Opinion of the Committee on Electrical Engineering of the Polish Academy of Sciences on the implementation of nuclear power in Poland,

adopted by resolution on 25 November 2020 at the plenary meeting of the PAS Committee on Electrical Engineering

1. Introduction

The need to develop nuclear power in Poland is warranted by the necessity to safeguard, in the long-term, the operational security of the Polish National Electric Power System (NEPS), which in turn is essential for ensuring the continuity of electricity supply to industrial recipients, transport, services and households.

Continuous and uninterrupted supply of electricity is an aspect of national energy security, which comprises one element of national security, alongside territorial, health, food, water, and digital security.

The Climate Agreement, adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris (12.12.2015), and the decision of the European Council of October 2014 on the level of CO_2 emission reductions in the European Union Member States by 2030 pose a serious challenge to the Polish power sector: implementing – in the first half of this century – energy generation technologies that will bring about a significant reduction in CO_2 emissions. Having signed the Paris Agreement on 27 April 2016 at the UN headquarters in New York, Poland is obliged to implement the provisions of both the Agreement and the European Council decision of October 2014. The most important tasks resulting from these agreements concern the electricity generation sector [7, 8].

This opinion attempts to outline a long-term strategy for the development of the Polish power generation sector, including a solution to the CO_2 emission reduction problem. As a starting point for an attempt to solve this issue, Article 5 of the Constitution of the Republic of Poland was adopted. `This provision stipulates that Poland ensures environmental protection in keeping with the principle of sustainability. In relation to sustainable development of the power system, this principle can be summed up by stating that the system should safeguard economic development of the country, while protecting the balance of the ecosystem. Taking this into account, the sustainable development of the electric power generation sector should meet the following four criteria: (1) ensure the secure operation of the National Electric Power System (NEPS), (2) ensure the availability of low-cost (generated at the lowest possible cost) electricity that promotes the economic development of the country, (3) ensure economical consumption of non-renewable primary energy resources, and (4) ensure the protection of the environment and prevent climate change by minimizing CO_2 emissions per amount of electricity generated (kg CO_2/kWh) [10].

When searching for a solution to the problem of sustainable development of generation sources in the NEPS, the issue is to strike a balance between the environmental protection goals, the electricity generation costs and the security of its supply.

2. Status of generation sources in the National Electric Power System

As of 31.12.2019 the installed capacity of generation sources in the National Electric Power System (NEPS) was about 46.6 GW, with 36.0 GW of that in power plants and 10.7 GW in combined heat and power (CHP) plants. On the other hand, the generating capacity of generation units operating in power plants and CHP plants was approx. 36.1 GW and 10.3 GW, respectively [3].

The largest generation potential of power plants' installed capacity is offered by condensing steam units, with a total installed capacity of approx. 26.2 GW and a maximum generating capacity of approx. 26.3 GW. These include 6 modern supercritical steam units with a unit capacity ranging from 460 MW to 1,075 MW, fired by hard coal and lignite, 90 subcritical steam units with a unit capacity ranging from 60 MW to 560 MW, fired by hard coal and lignite, 3 subcritical steam units, burning coke oven gas, and 4 subcritical steam units, fired by biomass. A significant generation potential, very important for the NEPS's operation, is represented by 11 units in pumped-storage hydroelectric power plants with a total capacity of 1,413 MW and over 2,500 units in run-of-river power plants with a total capacity of approx. 983 MW. The capacity of the power plants using renewable energy sources (RES), in addition to the capacity of the already mentioned hydroelectric power plants and biomass-fired power plants, comprises the capacity of onshore wind and photovoltaic power plants of 5,898 MW and 1,526 MW, respectively [4].

The second group of generation sources operating in the NEPS consists of combined heat and power (CHP) units. Their total installed electricity capacity is approx. 10.7 GW, which accounts for about 23% of the installed capacity in the NEPS. In 2018 cogeneration generated electricity accounted for about 16.4% of all electricity generation in Poland and for about 21.5% of electricity sold to end users [4], while the share of heat generated in CHP plants in the total production of system heat was approx. 65% [5]. The combined heat and power generation units exhibit significant technological diversity. The largest production potential is offered by CHP steam units, whose electrical installed capacity is approx. 7.9 GW, representing about 73.8% of the electrical capacity of all cogeneration sources operating in the NEPS. These include CHP units fired by hard coal, natural gas, coke oven gas, biomass and municipal waste. The modern CHP units are natural gas-fired gas-steam CHP units, built in 1999–2018, with a total installed electrical capacity of approx. 2,080 MW. They employ gas turbines from leading companies, such as General Electric, Siemens, Ansaldo and Solar Turbines. One interesting group of CHP units are natural gas-fired simple-cycle gas turbine CHP units, with a total installed electrical capacity of about 194 MW.

Cogenerational gas-fired CHP units with gas engines, with a total installed electrical capacity of over 500 MW, are an important and developing technology. These CHP units burn natural gas or gas from mine degassing or biogas produced in the process of biological conversion of biomass chemical energy into biogas chemical energy in biogas plants (agricultural, sewage treatment plants and municipal waste landfills). There are also several biomass-fired Organic Rankine Cycle (ORC) CHP units operating in the NEPS, with a total installed electrical capacity of about 11 MW [4]. Out of more than 760 different types of CHP units operating in the NEPS, only 4 (2 steam units and 2 gas-steam units), with a total installed electrical capacity of approx. 1,380 MW, function to a limited extent as centrally dispatched generation units (CDGUs) in the NEPS.

In recent years, the NEPS has witnessed a significant increase in the capacity of distributed generation sources (non-CDGUs), particularly in the form of RES-based generation units and, to a lesser extent, cogeneration sources whose operation (output) depends on weather conditions or heat demand in district heating systems. The growth of non-CDGU capacity in the NEPS will continue in the coming years. Therefore, in order to ensure security of NEPS operation, it is necessary to simultaneously increase the new capacity of centrally dispatched generation units (CDGUs), whose capacity in the NEPS will be decreasing due to the decommissioning of coal-fired condensing steam units, while demand for capacity in the NEPS will be growing. The CDGUs operating in the NEPS are highly diversified in terms of energy effectiveness, their technical condition and flexibility in responding to load changes. A significant number of them, with a total capacity of about 10 GW, have been operating in the NEPS for over 40 years and their operation time has exceeded 200,000 hours. Therefore, a significant number of them are expected to be decommissioned in the coming years [11].

3. Security of the National Electric Power System operation

The criteria that need to be met by the sustainable development of generation sources in the NEPS were formulated in the above Introduction. The primary objective of sustainable development of the power system is to ensure security of electricity supply to consumers, while protecting the environment. The overriding criterion of sustainable development of generation sources in the NEPS is therefore that of ensuring its operational security. The security of the NEPS operation hinges on striking an equilibrium between the demand for electric power and the available capacity of generation sources [1]. The capacity and technical condition of centrally dispatched generation units (CDGUs) are of fundamental importance for ensuring secure and stable operation of the NEPS. Their installed capacity in the NEPS as of 31.12.2019 was about 28.1 GW. They consist of the following: condensing steam units fired by hard coal and lignite, with a unit capacity of more than 200 MW, connected mainly to the 440 kV and 220 kV transmission grid and partially to the 110 kV distribution grid, pumped-storage hydroelectric units, two coal-fired CHP steam units and two new CHP combined cycle units of 465 MW and 630 MW, fired with natural gas. Of the total CDGU capacity, 87.6% is represented by coal-fired steam units, of which:

– 8 steam units with a unit capacity of 125 MW and 3 steam units with a unit capacity of 200 MW have been operating in the NEPS for at least 50 years,
– 22 steam units with a unit capacity of 200 MW have been operating in the NEPS for 46 to 50 years,
– 16 steam units with a unit capacity of 200 MW have been operating in the NEPS for 40 to 45 years.

These coal- and lignite-fired units will most likely be decommissioned in the next ten to twenty years. By that time, only two new coal-fired supercritical steam units with a total capacity of 1,406 MW (in Jaworzno and Turów power plants), two condensing gas-fired gas-steam units with a total capacity of 1,400 MW (in Dolna Odra power plant) and two natural gas-fired gas-steam CHP units with a total capacity of 966 MW (in Stalowa Wola CHP plant and Żerań CHP plant) will be added to the NEPS. This will result in a serious shortage of CDGU capacity in the NEPS that will threaten its operational security and, therefore, there will be a need to replace the decommissioned coal-fired condensing steam units with new zero-emission CDGUs characterized by continuity and stability of operation – at present, these can only be nuclear units.

By 2040, only supercritical coal-fired steam units and subcritical steam units with a unit capacity of 360 MW and 500 MW as well as a certain portion of steam cogeneration units are likely to remain in operation in the NEPS and by 2050 the only ones remaining will be supercritical condensing steam units and some cogeneration steam units. Therefore, a very important challenge in the necessary technological transformation of generation sources in the NEPS is posed by the fuel transformation of CDGUs, which are decisively responsible for its operational security.

Poland's scarce domestic resources of natural gas, the limited resources of the fuel globally, the lack of a fully liberal international market for it and its high per-unit energy cost (approx. 30 PLN/GJ) make it impossible, in the long term, to consider natural gas as a strategic fuel for low-emission CDGUs, which are intended to ensure security of the NEPS operation. Moreover, gas-fired condensing gas-steam units are also a source of CO_2 emissions at a level of approx. 45% of emissions from coal-fired power plants. Therefore, from the point of view of NEPS operation security, CDGUs in the form of coal-fired condensing steam units being withdrawn from operation should be replaced by zero-emission nuclear units, and they may only be partially replaced by natural gas-fired gas-steam CHP units. Natural gas in the electric power industry in Poland should be used primarily as a fuel for high-efficiency CHP units whose overall efficiency (conversion of chemical energy of fuel into electricity and heat) exceeds 80% [2].

The required capacity of CDGUs to ensure secure and stable operation of the NEPS depends on the following factors: the electric power demand at the NEPS winter and summer peaks, average annual electric power demand, and the available capacity of non-CDGUs. Projected values of gross electricity consumption, the NEPS load in the winter and summer peaks, the required capacity of CDGUs and the capacity of distributed sources (non-CDGUs) are presented in Table 1, cumulatively for 2020, 2025, 2030 and 2035. The projected values of gross electricity consumption were determined on the basis of an analysis of annual increments in this consumption in the NEPS for 2000–2019, assuming an annual growth rate of 1.27% for 2020–2050. The projected demand for NEPS peak capacity for the winter and summer peaks as well as planned decommissioning of CDGUs was based on a study by the grid operator, PSE S.A. [11].

Table 2 presents a forecast of the desired capacity structure of power plants and CHP plants as well as of electricity production in Poland in 2030, 2040 and 2050. The forecast was guided by the following assumptions: (1) the capacity of CDGUs, required for secure operation of the NEPS, includes the capacity of power units of system power plants, fired by coal and nuclear fuel, the capacity of gas-fired

Table 1.
Forecast capacity balance in the NEPS in 2020–2035

Volume	Year			
	2020	2025	2030	2035
Forecast gross electricity consumption [TWh]	179.1	190.7	203.1	216.4
Projected winter peak demand for peak capacity [GW]	28.0	30.3	32.7	35.2
Projected summer peak demand for peak capacity [GW]	24.8	27.5	30.5	32.7
Planned decommissioning of CDGUs [GW]	1.8	2.5	4.7	13.6
Planned construction of new CDGUs (steam, coal-fired and gas-steam, natural gas-fired) [GW]	1.9	3.8	3.8	3.8
Projected capacity of CDGUs after decommissioning and construction of planned new CDGUs [GW]	28.2	29.4	27.2	18.3
Projected capacity of distributed sources (non-CDGU) [GW]	17.0	21.0	25.0	31.3
Required new capacity of CDGUs [GW]			**3.0**	**6.0**

Table 2.
Forecast desired power plant and CHP plant capacity structure and electricity generation structure in 2030, 2040, and 2050

Primary energy type (fuel or RES type)	Forecast desired power plant and CHP plant capacity structure and electricity generation structure in 2030, 2040, and 2050								
	2030			2040			2050		
	GW	TWh	%	GW	TWh	%	GW	TWh	%
Hard coal and lignite	28.3	127.1	62.6	18.5	79.2	34.3	9.5	43.7	16.7
Nuclear fuel				5.0	39.4	17.1	9.0	70.9	27.1
Natural gas	5.0	21.2	10.4	6.8	28.6	12.4	9.4	39.5	15.1
Biomass and biogas	2.6	10.4	5.1	3.0	12.0	5.2	3.8	16.0	6.1
Water	2.5	2.7	1.3	2.7	2.9	1.3	2.8	3.0	1.1
Wind	11.2	29.8	14.7	17.0	47.5	20.6	21.5	63.7	24.4
Sun	12.5	11.9	5.9	22.0	20.9	9.1	26.0	24.7	9.5
Total	**62.1**	**203.1**	**100.0**	**75.0**	**230.5**	**100.0**	**82.0**	**261.5**	**100.0**

condensing and CHP units, with a unit electrical capacity exceeding 200 MW, fired by natural gas, the capacity of cogeneration steam units with extraction-condensing turbines, with a unit electrical capacity exceeding 100 MW, fired by coal, and the capacity of pumped-storage hydroelectric power plants, (2) generation units of small capacity (dispersed sources), due to the required high energy effectiveness (optimal use of primary energy) – with the exception of wind, hydro and photovoltaic power plants – should be built only as CHP units [2], and (3) the projected capacity of nuclear power plants and power plants and CHP plants using renewable energy sources (RES) is based on the capacity needed to ensure the operational security of the NEPS and to fulfill Poland's international commitments to reduce CO_2 emissions, resulting from the Paris Agreement and the decision of the European Council of October 2014.

4. Nuclear power development in the world

As of 31 December 2019, there were 443 nuclear units in operation in 30 different countries around the world, with a total capacity of 392,098 MW. In 2019 they produced 2,586.2 TWh of electricity, accounting for 10.4% of total global electricity generation. The nuclear units currently in operation predominantly employ pressurized water reactors (PWRs), installed in 300 units, boiling water reactors (BWRs) present in 65 units, pressurized heavy-water reactors (PHWRs) – 48 units, gas-cooled reactors (GCRs) – 14 units (only in the UK), light-water boiling reactors (LWGR) – 13 units (only in Russia as RBMK reactors), plus fast breeder reactors (FBR) operating in 3 units (2 in Russia and 1 in China). The number of reactors and the capacity of nuclear power plants and the electricity produced by them in 2019 are shown in Table 3 [6].

Table 3.
Number of nuclear power units in operation and nuclear electric power capacity and production, as of 31.12.2019

No.	Country	Number of units (reactors)	Nuclear power plants capacity [MW]	Electricity generation in nuclear power plants [TWh]	Share of nuclear power plants in total electricity generation [%]
1	France	58	63,130	382.4	70.6
2	Slovakia	4	1,814	14.3	53.9
3	Ukraine	15	13,107	78.1	53.9
4	Hungary	4	1,902	15.4	49.2
5	Belgium	7	5,930	41.4	47.6
6	Bulgaria	2	2,006	15.9	37.5
7	Slovenia	1	688	5.5	37.0
8	Czechia	6	3,932	28.6	35.2
9	Finland	4	2,794	22.9	34.7
10	Sweden	7	7,740	64.4	34.0
11	Armenia	1	375	2.0	27.8
12	South Korea	24	23,172	138.8	26.2
13	Switzerland	4	2,960	25.4	23.9
14	Spain	7	7,121	55.9	21.4
15	US	96	98,152	809.4	19.7
16	Russia	38	28,437	195.5	19.7
17	Romania	2	1,300	10.4	18.5
18	UK	15	8,923	51.0	15.6
19	Canada	19	13,554	94.9	14.9
20	Germany	6	8,113	75.1	12.3
21	Japan	33	31,679	65.7	7.5
22	South Africa	2	1,860	13.6	6.7
23	Pakistan	5	1,318	9.1	6.6

No.	Country	Number of units (reactors)	Nuclear power plants capacity [MW]	Electricity generation in nuclear power plants [TWh]	Share of nuclear power plants in total electricity generation [%]
24	Argentina	3	1,641	7.9	5.9
25	China	48	45,518	330.1	4.9
26	Mexico	2	1,552	10.9	4.5
27	India	22	6,255	40.7	3.2
28	Netherlands	1	482	3.7	3.1
29	Brazil	2	1,884	15.2	2.7
30	Iran	1	915	5.9	1.8
	World	443	**392,098**	**2,586.2**	**10.4**

On the other hand, as of 31 December 2019 there were 60 more nuclear power units under construction, with an expected total capacity of 63,271 MW. New nuclear power units are being built primarily in Asian countries (40 units), namely: in China (16), India (9), South Korea (4), the United Arab Emirates (4), Bangladesh (2), Japan (2), Pakistan (2) and Iran (1), and in European countries (16 units), namely: Russia (4), Belarus (2), Slovakia (2), Turkey (2), Ukraine (2), the UK (2), Finland (1) and France (1). The remaining 4 nuclear units are being built in North and South America, namely in the United States (2), Argentina (1) and Brazil (1). In the coming years Bangladesh, Belarus, Turkey and the United Arab Emirates will join the club of nuclear power plant users. Among the 60 new nuclear units under construction, PWRs predominate (49 reactors), the others being as follows: 6 PHWRs (India), 2 ABWRs (Japan), 2 FBRs (China and India) and 1 HTGR (China). The number of units and reactor types under construction are shown in Table 4 [6].

Table 4.
Nuclear power units under construction, as of 31 December 2019

No.	Country	Number of units (reactors)	Reactor types	Total capacity [MW]
1	China	16	10 (Hualong One), 2 (CAP 1400), 2 (ACPR), 1 (HTGR), 1 (SFR 600)	16,600
2	India	9	6 (PHWR), 2 (VVER-1000), 1 (FBR 470)	6,084
3	South Korea	4	4 (APR-1400)	5,360
4	Russia	4	2 (VVER-1200), 2 (VVER-TOI)	4,525
5	UAE	4	4 (APR-1400)	5,380
6	Bangladesh	2	2 (VVER-1200)	2,180
7	Belarus	2	2 (VVER-1200)	2,220
8	Japan	2	2 (ABWR)	2,653
9	Pakistan	2	2 (Hualong One)	2,028
10	Slovakia	2	2 (VVER-440)	880
11	Ukraine	2	2 (VVER-1000)	2,070
12	Turkey	2	2 (VVER-1200)	2,228

No.	Country	Number of units (reactors)	Reactor types	Total capacity [MW]
13	US	2	2 (AP1000)	2,234
14	UK	2	2 (EPR)	3,260
15	Argentina	1	1 (CAREM 25)	25
16	Brazil	1	1 (PRE KONOI)	1,340
17	Finland	1	1 (EPR)	1,600
18	France	1	1 (EPR)	1,630
19	Iran	1	1 (VVER-1000)	974
	Total	**60**		**63,271**

The largest market shares in building new nuclear units are held by: China – 18 units, Russia (Rosatom) – 17 units, South Korea – 8 units, India – 7 units, and France (EdF) and the United States (Westinghouse and GE) – 4 units each. Chinese nuclear power companies are building 16 units in China and 2 in Pakistan. Russia's Rosatom is constructing nuclear units in the following countries: Russia (4), Bangladesh (2), Belarus (2), India (2), Slovakia (2), Turkey (2), Ukraine (2), and Iran (1). This company is building nuclear units with several types of PWR power reactors, including the VVER 440, VVER 1000, VVER 1200 and VVER TOI. The Korean Hydro and Nuclear Power (KHNP) company is building 4 units with APR 1400 reactors in South Korea and 4 units with the same reactors in the United Arab Emirates. Nuclear Power Corporation of India Limited (NPCIL) is building 6 PHWR 700 units and 1 FBR 470 unit in India. France's EDF is building 1 EPR unit in Finland, 1 EPR unit in France and 2 EPR units in the UK. Westinghouse is building 2 AP1000 units in the United States and the US-Japanese group General Electric Hitachi Nuclear Energy (GEH) is building 2 ABWR units in Japan.

In addition to the 60 new nuclear units under construction, many countries are planning further nuclear generation units, most notably China (81), India (36), Russia (32), Turkey (10) and South Africa (8). There are plans to build a total of more than 240 nuclear units worldwide, the vast majority of them with PWRs installed, as the most mature designs and the safest to operate.

Australia is among the countries planning to enter the path of nuclear power development. In 2019 it produced 256.6 TWh of electricity in total, of which as much as 56.39% was generated from coal. The Australian House of Representatives Standing Committee on the Environment and Energy conducted an inquiry and produced a report based on it, entitled "Not without your approval: a way forward for nuclear technology in Australia." Citing data collected by the Massachusetts Institute of Technology (MIT) among other sources, this report states that the Commission found evidence that nuclear power has the lowest mortality rates of all power generating technologies, namely per PWh of electricity generated from coal it ranges from 15,000 deaths/PWh in the United States to 90,000/PWh in China, from oil – 36,000/PWh, from natural gas – 4,000/PWh, from hydro – 1,400/PWh, from solar – rooftop – 400/PWh, from wind 150/PWh, and from nuclear – 90/PWh. The Commission's Chair Ted O'Brien, in discussing the results of the inquiry on Sky News, stated that nuclear power "is the safest form of energy." It should be noted here that Australia is one of the largest producers and exporters of coal in the world.

It is also worth noting that another large producer of electricity from coal (89.06% in 2019), South Africa, already operates two large power units with PWR reactors, with a total capacity of 1,860 MW, and plans to build further 8 large units with PWR reactors, with a total capacity of 10,400 MW. Nuclear power development is also planned by another large producer (3rd in the world), user and exporter (1st in the world) of coal, namely Indonesia, which produces approx. 255 TWh of electricity per year, of which over 58% from coal. The country plans to build 6 Russian nuclear units, VVER 1000 and VVER 1200, by 2030, with a total capacity of 6,800 MW.

An extensive nuclear power development program is also in place in a country similar in scale to Poland, namely in Vietnam. It intends to build one 1,000 MW nuclear unit by 2040, and further 4 units of the same size by 2045, despite the fact that it has significant hydropower capacity that in 2019 produced almost 31% of the country's electricity. Egypt and Kenya are the second and third African countries, after South Africa, to embark on the path of nuclear power development. Egypt, which is Africa's second largest electricity producer, has a grand plan to build 8 nuclear units, in two phases of 4 units each, with a total capacity of 9,600 MW. The construction of the first unit is expected to begin in 2021. Kenya's Nuclear Energy Agency announced on 5 August 2020 that it had applied for approval to build a 1,000 MW nuclear unit expected to come online in 2027, along with plans to increase Kenya's nuclear capacity to 4,000 MW by 2035.

Several Central European countries, such as Bulgaria, Czechia, Romania, Slovakia, Slovenia and Hungary, are making intensive preparations to start building new nuclear power plants or to increase the capacity of their existing ones.

The impact of nuclear power generation on zero-carbon electricity production in selected countries in 2019 is shown in Table 5. This list includes 12 European Union Member States.

Table 5.
Share of electricity generation from zero-carbon sources in selected countries in 2019

No.	Country	Share of electricity generation from zero-emission sources [%]	Share of electricity production from RES sources [%]	Share of electricity generation in nuclear power plants [%]
1	Sweden	98.91	58.91	40.00
2	Switzerland	98.80	65.50	32.30
3	France	88.82	17.96	70.86
4	Brazil	85.22	82.63	2.59
5	Finland	81.18	47.89	33.29
6	Canada	80.62	65.40	15.22
7	Slovakia	79.63	25.27	54.35
8	Belgium	70.58	21.82	48.76
9	Slovenia	67.54	29.02	38.52
10	Hungary	60.36	11.38	48.98
11	Spain	59.21	38.04	21.17
12	UK	56.63	39.27	17.36
13	Germany	56.35	44.09	12.26
14	Romania	55.64	38.32	17.90
15	Bulgaria	49.04	14.95	34.09
16	Czechia	45.18	12.62	32.56
17	US	36.96	17.60	19.36
18	Russia	36.62	17.93	18.69
19	China	36.23	27.43	3.90
	World	**37.24**	**26.89**	**10.35**

All told, there have been three major nuclear power plant accidents in the over 65-year history of nuclear power: 28 March 1979 at the Three Mile Island plant, 26 April 1986 at the Chernobyl plant, and 11 March 2011 at the Fukushima Daiichi nuclear power plant. In all of these accidents, the reactor core melted due to the loss of coolant caused by failures of the primary and emergency cooling systems, as well as erroneous decisions by the operators. Therefore, after these accidents, great attention was paid to the design of passive backup reactor core cooling systems. No accident in the history of nuclear power has resulted in an uncontrolled nuclear reaction.

The above-discussed accidents have contributed to a slowdown in the development of nuclear power in the world. However, despite the losses incurred, most of the companies involved in building power equipment for nuclear power plants have learned the right lessons from these accidents. New reactor designs were developed, characterized by improved safety of operation, in particular Generation III+ reactors, and conditions were created for a return to dynamic development of this energy sector. At that seemingly critical time, new countries, such as China and South Korea, appeared on the map of nuclear companies. Together with Russia, they are today – at a time when the balance of the ecosystem is under threat – giving new impetus to the development of nuclear power in the world, when the need for zero-carbon, stable sources of electricity to ensure the secure operation of electricity systems has increased significantly.

5. Cost of electricity generation in nuclear power plants

The implementation of nuclear power in Poland involves a number of important issues, including not only societal acceptance but also economic efficiency. The cost structure in nuclear power generation is characterized by heavy financial expenditure on the construction of a power plant, followed by low operating costs, including fuel costs. One of the major economic criteria of an investment project in the field of power generation sources is the projected per-unit electricity generation costs, discounted for the year of project start-up, taking into account the impact of both capital expenditure and operating costs. Calculations of these costs made for the purposes of this opinion support the conclusion that per-unit costs of electricity generation in nuclear power plants, as discounted for 2020, under Polish conditions, are comparable to the same costs (including the costs of CO_2 emission allowances) in system power plants fired by fossil fuels (i.e. in coal-fired steam plants and natural gas-fired combined cycle plants), being on the level of 350–360 PLN/MWh. Significant differences exist in the fuel component of these costs, with the costs of CO_2 emission allowances, as shown in Table 6.

Table 6.
Projected unit electricity generation costs in system power plants (CDGUs), with costs of CO_2 emission allowances, discounted for 2020

No.	Type of generation unit	Unit electricity generation costs, including the costs of CO_2 emission allowances [PLN/MWh]	Costs of fuel and CO_2 emission allowances in unit electricity generation costs [PLN/MWh]
1	Lignite-fired supercritical steam unit	350	181
2	Hard coal-fired supercritical steam unit	355	189
3	Natural gas-fired combined cycle unit	360	218
4	Nuclear unit with Generation III+ PWR	352	49

A sensitivity analysis of the impact of a nuclear power plant's specific design and operating parameters on its economic efficiency supports the conclusion that unit electricity generation costs in nuclear power plants discounted for 2020 are most affected by unit capital expenditure, the time of use of the installed capacity and the discount rate (cost of capital). The fuel price and power plant lifespan, on the other hand, have a much smaller impact on these costs. A 10% decrease in unit capital expenditure or a 10% increase in the time of use of the installed capacity would reduce unit electricity generation costs by 7.67%, whereas a 10% decrease in the discount rate would lower unit electricity generation costs by 7.38%. In contrast, a 10% increase in the fuel price would increase the per-unit cost of electricity generation by only 1.45%. This is important in assessing the risks associated with future fuel prices and their impact on electricity generation costs.

These results indicate that at the stage of preparing an investment related to the construction of a nuclear power plant, efforts should be made to seek ways to reduce unit capital expenditure and the discount rate. Experience from nuclear power plants currently under construction in several countries around the world shows that significant savings can be achieved in capital expenditure when constructing two twin units simultaneously, particularly in terms of the labor involved in reinforcing and laying the concrete foundations for the reactor, safety housing and the cooling system. This is why over 80% of current nuclear power plant construction projects involve building two twin units, with a slight time lag of six months to a year between them. Significant savings in capital expenditure can also be achieved through proper preparation of the project, enabling it to be carried out according to schedule, without prolongation. A very important problem with as capital- and time-intensive project as the construction of a nuclear power plant is the cost of capital (the capital discount rate). State involvement, in the form of loan guarantees and purchase of generated electricity at a guaranteed price, has a great influence on lowering this cost. In addition, we are currently witnessing historically low interest rates, making the cost of capital low not only in Poland but worldwide, thus making for a good moment to invest in the nuclear power sector. Experience gained from EdF's construction of nuclear units at the Hinkley Point C power station in the UK shows that almost two-thirds of the value of construction contracts are being carried out by domestic companies. All these aspects, including the Polish State's involvement in the nuclear power plant construction, should be factored into in the project's financial model (financial plan) [9].

Another important issue related to the implementation of nuclear energy in Poland is international cooperation, including among the European Union (EU) Member States. The EU should promote the development of the nuclear industry in its Member States and include nuclear power in the European Green Deal and support programme, alongside renewable energy sources (RES), since without nuclear power it will be unable to meet its climate commitments. Among those to have pointed out this fact is the Prime Minister of Slovakia, who has called for setting up a European alliance of countries using nuclear energy in order to make it easier for the countries which do not yet have nuclear power plants to implement this technology. At present, nuclear power plants are operating in 13 EU Member States, allowing the European Union to achieve the world's largest share of zero-carbon nuclear electricity generation in its total production, namely 25.15% in 2018.

6. Summary

The analyses included in this opinion support the following conclusions:

1. Poland's commitments under the signed Paris Agreement (2015) and the decision of the European Council of October 2014, as well as the condition of generation sources in the Polish National Electric Power System (NEPS), especially of the centrally dispatched generation units (CDGUs), of which several dozen with a total capacity of about 10 GW will have to be decommissioned already in the coming years, pose a serious challenge to the Polish electric power sector in terms of the fuel and technological transformation of generation sources in the NEPS.
2. Technological transformation of generation sources in the NEPS needs to take into account the sustainable development criteria, the most important being to ensure the security of NEPS operation and environmental protection, including striving for climate neutrality. This forces the Polish electric power sector to face the challenge of starting to build a secure, zero-emission power system that should hinge on two pillars: nuclear power plants and power plants using renewable energy sources (RES), including onshore and offshore wind power plants and photovoltaic power plants.
3. A long-term strategy of sustainable development of the electric power system, leading to climate neutrality, in a country that lacks substantial economic hydropower resources that might enable it to construct high-capacity hydroelectric power plants in the power system to ensure its secure and stable operation, can only be based on a combination of RES and nuclear energy development. Without nuclear power, it will not be possible for Poland to achieve the goal of climate neutrality.

4. In recent years, modern Generation III+ pressurized water reactors (PWR), characterized by high safety and operational reliability, such as the AP 1000 (Westinghouse), EPR 1650 (EdF), VVER 1200 (Rosatom), Hualong One (CNNC) and APR 1400 (KHNP), have been launched and integrated into power systems in a number of countries. Thus, the beginning of nuclear power development in Poland will be at a time when the pressurized water reactor technology has reached its full design and operational maturity worldwide.
5. There are two important problems that need to be solved for Poland to embark upon the path of nuclear power development, namely societal acceptance and the economic effectiveness of the associated investment project. Both problems are solvable. A rational, evidence-based debate and development perspective for a particular region should convince the local community that nuclear power based on proven and safe technology is a good solution. Adoption of a financial model for the investment project in which the Polish State will be involved, in consortium with the supplier of reactors and basic power equipment, with guarantees of purchase of produced electricity, should enable – in the shortest time possible – the launch and timely completion of projects related to the nuclear power program in Poland, moving on to safe operation in a long-term horizon, with relatively low costs of electricity generation that remain almost constant over time.
6. The implementation of nuclear power in Poland would contribute to assuring the secure operation of the National Electric Power System, thus improving Poland's energy security, increase fuel diversification in the Polish electric power generation sector, stabilize production costs and thus electricity prices for consumers in the long term, and also significantly reduce CO_2 emissions and bring our country closer to achieving the goal of building a secure and zero-emission power system, and thus to achieving the Paris Agreement goal of climate neutrality.
7. The fuel and technological transformation of generation sources in the National Electric Power System will be a long-term process, spanning about 30 years. During this time, many sectors of the economy, including the hard coal and lignite mining industry, will be able to transform, availing to a large extent of the opportunities created by the development of zero-carbon generation technologies in the power industry.
8. Implementation of nuclear power in Poland will require more intensive training of specialists and the advancement of research work in this field.

Further reading:

[1] Directive 2005/89/UE of the European Parliament and Council of 18 January 2006 on concerning measures to safeguarded security of electricity supply and infrastructure investment. *Official Journal of the European Union*, 2006, L 33/1–L33/22.

[2] Directive 2012/27/UE of the European Parliament and Council of 25 October 2012 on energy efficiency. *Official Journal of the European Union*, 2012, L315/1–L315/56.

[3] *Informacja statystyczna o energii elektrycznej* [Statistical Information on Electricity], ARE S.A., 12, 2019, Warsaw, 2020.

[4] *Statystyka Elektroenergetyki Polskiej 2018* [Statistics of Polish Electric Power Sector], ARE S.A., Warsaw, 2019.

[5] *Statystyka Ciepłownictwa Polskiego 2018* [Statistics of Polish Thermal Power Sector], ARE S.A., Warszawa, 2019.

[6] *Nuclear Power Reactors in the World*, International Atomic Energy Agency, 2020 Edition.

[7] *Projekt Polityki energetycznej Polski do 2040 roku* [Draft "Energy Policy of Poland Until 2040"], Ministry of Energy, 2019.

[8] *Krajowy plan na rzecz energii i klimatu na lata 2021–2030* [National Energy and Climate Plan for 2021-2030], Ministry of State Assets, 2019.

[9] Program polskiej energetyki jądrowej [Polish Nuclear Energy Program]. *Monitor Polski* 2020, item 946.

[10] Zaporowski B., Zrównoważony rozwój źródeł energii elektrycznej [Sustainable Development of Electric Power Sources], *Polityka Energetyczna*, 19(3), 2016, 35-48.

[11] *Prognoza pokrycia zapotrzebowania szczytowego na moc w latach 2016-2035* [Forecast of Peak Power Demand Coverage in 2016-2035], PSE S.A., 2016, https://www.pse.pl/-/prognoza-pokrycia-zapotrzebowania-szczytowego-na-moc-w-latach-2016-2035. (accessed 10.07.2018).

The Chairman of the Committee
on Electrical Engineering
of the Polish Academy of Sciences:
Prof. Marian Łukaniszyn, ME, PhD, DSc

INDIFFERENCE

www.academia.pan.pl

ACADEMIA