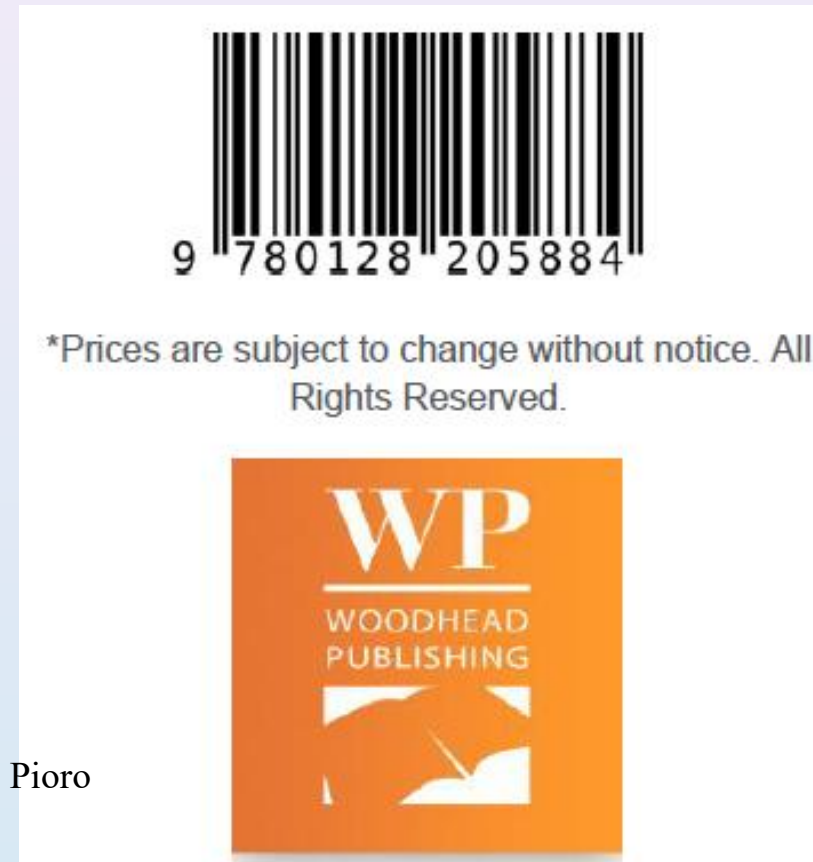
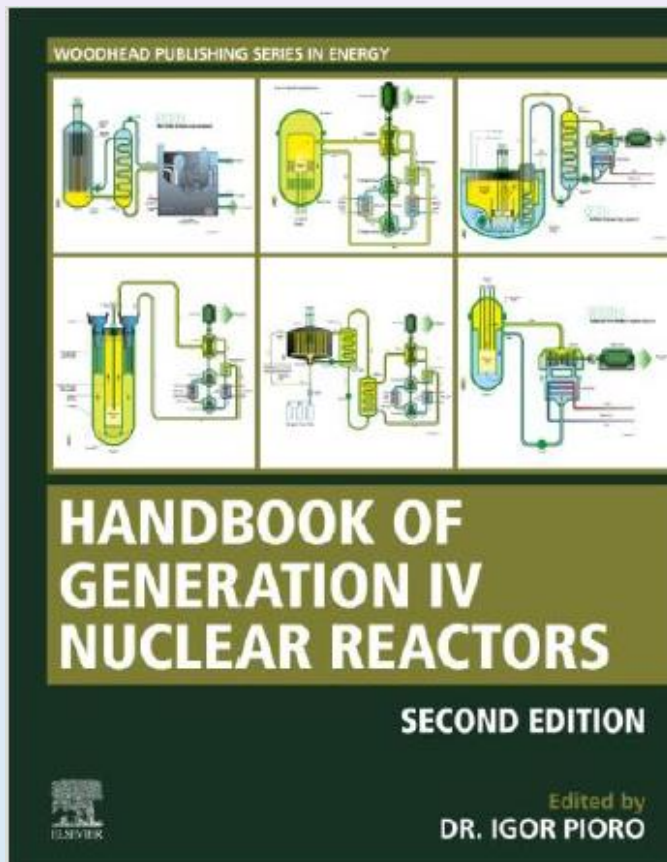
<sup>1</sup> Capacity factors depend significantly on a design, size and location (water availability) of a hydroelectric power plant. Small plants built on large rivers will always have enough water to operate at a full capacity. I. Pioro

<sup>2</sup> Based on information from Torresol Energy (Spain) their Gemasolar a 19.9-MW<sub>el</sub> 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%.

## Slides in this presentation are mainly based on:

**Handbook of Generation IV Nuclear Reactors, 2023. 2<sup>nd</sup> edition, Editor: I.L. Pioro, Elsevier – Woodhead Publishing (WP), Kidlington, UK, 1079 pages (hard copy):**

<https://shop.elsevier.com/books/handbook-of-generation-iv-nuclear-reactors/pioro/978-0-12-820588-4> and <https://www.sciencedirect.com/book/9780128205884/handbook-of-generation-iv-nuclear-reactors#book-info>; and **197 pages (Appendices 3 – 9) on website:** <https://www.elsevier.com/books-and-journals/book-companion/9780128205884>).



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## PART III: RELATED TOPICS TO GENERATION IV NUCLEAR REACTOR CONCEPTS

- 16. The Safety and Risk Assessment of Advanced Reactors (Ars)
- 17. Non-proliferation for Advanced Reactors (Ars): Political and Social Aspects
- 18. Thermal Aspects of Conventional and Alternative Nuclear Fuels
- 19. Hydrogen Production Pathways for Generation-IV Reactors
- 20. Systems of Advanced Small Modular Reactors (ASMRs)
- 21. Alternative Power Cycles for Generation-IV Reactors
- 22. Regulatory and Licensing Challenges with Generation-IV Nuclear Energy Systems

## PART IV: NUCLEAR-POWER TECHNOLOGIES BEYOND GENERATION-IV CONCEPTS

- 23. ITER, the way to fusion energy

## APPENDICES

- A1: Additional materials (schematics, layouts, T-S diagrams, basic parameters, photos, etc.) on thermal and nuclear power plants
- A2: Comparison of thermophysical properties of reactor coolants
- A3: Thermophysical properties of supercritical fluids
- A4: current status of research on thermalhydraulics in forced convection of fluids at supercritical pressures in bare tubes, annular- and bundle-flow geometries
- A5: World experience in nuclear steam reheat
- A6: Comparison of thermophysical properties of selected gases at atmospheric pressure
- A7. Thermophysical properties of molten salts as reactor coolants
- A8: Supplementary tables
- A9: Unit conversion

**Thank you for your attention!**