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Electricity generation in the world and Ukraine: Current status and future developments*

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Abstract. *Electricity generation is the key factor for advances in industry, agriculture, technology and the level of living. Also, strong power industry with diverse energy sources is very important for country independence. In general, electricity can be generated from: 1) non-renewable energy sources such as coal, natural gas, oil, and nuclear; and 2) renewable energy sources such as hydro, biomass, wind, geothermal, solar, and wave power. However, the major energy sources for electricity generation in the world are: 1) thermal power – primarily using coal (~40%) and secondarily natural gas (~23%); 2) "large" hydro power plants (~17%) and 3) nuclear power from various reactor designs (~11%). The rest of the energy sources for electricity generation is from using oil (~4%) and renewable sources such as biomass, wind, geothermal and solar (~5%), which have just visible impact in selected countries. In addition, energy sources, such as wind and solar, and some others, like tidal and wave-power, are intermittent from depending on Mother Nature. And cannot be used alone for industrial electricity generation.*
Nuclear power in Ukraine is the most important source of electricity generation in the country. Currently, Ukrainian Nuclear Power Plants (NPPs) generate about 45.5% of the total electricity followed with coal generation – 38%, gas generation 9.6% and the rest is based on renewable sources, mainly on hydro power plants – 5.9%. Nuclear-power industry is based on four NPPs (15 Pressurized Water Reactors (PWRs) including the largest one in Europe – Zaporizhzhya NPP with about 6,000 MWel gross installed capacity. Two of these 15 reactors have been built and put into operation in 70-s, ten in 80-s, one in 90-s and just two in 2004. Therefore, based on an analysis of the world power reactors in terms of their maximum years of operation (currently, the oldest reactors are ~45-year old) several projections have been made for future of the nuclear-power industry in the world and Ukraine. Unfortunately, all these projections are quite pessimistic. There is a possibility that around 2030–2040 the vast majority of the world reactors and Ukrainian reactors will be shut down, and, in particular, Ukraine can be left without the basic and vital source of electricity generation..

Keywords: *Electricity Generation, Nuclear Power Plant, Nuclear-Power Reactor, Thermal Efficiency, Capacity Factor.*

1. INTRODUCTION

It is well known that electricity generation is the key factor for advances in industry, agriculture, technology and the level of living (for details, see Table 1 and Figure 1) (Handbook, 2016; Pioro and Duffey, 2015; Pioro and Kirillov, 2013a). Also, strong power industry with diverse energy sources is very important for country independence. In general, electricity can be generated from: 1) non-renewable energy sources such as coal, natural gas, oil, and nuclear; and 2) renewable energy sources such as hydro, biomass, wind, geothermal, solar, and wave power. However, as of today the major energy sources for electricity generation in the world (for details, see Figure 1a) are: 1) thermal power – primarily using coal (~40%) and secondarily - natural gas (~23%); 2) "large" hydro power plants (~17%) and 3) nuclear power from various reactor designs (~11%). The rest of the energy sources for electricity generation is from using oil (~4%) and renewable sources such as biomass, wind, geothermal and solar (~5%), which have just visible impact in selected countries (for details, see Figures 1 and 2; Tables 2 and 3). In addition, energy sources, such as wind and solar, and some others, like tidal and wave-power, are intermittent from depending on Mother Nature (see Figures 3 and 4; for more details, see Handbook, 2016; and Pioro and Duffey, 2015), and cannot be used alone for industrial electricity generation.

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Table 1

Electrical-Energy Consumption (EEC) per capita in selected countries (listed here just for reference purposes) (based on Handbook, 2016; The World Fact Book, 2013; Human Development Report, 2013)

No	Country	Population Millions	Electrical Energy Consumption		HDI* (~2014)	
			TW h/year	W/Capita	Rank	Value
1	Norway	5.2	120.5	2618	1	0.944
2	Australia	22.8	222.6	1116	2	0.935
3	Germany	80.9	540.1	762	6	0.916
4	USA	321.4	3832.0	1360	8	0.915
5	Canada	35.1	524.8	1706	9	0.913
6	UK	64.1	319.1	568	14	0.907
7	Japan	126.9	921.0	828	20	0.891
8	France	66.6	451.1	773	22	0.888
9	Italy	61.9	303.1	559	27	0.873
10	Russia	142.4	1037.0	831	50	0.798
11	Brazil	204.3	483.5	270	75	0.755
12	Ukraine	44.4	159.8	410	81	0.747
13	China	1,367.5	5523.0	461	90	0.727
14	World (average)	7,256.5	19,710.0	310	103	0.711
15	India	1,251.7	864.7	79	130	0.609
16	Afghanistan	32.6	3.9	14	171	0.465
17	Chad	11.6	0.2	2	185	0.392
18	Niger	18.1	0.9	6	188	0.348

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

** 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= $\sqrt[3]{\text{LEI} \times \text{EI} \times \text{II}}$, 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, 2016).

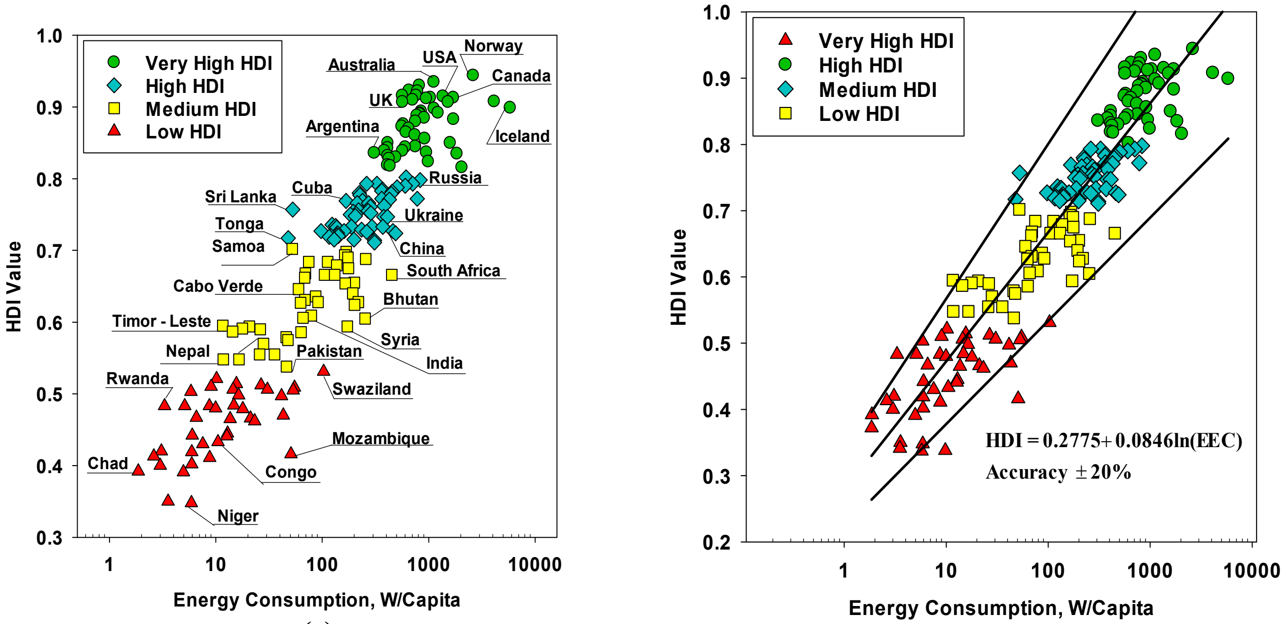
It should be noted that the following two parameters are important characteristics of any power plant: 1) overall (gross) or net efficiency[1] of a plant (for details, see Table 4a,b); and 2) Capacity factor[2] of a plant (for details, see Table 5).

Usually, thermal- and nuclear-power plants operate semi-continuously, because of a high capital cost and low operating costs. The relative costs of electrical energy generated by any system are not only dependent on building capital costs and operating expenses, but also dependent on the capacity factor. The higher the capacity factor the better, as generating costs fall proportionally. However, some renewable-energy sources with exception of large hydro-electric power plants can have significantly lower capacity factors compared to those of thermal- and nuclear-power plants (Handbook, 2016; Pioro and Duffey, 2015).

Therefore, thermal power plants, NPPs and large hydro power plants are considered as the basis for any electrical grid as concentrated and reliable sources of electricity generation. Also, NPPs have essentially negligible operating emissions of carbon dioxide into atmosphere compared to alternate thermal plants. Due to that this source of energy is considered as the most viable one for electrical generation for the next 50 – 100 years (Handbook, 2016; Pioro and Duffey, 2015) (see Tables 6 and 7).

[1] 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).

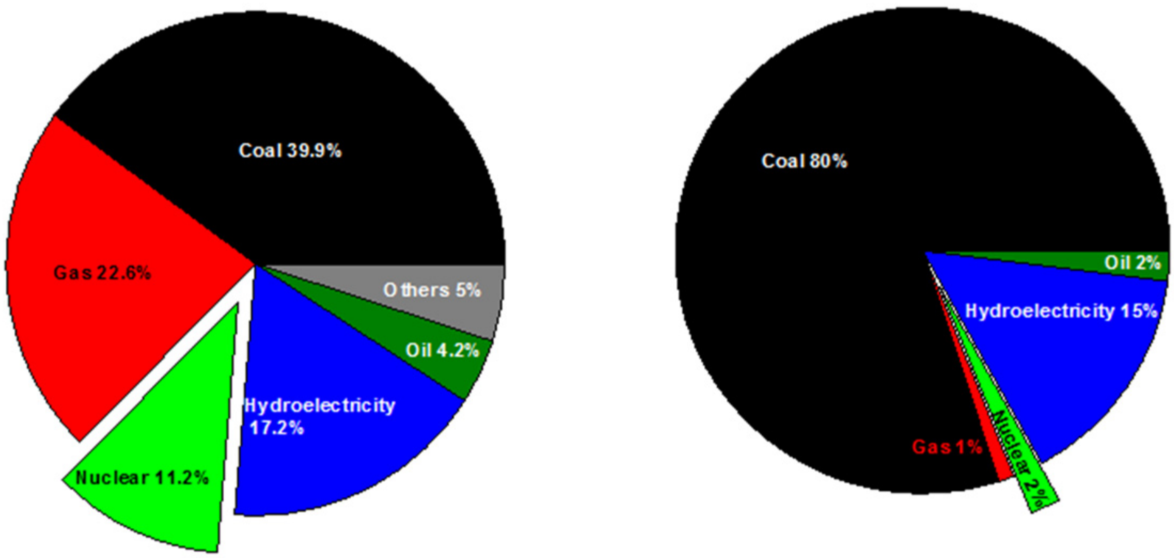
[2] The net capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time (usually, during a year) and its potential output if it had operated at full nameplate capacity the entire time. To calculate the capacity factor, the total amount of energy a plant produced 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.



(a)

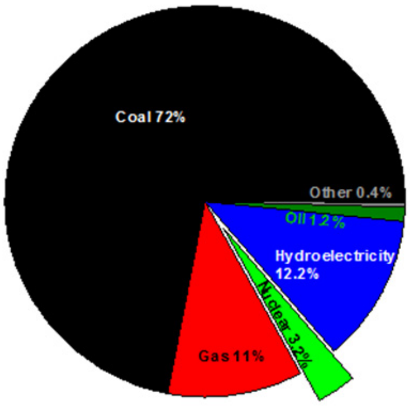
(b)

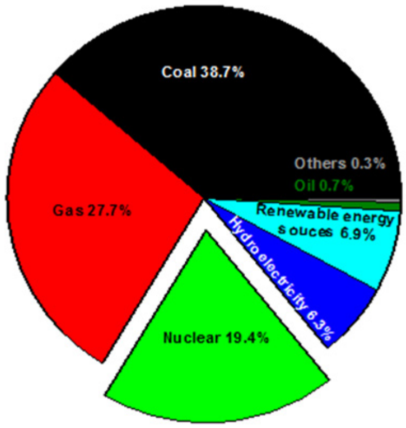
Fig. 1 Effect of Electrical-Energy Consumption (EEC) on Human Development Index (HDI) for all countries of the world (based on data from Handbook (2016); Human Development Report (2013); The World Fact Book (2013)): (a) graph with selected countries shown and (b) HDI correlation (in general, the HDI correlation might be an exponential rise to maximum (1), but based on the current data it is a straight line in regular – logarithmic coordinates)



(a) World: Population 7,257 millions; EEC 19,710 TW h/year or 310 W/Capita; HDI 0.711 or HDI Rank 103

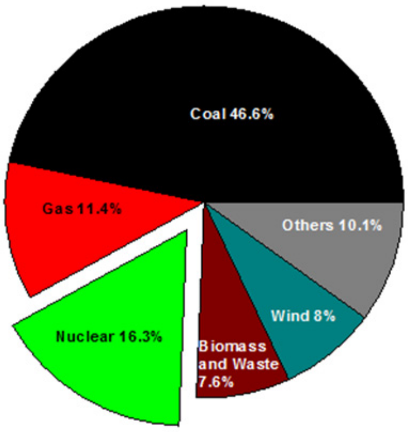
(b) China: Population 1,368 millions; EEC 5,523 TW h/year or 461 W/Capita; HDI 0.727 or HDI Rank 90

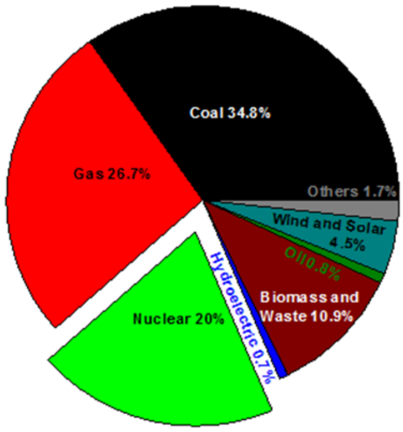




(c) India: Population 1,252 millions; EEC 865 TW h/year or 79 W/Capita; HDI 0.609 or HDI Rank 130

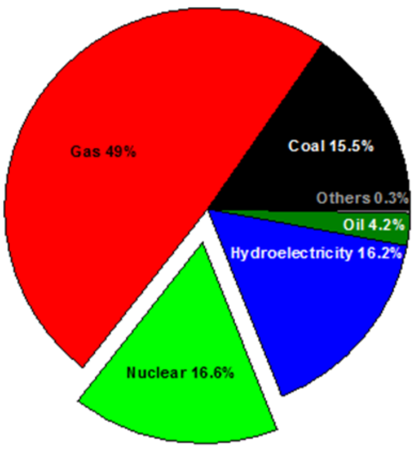
(d) USA: Population 321 millions; EEC 3,832 TW h/year or 1,360 W/Capita; HDI 0.915 or HDI Rank 8; Renewables (6.9%): Wind (4.4%); Biomass (1.7%); Geothermal (0.4%); and Solar (0.4%)

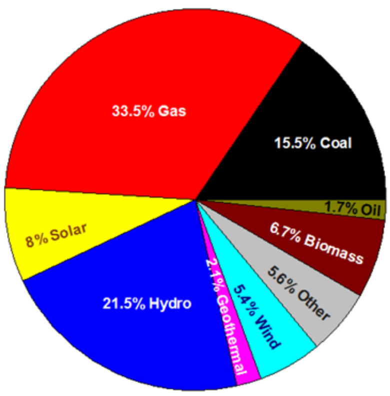




(e) Germany: Population 81 millions; EEC 540 TW h/year or 762 W/Capita; HDI 0.916 or HDI Rank 6

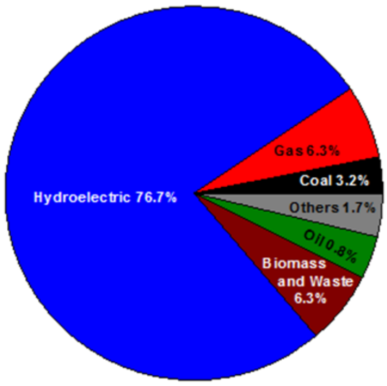
(f) UK: Population 64 millions; EEC 319 TW h/year or 568 W/Capita; HDI 0.907 or HDI Rank 14



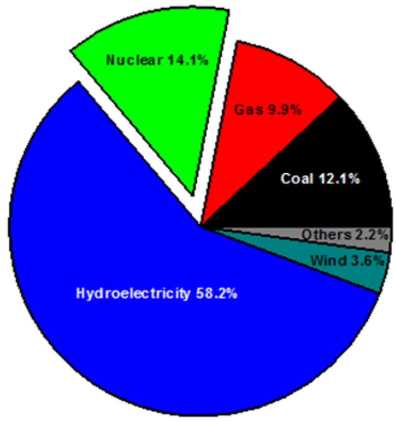


(g) Russia: Population 142 millions; EEC 1,037 TW h/year or 831 W/Capita; HDI 0.798 or HDI Rank 50

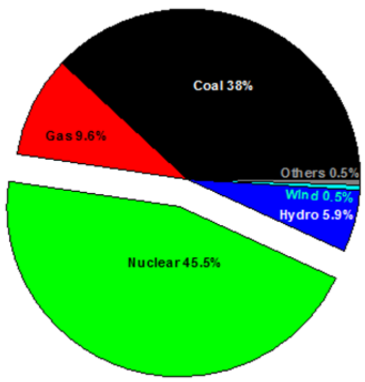
(h) Italy: Population 62 millions; EEC 303 TW h/year or 559 W/Capita; HDI 0.873 or HDI Rank 27



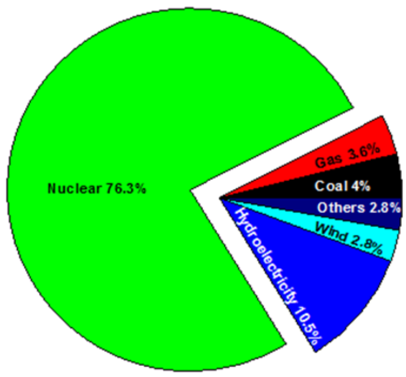
(i) Brazil: Population 204 millions; EEC 484 TW h/year or 270 W/Capita; HDI 0.755 or HDI Rank 75



(j) Canada: Population 35 millions; EEC 525 TW h/year or 1,706 W/Capita; HDI 0.913 or HDI Rank 9



(k) Ukraine: Population 44 millions; EEC 160 TW h/year or 410 W/Capita; HDI 0.747 or HDI Rank 81



(l) France: Population 67 millions; EEC 451 TW h/year or 773 W/Capita; HDI 0.888 or HDI Rank 22

Fig. 2 Electricity generation by source in the world and selected countries (data from 2010 – 2014 presented here just for reference purposes) Handbook (2016)

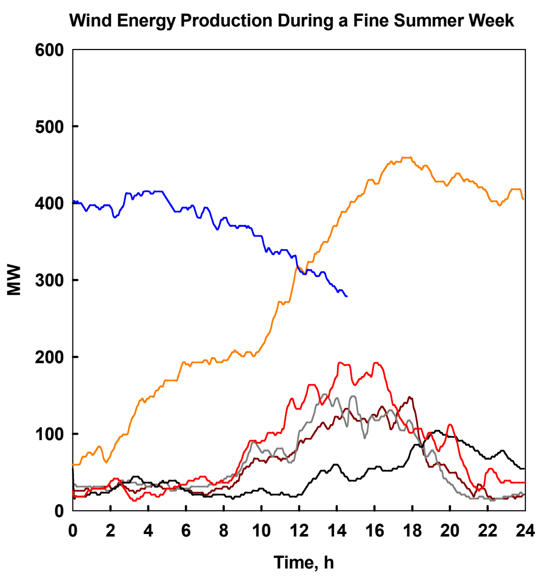


Fig. 3. Power generated by 650-MWel wind turbines in the Western Part of Denmark (based on data from wdww.wiki.windpower.org). **Shown summer week (6 days, i.e., various color lines) of wind-power generation**

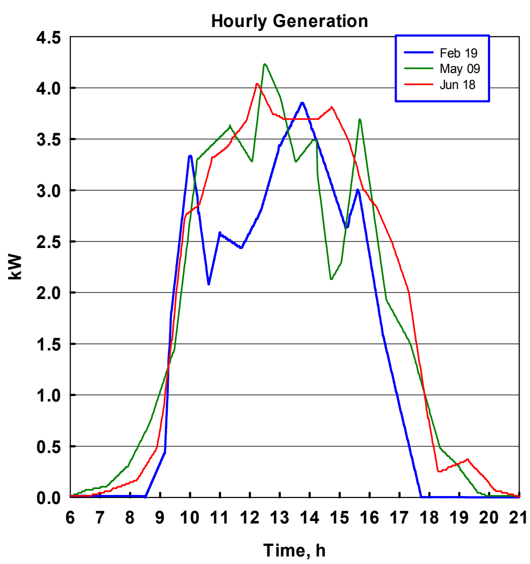


Fig. 4. Power generated by photovoltaic system in New York State (USA) (based on data from www.burningcutlery.com/solar)**: Shown three mostly sunny days: February 19th; May 9th and June 18th**

Table 2

Eleven top power plants of the world by installed capacity[3] (Wikipedia, 2017)

No	Plant	Country	Capacity MW_{el}	Average annual generation TWh	Capacity factor, %	Plant type
1	Three Gorges Dam	China	22,500	98.8	50	Hydro
2	Itaipu Dam	Brazil/Paraguay	14,000	98.6	72	Hydro
3	Xiluodu	China	13,860	57.1	47	Hydro
4	Guri Dam	Venezuela	10,200	-	-	Hydro
5	Tucurui Dam	Brazil	8,370	-	-	Hydro
6	Kashiwazaki-Kariwa	Japan	7,965	-	-	Nuclear
7	Grand Coulee Dam	USA	6,809	21.0	35	Hydro
8	Longtan Dam	China	6,426	18.7	33	Hydro
9	Sayano-Shushenskaya	Russia	6,400	24.0	43	Hydro
10	Bruce NPP	Canada	6,231	45.6	83	Nuclear
11	Krasnoyarsk Dam	Russia	6,000	23.0	44	Hydro

Currently, Bruce Nuclear Power Plant (NPP) is the largest fully-operating nuclear plant in the world.

Table 3

Largest operating power plants of the world (based on installed capacity) by energy source (Wikipedia, 2017)

Rank	Plant	Country	Capacity, MW_{el}	Plant type
1	Three Gorges Dam Power Plant	China	22,500	Hydro
2	Bruce NPP	Canada	6,231	Nuclear
3	Taichung Power Plant	Taiwan	5,780	Coal
4	Shoaiba	S. Arabia	5,600	Fuel oil*
5	Surgut-2	Russia	5,597	Natural gas
6	Eesti Power Plant	Estonia	1,615	Oil shale
7	Shatura Power Plant	Russia	1,500	Peat*
7	Gansu	China	5,160	Wind
8	Ivanpah Solar Power Facility	USA	392	Solar (thermal)
9	The Geysers	USA	1,808	Geothermal
10	Drax Power Plant	UK	660	Biofuel*
11	Sihwa Lake Tidal Power Plant	S. Korea	254	Tidal
12	Topaz	USA	550	Solar (PV**)
13	Vasavi Basin Bridge Diesel Power Plant	India	200	Diesel
14	Islay Limpet	UK	0.5	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. ** PV – PhotoVoltaic. ***Currently, not in operation anymore.

[3] Information provided in Table 2 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., May of 2017, 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.

Table 4a

Typical ranges of thermal efficiencies (gross) of modern thermal power plants (Handbook, 2016; Pioro and Kirillov, 2013b)

No	Thermal Power Plant	Gross Eff., %
1	Combined-cycle power plant (combination of Brayton gas-turbine cycle (fuel - natural gas or LNG; combustion-products parameters at the gas-turbine inlet: T_{in}≈1650°C) and Rankine steam-turbine cycle (steam parameters at the turbine inlet: 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}≈23.5–38 MPa (P_{cr}=22.064 MPa), T_{in}≈540-625°C (T_{cr}=374°C) and 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 T_{reheat}≈540°C)	Up to 43
5	Concentrated-solar thermal power plants with heliostats, solar receiver (heat exchanger) on a tower and molten-salt heat-storage system: Molten-salt maximum temperature is about 565°C, Rankine steam-turbine power cycle used	Up to 20

Table 4b

Typical ranges of thermal efficiencies (gross) of modern NPPs (Handbook, 2016; Pioro and Kirillov, 2013c)

No	Nuclear Power Plant	Gross Eff., %
1	Carbon-dioxide-cooled reactor NPP (Generation-III) (reactor coolant: P=4 MPa & T=290-650°C; steam: P=16.7 MPa (T_{sat}=351°C and T_{cr}=374°C) & T_{in}=538°C; reheat: P=4.1 MPa & T_{in}=538°C)	Up to 42
2	Sodium-cooled fast reactor NPP (Generation-IV) (steam: P=14 MPa (T_{sat}=337°C) & T_{in}=505°C and reheat: P=2.45 MPa & T_{in}=505°C)	Up to 40
3	Pressurized Water Reactor NPP* (Generation-III+, to be implemented within next 1-10 years) (reactor coolant: P=15.5 MPa & T_{out}=327°C; steam: P=7.8 MPa & T_{in}=T_{sat}=293°C and reheat)	Up to 38
4	Pressurized Water Reactor NPP* (Generation-III, current fleet) (reactor coolant: P=15.5 MPa & T_{out}=329°C; steam: P=6.9 MPa & T_{in}=T_{sat}=285°C and reheat)	Up to 36
5	Boiling Water Reactor NPP* (Generation-III, current fleet) (direct cycle) (P_{in}=7.2 MPa & T_{in}=T_{sat}=288°C and reheat)	Up to 34
6	RBMK NPP*(boiling, pressure-channel) (Generation-III, current fleet) (direct cycle) (P_{in}=6.46 MPa & T_{in}=T_{sat}=280°C; reheat: P=0.29 MPa & T_{reheat}=263°C)	Up to 32
7	Pressurized Heavy Water Reactor NPP* (Generation-III, current fleet) (reactor coolant: P=11 MPa & T=260-310°C; steam: P=4.6 MPa & T_{in}=T_{sat}=259°C and reheat)	Up to 32

Note to table: 1) All NPPs with water-cooled reactors use only Rankine cycle with saturated steam at the inlet of a turbine and steam reheat, which uses primary saturated steam as the heating medium.

Table 5

Average (typical) capacity factors of various power plants (listed here just for reference purposes) (Handbook, 2016)

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[4]	USA and UK	2011	40
		World (average)	-	44
		World (range)	-	10-99
5	Wind	UK	2011	30
		World	2008	20-40
6	Wave	Portugal	-	20
7	Concentrated-solar thermal	USA California Spain	- -	21 75
8	Photovoltaic (PV) solar	USA Arizona	2008	19
		USA Massachusetts	-	12-15
		UK	2011	5-8
9	Concentrated-solar PV	Spain	-	12

Table 6

Number of nuclear-power reactors in operation and forthcoming as per March 2017 (Nuclear News, 2017) and before the Japan earthquake and tsunami disaster (March 2011; Nuclear News, 2011)

No	Reactor type (Some details on reactors)	No. of units		Installed capacity, GW_{el}		Forthcoming units	
		As of March 2017	Before March 2011	As of March 2017	Before March 2011	No. of units	GW_{el}
1	Pressurized Water Reactors (PWRs) (largest group of nuclear reactors in the world – 64%)	287 ↑	268	271 ↑	248	77	83.5
2	Boiling Water Reactors (BWRs) or Advanced BWRs (2nd largest group of reactors in the world – 18%; ABWRs – the only ones Generation-III+ operating reactors)	78 ↓	92	76 ↓	84	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	6.0
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	7.7 ↓	9	1[1]	0.2

[4] 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.

No	Reactor type (Some details on reactors)	No. of units		Installed capacity, GW_{el}		Forthcoming units	
		As of March 2017	Before March 2011	As of March 2017	Before March 2011	No. of units	GW_{el}
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) (3%)	15	15	10	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		**444**	**444**	**391** ↑	**378**	**96**	**98**

Table 7

Number of nuclear-power reactors by nation (11 nations with the largest installed nuclear-power capacities) as per March of 2017 (Nuclear News, 2017) and before the Japan earthquake and tsunami disaster (March of 2011) (Nuclear News, 2011)

No	Nation	No. of units (PWRs/BWRs)		Installed capacity, GW_{el}		Changes in number of reactors from March 2011
		As of March 2017	Before March 2011	As of March 2017	Before March 2011	
1	USA	99 (65/34)	104	101	103	↓ Decreased by 5 reactors
2	France	58 (58/-)	58	63	63	No changes
3	Japan*	42 (19/23)	54	40	47	↓ Decreased by 12 reactors
4	China	35 (33/-/2[3])	13	31	10	↑ Increased by 22 reactors
5	Russia	34 (17/-/15[1]/2[2])	32	25	23	↑ Increased by 2 reactors
6	S. Korea	25 (21/-/4[3])	20	23	18	↑ Increased by 5 reactors
7	Canada	19 (-/-/19[3])	22	13	15	↓ Decreased by 3 reactors
8	Ukraine	15 (15/-)	15	13	13	No changes
9	Germany	8 (6/2)	17	11	20	↓ Decreased by 9 reactors
10	Sweden	10 (7/3)	10	9.7	9.3	No changes
11	UK	15 (1/-/14[4])	19	8.9	10	↓ Decreased by 4 reactors

Arrows mean decrease or increase in a number of reactors.
[1] No of LGRs; [2] LMFBRs; [3] PHWRs; [4] AGRs.

Figure 5 shows a number of nuclear-power reactors of the world put into commercial operation vs. years and age of operating reactors (Handbook, 2016). Five reactors have been put into operation in 1969, i.e., they operate for more than 46 years. It is clear from this diagram that the Chernobyl NPP accident has tremendous negative impact on the world nuclear-power industry, which lasts for decades. And currently, we have additional negative impact of the Fukushima Daiichi NPP accident. Figure 6 shows possible scenarios of nuclear-power development in the world.
In general, in spite of all current advances into nuclear power, modern 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 in next generation – Generation IV NPPs (for details, see Table 8.

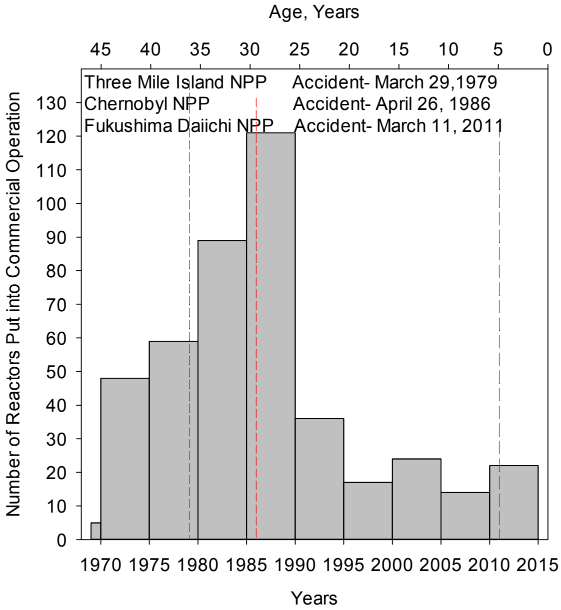


Fig. 5. Number of nuclear-power reactors of the world put into commercial operation vs. years and age of operating reactors (Handbook, 2016)

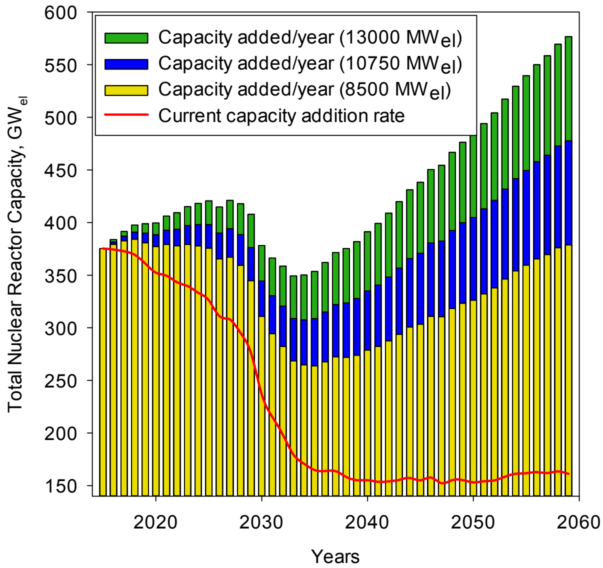


Fig. 6. Possible scenarios of nuclear-power development in the world (based on assumption that average term of reactors' operation is 45 years)

Table 8

Estimated ranges of thermal efficiencies (gross) of Generation-IV NPP concepts (Generation IV concepts are listed according to thermal efficiency decrease) (shown here just for reference purposes) (Handbook, 2016)

No	Nuclear Power Plant	Gross 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%

No	Nuclear Power Plant	Gross Eff., %
5	Lead-cooled Fast Reactor (LFR) NPP (Russian design Brest-300: reactor coolant – liquid lead: P≈0.1 MPa and T_{in}/T_{out}=420/540°C; primary power cycle – 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); 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≈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

Interaction between various electricity-generating sources inside one system (electrical grid) can be illustrated based on that in the Province of Ontario[5] (Canada) (Handbook, 2016). Figure 7a shows installed capacity and Figure 7b – electricity generation by energy source in Ontario (Canada) in 2012. Figure 7a shows that in Ontario major installed capacities in 2012 were nuclear (34%), gas (26%), hydro (22%), coal (8%), and renewables (mainly wind) (8%). However, the electricity (see Figure 7b) was mainly generated by nuclear (56%), hydro (22%), natural gas (10%), renewables (mainly wind) (5%), and coal (2%).

Figure 8a shows power generated by various energy sources in Ontario (Canada) on June 19, 2012 (a peak power on hot summer day, when major air-conditioning was required) and corresponding to that Figure 8b shows capacity factors of these energy sources. Figure 8 shows that electricity that day from midnight till 3.00 in the morning was mainly generated by nuclear, hydro, gas, wind, "other" and coal. After 3.00 in the morning, wind power fell due to Mother Nature, but electricity consumption started to rise. Therefore, "fast-response" gas-fired power plants and, later, hydro and coal-fired power plants plus "other" power plants started to increase electricity generation to compensate for both decreasing in wind power and increasing demand for electricity. After 18.00 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. After 22.00 o'clock in the evening, energy consumption dropped even more. Therefore, coal-fired power plants with the most emissions decreased abruptly their electricity generation followed by gas-fired and hydro-power plants.

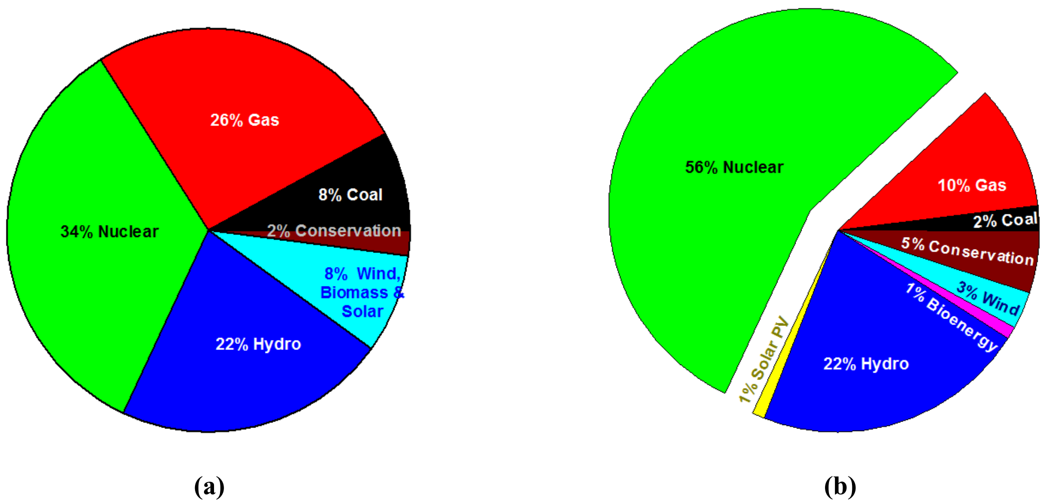
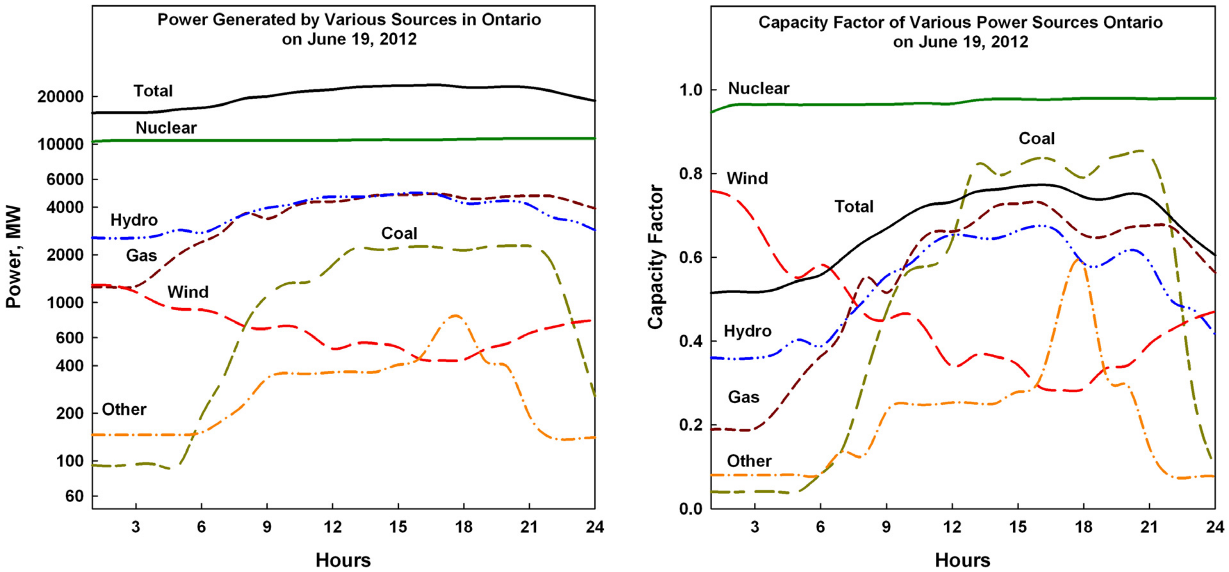


Fig. 7. Installed capacity (a) and electricity generation (b) by energy source in Ontario (Canada), 2012-2013 (based on data from Ontario Power Authority: http://www.powerauthority.on.ca and Ontario's Long-Term Energy Plan)

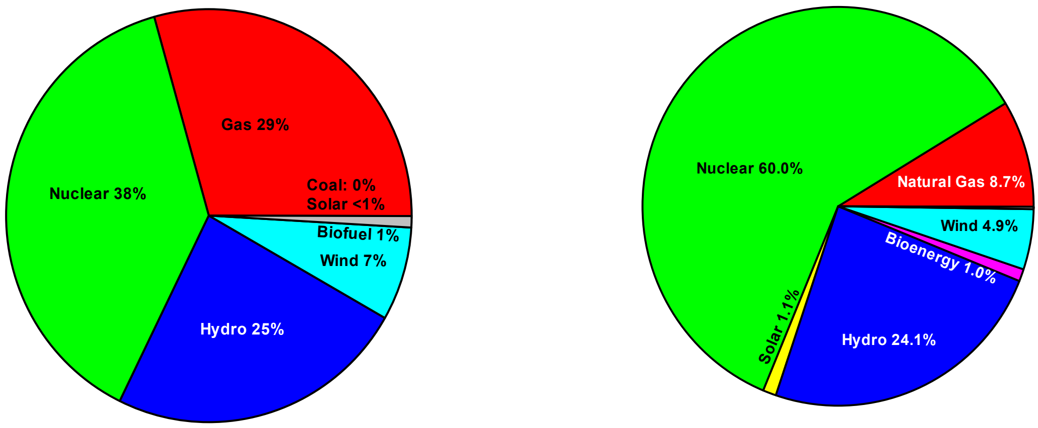
[5] Population: ~14 million (2016); Area: 1.076 million km²; Capital: Toronto (location 43.65° North) (for comparison, location of Nice, France 43.71° North).



(a) (b)

Fig. 8. Power generated (a) and capacity factors (b) of various energy sources in Ontario (Canada) on June 19, 2012 (based on data from http://ieso.ca/imoweb/marketdata/genEnergy.asp) (shown here just for reference purposes)

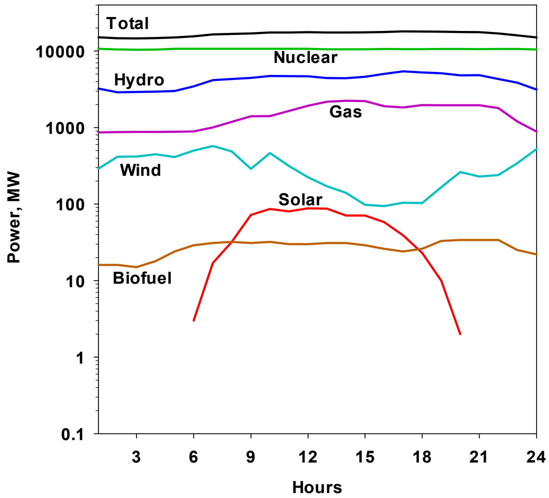
However, currently, the Province of Ontario (Canada) has completely eliminated coal-fired power plants from the electrical grid (Handbook, 2016). Some of them were closed, others – converted to natural gas. Figure 9a shows installed capacity, and Figure 9b – electricity generation by energy source in the Province of Ontario (Canada) in 2015. Figure 9a shows that in Ontario major installed capacities in 2015 were nuclear (38%), gas (29%), hydro (25%), and renewables (mainly wind) (8%). However, electricity (see Figure 9b) was mainly generated by nuclear (60%), hydro (24%), natural gas (8.7%), and renewables (mainly wind) (4.9%).



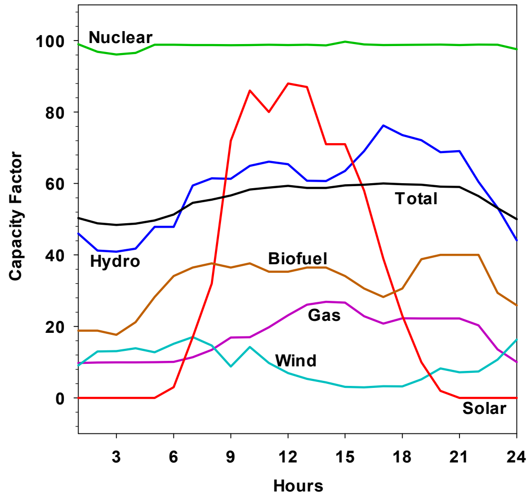
(a) (b)

Fig. 9. Installed capacity (a) and electricity generation (b) by energy source in Ontario (Canada), 2014-2015 (based on data from Ontario Energy Board: http://www.ontarioenergyboard.ca/ and Ontario Energy Report http://www.ontarioenergyreport.ca/)

Figure 10a,b shows power generated by various energy sources in Ontario (Canada) on June 17, 2015 and corresponding to that capacity factors of various energy sources. Figure 10 shows that electricity that day from midnight till 3.00 in the morning was mainly generated by nuclear, hydro, gas, wind, and biofuel. After 3.00, biofuel power plants increased slightly electricity generation followed by hydro and gas-fired power plants. Also, at the same time, wind-power plants started to generate slightly more electricity due to Mother Nature. However, after 7.00 wind power started to fluctuate and, eventually, decreased quite significantly. After 6.00 in the morning, solar-power plants started to generate some electricity[6]. During a day, hydro, gas-fired and biofuel power plants had variable electricity generation to compensate changes in consumption of electrical energy and variations in generating electricity with wind and solar power plants. After 21.00 in the evening, energy consumption started to drop in the province, and at the same time, wind power increased by Mother Nature. Therefore, gas-fired, hydro and biofuel power plants decreased energy generation accordingly. In both cases, i.e., June 19 of 2012 and June 17 of 2015, NPPs operated at about 100% of installed capacity providing reliable basic power to the grid.



(a)



(b)

Fig. 10. Power generated (a) and capacity factors (b) of various energy sources in Ontario (Canada) on June 17, 2015 (based on data from http://ieso.ca/imoweb/marketdata/genEnergy.asp) (shown here just for reference purposes)

These examples show clearly that any grid that includes NPPs and/or renewable-energy sources must also include “fast-response” power plants such as gas- and/or coal-fired and/or large hydro-power plants. This is due not only to diurnal and seasonal peaking of demand, but also the diurnal and seasonal variability of supply. Thus, for any given market, the generating mix and the demand cycles must be matched 24/7/365, independent of what sources are used, and this requires flexible control and an appropriate mix of base-load and peaking plants.

Also, it should be noted here that having a large percent of variable power sources mainly such as wind and solar, and other, i.e., which generating capacity depends on Mother Nature, an electrical grid can collapse due to significant and unpredicted power instabilities! In addition, the following detrimental factors are usually not considered during estimation of variable power-sources costs: 1) costs of fast-response power plants with service crews on site 24/7 as a back-up power and 2) faster amortization / wear of equipment of fast-response plants.

2. CURRENT AND FUTURE STATUS OF UKRAINIAN POWER INDUSTRY

Ukraine has about 42 million people and is the largest European country by a territory with exception of Russia. Ukraine consumes about 182 TW h/year electrical energy from various sources (mainly from nuclear - ~45.5 % and coal – 38% (for details, see Figure 2c)) or has about 461 W/Capita (see Table 1 and Figure 1). Due to that Ukraine is currently on the 78th place by HDI in the world, which is at the lower end of the second group of countries with High HDI (countries from 43rd and up to 85th places by HDI).

The Ukrainian nuclear-power industry consists of four NPPs with the total of 15 reactors (see Table 9 and Figure 11). Thermodynamic layout of a VVER-1000 NPP is shown in Figure 12. Major parameters of the Russian-design PWRs – VVERs operated in Ukraine are listed in Table 10 and *T-s* diagram of the VVER-1000 turbine cycle – in Figure 13.

Analysis of the Ukrainian power industry shows that two of these 15th reactors have been built and put into operation in 70-s, ten in 80-s, one in 90-s and just two – in 2004. Also, it should be noted current problems of Ukrainian NPPs, which are: 1) lower capacity factors (around 80%) compared to those in other countries (~90%) (Handbook, 2016); 2) uncertainties with nuclear-fuel supply due to political situation; and 3) service and repairs of relatively old reactors.

[6] It should be noted that usually, solar power plants might generate only a small amount of electricity within late fall, winter and early spring compared to that during summer.

Based on an analysis of the world power reactors in terms of their maximum years of operation (currently, the oldest reactors are 45-year old Nuclear News, 2016)) several projections have been made for future of the nuclear-power industry in Ukraine (for details, see Figure 14). Unfortunately, all these projections are quite pessimistic.

There is a possibility that around 2030–2035 the vast majority of the Ukrainian reactors will be shut down, and Ukraine can be left without the basic and vital source of electricity generation.

Table 9

General information on Ukrainian NPPs (http://www.energoatom.kiev.ua/en/)

Ukrainian NPP	Unit #	Reactor	Power	Year	
			MW_{el}	Startup	Shutdown (based on original 30-year term)
Rivne (planned 2 more reactors)	1	VVER- 440 (B-213 type)	440	1977	2007 (ext. 2030)
	2	VVER- 440 (B-213 type)	440	1978	2008 (ext. 2030)
	3	VVER-1000 (model 320)	1000	1989	2019
	4	VVER-1000 (model 320)	1000	2004	2034
South-Ukraine (planned 1 more reactor)	1	VVER-1000 (“small series”)	1000	1982	2012 (ext. 2023)
	2	VVER-1000 (“small series”)	1000	1985	2015 (ext. 2025)
	3	VVER-1000 (model 320)	1000	1989	2019
Khmel’nitsky (planned 2 more reactors)	1	VVER-1000 (model 320)	1000	1984	2014 (to be extended)
	2	VVER-1000 (model 320)	1000	2004	2034
Zaporizhzhya (largest in Europe)	1	VVER-1000 (model 320)	1000	1985	2015 (to be extended)
	2	VVER-1000 (model 320)	1000	1986	2016 (to be extended)
	3	VVER-1000 (model 320)	1000	1987	2017
	4	VVER-1000 (model 320)	1000	1989	2019
	5	VVER-1000 (model 320)	1000	1989	2019
	6	VVER-1000 (model 320)	1000	1995	2025

Explanations to the Table: ext. – extended till

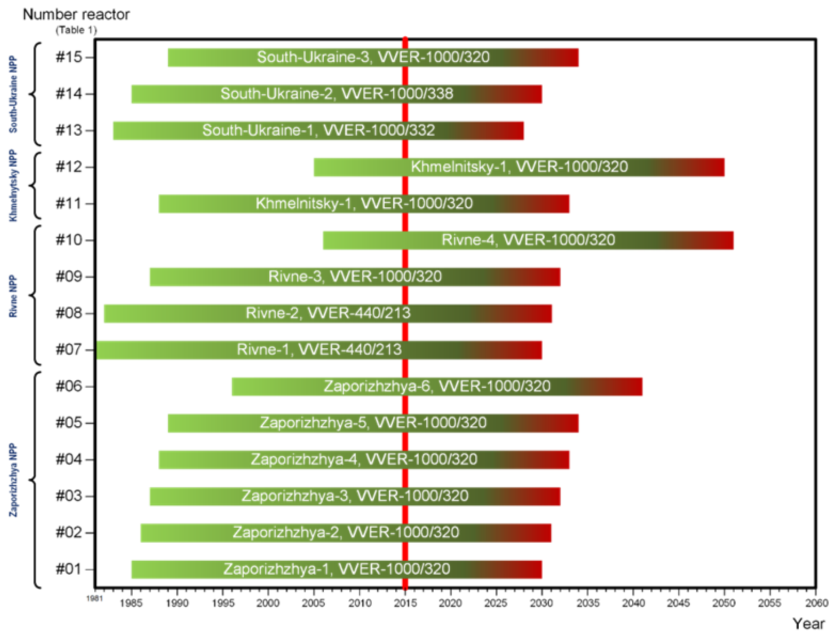


Fig. 11. Shutdown year per each Ukrainian reactor based on possible 45-year extension

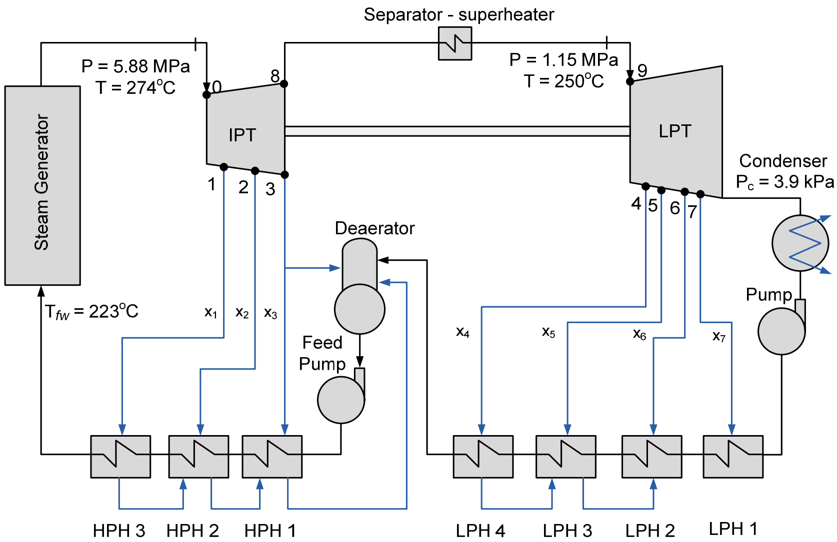


Fig. 12. Thermodynamic layout of 1000-MW$_{el}$ VVER-1000 PWR NPP (Dragunov et al., 2015)

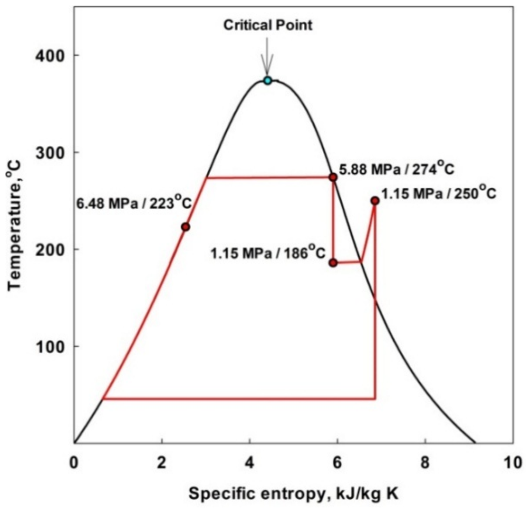


Fig. 13. *T–s* diagram for a VVER-1000 turbine cycle

Table 10

Major parameters of Ukrainian power reactors (Russian PWR – VVER-type) (Grigor'ev and Zorin, 1988)

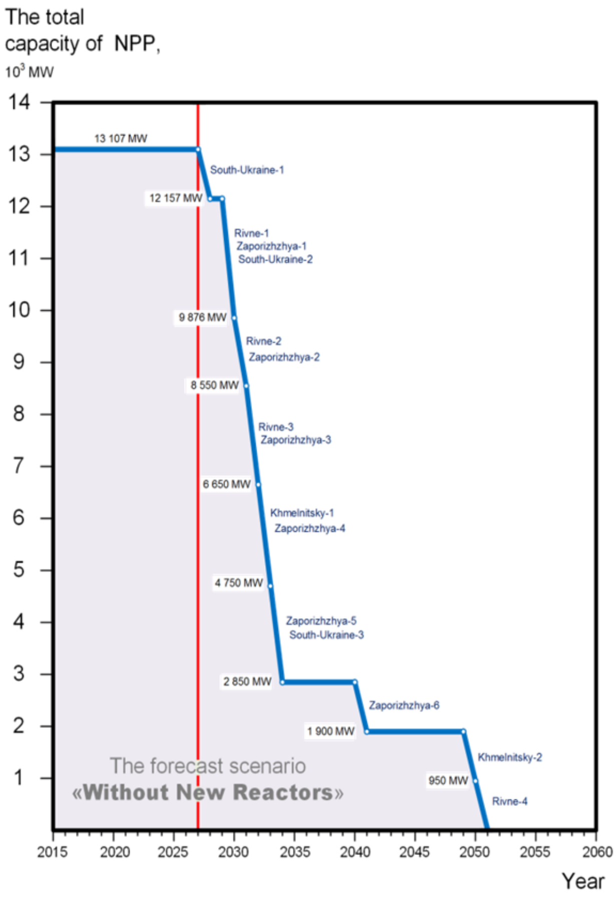
Parameter	VVER-440	VVER-1000
Thermal power, MW$_{th}$	1375	3000
Electrical power, MW$_{el}$	440	1000
Thermal efficiency (gross)*, %	32.0	33.0
Coolant pressure, MPa	12.3	15.7
Coolant flow, t/h	42,600	80,000
Coolant temperature, C	270/298	290/322
Average heat flux, MW/m^2	0.378	0.545
Steam flow rate, t/h	2700	5880
Steam pressure, MPa	4.6	6.48
Steam temperature, C	258.8	280.7
Core: Diameter/Height, m/m	3.84/11.8	4.5/10.9
Equivalent diameter of core, m	2.88	3.12
Fuel enrichment (max), %	3.6	4.3
No. of fuel assemblies	349	151
No. of rods in fuel assembly	126	317

* Thermal efficiencies have been calculated with the IAEA Desalination Thermodynamic Optimization Programme DE-TOP (IAEA, 2013) and compared to the actual ones.

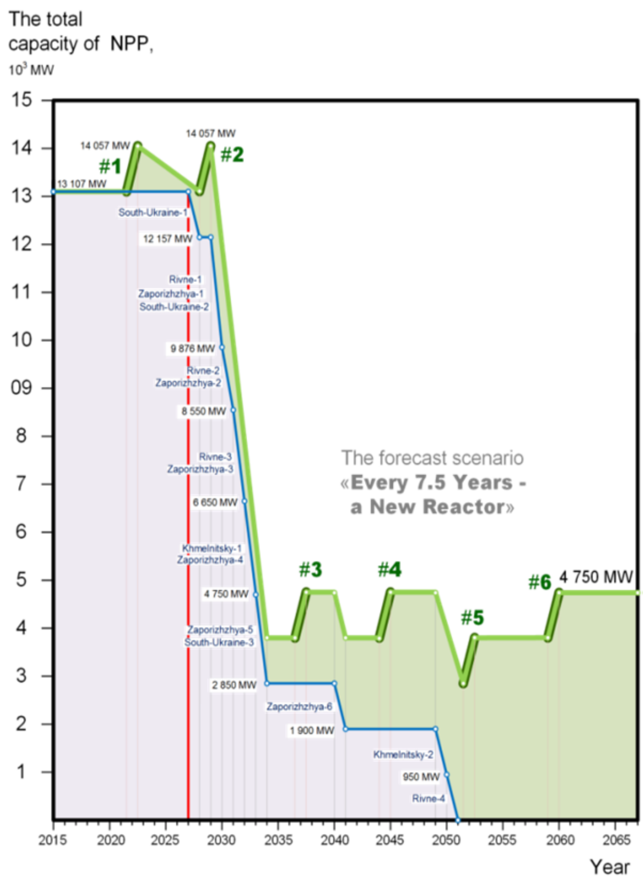
Analysis of the Ukrainian thermal-power industry shows that 8 large thermal power plants have been built in 60s, 9 – in 70s, and 3 in 80s. Due to this, the vast majority of them quite old and not very efficient plants.

Therefore, Ukraine has to move quickly with building new NPPs with modern reactors. Interesting point here is that Ukraine has its own resources of uranium (up to 800 tonnes per year, which is about 30% of the country's requirements) and own resources of Zirconium. In addition, there are ten scientific-research institutes related to nuclear science/engineering, nuclear energy, fuel and waste management. Based on that Ukraine might consider as an option to build CANDU reactors, which operate with natural uranium. Through that Ukraine has a possibility to develop its own closed fuel cycle and to have more independent and diversified nuclear-power industry.

Of course, NPPs require to be supported with fast-response thermal power plants, which will cover peaks and drops in electricity consumption per day. Therefore, Ukraine has to move to modern high-efficiency thermal power plants such as combined-cycle power plants (combination of Brayton gas-turbine cycle (fuel – natural gas or liquefied natural gas; combustion-products parameters at the gas-turbine inlet: T_{in}≈1650°C) and Rankine steam-turbine cycle (steam parameters at the turbine inlet: T_{in}≈620°C (T_{cr}=374°C)) with gross thermal efficiencies of up to 62% and/or supercritical-pressure coal-fired power plants (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 T_{reheat}≈540-625°C) with thermal efficiencies of up to 55% (Handbook, 2016; Pioro and Kirillov, 2013).



(a)



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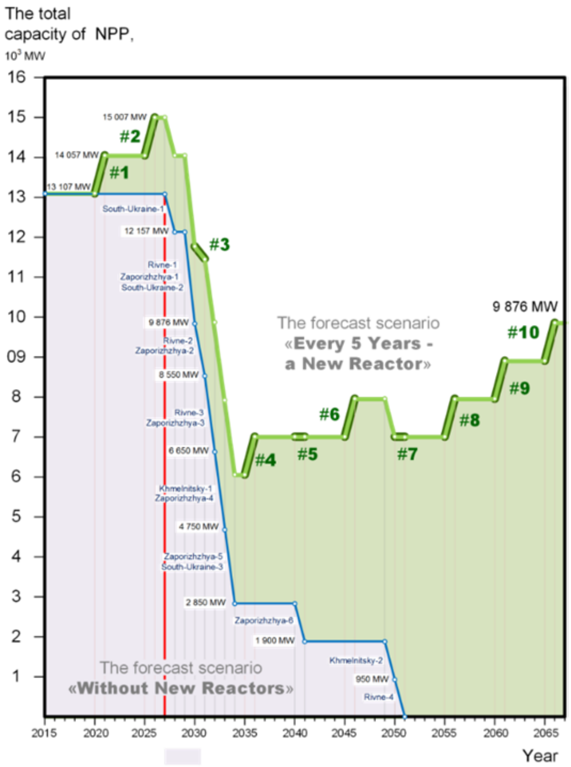

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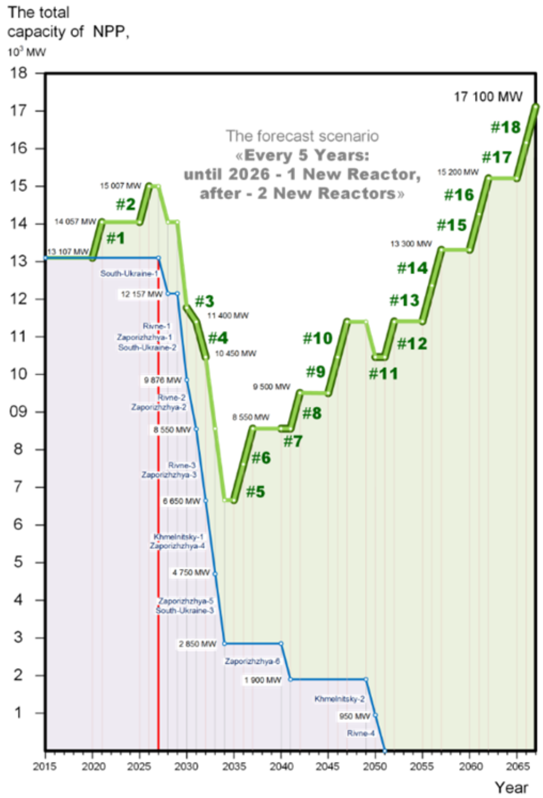

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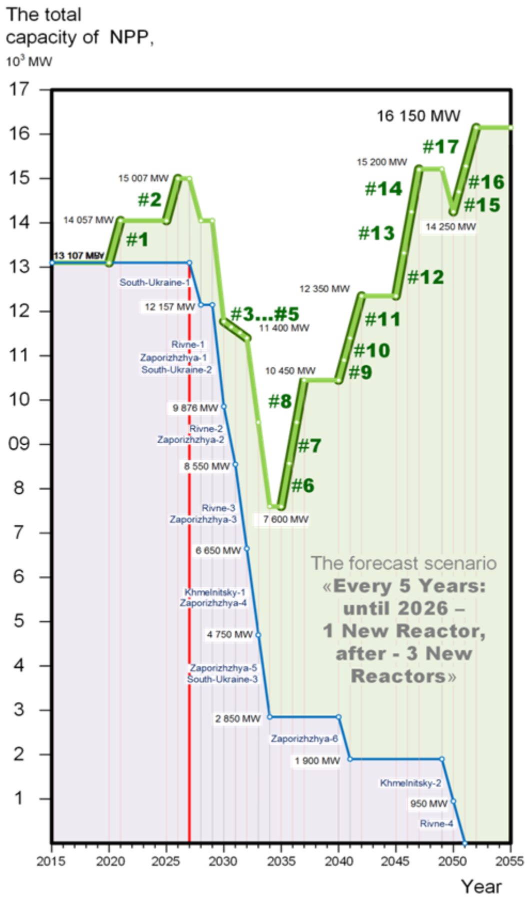

(e)

Fig. 14. Possible scenarios for future of nuclear-power industry in Ukraine

3. CONCLUSIONS

1. Electricity generation is the key factor for advances in industry, agriculture, technology and the level of living. Also, strong power industry with diverse energy sources is very important for country independence.
2. In general, electricity can be generated from: 1) non-renewable energy sources such as coal, natural gas, oil, and nuclear; and 2) renewable energy sources such as hydro, biomass, wind, geothermal, solar, and wave power. However, the major energy sources for electricity generation in the world are: 1) thermal power – primarily using coal (~40%) and secondarily - natural gas (~23%); 2) "large" hydro power plants (~17%) and 3) nuclear power from various reactor designs (~11%). The rest of the energy sources for electricity generation is from using oil (~4%) and renewable sources such as biomass, wind, geothermal and solar (~5%), which have just visible impact in selected countries. In addition, energy sources, such as wind and solar, and some others, like tidal and wave-power, are intermittent from depending on Mother Nature. And cannot be used alone for industrial electricity generation.
3. Currently, Ukraine covers its needs for electricity through using nuclear, thermal and hydro power plants. However, nuclear and thermal power plants are quite old and less efficient than modern NPPs and thermal plants. Also, hydro resources almost used completely.
4. Nuclear power in Ukraine is the most important source of electricity generation in the country. Currently, Ukrainian Nuclear Power Plants (NPPs) generate about 45.5% of the total electricity followed with coal generation – 38%, gas generation 9.6% and the rest is based on renewable sources, mainly on hydro power plants – 5.9%. Nuclear-power industry is based on four NPPs (15 Pressurized Water Reactors (PWRs) including the largest one in Europe – Zaporizhzhya NPP with about 6,000 MW_{el} gross installed capacity.
5. Two of these 15 reactors have been built and put into operation in 70-s, ten in 80-s, one in 90-s and just two in 2004. Therefore, based on an analysis of the world power reactors in terms of their maximum years of operation (currently, the oldest reactors are ~45-year old) several projections have been made for future of the nuclear-power industry in the world and Ukraine. Unfortunately, all these projections are quite pessimistic. There is a possibility that around 2030–2040 the vast majority of the world reactors and Ukrainian reactors will be shut down, and, in particular, Ukraine can be left without the basic and vital source of electricity generation.
6. Therefore, to decrease these negative trends the following measures should be taken: (a) extension of current NPPs terms of operation; (b) building new NPPs with reactors from various nuclear vendors; and (c) building modern high-efficiency thermal power plants.

4. NOMENCLATURE

P	pressure, Pa
s	specific entropy, J/kg K
T	temperature, °C
x	steam quality
Subscripts	
c	condenser
cr	critical
el	electrical
fw	feedwater
in	inlet
th	thermal
Acronyms	
AGR	Advanced Gas-cooled Reactor
BWR	Boiling Water Reactor
DE-TOP	DEesalination Thermodynamic Optimization Program
EEC	Electrical-Energy Consumption
ext.	extended
HDI	Human Development Index
HPH	High Pressure Heater
IAEA	International Atomic Energy Agency
IPT	Intermediate Pressure Turbine
LGR	Light-water Graphite-moderated Reactor
LMFBR	Liquid Metal Fast Breeder Reactor
LNG	Liquefied Natural Gas
LPH	Low Pressure Heater
LPT	Low Pressure Turbine
NPP	Nuclear Power Plant
PHWR	Pressurized Heavy Water Reactor
PP	Power Plant
PWR	Pressurized Water Reactor
VVER	Water-cooled Water-moderated Power Reactor (in Russian abbreviations)

Производство электроэнергии в мире и Украине: состояние на сегодня и развитие в будущем

А. Зворыкин, И. Пиоро, Н. Фиалко

Анотация. *Производство электроэнергии является ключевым фактором развития промышленности, сельского хозяйства, технологий и уровня жизни. Также, развитая и мощная энергетика с различными источниками энергии очень важна для независимости страны. В целом, электричество может быть получено из: 1) не возобновляемых источников энергии, таких как уголь; природный газ; нефть; и атомная энергия; и 2) возобновляемых источников энергии, таких как гидроэнергетика; биомасса; ветряная, геотермальная, и солнечная энергии; и энергия приливов и волн. Однако основными источниками для производства электроэнергии в мире являются: 1) тепловая энергия - преимущественно уголь (~40%) и природный газ (~23%); 2) «мощные» гидроэлектростанции (~17%); и 3) ядерная энергия (~11%). Для остального производства электроэнергии используется нефть (~4%) и возобновляемые источники, такие как биомасса, ветер, геотермальные и солнечные станции (~5%), которые используются в отдельных странах. Кроме того, источники энергии, такие как ветер и солнце, и некоторые другие (приливные и волновые станции), являются ненадёжными поставщиками электроэнергии из-за зависимости от Матери-природы. И не могут использоваться отдельно для промышленного производства электроэнергии.*

Ядерная энергетика в Украине является важнейшим источником производства электроэнергии в стране. В настоящее время украинские Атомные ЭлектроСтанции (АЭС) производят около 45,5% всей электроэнергии, за которыми следуют тепловые станции (~47,6%) (угольные - 38% и газовые - 9,6%), а остальная часть - возобновляемые источники, в основном гидроэлектростанции - 5,9%. Атомная энергетика базируется на четырех АЭС (15 реакторов с водой под давлением (PWR), включая крупнейшую в Европе - Запорожскую АЭС с общей установленной мощностью около 6 000 МВт).

Два из этих 15 реакторов были построены и введены в эксплуатацию в 70-е годы, десять в 80-е, один в 90-е годы и только два в 2004 году. Поэтому на основе анализа мировых энергетических реакторов с точки зрения их максимальной годовой эксплуатации (в настоящее время самые старые реакторы возрастом в 47 лет) было сделано несколько прогнозов для будущего атомной энергетики в мире и в Украине. К сожалению, все эти прогнозы весьма пессимистичны. Существует вероятность того, что около 2030-2040 гг. подавляющее большинство мировых реакторов и украинских реакторов будут закрыты, и, в частности, Украина может остаться без основного и жизненно важного источника выработки электроэнергии.

Ключевые слова: *производство электроэнергии, атомная электростанция, ядерный реактор, тепловая эффективность, коэффициент мощности*

Виробництво електроенергії у світі та Україні: стан на сьогодні і розвиток в майбутньому

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Анотація. *Виробництво електроенергії є ключовим фактором розвитку промисловості, сільського господарства, технологій і рівня життя. Також, розвинена і потужна енергетика з різними джерелами енергії дуже важлива для незалежності країни. В цілому, електрику може бути отримано з: 1) невідновлюваних джерел енергії, таких як вугілля; природний газ; нафту; і атомна енергія; і 2) поновлюваних джерел енергії, таких як гідроенергетика; біомаса; вітряна, геотермальна, і сонячна енергії; і енергія припливів і хвиль. Однак основними джерелами для виробництва електроенергії в світі є: 1) теплова енергія - переважно вугілля (~ 40%) і природний газ (~ 23%); 2) «потужні» гідроелектростанції (~ 17%); і 3) ядерна енергія (~ 11%). Для решти виробництва електроенергії використовується нафту (~ 4%) і поновлювані джерела, такі як біомаса, вітер, геотермальні і сонячні станції (~ 5%), які використовуються в окремих країнах. Крім того, джерела енергії, такі як вітер і сонце, і деякі інші (приливні і хвильові станції), є ненадійними постачальниками електроенергії через залежність від Матері-природи. І не можуть використовуватися окремо для промислового виробництва електроенергії.*

Ядерна енергетика в Україні є найважливішим джерелом виробництва електроенергії в країні. В даний час українські атомні електростанції (АЕС) виробляють близько 45,5% всієї електроенергії, за якими слідують теплові станції (~ 47,6%) (вугільні 38% і газові 9,6%), а інша частина - поновлювані джерела, в основному гідроелектростанції 5,9%. Атомна енергетика базується на чотирьох АЕС (15 реакторів з водою під тиском (PWR), включаючи найбільшу в Європі - Запорізьку АЕС із загальною встановленою потужністю близько 6 000 МВт).

Два з цих 15 реакторів були побудовані і введені в експлуатацію в 70-і роки, десять в 80-е, один в 90-і роки і тільки два в 2004 році. Тому на основі аналізу світових енергетичних реакторів з точки зору їх максимальної річної експлуатації (в даний час найстаріші реактори віком в 47 років) було зроблено кілька прогнозів для майбутнього атомної енергетики в світі та в Україні. На жаль, всі ці прогнози досить песимістичні. Існує ймовірність того, що близько 2030-2040 рр. переважна більшість світових реакторів і українських реакторів будуть закриті, і, зокрема, Україна може залишитися без основного і життєво важливого джерела вироблення електроенергії.

Ключові слова: *виробництво електроенергії, атомна електростанція, ядерний реактор, теплова ефективність, коефіцієнт потужності*

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