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Nuclear Power as a Basis for Future Electrical Generation (Review)

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 generated by: 1) non-renewable-energy sources such as coal, natural gas, oil, and nuclear; and 2) renewable-energy sources such as hydro, wind, solar, biomass, geothermal and marine. However, the main sources for electrical-energy generation are: 1) thermal — primary coal and secondary — natural gas; 2) «large» hydro and 3) nuclear. The rest of the energy sources might have visible impact just in some countries. The paper presents the current status of nuclear-power industry in the world and a comparison of nuclear-energy systems to other energy systems. *Bibl. 16, Fig. 11, Table 11.*

Key words: nuclear power, electrical-power generation, non-renewable-energy sources, renewable-energy sources.

Introduction: Current Status of Electricity Generation in the World

It is well known that the electrical-power generation is the key factor for advances in any other industries, agriculture and level of living (see Table 1 and Fig. 1) [1, 2]. In general, electrical energy (see Table 2) can be generated by: 1) non-renewable-energy sources such as coal, natural gas, oil, and nuclear; and 2) renewable-energy sources such as hydro, wind, solar, biomass, geothermal and marine. However, the main sources for electrical-energy generation are: 1) thermal — primary coal (41 %) and secondary natural gas (21 %); 2) «large» hydro (16 %) and 3) nuclear (14 %). The rest of the energy sources might have visible impact just in some countries. In addition, the renewable-energy sources, for example, such as wind (see Fig. 2) and solar (see Fig. 3) and some others, are not really reliable energy sources for industrial-power generation, because they depend on Mother nature and relative costs of electrical energy generated by these and some other renewable-energy sources with exception of large hydro-electric power plants can be large hydro-electric power plants can be significantly higher than those generated by the non-renewable sources.

Table 3 lists 11 top largest power plants of the world, and Table 4 — largest power plants of the world by energy source. Figures 4—8 show photos of selected power plants of the world, mainly, hydro and renewable-energy power plants. Thermal and nuclear power plants are discussed in Sections 2 and 3, 4, respectively. It should be noted that the following two parameters are important characteristics of any power plant: 1) Overall (gross) or net efficiency of a plant. Gross efficiency of a unit during a given period of time is the ratio of the gross electrical energy generated by a unit to the energy consumed during the same period by the same unit. The difference between gross and net efficiencies is internal needs for electrical energy of a power plant, which might be not so small (5 % or even more). 2) Capacity factor of a plant. The net capacity factor of a power plant is the ratio of the actual out put of a power plant over a period of time (usually, during a year) and itspotential output if it had operated at full nameplate capacity the entire time. To calculate the capacity factor, the total amount of energy a plant produced during a period of time should be divided by the amount of energy the plant would have produced at the full capacity. Capacity factors vary significantly depending on the type of a plant. Some power-plant efficiencies are listed in captions to figures, but also, will be discussed in Sections 1—3 for thermal and nuclear power plants.

Information provided in Table 3 is considered to be correct within some timeframe. New units can be added and/or some units can be out of service; for example, currently, i.e., April of 2014, the Kashiwazaki-Kariwa NPP is out of service after the earthquake and tsunami disaster and as the result – the severe accident at the Fukushima NPP in Japan in March of 2011.

Fig. 4 presents the largest in the world by installed capacity (21,100-MW_{el}; planned power 22,500 MWel) hydroelectric power plant (700-

Table 1. Electrical-energy consumption per capita in selected countries (listed here just for reference purposes) [3, 4]

No.	Country	Population, Millions	Energy Consumption		Year	HDI* (2012)	
			TW h/year	W/Capita		Rank	Value
1	Norway	5	116	2603	2013	1	0.955
2	Australia	23	225	1114	2013	2	0.938
3	USA	316	3,886	1402	2012	3	0.937
4	Germany	80	607	822	2009	5	0.920
5	Japan	127	860	774	2012	10	0.912
6	Canada	33	550	1871	2011	11	0.911
7	S. Korea	50	455	1038	2012	12	0.909
8	France	65	461	804	2012	20	0.893
9	UK	63	345	622	2011	26	0.875
10	Russia	143	1,017	808	2013	55	0.788
11	Ukraine	45	182	461	2012	78	0.740
12	Brazil	194	456	268	2012	85	0.730
13	China	1,354	4,693	395	2012	101	0.699
14	World	7,035	19,320	313	2005–2012	103	0.694
15	India	1,210	959	90	2011	136	0.554
16	Afghanistan	30	0.23	1	2012	175	0.374
17	Chad	10	0.93	1	2009	184	0.340
18	Niger	17	0.63	4	2012	187	0.304

*HDI – Human Development Index by United Nations; HDI is a comparative measure of life expectancy, literacy, education and standards of living for countries worldwide. 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.

MW_{el} × 30 + 2 × 50-MW_{el} Francis turbines) (Yangtze River, China) (Courtesy of Chinese National Committee on Large Dams). The project costs 26 billion USD. Height of the gravity dam is 181 m, length – 2.335 km, top width – 40 m, base width – 115 m, flowrate – 116,000 m^3/s, artificial lake capacity – 39.3 km^3, surface area – 1,045 km^2, length – 600 km, maximum width – 1.1 km, normal elevation – 175 m, hydraulic head – 80.6–113 m.

Table 2. Electricity generation by energy source in the world and in selected countries

Attribute	World	USA	Ukraine	France
Coal	41.0	49.6	27.0	3.9
Gas	21.3	18.8	17.0	3.8
Hydro	15.9	6.5	6.0	11.1
Nuclear	13.3	19.3	50.0	78.1
Oil	5.5	3.0	–	–
Renewable:	2.8	2.8	–	–
Biomass	1.3	1.3	–	–
Geothermal	0.3	0.4	–	–
Wind	1.1	0.4	–	1.3
Solar	0.06	0.01	–	–
Other		0.7	–	1.8

Data from 2010–2012 presented here just for reference purposes, partially based on [4].

Fig. 5 shows second largest in the world 781-MW_{el} onshore Roscoe wind-turbine power plant (Texas, USA) (photo from Wikimedia Commons, author/ username: Fredlyfish4). Plant equipped with 627 turbines: 406 MHI 1-MW_{el}; 55 Siemens 2.3-MW_{el} and 166 GE 1.5-MW_{el}. The project cost more than one billion dollars, provides enough power for more than 250,000 average Texan homes and covers area of nearly 400 km^2, which is several times the size of Manhattan, New York, NY, USA. In general, wind power is suitable for harvesting when an average air velocity is at least 6 m/s (21.6 km/h).

Average capacity factors of power plants are listed in Tables 3 and 5.

The aerial view showing portions of Solar Energy Generating Systems (SEGS) (California, USA) (photo from Wikimedia Commons, author A. Radecki). SEGS is the largest solar-energy power plant in the world is displayed on Fig. 7.

The arial view of the first of such kind Gemasolar – a 19.9-MW_{el} concentrated solar power plant with a 140-m high tower and molten-salt heat-storage system (Seville, Spain) (Wikipedia, 2012) (courtesy of SENER/ TORRESOL ENERGY). The plant consists of 2650 heliostats (each 120 m^2 and total reflective area 304,750 m^2), covers 1.95 km^2 (195 ha) and

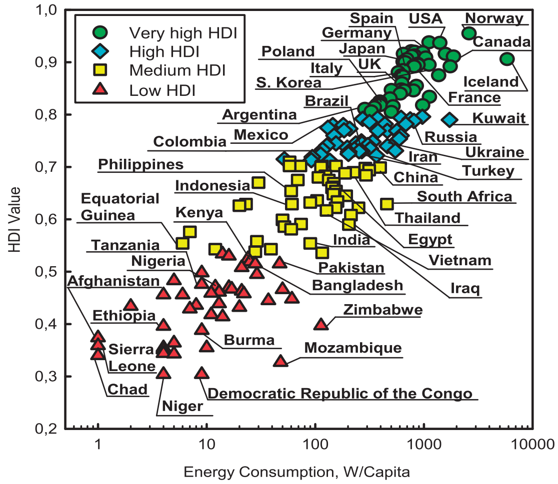

Figure 1. Effect of Energy Consumption on Human Development Index (HDI) for all countries of the world (based on data from [3, 4]).

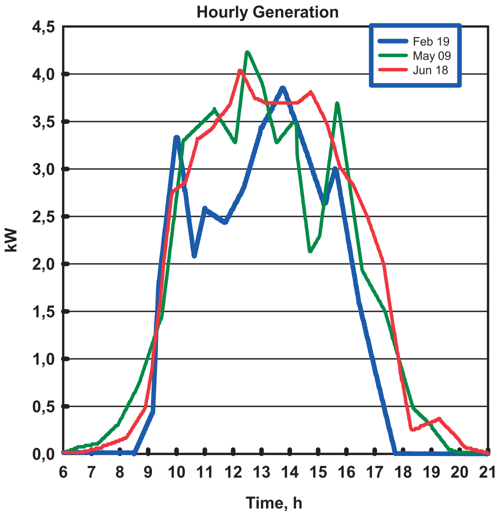

Figure 3. Power generated by photovoltaic system in NY State (USA) (based on data from www.burningcutlery.com/solar): Shown three mostly sunny days: February 19th; May 9th and June 18th.

Figure 5. Second largest in the world 781-MW$_{el}$ onshore Roscoe wind-turbine power plant (Texas, USA).

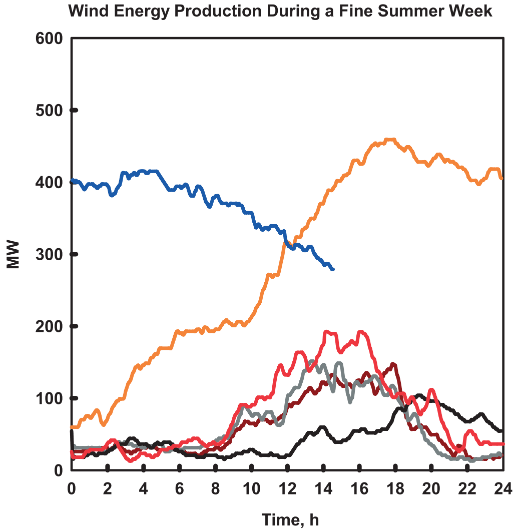

Figure 2. Power generated by 650-MW$_{el}$ wind turbines in the Western Part of Denmark (based on data from www.wiki.windpower.org). Shown a summer week (6 days, i.e., various color lines) of wind-power generation.

Figure 4. Largest in the world by installed capacity.

Figure 6. Aerial view showing portions of Solar Energy Generating Systems (SEGS) (California, USA).

Figure 7.

Figure 8.

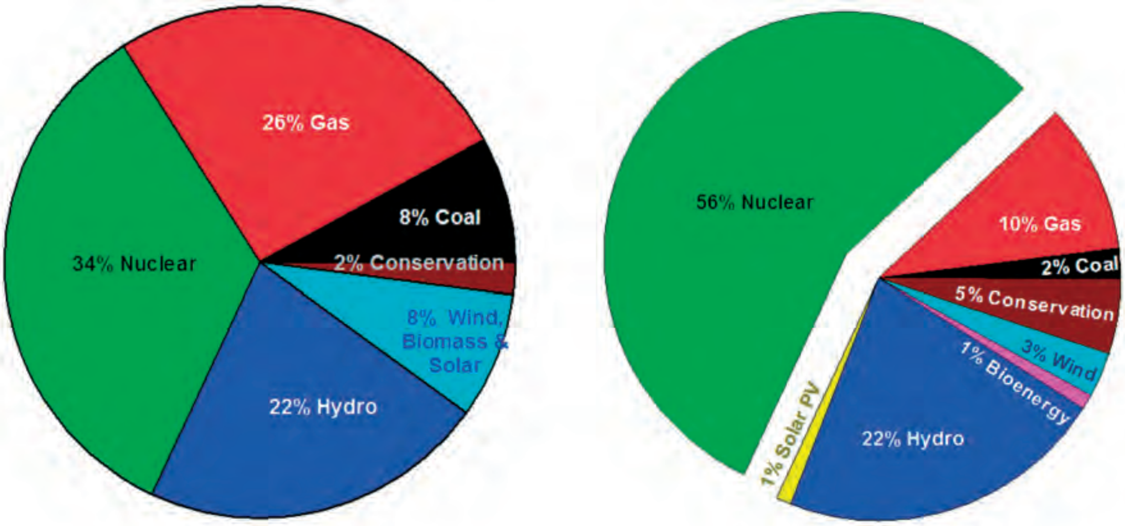

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Figure 9.

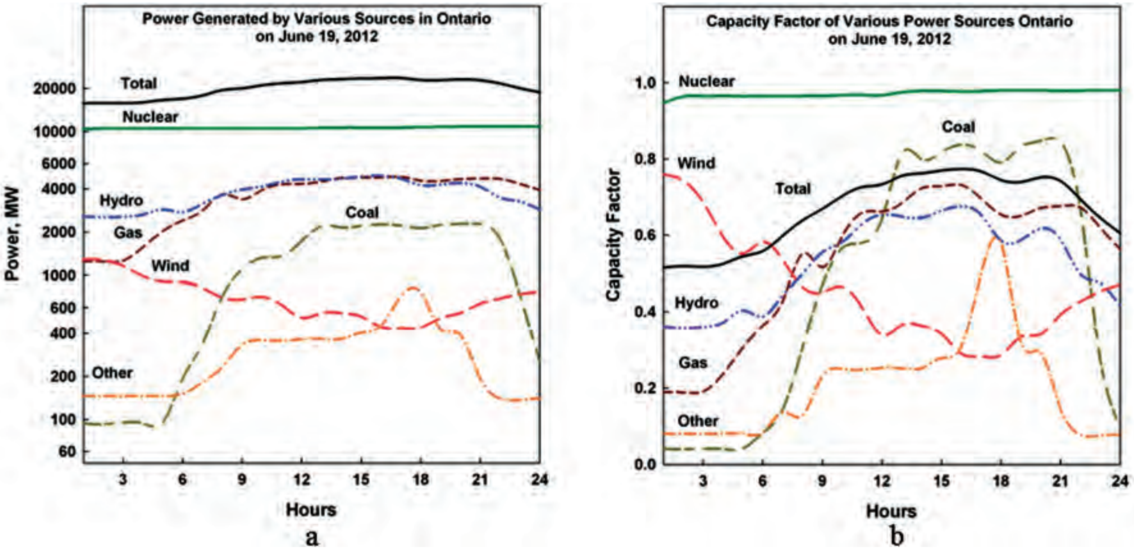

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Figure 10

Table 3. Eleven top power plants of the world by installed capacity

No	Plant	Country	Capacity, MW_{el}	Ave. ann. el. gen., TWh	Capacity factor, %	Plant type
1	Three Gorges Dam	China	21,000[1]	84.5	46	Hydro
2	Itaipu Dam	Brazil/Paraguay	14,000[2]	94.7	77	Hydro
3	Guri Dam	Venezuela	10,235	53.4	60	Hydro
4	Kashiwazaki-Kariwa NPP	Japan	8,212[3]	24.6	–	Nuclear
5	Tucurui Dam	Brazil	8,125[4]	21.4	30	Hydro
6	Bruce NPP	Canada	7,276[5]	35.3	55	Nuclear
7	Grand Coulee Dam	USA	6,809	21.0	35	Hydro
8	Longtan Dam	China	6,426	18.7	33	Hydro
9	Uljin NPP	S. Korea	6,157	48.0	89	Nuclear
10	Krasnoyarsk Dam	Russia	6,000	20.4	39	Hydro
11	Zaporizhzhia NPP	Ukraine	6,000	40.0	76	Nuclear

Footnotes related to inside table information: [1] — another 1,500 MW_{el} under construction; [2] — the maximum number of generating units allowed to operate simultaneously cannot exceed 18 (12,600 MW_{el}); [3] — 4,912 MW_{el} are operational, 3 units (3,300 MW_{el}) have not been restarted since 2007 Chūetsu earthquake; [4] — another 245 MW_{el} under construction; [5] — currently, the largest fully operating NPP in the world.

produces 110 GW h annually, which equals to 30,000 t/year carbon-dioxide emission savings. This energy is enough to supply 25,000 average Spanish houses. The storage system allows the power plant to produce electricity for 15 h without sunlight (at night or on cloudy days). Capacity factor is 75 %. Solar-receiver thermal power is 120 MW_{th}, and plant thermal efficiency is about 19 %. Molten salt is heated in the solar receiver from 260 to 565 °C by concentrated sun light reflected from all heliostats, which follow the sun, and transfers heat in a steam generator to water as a working fluid in a subcritical-pressure Rankine-steam-power cycle is displayed on Figure 7.

Photo of 5th in the world 1.2-MW_{el} concentrated PhotoVoltaic (PV) solar-power plant (Spain) (Fig. 8) (Wikimedia Commons, author/username: afloresm). The plant has 154 two-axis tracking units, consisting of 36 PV modules each, which cover area of 295,000 m^2 with a total PV-surface area of 5,913 m^2. Plant generates 2.1 GWh annually. Conversion efficiency is 12 %.

An example of how various energy sources generate electricity in a grid can be illustrated based on the Province of Ontario (Canada). Figure 9 shows installed capacity (a) and electricity generation (b) by energy source in Ontario (Canada); and Fig. 10 shows power generated by various energy sources and their capacities (June, 2012). Analysis of Fig. 9 a shows that in Ontario major installed capacities are nuclear (34 %), gas (26 %), hydro (22 %), coal (8 %), and renewables (mainly wind) (8 %). However, electricity (see

Table 4. Largest power plants of the world (based on installed capacity) by energy source

Rank	Plant	Country	Capacity, MW_{el}	Plant type
1	Three Gorges Dam Power Plant (see Fig. 5)	China	21,000	Hydro
2	Kashiwazaki-Kariwa NPP	Japan	8,210	Nuclear
3	Taichung Power Plant	Taiwan	5,780	Coal
4	Surgut-2 Power Plant	Russia	5,600	Fuel oil*
5	Futtsu Power Plant	Japan	5,040	Natural gas
6	Eesti Power Plant	Estonia	1,615	Oil shale
7	Shatura Power Plant	Russia	1,020	Peat*
8	Alta Wind Energy Center	USA	1,020	Wind
9	Hellisheidi Power Plant	Iceland	303	Geothermal
10	Alholmens Kraft Power Plant	Finland	265	Biofuel*
11	Sihwa Lake Tidal Power Plant	S. Korea	254	Tidal
12	Charanka Solar Park	India	214	Solar
13	Vasavi Basin Bridge Diesel Power Plant	India	200	Diesel
14	Agucadoura Wave Farm	Portugal	2	Marine (wave)**

* It should be noted that actually, 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 %), Alholmens Kraft (primary fuel — biomass, secondary — peat and tertiary — coal) power plants. ** Currently, not in operation anymore.

Table 5. Average (typical) capacity factors of various power plants (listed here just for reference purposes) (partially based on [5])

No	Power Plant type	Location	Year	Capacity factor, %
1	Nuclear	USA	2010	91
		UK	2011	66
2	Combined-cycle	USA	2009	42
		UK	2011	48
3	Coal-fired	USA	2009	64
		UK	2011	42
4	Hydroelectric[13](see Fig. 4)*	USA and UK	2011	40
		World (average)	–	44
		World (range)	–	10-99
5	Wind (see Fig. 5)	UK	2011	30
		World	2008	20-40
6	Wave	Portugal	–	20
7	Concentrated-solar thermal (see Figs. 6 and 7)	USA (California)	–	21
8	Photovoltaic (PV) solar	USA (Arizona)	2008	19
		USA (Massachusetts)	–	12-15
		UK	2011	5.5
			2007-2011	8.3
9	Concentrated-solar PV (Fig. 8)	Spain	–	12

* 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.

Fig. 9 b) is mainly generated by nuclear (55 %), hydro (22 %), natural gas (10 %), renewables (mainly wind) (just 5 %) and coal (2 %).

Figure 10 shows power generated by various energy sources in Ontario (Canada) on June 19, 2012 (hot summer day, when a lot of air-conditioning was required) (this date is taken as an example) and corresponding to that shows capacity factors of various energy sources. Analysis of Fig. 10 shows that electricity that day from midnight till 3 o'clock in the morning was mainly generated by nuclear, hydro, gas, wind, «other» and coal. After 3 o'clock in the morning, wind power started to be decreased by Mother nature, but electricity consumption started to rise.

Therefore, «fast-response» gas-fired power plants and later on, hydro and coal-fired power plants plus «other» power plants started to increase electricity generation to compensate both: decreasing in wind power and increasing demand for electricity. After 6 o'clock in the evening, energy consumption slightly dropped in the province, and at the same time, wind power started to be increased by Mother nature. Therefore, gas-fired, hydro and «other» power plants decreased energy generation accordingly («other» plants dropped power quite abruptly, but their role in the total energy generation is very small). After 10 o'clock in the evening, energy consumption started to drop even more, therefore, coal-fired power plants as the most «dirty» plants decreased abruptly electricity generation followed by gas-fired and hydro plants.

This example shows that if a grid has Nuclear Power Plants (NPPs) and/or renewable-energy sources the grid must include «fast-response» power plants such as gas- and coal-fired and/or large hydro-power plants.

Thermal Power Plants

In general, all thermal power plants [2, 6] are based on the following thermodynamic cycles: 1) Rankine steam-turbine cycle (the mostly used in various power plants; usually, for solid and gaseous fuels, however, other energy sources can be also used, for example, solar, geothermal, etc.); 2) Brayton gas-turbine cycle (the second one after the Rankine cycle in terms of application in power industry; only for clean gaseous fuels); 3) combined cycle, i.e., combination of

Table 6. Typical ranges of thermal efficiencies (gross*) of modern thermal power plants [2, 6]

No	Power plant	Gross efficiency, %
1	Combined-cycle power plant (combination of Brayton gas-turbine cycle (fuel — natural or LNG; combustion-products parameters at the gas-turbine inlet: $T_{in} \approx 1650$ °C) and Rankine steam-turbine cycle (steam parameters at the turbine inlet: $T_{in} \approx 620$ °C ($T_{cr} = 374$ °C))	Up to 62
2	Supercritical-pressure coal-fired power plant (Rankine-cycle steam inlet turbine parameters: $P_{in} \approx 25–38$ MPa ($P_{cr} = 22.064$ MPa), $T_{in} \approx 540–625$ °C ($T_{cr} = 374$ °C) and $T_{reheat} \approx 540–625$ °C)	Up to 55
3	Internal-combustion-engine generators (Diesel cycle & Otto cycle with natural gas as a fuel)	Up to 50
4	Subcritical-pressure coal-fired power plant (older plants) (Rankine-cycle steam: $P_{in} \approx 17$ MPa, $T_{in} \approx 540$ °C ($T_{cr} = 374$ °C) and $T_{reheat} \approx 540$ °C)	Up to 40
5	Concentrated-solar thermal power plants with heliostats, solar receiver (heat exchanger) on a tower and molten-salt heat-storage system (for details, see Fig. 7): Molten salt maximum temperature is about 565 °C, Rankine steam-turbine power cycle used.	Up to 20

* 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 ther-

Table 7. Number of nuclear-power reactors in operation and forthcoming as per March 2014 [7] and before the Japan earthquake and tsunami disaster (March 2011) [8]

No	Reactor type (Some details on reactors)	No. of units		Installed capacity, GW_{el}		Forthcoming units	
		As of March 2014	Before March 2011	As of March 2014	Before March 2011	No. of units	GW_{el}
1	**Pressurized Water Reactors (PWRs)** (largest group of nuclear reactors in the world – 63 %)	270 ↑	268	250 ↑	248	89	93
2	**Boiling Water Reactors (BWRs)** or Advanced BWRs (2nd largest group of reactors in the world – 19 %; ABWRs – the only ones Gen-III+ operating reactors)	81 ↓	92	76 ↓	85	6	8
3	**Pressurized Heavy Water Reactors (PHWRs)** (3rd largest group of reactors in the world – 11 %; mainly CANDU-reactor type)	48 ↓	50	24 ↓	25	9	5.8
4	**Gas Cooled Reactors (GCRs)** (UK, Magnox reactor) or 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)	15 ↓	18	8 ↓	9	1	0.2
5	**Light-water, Graphite-moderated Reactors (LGRs)** (Russia, 11 RBMKs and 4 EGPs *; these pressure-channel boiling-water-cooled reactors will be shut down in the nearest future and will not be built again)	15	15	10	10	0	0
6	**Liquid-Metal Fast-Breeder Reactors (LMFBRs)** (Russia, SFR – BN-600; the only one Gen-IV operating reactor)	1	1	0.6	0.6	5	1.6
	In total	430 ↓	444	369 ↓	378	110	109

Data in Table 7 include 48 reactors from Japan, which are currently not in operation. Arrows mean decrease or increase in a number of reactors. Forthcoming GCR is a helium-cooled reactor.

* EGP – Power Heterogeneous Loop reactor (in Russian abbreviations), channel-type, graphite-moderated, light-water coolant, boiling reactor with natural circulation.

Brayton and Rankine cycles in one plant (only for clean gaseous fuels); 4) Diesel internal-combustion-engine cycle (only for Diesel fuel) (used in Diesel generators); and 5) Otto internal-combustion-engine cycle (usually, for natural or liquefied gas, but also, gasoline can be used for power generation, however, it is more expensive fuel compared to gaseous fuels) (also, used in internal-combustion-engine generators).

In general, the term «thermal power plants» can include: 1) solid-fuel-fired power plants based on Rankine steam-turbine cycle, fuels – coal, lignite, peat, oil-shale, etc.; 2) gas-fired power plants – (a) Rankine steam-turbine cycle, (b) Brayton gas-turbine cycle and (c) combined cycle (combination of Brayton and Rankine cycles in one plant); 3) geothermal power plants (usually, Rankine steam-turbine cycle used); 4) biofuel thermal power plants (usually Rankine steam-turbine cycle used); 5) Diesel- and Otto-cycle-generators power plants; 5) concentrated-solar thermal power plants (Rankine steam-turbine cycle used) and 6) recovered-energy generation thermal power plants (electricity at these plants is generated from waste energy such as high-temperature flue gases, etc.; Rankine steam-turbine cycle used) (http://www.ormat.com/recovered-energy).

The major driving force for all advances in thermal power plants is thermal efficiency. Ranges of thermal efficiencies of modern thermal power plants are listed in Table 6 for reference purposes.

In spite of advances in thermal power-plants design and operation worldwide they are still considered as not environmental friendly due to producing a lot of carbon-dioxide emissions as a result of combustion process. For example, the largest in the world 5,780-MW_{el} Taichung coal-fired power plant (Taiwan) is the world's largest emitter of carbon dioxide with over 40 million tons per year. In addition, coal-fired power-plants produce also slag, ash, and even acid rains. Therefore, nuclear power plants have to be considered.

Modern Nuclear Power Plants

In general, nuclear power is also a non-renewable-energy source as the fossil fuels, but nuclear resources can be used for significantly longer time than some fossil fuels, especially, if thoria-fuel resources and fast reactors will be used. Major advantages of nuclear power are: 1) No emissions of carbon dioxide into atmosphere; 2) Relatively small amount of fuel required (for example, a 500-MW_{el} coal-fired supercritical-pressure power plant requires 1.8 million ton of coal annually, but a fuel load into 1300-MW_{el} PWR is 115 t (3.2 % enrichment) or 1330-MW_{el} BWR – 170 t

Table 8. Number of nuclear-power reactors by nation (11 nations with the largest number of reactors ranked by installed capacity) as per March of 2014 [7] and before the Japan earthquake and tsunami disaster (March of 2011) [8]

No	Nation	No. of units		Installed capacity, GW_{el}		Changes in number of reactors from March 2011
		As of March 2014	Before March 2011	As of March 2014	Before March 2011	
1	USA	100	104	101	103	↓ Decreased by 4 reactors
2	France	58	58	63	63	No changes
3	Japan*	48	54	42	47	↓ Decreased by 6 reactors
4	Russia	33	32	24	23	↑ Increased by 1 reactor
5	S. Korea	23	20	21	18	↑ Increased by 3 reactors
6	China	17	13	14	10	↑ Increased by 4 reactors
7	Canada	19	22	13	15	↓ Decreased by 3 reactors
8	Ukraine	15	15	13	13	No changes
9	Germany	9	17	12	20	↓ Decreased by 8 reactors
10	Sweden	10	10	9.3	9.3	No changes
11	UK	16	19	9.2	10	↓ Decreased by 3 reactors

Arrows mean decrease or increase in a number of reactors. * Currently, i.e., in February of 2014, no one reactor is in operation. However, some reactors are planned to be put into operation.

Table 9. Selected Generation III + reactors (deployment in 5–10 years) (partially based on [7])

No	Reactor type	Nuclear vendor
1	ABWR	Toshiba, Mitsubishi Heavy Industries (MHI) and Hitachi-GE (Japan-USA) (the only one Generation III+ reactor design already implemented in power industry)
2	Advanced CANDU Reactor (ACR-1000)	CANDU Energy (former AECL), Canada
3	Advanced Plant (AP-1000)	Toshiba-Westinghouse (Japan-USA) (6 under construction in China and 6 planned to be built in China and 6 – in USA)
4	Advanced PWR (APR-1400)	South Korea (4 under construction in S. Korea and 4 planned to be built in UAE)
5	European Pressurized-water Reactor (EPR)	AREVA, France (1 should be put into operation in Finland, 1 under construction in France and 2 – in China and 2 planned to be built in USA)
6	ESBWR (Economic Simplified BWR)	GE-Hitachi (USA-Japan)
7	VVER * (design AES **–2006 or VVER-1200 with ~ 1200 MW_{el})	GIDROPRESS, Russia (4 under construction in Russia and several more planned to be built in various countries: Belarus', Finland, Turkey, Vietnam, etc.)

* VVER or WWER – Water Water Power Reactor (in Russian abbreviations). ** AES – Atomic Electrical Station (Nuclear Power Plant) (in Russian abbreviations).

(1.9 % enrichment)). Therefore, this source of energy is considered as the most viable one for electrical generation for the next 50– 100 years.

In spite of all current advances into nuclear power, 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 (see Table 6)); 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.

First success of using nuclear power for electrical generation [2, 9] was achieved in several countries within 50-s, and currently, Generations II and III nuclear-power reactors are operating around the world (see Tables 7 and 8, and Fig. 11). In general, definitions of nuclear-reactors generations are as the following: 1) Generation I (1950–1965) – early prototypes of nuclear reactors; 2) Generation II (1965–1995) – commercial power reactors; 3) Generation III (1995–2010) – modern reactors (water-cooled NPPs with thermal efficiencies within 30–36 %; carbon-dioxide-cooled NPPs with thermal efficiencies up to 42 % and liquid sodium-cooled NPP with the thermal efficiency up to 40 %) and Generation III+ (2010–2025) – reactors with improved parameters (evolutionary design improvements) (water-cooled NPPs with thermal efficiencies up to 36–38 %) (see Table 9); and 4) Generation IV (2025–...) (see Section 3) [2, 10] – reactors in principle with new parameters (NPPs with thermal efficiencies within 40–50 % and even higher for some types of reactors).

Solar Energy Generating Systems (SEGS) consist of 9 concentrated-solar-thermal plants with 354 MW_{el} installed capacity. The average gross solar output of SEGS is about 75 MW_{el}

Table 10. Casualties due to various accidents in power and chemical industries, transportation and from firearms (listed here just for reference purposes)

No	Causes of death	Year	Region	No. of deaths
1	Sayano-Shushenskaya hydro-power plant accident	2009	Russia	75
2	Banqiao Dam[1] [11]	1975	China	26,000
3	Chernobyl NPP accident	1986[2]	Ukraine	40
		1986-now[3]	Ukraine	>40
4	Fukushima NPP accident (deaths due to earthquake, not radiation)	2011	Japan	Few workers
5	Bhopal Union Carbide India Ltd. accident [12]	1984	India	
	Immediate deaths (official data)			2,259
	By Government of Madhya Pradesh			3,787
	Other estimations (since the disaster)			8,000
	No. of people exposed to methyl iso-cyanate gas and other chemicals			500,000
6	Car accidents[4] [13]	2013	World	1,240,000
		2013	USA	33,808
7	Shipwreck accidents	2011	World	3,335
8	Railway accidents	2009	EU	1,428
9	Air accidents[5]	11.09.2011	USA New York	>4500
		12.11.1996	India Delhi	349
		12.08.1985	Japan Mt. Fuji	520
		27.03.1977	Canary Islands	583
		2009	EU	29
		2008	EU	177
		2007	EU	59
10	Firearms [14]:			
	Total	2011	USA	32,163
	Suicides			19,766
	Homicides			11,101

[1] Based on other sources eleven million people were severely affected, and over 85 thousand died as a result of the dam failures.

[2] Deaths due to the explosion and initial radiation release.

[3] Deaths from cancer, heart disease, birth defects (in victims' children) and other causes, which may result from exposure to radiation; however, these deaths may also result from other causes not related to the accident, for example pollution from non-nuclear sources — industry, transportation; etc.), stress, etc. In general, accurate estimation of all deaths related to the Chernobyl NPP accident is impossible.

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

[5] 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.

(capacity factor is ~ 21 %). At night, turbines can be powered by combustion of natural gas. NextEra claims that the SEGS power 232,500 homes and decrease pollution by 3,800 t/year (if the electricity had been provided by combustion of oil). The SEGS have 936,384 mirrors, which cover more than 6.5 km^2. If the parabolic mirrors would be lined up, they will extend over 370 km. In 2002, one of the 30-MW_{el} Kramer Junction sites required 90 million dollars to construct, and its O&M costs are about 3 million dollars per year, which are 4.6 canadian cent/(kW·h). However, with a considered lifetime of 20 years, the O&M and investments interest and depreciation triples the price, to approximately 14 canadian cent/(kW·h).

Currently, 31 countries in the world have operating nuclear power reactors [7]. Unfortunately, 16 countries have no plans to build new reactors at least for now. However, some non-nuclear countries (Bangladesh, Belarus', Turkey and United Arab Emirates (UAE)) work towards introducing nuclear energy on their soils.

Important question for a wide-spread of nuclear-based electrical-energy generation is how reactors are safe. Table 10 lists selected accidents with casualties in various industries, transportation and from firearms. Analysis of data in Table 10 clearly shows that the major cause of huge number of deaths in the world is car accidents. Nevertheless, the international community has to do everything possible and impossible to prevent any future severe accidents at NPPs with radiation release and other consequences.

Data in Table 6 include 48 reactors from Japan, which are currently not in operation.

Table 11. Estimated ranges of thermal efficiencies (gross) of Generation IV NPP concepts (shown just for reference purposes)

No	Power Plant	Gross Efficiency
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-300: reactor coolant — liquid lead: $P \approx 0.1$ MPa and $T_{in}/T_{out} = 420/540$ °C; primary power cycle — indirect supercritical-pressure Rankine steam cycle:$P_{in} \approx 24.5$ MPa ($P_{cr} = 22.064$ MPa) and $T_{in}/T_{out} = 340/520$ °C ($T_{cr} = 374$ °C); high-temperature steam superheat; possible back-up in some other countries – indirect supercritical-pressure carbon-dioxide Brayton gas-turbine cycle)	~ 43 %
6	Sodium-cooled Fast Reactor (SFR) NPP (Russian design BN-600: reactor coolant – liquid sodium (primary circuit): $P \approx 0.1$ 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: $P_{in} \approx 14.2$ MPa ($T_{sat} \approx 337$ °C) and $T_{in\ max} = 505$ °C ($T_{cr} = 374$ °C); steam superheat: $P \approx 2.45$ 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 %

Arrows mean decrease or increase in a number of reactors.

Forthcoming GCR is a helium-cooled reactor. EGP — Power Heterogeneous Loop reactor (in Russian abbreviations), channel-type, graphite-moderated, light-water coolant, boiling reactor with natural circulation.

Next Generation NPPs

The demand for clean, non-fossil-based electricity is growing; therefore, the world needs to develop new nuclear reactors with inherent safety and higher thermal efficiencies in order to increase electricity generation per kg of fuel and decrease detrimental effects on the environment. The current fleet of NPPs is classified as Generation II and III (just a limited number of Generation III + reactors (mainly, Advanced Boiling Water Reactors (ABWRs) operate in some countries). However, all these designs (here we are talking about only water-cooled power reactors) are not as energy efficient as they should be, because their operating temperatures are relatively low, i.e., below 350 °C for a reactor coolant and even lower for steam in the power-conversion cycle.

Currently, a group of countries, including Canada, EU, Japan, Russia, USA and others have initiated an international collaboration to develop the next generation nuclear reactors (Generation IV reactors) [2, 10]. The ultimate goal of developing such reactors is an increase in thermal efficiencies of NPPs from 30–36 % to 45–50 % and even higher (see Table 11). This increase in thermal efficiency would result in a higher generation of electricity compared to current Light Water Reactor (LWR) technologies per 1 kg of uranium.

The Generation IV International Forum (GIF) Program has narrowed design options of nuclear reactors to six concepts [2, 10]. These concepts are: 1) Gas-cooled Fast Reactor (GFR) or just High Temperature Reactor (HTR);

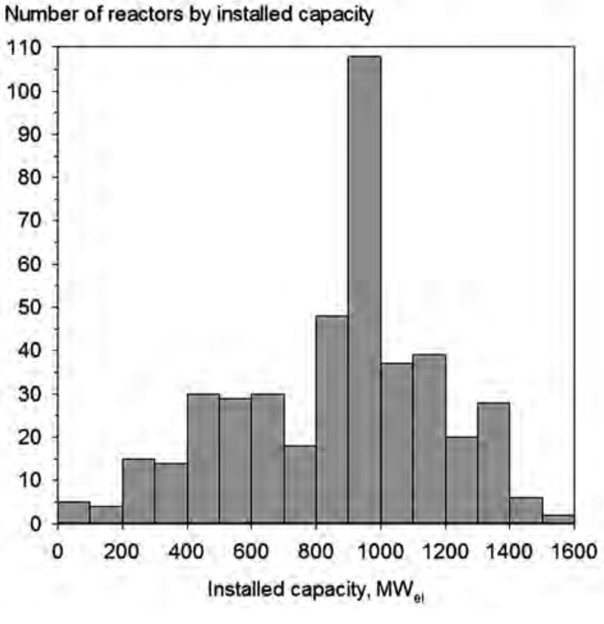

Fig. 11. Number of nuclear power reactors in the world by installed capacity (based on data in [7]): for better understanding of this graph — the largest number of reactors have installed capacities within the range of 900–999 MW$_{el}$.

2) Very High Temperature Reactor (VHTR); 3) Sodium-cooled Fast Reactor (SFR); 4) Lead-cooled Fast Reactor (LFR); 5) Molten Salt Reactor (MSR); 6) SuperCritical Water-cooled Reactor (SCWR) [15, 16].

Currently, from all 6 concepts of Generation IV reactors only an SFR is in operation in Russia (BN-600). Next concept, which will be possibly put into operation in Russia, is an LFR (Brest-300) [2, 10]. In general, we need to have bright future for the most «popular» reactors, i.e., water-cooled ones (96 % of the total number of operating power reactors in the world). Therefore, an SCWR concept [15, 16] looks quite attractive as the Generation IV water-cooled reactor with high thermal efficiency. However, more research is required, especially, in material science to define candidate materials for reactor-core elements, which will be subjected to very aggressive medium such as supercritical water, high pressures and temperatures, and high neutron flux.

Conclusions

Major sources for electrical-energy production in the world are: 1) thermal — primary coal (41 %) and secondary natural gas (21 %); 2) «large» hydro (16 %); 3) nuclear (14 %). The rest of the energy sources might have visible impact just in some countries.

The renewable energy sources such as wind, solar, etc. are not really reliable sources for industrial-power generation. Therefore, a grid must include «fast-response» power plants such as gas- and coal-fired and/or large hydro power plants.

In general, the major driving force for all advances in thermal and nuclear power plants is thermal efficiency. Ranges of gross thermal efficiencies of modern power plants are as the following: 1) Combined-cycle thermal power plants — up to 62 %; 2) Supercritical-pressure coal-fired thermal power plants – up to 55 %; 3) Carbon-dioxide-cooled reactor NPPs — up to 42 %; 4) Sodium-cooled fast reactor NPP — up to 40 %; 5) Subcritical-pressure coal-fired thermal power plants — up to 40 %; and 6) Modern water-cooled reactors — 30–36 %.

In spite of advances in coal-fired thermal power-plants design and operation worldwide they are still considered as not environmental friendly due to producing a lot of carbon-dioxide emissions as a result of combustion process plus slag, ash, and even acid rains.

Combined-cycle thermal power plants with natural-gas fuel are considered as relatively clean fossil-fuel-fired plants compared to coal and oil power plants, but still emit a lot of carbon dioxide due to combustion process.

Nuclear power is, in general, a non-renewable source as the fossil fuels, but nuclear resources can be used significantly longer than some fossil fuels plus nuclear power does not emit carbon dioxide into atmosphere. Currently, this source of energy is considered as the most viable one for electrical generation for the next 50–100 years.

However, all current and oncoming Generation III + NPPs are not very competitive with modern thermal power plants in terms of thermal efficiency, the difference in values of thermal efficiencies between thermal and nuclear power plants can be up to 20–25 %.

Therefore, new generation (Generation IV) NPPs with thermal efficiencies close to those of modern thermal power plants, i.e., within a range of at least 45–50 %, should be designed and built in the nearest future.

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Nomenclature

P – pressure, MPa
T – temperature, °C

Abbreviations:

ABWR – Advanced Boiling Water Reactor
AECL – Atomic Energy of Canada Limited
AGR – Advanced Gas-cooled Reactor
ann. – annual
Ave. – Average
BN – Fast Neutrons (reactor) (in Russian abbreviation)
BWR – Boiling Water Reactor
CANDU – CANada Deuterium Uranium
EGP – Power Heterogeneous Loop reactor (in Russian abbreviations)
el. – electrical
EU – European Union
GCR – Gas-Cooled Reactor
GE – General Electric
gen. – generation
HDI – Human Development Index

LFR – Lead-cooled Fast Reactor
LGR – Light-water Graphite-moderated Reactor
LMFBR – Liquid-Metal Fast-Breeder Reactor
LNG – Liquefied Natural Gas
LWR – Light-Water Reactor
MHI – Mitsubishi Heavy Industries
NPP – Nuclear Power Plant
PHWR – Pressurized Heavy-Water Reactor
PV – Photo Voltaic
PWR – Pressurized Water Reactor
RBMK – Reactor of Large Capacity Channel type (in Russian abbreviations)

Subscripts: cr — critical; el — electrical; in — inlet; th — thermal

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Атомная энергетика как основа для генерирования электрической энергии в будущем (Обзор)

Производство электроэнергии является ключевым вопросом для любой отрасли промышленности, сельского хозяйства и повышения жизненного уровня. Электрическая энергия может быть генерирована с использованием невозобновляемых источников энергии (уголь, природный газ, нефть и ядерное топливо) и с помощью источников возобновляемой энергии (гидроэнергетика, ветровая, солнечная энергия, биомасса, геотермальная и морская). Основными источниками выработки электрической энергии являются соответственно подготовленный к извлечению тепловой энергии добытый уголь и природный газ вторичной очистки, крупные гидростанции, ядерное топливо. Остальные источники энергии могут оказывать заметное влияние на энергетику только в некоторых странах. В статье описано текущее состояние атомной энергетики в мире и выполнено сравнение ядерно-энергетических систем с другими энергетическими системами. *Библ. 16, рис. 11, табл. 11.*

Ключевые слова: атомная энергетика, производство электроэнергии, невозобновляемые источники энергии, возобновляемые источники энергии.

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Атомна енергетика як основа для генерування електричної енергії у майбутньому (Огляд)

Виробництво електроенергії є ключовим питанням для будь-якої галузі промисловості, сільського господарства та підвищенняі життєвого рівня. Електрична енергія може бути генерована з використанням невідновлюваних джерел енергії (вугілля, природний газ, нафта та ядерне паливо) та за допомогою джерел відновлюваної енергії (гідроенергетика, вітрова, сонячна енергія, біомаса, геотермальна та морська). Основними джерелами вироблення електричної енергії є відповідно підготоване до вилучення теплової енергії видобуте вугілля та природний газ вторинного очищення, потужні гідростанції, ядерне паливо. Інші джерела енергії можуть помітно впливати на енергетику тільки у деяких країнах. У статті описано поточний стан атомної енергетики світу та зроблено порівняння ядерно-енергетичних систем з іншими енергетичними системами. *Бібл. 16, рис. 11, табл. 11.*

Ключові слова: атомна енергетика, виробництво електроенергії, невідновлювані джерела енергії, відновлювані джерела енергії.