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NUCLEAR POWER FOR POLAND

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NUCLEAR POWER FOR POLAND

Ministry of Climate
and Environment

Polskie Sieci
Elektroenergetyczne

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PREFACE BY MICHAŁ KURTYKA – MINISTER OF CLIMATE AND ENVIRONMENT

Electricity consumption and demand continue to increase worldwide. This makes further dynamic growth of the electricity sector inevitable. However, while contributing to its development, we must not forget about the climate, the environment, and our planet where we live together. The use of fossil fuels to generate electricity increases emissions of greenhouse gases and other harmful substances, which affects not only the overall climate but also local wildlife. In our efforts to ensure the best life for future generations, we must develop low- and zero-emission energy sources. Transition towards low-emission power generation is literally an urgent necessity: as the vast majority of electricity production in Poland is still based on coal-fired power plants that are approaching the end of their service lives, a new source of energy has to be found. If we want to act responsibly, but also to meet the objectives set in global and European climate policies, we must switch our economy and energy sector to clean sources of production based on two main pillars: renewable energy sources and zero-emission nuclear power.

As we implement the transition of our energy sector, we must also remember about energy security, whose fundamental part is to ensure constant, uninterrupted energy supplies to our homes, businesses, and public facilities. This means that as we shut down increasingly older coal-fired power plants, we must replace them with sources that are not only environmentally friendly, but also guarantee a constant supply of energy regardless of the time of day or weather.

Nuclear power plants produce clean energy all the time, regardless of weather conditions. Nuclear fuel is loaded into the reactor once every year and a half and can be stockpiled on site in quantities sufficient for over ten years. As recent experience in the energy sector shows, nuclear power plants are able to operate for up to 80 years. In addition, in relation to the volume of energy produced, these installations take up very little space and require little material, which makes their environmental footprint and, therefore, the scale of their impact on nature, small compared to other energy sources.

I read this report with great interest, and I thank the authors very much for making the effort to present so many issues related to nuclear energy in such a comprehensive manner. The report discusses both economic and social issues, as well as touches on the extremely important issues of safety and environmental impact. Knowledge of nuclear power is critical to understanding of the nature of this source of energy in the power system and to addressing the concerns associated with it. I believe that this publication will be an important contribution to the spread of this knowledge and to an increased public awareness of nuclear power.

I sincerely encourage you to read the report. I am sure it will be time well spent.

Minister of Climate and Environment

Michał Kurtyka

PREFACE BY PROF. SZYMON MALINOWSKI – ATMOSPHERE PHYSICIST AND POPULARIZER OF CLIMATE CHANGE KNOWLEDGE

I read with great interest the report of the Sobieski Institute (SI) on nuclear power in Poland which, to be more precise, is a report that justifies investments in large-scale professional nuclear power plants of the latest generation. I was a bit surprised by the request to write a short foreword for the Report. This is because I am not an expert on the power sector, the economics of energy production, or many other matters raised in the report. I am an expert in atmospheric physics and I understand climate mechanisms and some of the fundamentals of nuclear reactions, energy, and complex systems. Eventually I agreed to write a few words, because this gives me an opportunity to present the SI report not in the context of political, social, and economic conditions (which is discussed in the report itself), but in the context of the growing threat of global warming and loss of biodiversity.

Let me begin by quoting the most important scientific findings as summarized in the most recent Reports of the Intergovernmental Panel on Climate Change, particularly the ***2018 IPCC Special Report on limiting global warming by 1.5 °C***, with additional brief summaries of many important conclusions:

Human activities are estimated to have caused approximately 1.0 °C of global warming above pre-industrial levels... Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate.

Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts.

Climate-related risks for natural and human systems are higher for global warming of 1.5 °C than at present, but lower than at 2 °C. These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options.

Any increase in warming above 1.5°c is projected to cause ***an increase in the negative effects of warming disproportionate to the temperature increase***. As far as the possibility to adapt to climate change is concerned, the IPCC Report states that:

Limits to adaptive capacity exist at 1.5°C of global warming, become more pronounced at higher levels of warming and vary by sector, with site-specific implications for vulnerable regions, ecosystems and human health.

What can we do to stay within the limits of adaptability? I am not going to present my own consideration; on this point, the IPCC Report cited above gives a clear answer:

Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the pre-industrial period, that is, staying within a total carbon budget.

Pathways limiting global warming to 1.5 °C (...) would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems. These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options.

Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition.

Nuclear power increases its share in most 1.5°C pathways, but in some pathways both the absolute capacity and share of power from nuclear generators decrease. There are large differences in nuclear power between models and across pathways. One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways.

Which part of is scientific report is important to us and to our country? Poland's power industry is characterized by one of the highest emissions in Europe and in the world. We must make a quick, determined, and consistent effort to decarbonize the energy sector and the whole economy. What is needed is decarbonization, i.e. stopping burning carbon contained in fossil fuels (hard and lignite coal, oil and petrol based fuels, and natural gas) as well as carbon contained in biomass. The latter is critically important in light of the recent report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on the threat of biodiversity loss.

What resources for rapid decarbonization do we have? We must keep in mind that our social and economic activities involve the use of resources available in nature to perform useful work. This requires access to energy sources. We must very quickly, within the next 30 years, stop using carbon-based energy sources altogether and replace them with others. We should also ensure that we get as much useful work as possible from a unit of energy extracted from these sources. In practice, this means that we need to switch as soon as possible, in every aspect of energy production and use, to zero-emission sources (ones that do not burn any carbon in any form), while making a huge effort to be energy efficient, since energy wastage has an adverse effect on biodiversity and the climate.

This is the context in which the SI report should be read. It concerns nuclear power, which is a very important zero-emission (strictly speaking, low-emission) energy source, and the legitimacy of its development in Polish conditions. In my opinion, this is a very strong voice in support for development of nuclear power in Poland. Is this a perfect report? No, it has its shortcomings, both substantive and non-substantive. As for the latter, it is not a government report prepared by a diverse group of the best experts our country can has. Substantively, it focuses solely on nuclear energy and not on the entire energy mix or, more broadly, the necessary complex of mitigating measures that our country must take in the near future, and in fact should have taken some time ago. I highly recommend all interested parties to read this report and to draw conclusions. These conclusions should be up-to-date, realistic, and based on existing tools and possibilities, because decisions on energy and economic transition are already too late in relation to the challenges and needs. They need to be made taking into account the most important principles of risk management, including the possible both good and bad scenarios.

RECOMMENDATIONS

The recommendations presented below are the result of considerations of the issues raised in the report. They include insights, conclusions, and key information on nuclear power.

1 Nuclear power is a proven zero-emission energy source that should be implemented in Poland.

In Poland, it is necessary to make a decision on the construction of new generation capacities based on technologies that guarantee safety and reliability of energy supplies. Nuclear power uses mature and proven technologies that enable decarbonization of the electricity sector without the need to make revolutionary changes in the way it operates. The large-scale light-water reactor (LWR) designs (conventionally referred to as Generation III) offered today are an evolutionary development of solutions that have been in use for many years, which makes them refined and reliable. Although there are numerous proposals for different solutions in the market, in terms of both the mode of operation (e.g. high-temperature reactor (HTR)) and the power (small modular reactor (SMR)), these technologies are not ready for implementation on a significant scale in commercial power generation at present, which does not allow the energy transition plans currently under development to be based on them.

2 Nuclear power uses safe technologies

The operating experience gained since the 1950s proves that nuclear power is one of the safest ways to generate electricity. Further safety improvements continue to be a priority for development of nuclear technologies and this is reflected in the current designs on offer. Industry transparency and international oversight play an important role in ensuring continued safety of nuclear power plants. In addition, the nuclear industry provides full oversight of the waste generated at all stages of power plants' life and fuel cycle (including uranium mining and processing), which is a unique approach compared to other industries. In addition, due to the small volume of nuclear fuel (which, among other things, makes it possible to store supplies for several years in advance) and flexibility in the choice of the source of supply, nuclear power has a positive impact on the country's energy security, among other things.

3 Nuclear power is essential for Poland to achieve climate neutrality

Poland should work towards achieving climate neutrality and adapting to the ongoing regulatory changes and environmental requirements.

The participation of nuclear power in the energy transition guarantees a lower cost of transition to a zero-emission energy system and ensures a rapid increase of stable and zero-emission capacity in the system, thus ensuring its effective and deep decarbonization. Continued use and dynamic development of nuclear energy are necessary in order to meet the climate neutrality targets.

4 Nuclear power has a positive impact on the economy

It can be estimated that implementation of a project of construction and operation of nuclear power plants in Poland with the total capacity of 6 to 9 GWe will create tens of thousands of jobs, directly and indirectly, depending on the pace and the final scope of the Polish Nuclear Power Program (PNPP). Additional jobs created by the emergence of a new industry and increased consumer spending could double those numbers. Research indicates that regions attractive for tourists in which a NPP is located can reap additional benefits from its presence in their territory. By implementing a nuclear power program, Poland would have a chance to stimulate its economy and make it resilient in the event of future economic crises similar to the one that has occurred in connection with the C0VID-19 pandemic.

5 Nuclear power plants supply cheap electricity

Basing the transition of the Polish power sector on nuclear power plants, which are the cheapest energy sources, should be a priority for the government, and decisions on investments should be made immediately. Each year of delay causes measurable and significant economic losses, leads to gradual disappearance of industry and jobs, increases the risk of a socio-economic crisis, and weakens the country's defense capabilities. The reason for this state of affairs are the rapidly rising energy costs for industrial consumers and the progressive loss of competitiveness of Polish companies in EU and global markets. The business model for Polish nuclear power plants must be well thought-out, comprehensive, acceptable, and socially just, as it will determine Poland's development for the next 100 years.

6 There is a stable high social support for nuclear power in Poland

There is a stable high support for nuclear energy in Poland, both on the national level and locally. Polish public opinion remains sensitive to arguments related to economy, safety, and energy independence, as well as to the argument related to the prestige resulting from development of the nuclear power sector. The experience of other countries shows that consistent implementation of nuclear programs by the government makes public support even stronger. In the case of Poland, this means a need to make decisions quickly and to pursue target consistently. At the same time, extensive communication activities will be needed to provide reliable information on the benefits of nuclear power.

7 Polish industry has experience with nuclear projects and will benefit from development of nuclear power in Poland

It is also necessary to start activities related to construction of technical facilities for the new industry as soon as possible. In Poland, there are about 70 companies that have competencies and newly acquired experience in construction of nuclear facilities abroad, and several hundred more Polish companies are in a position to acquire such competencies in a short time once the Polish Nuclear Power Program (PNPP) is launched.

8 The business model for the Polish nuclear power should take into account the interests of both investors and energy consumers.

The government should develop a new business model for nuclear power that meets all of the following criteria:

- investment certainty (stability) and attractiveness for investors;
- guarantee of take-up of the electricity produced;
- guarantee of a fixed selling price for the electricity produced;
- ensuring low energy costs for consumers and certainty of supply;
- compliance with EU legislation and strategies, and the highest possible degree of resistance to possible obstructionist actions by the EC;
- ease and speed of implementation;
- comprehensiveness and reproducibility - applicability to the entire PNPP;
- minimized burden on the state budget and public finances;
- flexibility; and
- social acceptability.

The adopted model should also help rebuild the Polish economy after the crisis caused by the COVID-19 pandemic. It should support reindustrialization of the country and development of Polish companies, and should use Polish capital as much as possible, so as to avoid excessive increases in foreign debt and deepening of the trade deficit.

1 INTRODUCTION

Poland's decarbonization and energy transition is a challenge for the coming decades that will require a change of approach in many aspects: planning, organization of businesses, providing funds for the project and, most importantly, a coherent and sustainable strategy aimed at building a modern, competitive, and climate-neutral economy. Development of the nuclear power industry in synergy with RES is the only viable pathway to achieve climate neutrality quickly and efficiently. A half of the member states of the European Union (including Poland) use, or intend to develop, nuclear power as a part of a faster and more efficient decarbonization program. In early October 2020, Poland's Council of Ministers adopted a resolution on the update of the Polish Nuclear Power Program. The objective of the program is to build and commission nuclear power plants with the total installed capacity between 6 and approx. 9 GW. This Report, divided into 6 parts, reflects individual aspects of implementation and operation of the nuclear power sector, including with reference to the conditions prevailing in Poland.

The report contains references to the debate on whether nuclear energy should be treated in the same way as "dirty" technologies or whether it is a source of clean energy with a much lower environmental impact. Misunderstanding of nuclear power, including the concerns related to it, stems from the complexity of the issues, which simultaneously raise many issues: technical, economic, political, social, environmental, and others.

2 MODERN NUCLEAR POWER

Paweł Gajda, Adam Rajewski

Nuclear power is the newest of the technologies that are currently used in commercial power generation[1]. In general, nuclear power plants replicate the concept of conventional thermal power plants, except that instead of burning a fuel (a chemical reaction), the heat is generated by nuclear fission. Thus, from a functional perspective, nuclear power plants are very similar to conventional power plants and their adoption on a larger scale does not require major changes in the way the power system operates.

All nuclear power reactor designs commercially available today have been developed through incremental, evolutionary improvements to reactors built and still in operation since the 1950s. The main areas of improvement have been to extend design life, improve fuel efficiency, increase flexibility of operation, and continually improve safety. Modern power reactor designs are referred to as Generation III[2], as opposed to generation II which are the units commonly operated today and built in the 1970s and 1980s. There are no strict criteria for this division and the terms have more of a marketing nature, as they emphasize the greater technical sophistication of the new designs which operate according to the same general principle.

2.1. The technologies available in the market

At present, the market for new nuclear installations is dominated by the pressurized water reactor (PWR) technology. This technology was originally developed in the 1950s by Westinghouse in the USA and later transferred to many other countries (France, South Korea, Japan, and West Germany), which gained the ability to develop their own designs independently. Similar designs were developed in parallel in the Soviet Union. There is currently a number of suppliers of modern reactors of this class that are capable of supplying their products to third countries. These include CNNC/CGN (China, Hualong 1 reactor), Framatome (France, EPR reactor), KEPCO (South Korea, APR1400 reactor), Rosatom (Russia, VVER-1200 and -1300 reactors), and Westinghouse (USA, AP1000 reactor).

[1] Despite the fairly widespread belief that some solutions are newer or more modern, in reality they are all based on processes and equipment that were invented and developed earlier, although in some cases they became disseminated in later years.

[2] Generation III+ is used for reactors with particularly extensive safety systems.

The designs on offer are evolutionary developments of earlier technologies and are highly technically mature and very safe; of the aforementioned reactors, only VVER-1300 and Hualong 1 have not yet been commissioned (although the first units are under construction). **All the aforementioned reactors are designed for high-capacity nuclear power units of the 1,000-1,700 MWe class. It is this design class that was indicated in the PNPP as the one that was selected for the nuclear power system in Poland.**

For many years, competition for pressurized water reactor technology came from the Boiling Water Reactor (BWR), which was developed in parallel with the PWR technology by General Electric in the USA. That technology has also been transferred to other countries, with designs developed and built later by companies in Japan, Sweden, and West Germany. At present, they are offered in the market practically only by consortia of General Electric and Hitachi[3] (ABWR and ESBWR reactors). BWR can be considered as mature as the pressurized water reactor technology, but due to a combination of adverse circumstances (disappearance of the nuclear industry in Sweden and Germany and suspension of projects in Japan, the USA, the UK, and Taiwan, where these designs have been used or planned), nuclear plants using this technology have not been built for many years. As with the PWR technology, the BWRs that are commercially available are designed for large, 1500 MWe-class power units.

In addition to the PWR and BWR technologies indicated above, there are a number of other technical solutions for nuclear power plants. Currently or recently built reactors include heavy water reactors (in India), liquid metal cooled fast reactors (Russia and India) and high-temperature reactors (China). However, none of these technologies is currently offered for export and the latter two should still be considered experimental. Therefore, it is not possible to base the strategy of transition of the commercial power sector in a country like Poland on such designs.

Small modular reactors (SMR) are a separate category that has received considerable media attention in recent years. These are designs intended for relatively small nuclear units with the capacity of 50-300 MW_e, potentially in larger groups (clusters). The term SMR in itself does not specify a reactor type, but most designs being developed by potential vendors represent the PWR technology. To date, however, no such plant has been commissioned and there are only two prototypes under construction: the Argentinean CAREM25 and the Chinese HTR-PM (which is also a high-temperature reactor), both of which are well behind schedule. None of these designs is currently offered for export and is the final configuration. However, several other designs, notably the American NuScale, developed by a company with the same name, are the object of intensive marketing efforts. To date, however, no investor has made a firm commitment to build such a reactor and the only project at an advanced preparation stage, the Carbon Free Power Project in Idaho, USA (the *NuScale* reactor), has already experienced numerous schedule delays and cost increases.

[3] Depending on the market and the project, acting as a GE-Hitachi or Hitachi-GE consortium

In October 2020, it was reported that a government grant had been awarded for this installation, but a final investment decision has not yet been made. In this situation, it is not possible to determine precisely when it will actually be possible to build the first installations of this class. In addition, their low unit capacity means that to achieve a significant effect in a country like Poland, a large number (tens or hundreds) of small-scale reactors would have to be built, which in the case of prototype designs with an unknown construction time makes it impossible to develop a realistic schedule for large-scale deployment. Therefore, the SMR technology cannot be considered today as a solution on which decarbonization of the national power sector could be based in the coming decades. This concept could be an interesting addition to large reactors in the future, so it is worth keeping an eye on its development.

2.2. Nuclear power plant safety

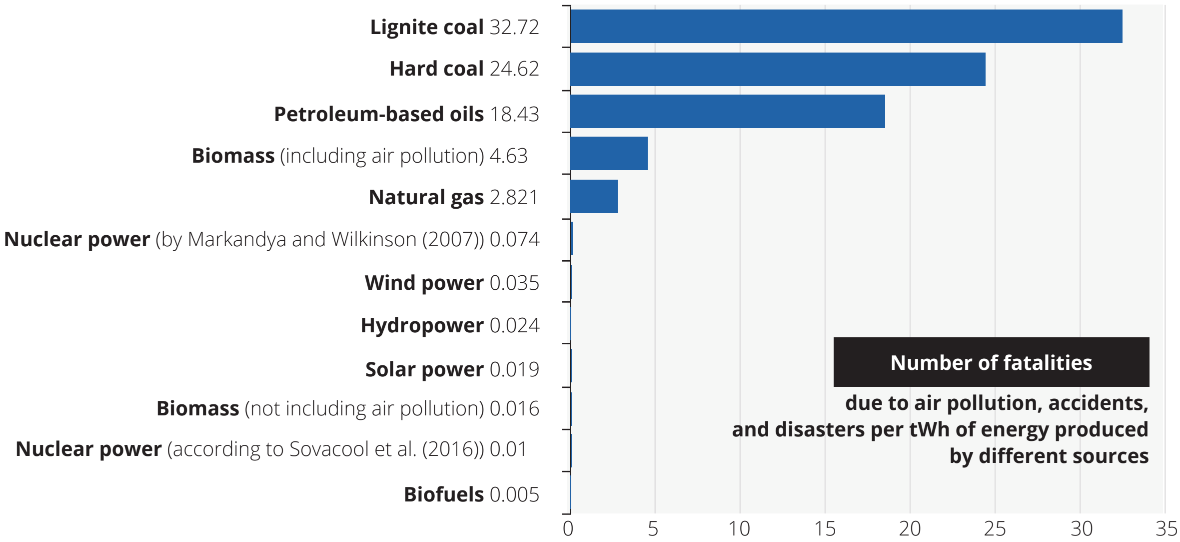
The most important safety functions that a nuclear power plant must provide are:

- control of the fission reaction;
- ensuring adequate cooling of the core; and
- separation of radioactive substances from the environment.

The first of these functions is accomplished by using control devices (control rods) capable of stopping fission reactions and by designing the reactor so that in emergency situations the power of the reaction does not increase but decreases. In this respect, all LWR (PWR and BWR) reactors are safe because of the laws of physics that govern their operation. Any significant disruption to the reactor's cooling process leads to its automatic shutdown, making it physically impossible for an event like the Chernobyl disaster to occur.

The need to ensure reactor cooling after shutdown is due to the phenomenon of decay heat heat, i.e. the decay of short-lived heat-generating isotopes in the fuel. This phenomenon diminishes with time, but requires dissipation of heat from the core even for several dozen hours after the reactor is shut down. For this reason, additional cooling systems are installed in reactors, ones equipped with independent power sources or so-called passive systems that do not require power supply and are based on natural physical phenomena, such as convection. Adequate design of such systems is a safeguard against accidents such as the one that occurred in Fukushima where passive systems sufficient to cool down reactors that were scrammed were not available and the power source for the active systems was not properly protected against external factors (flooding).

FIG. 1. **A COMPARISON OF THE NUMBER OF FATALITIES PER UNIT OF ENERGY PRODUCED FROM DIFFERENT SOURCES**



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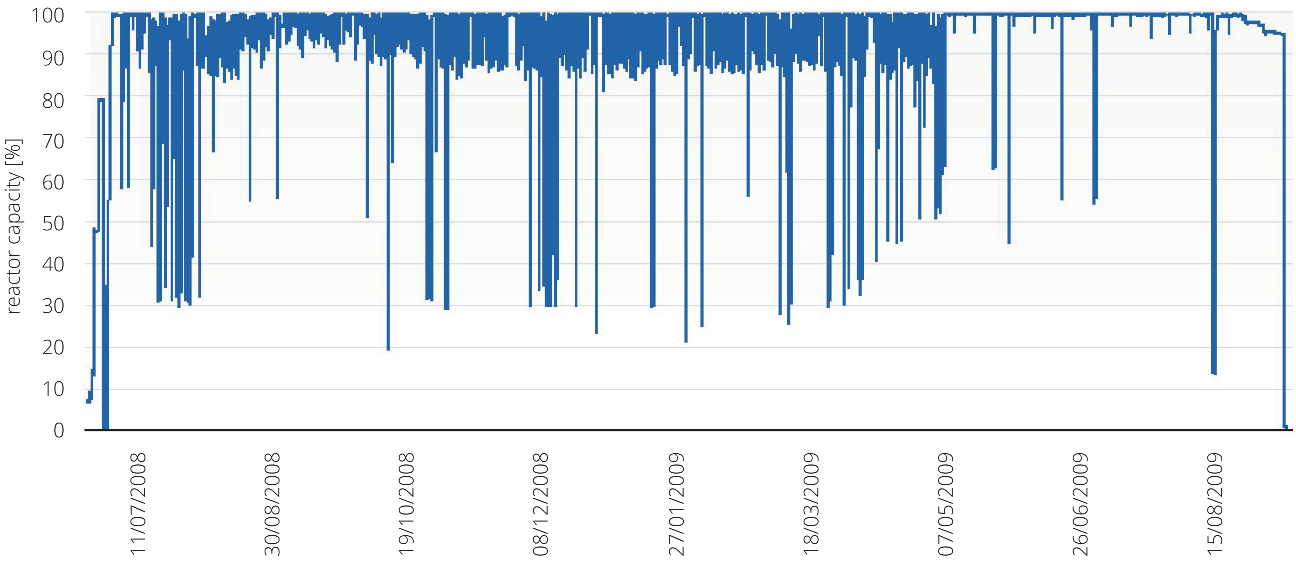
In a nuclear reactor, all fission products remain inside the nuclear fuel (they are sealed in cladding and removed from the reactor at the next fuel campaign). In normal conditions, the fission products do not enter the reactor coolant (e.g. water), although the coolant itself is activated by neutrons. Therefore, the coolant is incomparably less of a radiological hazard than spent fuel. The coolant is carefully separated from the environment thanks to the tightness of the circuit. This separation is complemented by appropriate plant design that ensures the presence of suitably impenetrable barriers between any radioactive substances (that can withstand damage from accidents, natural disasters, and deliberate human actions) and areas accessible to people, and by monitoring of any potential release. In the design of safety-related elements, the principle of redundancy is applied, so that if one of them fails, its function can be taken over by another, identical system, as well as the principle of in-depth protection, where if one layer of protection fails, the next one starts to work.

In the design of modern nuclear reactors, safety is paramount. When comparing older units with newer ones, one can see a trend towards increased redundancy of safety systems, greater use of passive emergency cooling systems, and use of components such as passive hydrogen recovery systems and core catchers.

This reduces the risk of serious events, such as fuel meltdowns or significant radioactive releases, by two orders of magnitude compared with older reactors (1). It should be stressed that historical data clearly shows that nuclear power is one of the safest energy sources. The ratio of fatalities to the energy produced is (2) similar to renewable energy sources such as wind power and photovoltaics (3).

FIG. 2. **AN EXAMPLE OF POWER OUTPUT PATTERN DURING A FUEL CAMPAIGN OF A NUCLEAR POWER UNIT OPERATED BY EDF** (4)



2.3. Operation of a nuclear power plant in the energy system

Nuclear power plants are generally operated as part of electric power systems to cover base load, which is the portion of the system's electricity demand that remains relatively constant. This involves months of continuous operation at near nominal power. However, technology allows nuclear power plants to operate in a wide range of loads: a nuclear power unit is able to provide ancillary services to the national transmission system, e.g. in terms of primary and secondary system frequency control , and thus can participate in the process of current system balancing. This is all the more important because many other zero-emission energy sources do not have this capability. Nuclear power plants are sometimes operating at capacity factors[4] above 90%[5], and sometimes, considered annually, above 100% (which is possible because, on the one hand, in certain ambient conditions the power output can exceed the rated output and, on the other hand, because of the increasingly common adoption of 18-month fuel campaigns that allow more than a year of uninterrupted operation)[6].

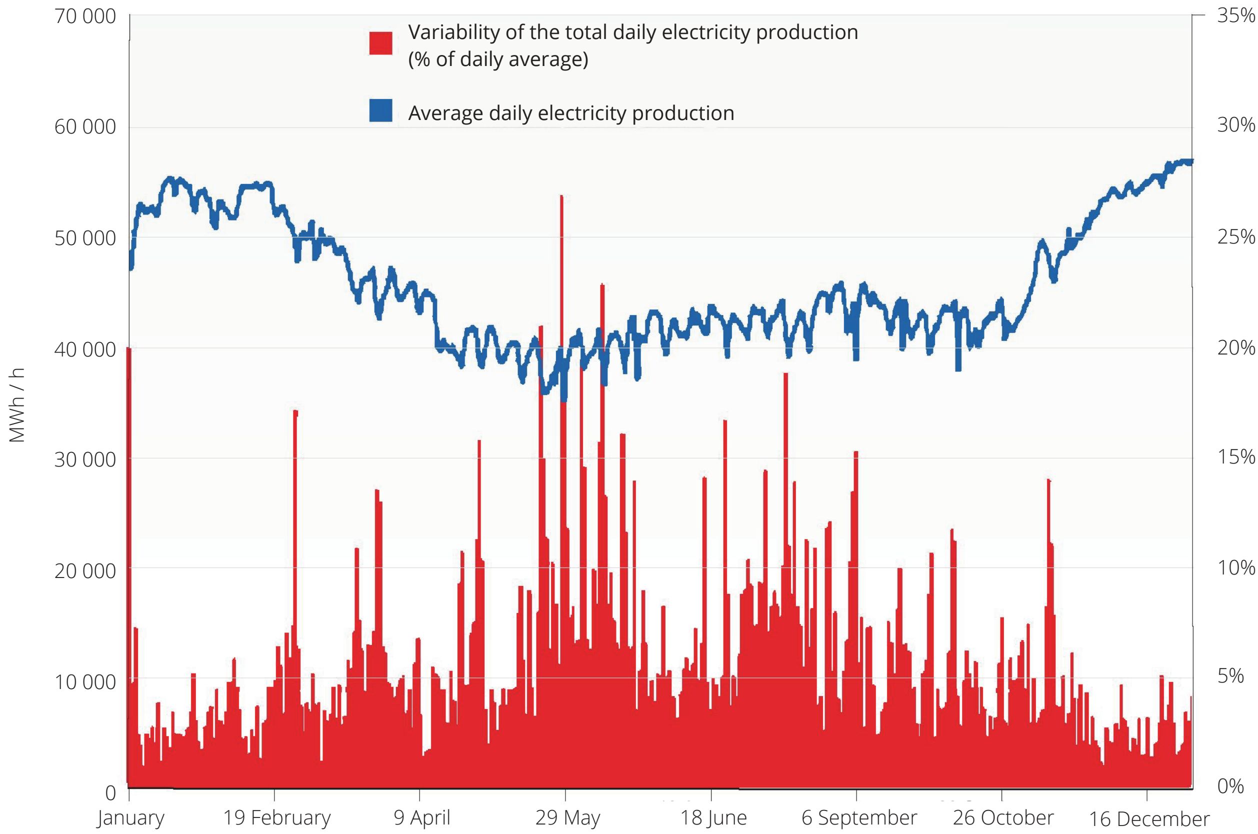
In systems with a high share of nuclear power or with collaboration with other sources that are unable to reduce their output at any time, nuclear plants are forced to operate flexibly. This is done, for example, in France where nuclear power accounts for about 70% of electricity generation and, as a result, nuclear units often operate at part load. A typical operating profile is shown in Fig. 2, while Fig. 3 shows the variation in total daily electricity production at French nuclear units for the whole of 2010.

[4] This is the ratio of the actual energy production to the theoretical production that would be obtained if the unit operated all year round at its rated capacity.

[5] The cumulative installed power utilization factor of the Finnish Olkiluoto-1 unit from 1978-2019 is 92.5%. For the sister Olkiluoto-2 unit, it is 93.0% (1980-2019) and for the German Neckarwestheim-2 unit (1989-2019) it is 91.5%. (87)

[6] This situation happens in units in the USA that do not participate in the regulation of the power system and has been registered, for example, at the Vermont Yankee (in 2006), Braidwood-1 (2014), Braidwood-2 (2019), Browns Ferry-1 (2017, 2019), Palo Verde-1 (2009, 2015), and Palo Verde-3 (2002) units. (87)

FIG. 3. **AVERAGE DAILY NUCLEAR GENERATION AND DAILY VARIATION OF NUCLEAR GENERATION IN FRANCE IN 2010** (5)



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Also in Germany, at a time when the share of nuclear power was higher than today, temporary capacity reduction of nuclear units was practiced. Fig. 4 shows an example of such a situation on a selected day.

Modern nuclear power plant designs are suitable for regulating operation, sometimes over a very wide range; e.g. the French units with N4 reactors (four units built in the 1990s) have a special operation mode that allows periods of operation at loads of 30% or lower (Figure 5). It is therefore completely possible to adjust the power generated by nuclear power plants to current needs. However, it may be more sensible to store surplus energy produced or to use it for zero-emission production of synthetic fuels, which are then used in various sectors of the economy. This would require development of suitable technologies for storage and production of synthetic fuels. It should be noted that stable zero-emission generation capacity, such as the capacity provided by nuclear power, significantly reduces the need for energy storage compared to systems based on variable renewable sources (6).

FIG. 4. **CHANGES IN THE VARIABILITY OF THE CAPACITY OF SELECTED GERMAN NUCLEAR POWER PLANTS IN A 24-HOUR PERIOD** (4)

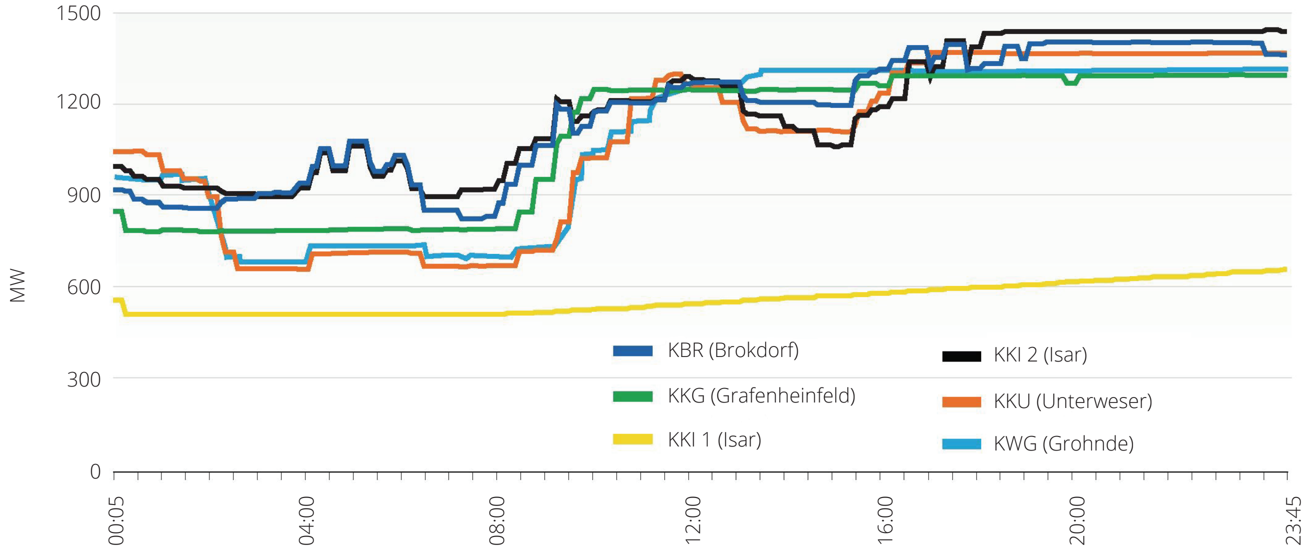

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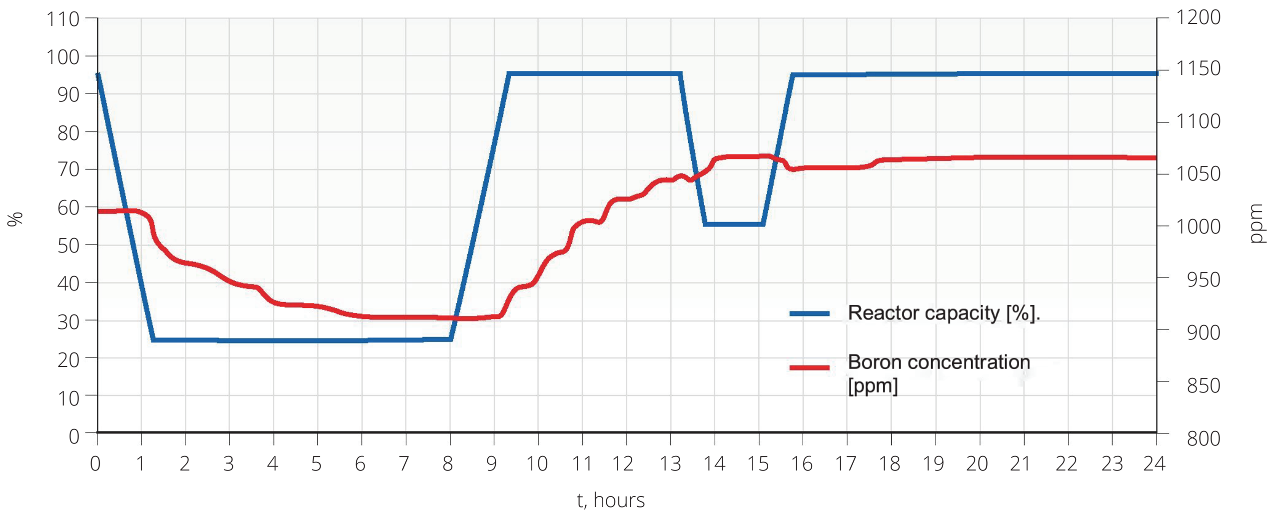
FIG. 5. **AN EXAMPLE OF LOAD-FOLLOWING OPERATION OF A FRENCH N4-TYPE REACTOR** (6)



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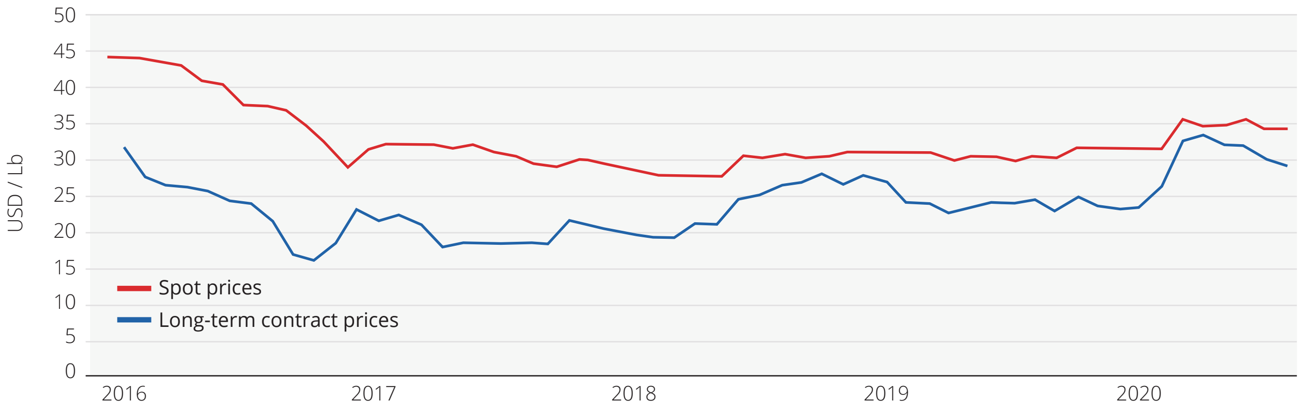
In 2019, the average capacity utilization factor of nuclear units worldwide was 76.2% (including Japanese units that have not been operating for years; if these were not included, the value would be around 80%, which is in line with levels recorded globally before the Fukushima accident).

FIG. 6. **URANIUM SPOT PRICES AND LONG-TERM CONTRACT PRICES** (8)



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2.4. Fuel procurement

A typical LWR reactor contains about 100-150 metric tons of uranium fuel during its operation. The fuel is in the form of uranium fuel tablets placed in fuel rods made of zirconium alloy, which in turn are assembled into fuel cartridge and are delivered in this form to the power plant[7]. Fuel is usually changed every 12 or 18 months, although in newer reactors this cycle is extended even up to 24 months. During the shutdown, when the reactor is out of operation, some of the fuel assemblies are replaced with new ones (about 30 tons of fuel/ year) and the remaining ones are repositioned. **Fresh fuel does not require special storage conditions, which makes it possible to easily to stock up fuel for as long as several years at the plant site, thus making such a facility independent of temporary disturbances in the energy commodity markets and increasing the energy security of the country that uses the nuclear technology** (more information on this can be found in Chapter 10).

The basic raw material for fuel production is uranium ore. Although uranium is quite abundant in nature, it is not economically reasonable to extract it from deposits with low uranium content. In 2017, the identified conventional resources with mining costs of up to $130/kgU were 6.142 million metric tons and those with costs of up to $260/kgU were 7.989 million tons (7). With demand remaining at the current level of approximately 60,000 metric tons per annum, these resources will last for approximately 130 years. It should be noted, however, that the resources in both of these categories have increased compared to 2015 by 7.4% and 4.5%, respectively, and the category of up to $130/kgU has seen an increase of 12.3% since 2007 (7). This is due to the fact that new uranium resources are discovered faster than they are extracted. Therefore, rapid depletion of conventional uranium deposits is not a concern. In addition, uranium prices in the global market are characterized by high stability, which is due, among other things, to the high competitiveness of the market (Fig. 6). This is also influenced by the existence of the International Atomic Energy Agency (IAEA) Low Enriched Uranium (LEU) Bank, which provides a reserve for countries affiliated to the International Atomic Energy Agency.

Procedures to facilitate purchase by member states of nuclear fuel and materials also exist in the EU. These mechanisms (resulting from the Euratom Treaty) are a solidarity measure and ensure the ability to purchase nuclear materials even in situations of potential reduced supply in the market for all actors in the EU.

[7] For example, the core of the AP1000 reactor contains 157 fuel cartridges and the core of the EPR reactor contains 241 fuel cartridges, each containing 264 (AP1000) or 265 (EPR) rods in a 17x17 arrangement and guides for the control rods.

It is also possible to obtain uranium from so-called unconventional sources, e.g. sea water. These methods, despite being successfully tested on a laboratory scale, are not yet economically viable. To operate a nuclear power plant, it is not the uranium itself that is needed, but the finished fuel, the production of which includes processing and enrichment of uranium and fabrication of the fuel elements themselves. The largest nuclear fuel suppliers are currently Framatome, Westinghouse, TVEL, and Global Nuclear Fuel. It should be emphasized that different suppliers have the capacity to produce fuel for different types of reactors and, as a result, the nuclear plant operator has the ability to change the contractors during operation.

2.5. Waste disposal

Nuclear power plants, like all other power installations, have an impact on the environment (more information on this issue can be found in Chapter 8) and generate waste in the course of their operation. In this case, some waste has special radioactive properties and can be divided into two general categories:

- spent nuclear fuel and
- other substances activated by neutron radiation and materials with surface contaminated by radioactive substances.

Spent fuel requires special handling. The nuclear fuel used in a nuclear reactor contains a number of highly radioactive substances with different half-lives. These are, on the one hand, the products of fission of uranium and plutonium isotopes and, on the other, isotopes created by neutron radiation, including the so-called transuranics. Both of these groups undergo natural, gradual radioactive decay accompanied by ionizing radiation emissions that are initially very intense and potentially pose a very high hazard to human health and life in the event of direct exposure. The intensity of radiation decreases over time as radioactive isotopes decay. Eventually, the activity of spent fuel reaches values typical of fresh, naturally occurring uranium ore, but this is a long process that takes several hundred thousand years. One can conclude that the fuel will not pose a significant risk earlier, but there is no doubt that long-term safeguarding of spent fuel is essential: 10 years after use, the dose rate at the surface of the fuel exceeds 100 Sv/h, which, when compared with the dose lethal to humans for a single exposure of approx. 5 Sv, clearly indicates the absolute necessity to isolate such material. In principle, such isolation is very simple — the spent fuel is surrounded by a barrier with adequate resistance to external factors and low permeability to radiation.

During the first period after unloading from a reactor, spent fuel emits significant amounts of heat in addition to radiation. This is the result of the process of radioactive decay of short lived isotopes. During this period, spent fuel is stored in special pools located at the site of nuclear power plants. The pools are filled with water, whose several meters thick layer provides sufficient shielding from radiation to allow the staff to work safely at the edge of the pool and to ensure dissipation of the heat generated by the spent fuel. After several or more years of storage in the pool, the fuel is reloaded into dry, airtight casks with sufficiently thick walls.

Such spent fuel casks, stored in temporary centralized storage facilities or at the power plant itself, pose no risk to the environment. However, this is a temporary solution; it can be used successfully for many decades, but ultimately the radioactive waste should go to a final repository, either directly or through a spent fuel reprocessing plant. The current consensus is that the final repository for high-level nuclear waste — whole fuel or isolated fractions thereof — should be a deep geological repository. In such a repository, nuclear waste is protected against corrosion and embedded in concrete. The large depth and the location away from aquifers are intended to provide protection against the ingress of water into the repository and to ensure that, in the unlikely event of moisture penetration, the time of possible transport of isotopes towards the surface will be long enough for them not to pose a hazard to humans and nature. In addition, it is worth noting that due to the different half-lives of the stored isotopes, after about 500 years most of the activity is concentrated in isotopes that are much less susceptible to potentially escaping from the repository, thus providing an additional safeguard (9).

Although the method of construction of final repositories is clear in principle, so far most countries that operate nuclear power plants have not even begun construction of such facilities, and no repository has yet become operational[8]. Finland's Onkalo repository is the closest to completion and is expected to be commissioned in 2023. The main reason is procrastination of political decision-makers in this regard, which is paradoxically facilitated by the unproblematic storage of spent fuel in interim facilities and the small quantities of this fuel. At the end of 2013, the high-level radioactive waste stored worldwide had a total volume of 22,000 m^3. This value[9] includes not only spent fuel but also waste from research and military installations, as well as 4,000 m^3 of waste from the Chernobyl disaster[10] (10). It is worth noting that the volume of high-level waste can be reduced several times by reprocessing spent fuel. This process makes it possible to recover fissile isotopes (uranium-235 and plutonium-239) for reuse, as well as to separate long-lived and high-level components. Although few countries (e.g. France and Russia) currently routinely perform this process for civilian nuclear fuel, the technology is fully mature. It is expected that between 29% and 44% of the fuel used to date will be reprocessed (in some countries this has yet to be decided) (10). Recycling of spent fuel is environmentally beneficial and compliant with the principles of sustainable development, and reduces the amount of waste stored in deep repositories and the duration of its storage.

[8] A deep geological repository for selected long-lived waste from US weapons programs, the Waste Isolation Pilot Plant in New Mexico, has been in operation since 1999.

[9] The volume of 22,000 m^3 corresponds to the volume of lignite extracted in Poland in 1.13 hours or the volume of crude oil extracted in that country in about a week. If this waste were placed on the a typical soccer field, the thickness of the layer would be about 3 meters.

[10] The same as above (note 9)

Although spent fuel is by far the most difficult waste to store, quantitatively it represents a tiny fraction of the total waste generated by nuclear power plants. The lion's share of the waste consists of neutron-activated materials, including structural elements of the installation itself and various types of materials (e.g. tools) that come into contact with radioactive substances and may be contaminated by them . For the most part, these are low-level, short-lived wastes that pose no significant threat to the environment. They must be handled in the same way as radioactive waste from other areas of human activity (industrial, research, and medical) by storing until their activity is reduced or by incineration in controlled conditions, depending on the type of material and activity, or by depositing in special sealed containers for further placement in a low- and intermediate-level waste repository (this issue is also discussed in Chapter 8). The largest amount of such waste is generated during dismantling of a nuclear power plant. Different approaches are used depending on the priorities of the country or the operator. If priority is given to the speed of dismantling, it is necessary to carry out the dismantling of the plant under radiation monitoring and to store certain dismantled components (e.g. made of steel). Another approach is to postpone the actual dismantling of the nuclear part of the installation until a significant proportion of the materials no longer qualify as radioactive waste due to the natural decay of radioactive isotopes, as this is simpler and less costly. Unlike high-level waste, the other types of nuclear waste have fully implemented storage and disposal systems. As of the end of December 2013, the total amount of radioactive waste generated worldwide from all human activities (medical, industrial, nuclear power plants, etc.) was estimated to be about 35 million m^3, of which 28.5 million m^3 had already undergone final disposal. About a half of it was related to decommissioning of nuclear (not only power) facilities. The total volume of waste from the European Union's existing nuclear power plants over their lifetime (i.e. including further planned operation and dismantling) is estimated at about 7 million m^3[11].

Waste handling costs are factored into the cost of electricity production at nuclear power plants (more information on this is presented in Chapter 6). This is usually done by setting up a special fund to cover the costs of dismantling of the plant and disposing of the waste, to which the plant operators pay a percentage of their revenue. **The nuclear power sector is therefore a unique industry that provides effective oversight of the waste generated throughout the lifecycle of the plant.**

[11] This corresponds to the volume of lignite mined in Poland in 15 days.

3 THE ECONOMIC ASPECTS OF NUCLEAR POWER

Łukasz Sawicki (3.1-3.2)
Anna Przybyszewska (3.3)

3.1. The importance of the cost of electricity to the economy

Electricity is a commodity of strategic importance that is even greater than that of oil. Unlike liquid fuels, it cannot be stored in larger quantities. Lack of supply of electricity over a large area means almost immediate and catastrophic consequences (in the case of liquid fuels, the consequences are spread over time and initially less severe). What matters is not only the ability to supply electricity to consumers, but also the costs, which affect all areas of life:

- living standards in households - use of household appliances, water supply and sewage drainage, use of heating and air conditioning equipment;
- food prices - plant and animal production, food storage in warehouses, cold stores, and refrigerators;
- prices of non-food essentials (e.g. cleaning and hygiene products) supplied by the energy-intensive chemical industry;
- prices of industrial products (e.g. steel, cement, and plastics) and final products (e.g. vehicles, electronics, and buildings).

All products and services, as well as tangible and intangible goods, are created with more or less electricity.

Lack of electricity or its limited supply (so-called brown-outs is one of the most important elements that determine economic and social development. But no less important is the cost of electricity. Low cost of electricity enables low-cost production, development of businesses, and their competition in the domestic and foreign markets, especially in energy-intensive industries, and also an increase in the purchasing power of households, which further drives demand and/or capital accumulation (increase in savings). If the electricity cost increases, it causes an increase in the costs of functioning of the entire economy and impoverishment of the society (including the so-called energy poverty), and gradually leads to deindustrialization of the country (disappearance of industry). This entails the flight of capital, i.e. investors and most of the actors in the financial sector, reduced activity in the services sector, and a gradual decline in economic activity. This leads to a decrease in government revenue. The result is further negative economic and social phenomena, such as increased emigration of the working-age population, social crises, reduction of social transfers (reduction of pension benefits and payments from social programs).

This is vicious cycle of a socio-economic crisis that is hard to stop. This threat has already begun to materialize in the form of clearly and rapidly rising electricity costs for businesses, especially the heavy industry, which is currently operating on the verge of profitability or has already crossed it, and in the medium to long term may not be able to withstand competition from industry of other EU countries (e.g. Czech Republic, Hungary, France, Romania, Finland) and non-EU countries that base their economies on low energy costs (mainly nuclear energy: Ukraine, partly Russia, and soon Belarus and Turkey). In 2016, businesses that operate in energy-intensive industries in Poland supported a total of 1.3 million jobs (11) (12) (13), which accounted for almost 10% of employment in the Polish economy. Jobs in other sectors, such as finance and services, are also linked to the industry. Some plants make products for the military. Some steel mills and foundries have already been closed (e.g. those located in Konin and Stalowa Wola) and others have announced that they would close in the nearest future (e.g. the steel mill and foundry in Kraków).

Given the above, **changing the Polish energy model towards basing it on the cheapest energy mix, of which nuclear power plants are an important part, should be a priority for the government and investment decisions should be made immediately. Each year of delay causes measurable and significant economic losses, increases the risk of a socio-economic crisis, and weakens the country's defense capabilities.**

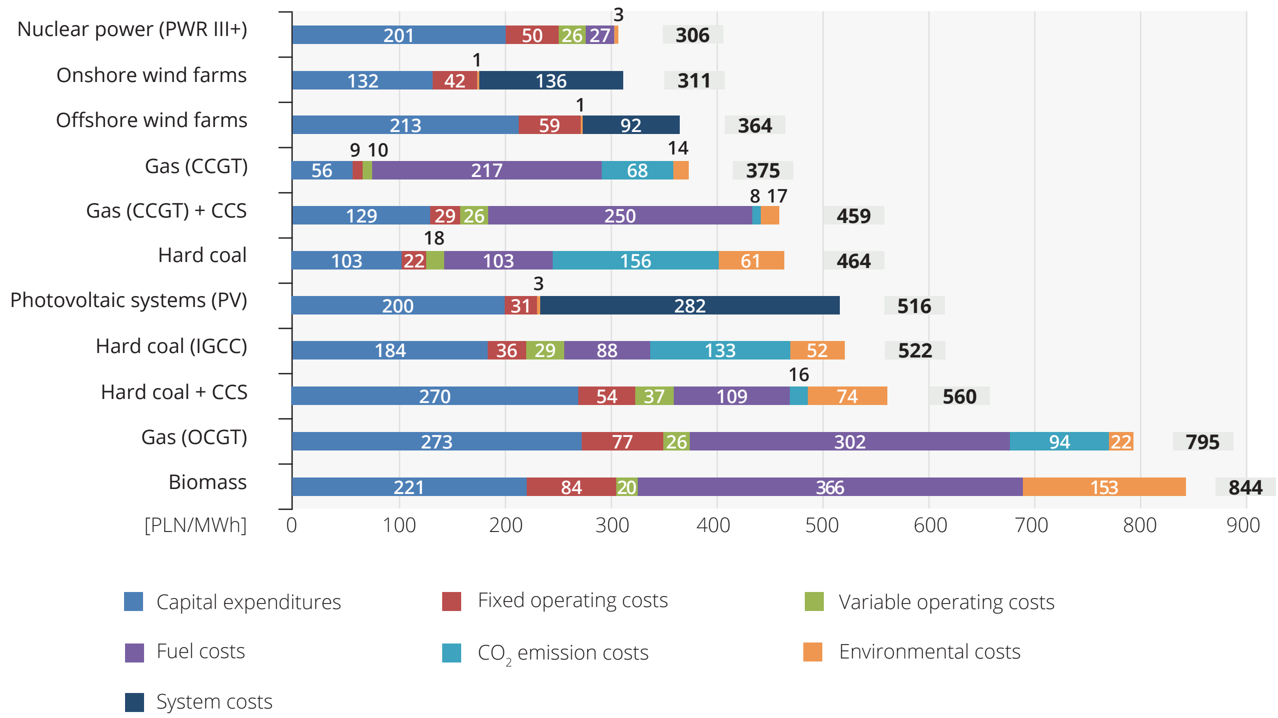
3.2. The full cost of electricity sources - comparison

There are at least a dozen methods for comparing the cost of electricity production from different sources from a country's standpoint. Until 10-20 years ago, a very popular method was the so-called Levelized Cost of Electricity (LCOE), which calculated the averaged unit cost of electricity production spread over the lifetime of a given type of power plant. The LCOE method reflected the reality of that period quite well, when the share of unstable RES in power systems was small. It is now being abandoned worldwide because it does not calculate the total cost of supplying energy to consumers and thus produces results that do not reflect the real situation and are often in gross contradiction to it. Methods that partially take into account the full cost for the consumer have been used for several years among others by the International Energy Agency of the (IEA/OECD) and the US Department of Energy (US DoE).

In 2020, a comparative analysis of the full cost of electricity production by different sources was performed for the government (14). The study was carried out using a total cost methodology that allows for inclusion of additional costs associated with electricity production that are not considered in standard power project evaluations (i.e. the LCOE methodology), i.e. the so-called external costs, which comprise:

- system costs: power reserve, grid expansion and maintenance, and balancing;
- environmental costs: health and the ecosystem; and
- macroeconomic costs: security, import-export balance, and employment.

FIG. 7. **A COMPARISON OF THE COSTS OF ELECTRICITY GENERATION IN DIFFERENT SOURCES - AN ANALYSIS BY BP AND PSE FOR THE MINISTRY OF CLIMATE** (14). **WACC 6%, RES SHARE 35%. THE TOTAL VALUES MAY DIFFER FROM THE SUM OF THE ELEMENTS DUE TO ROUNDING**



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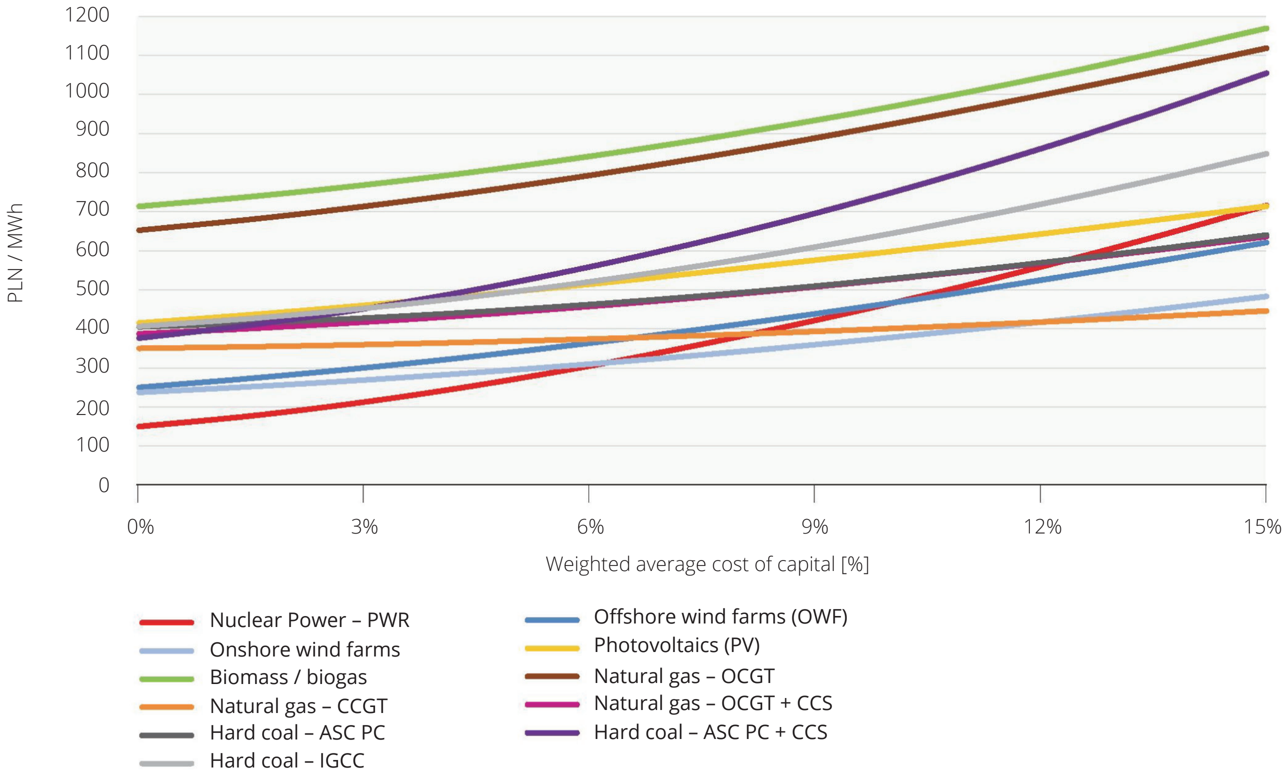
These costs are borne by electricity consumers, people, and the environment, but they are not priced by the so-called energy market, nor are they taken into account by investors when planning new generating units. When planning a long-term economic and social development, striving to ensure well-being of citizens and weighing the interests of all social groups, the state (government) should take into account the full costs associated with energy production and should not look only through the lens of short-term benefits for selected investors. Health and environmental costs are a growing challenge and can no longer be ignored in analyses.

The total cost methodology attributes external costs directly to their sources, aiming for a fair distribution of the costs between investors, end-users, and other actors in the energy market. It therefore shows what the true full costs of electricity production by individual generating sources are.

The model selects the optimal energy mix taking into account the full costs. The analysis contains 4 options (scenarios) of development of the energy mix in Poland until 2050, including two that assume a lack of governmental decision to build nuclear power plants. The purpose of such a selection of scenarios was to examine the impact of development of the nuclear power sector on the shape and cost of the energy mix. An analysis of the sensitivity of the total electricity production cost of individual technologies was also carried out. An investigation was conducted on how much the cost of electricity production is affected by changes in such factors as fuel costs, CO_2 emission allowance costs, cost of capital, capital expenditures, capacity factors, and extension of construction time.

FIG. 8. **THE AVERAGE TOTAL COST OF ELECTRICITY PRODUCTION (SOURCE: MINISTRY OF CLIMATE OF POLAND).**



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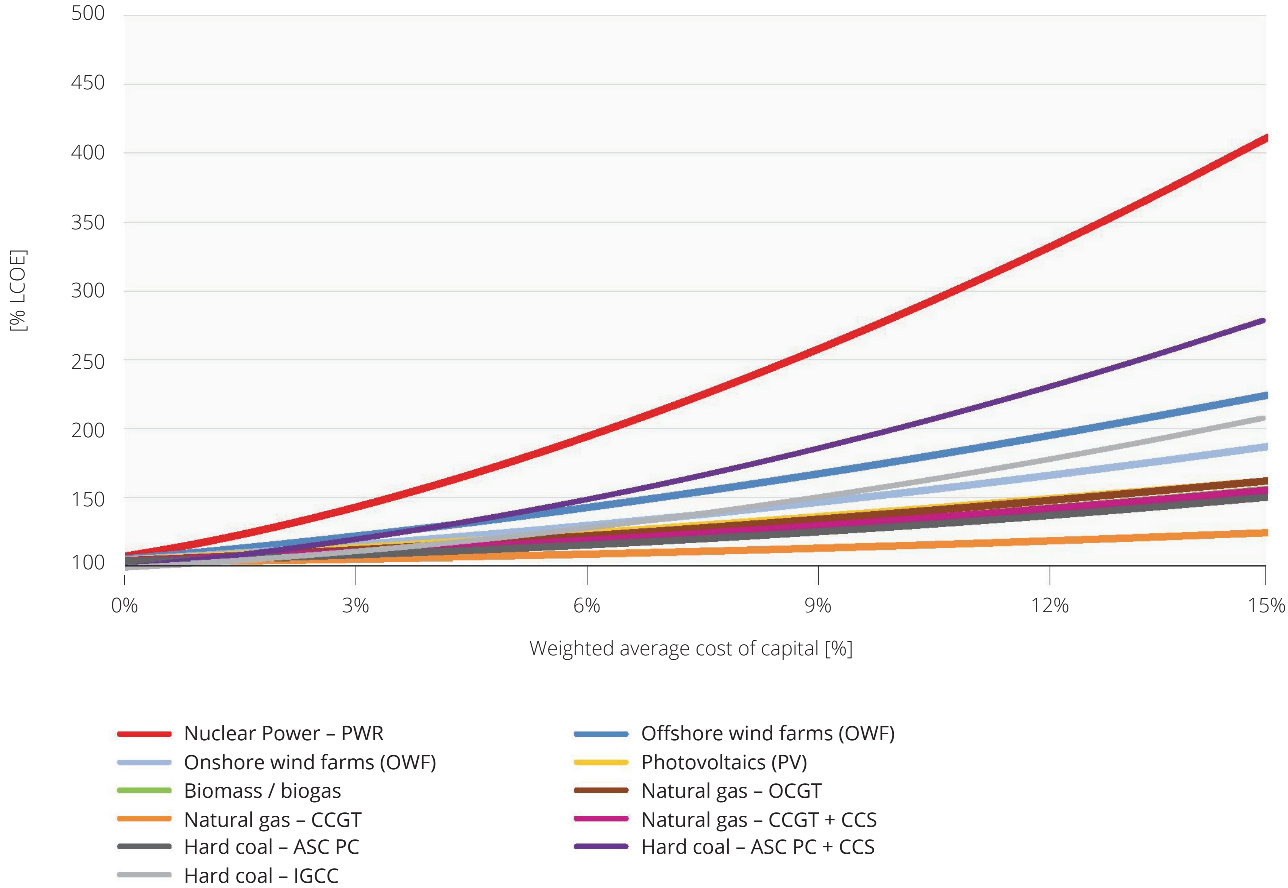
The study led to 5 key findings:

- according to the calculations of the total costs of electricity production, if appropriate development conditions are ensured, nuclear power plants are among the cheapest generating units in the perspective until 2050;
- in the perspective until 2045, the optimum nuclear capacity will be approx. 7.7 GWe net, which means a share of the nuclear power sector in the mix (generation) at the level of 27%; an extended perspective of the analysis indicates profitability of building a nuclear power capacity of approx. 10 GW net by 2050;
- nuclear power plants contribute to a reduction of the demand for natural gas in the electric power sector, thus minimizing the capital outflow related to the imports of this raw material;
- the system costs increase with an increase in the share of unstable (intermittent) RES sources in electricity production, thus significantly increasing the total cost of electricity production in the system; dispatchable sources, such as nuclear power plants, make it possible to limit these costs while ensuring operational security of the power system;
- the averaged total cost of electricity generation in 2020 amount to 352 PLN/MWh. In 2045, it will be the lowest in the scenario where electricity in nuclear power plants will be produced with free optimization (334 PLN/MWh) and the highest in the scenario without electricity produced in nuclear plants (358 PLN MWh). The extended time horizon of the model indicates a further decline in the total cost with continued development of nuclear power plants (317 PLN/MWh in 2050).

FIG. 9. **THE AVERAGE TOTAL COST OF ELECTRICITY PRODUCTION (SOURCE: MINISTRY OF CLIMATE OF POLAND).**



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The sensitivity analysis showed that the cost of capital is the factor with the strongest impact on the cost of electricity generation in nuclear power units.

In view of the above, one of the government's main tasks in implementing the **Polish Nuclear Power Program is to ensure the cheapest possible financing for nuclear power plant construction. It is the government that has the most influence on the credibility of the project, the efficiency of its implementation, and the guarantees for the investors (including offtake agreement for the electricity produced), which are the main elements that create the "risk premium" and determine the cost of capital**. In this context, the government's decision to have the State Treasury buy the PGE EJ1 company and assume full responsibility for the implementation of the investment project is right. One should keep in mind that the PGE Group is listed on the Warsaw Stock Exchange and, consequently, must appropriately value investment risk, which in the case of nuclear projects is higher than in the case of other electricity sources. It is possible to obtain low-cost financing, even by bypassing the rules of the EU taxonomy, which are disadvantageous for nuclear power, as it does not apply to non-EU entities (e.g. export credit agencies from Japan, Korea, USA, etc.). However, even if the EU taxonomy was to be taken into account, it is possible to obtain low-interest domestic funds from various sources. Nevertheless, cheap financing is only one of several key elements of the undertaking - more information on this issue can be found in Chapter 7.

3.3. The impact of nuclear power plants on the economy

The construction phase

Nuclear power has a positive and quantifiable impact on the economy as early as during the construction phase. As with other mega-projects, the construction, electrical machinery, chemicals, and financial services sectors benefit the most from nuclear power projects (15) (16) (17) (18) (19). This is confirmed e.g. by the case of South Korea, which is an outstanding example of successful development of the nuclear power sector from the stage of a technology recipient to successful exports of the country's own reactors (18) (20). The construction of a single nuclear unit (1,000 MWe) generates a total value of industrial output equal to EUR 3.67 billion in various industries. The participation of different sectors of the economy is the following: machinery manufacturing - 21%, financial services and insurance - 13%, construction - 12%, electronics - 11%, and business services - 11% (16). When this data is translated into Poland's conditions, the summary presented in Table 1 can be regarded as conservative. It can be assumed that the macroeconomic effects will be much greater, as Poland is planning to build 2 units in the same time horizon, each with the capacity of 1-1.5 GWe, and ultimately, according to the PNPP, to build facilities with the capacity of 6-9 GWe, which means a total of 4-8 power units, depending on the technology selected.

TABLE 1. **THE PRODUCTION VALUE AND THE ADDED VALUE IN SELECTED SECTORS OF SOUTH KOREA'S ECONOMY RESULTING FROM CONSTRUCTION (I.E. THE CONSTRUCTION PROCESS) OF ONE NUCLEAR POWER UNIT IN THE LAST YEAR OF ANALYSIS (2005) (EUR BILLION, 2019)** (16)

Sector	Production value	Added value
Production of metals	0.26	0.05
Manufacture of metal finished products	0.10	0.04
Manufacture of plant and machinery	0.77	0.24
Manufacture of electrical and electronic equipment	0.40	0.11
Power industry construction	0.44	0.16
Transport and warehousing	0.08	0.04
Financial services and insurance	0.49	0.35
Real estate services	0.06	0.05
Business services	0.42	0.24
Education and science	0.05	0.04
Other sectors	0.60	0.21
Total	**3.67**	**1.53**

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TABLE 2. **THE EMPLOYMENT RATIOS FOR PARTICULAR STAGES OF CONSTRUCTION OF A SINGLE 1,000 MWE LWR POWER UNIT AND THE ASSUMPTION OF 2,000 H/Y** (19)

Stage	Employment (person - years)	Average time
Construction	12,000	10 years
Operation	30,000	50 years
Dismantling	5,000	10 years
Nuclear waste management	3,000	40 years
TOTAL	**50,000**	
Indirect jobs (indirect jobs multiplier = 1) South Korea = 1.25 France = 0.912	50,000	

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Direct employment in the construction and operation of commercial nuclear power plants includes both permanent staff and subcontractors providing external services (security personnel, service technicians of various trades, cleaning staff, etc.). Indirect employment, on the other hand, includes personnel involved in the nuclear supply chain (indirect of the ith order) and the provision of products and services to that chain (indirect of the nth order). There are also the so-called induced jobs generated by the aforementioned personnel through increased consumer spending, which has a moderate positive impact on the food and beverage, cosmetics, telecommunications, hotel and restaurant, and transportation sectors. Most of these jobs are created in close proximity to the project. The estimates concerning the number of indirect and induced jobs are similar regardless of the country.

Based on the construction projects, it is assumed that the 4 Westinghouse AP1000 reactors under construction in the United States would require a total of 22,550 full-time workers at the construction site per year (2,000 h/year). The average number of direct jobs in any year during the 10 years of construction is about 1,025 per 1,000 MWe (net) (19).

TABLE 3. **THE IMPACT OF A NUCLEAR POWER PLANT PROJECT IN THE USA ON THE CREATION OF JOBS IN THE SUPPLY CHAIN DURING THE CONSTRUCTION OF THE POWER PLANT (INDIRECT IMPACT)** (3)

Area of the project	Multiplier
Construction of the NPP	0.33
Manufacture of major equipment	1.37

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It is estimated that the demand for employees only at the stage of construction of the first two units, based on the assumptions of the PNPP, amounts to 1-1.2 thousand jobs, while during the peak of the works the demand increases even up to 2.5-3 thousand direct jobs. However, the total number will be higher, as different skilled workers are needed at different stages of the construction and erection works. In addition, for every 100 workers employed at the construction site, 33 jobs will be created in the supply chain for the project itself, plus an additional 137 jobs related to manufacturing of equipment for both the nuclear part and the conventional part.

It can be assumed that Polish companies will participate in this part of the supply chain on a level of 50-70% in the first phase of the implementation of the PNPP (17). Consequently, it can be assumed that this will result, after adjustment, in a multiplier of 0.68-0.96 for these industrial jobs. Ultimately, 5-6.8 thousand direct and indirect jobs can be expected from the construction of 1 GWe capacity.

At this point it is worth referring to the Polish experience. The construction of the Żarnowiec NPP and the Warta NPP were expected to generate an average of 2.5-2.9 jobs per 1 MWe built (18). While technological progress and the automation of work since the 1980s have reduced the involvement of manual workers, they have increased the involvement of white collar workers. These ratios may therefore be lower for the first two power units built in Poland, while staying in the range indicated above for the employment during construction of the first two units.

TABLE 4. **JOB CREATION - PWR REACTORS IN THE USA** (19)

Sector of the industry according to the North American Industry Classification System	Costs: NPP employment – direct [USD thousands]	Costs: NPP employment – other [USD thousands]	Employment in the industry in relation to employment at the NPP [divided by 1,000]	Annual wages in the sector [USD]	Direct employment	Indirect employment – 1st order	Direct and indirect employment
Heavy and civil engineering construction NAICS 237	45,188	208,598	0.375%	56,915	794	782	1,576
Specialty trade contractors NAICS 238	290,469	205,413	0.601%	44,856	6,476	1,235	7,711
Metal production NAICS 33	18,679	40,431	0.146%	59,203	316	59	374
Fabricated metal product manufacturing NAICS 3321	97,203	491,036	0.408%	48,758	1,994	2,006	3,999
Machinery manufacturing NAICS 333	127,332	645,959	0.262%	56,743	2,244	1,695	3,939
Computer and electronic product manufacturing NAICS 334	53,562	97,944	0.273%	73,431	729	268	997

Sector of the industry according to the North American Industry Classification System	Costs: NPP employment – direct [USD thousands]	Costs: NPP employment – other [USD thousands]	Employment in the industry in relation to employment at the NPP [divided by 1,000]	Annual wages in the sector [USD]	Direct employment	Indirect employment – 1st order	Direct and indirect employment
Finance and insurance NAICS 52	0	149,261	0.166%	86,668	0	248	248
Professional, scientific and technical services	0	727,253	0.554%	70,871	0	4,030	4,030
Employment	853,302			61,405	13,896	10,577	24,473
Employment/ MWe					12.1	9.2	21.3
Multiplier: (first-order indirect employment)/ direct employment						0.761	

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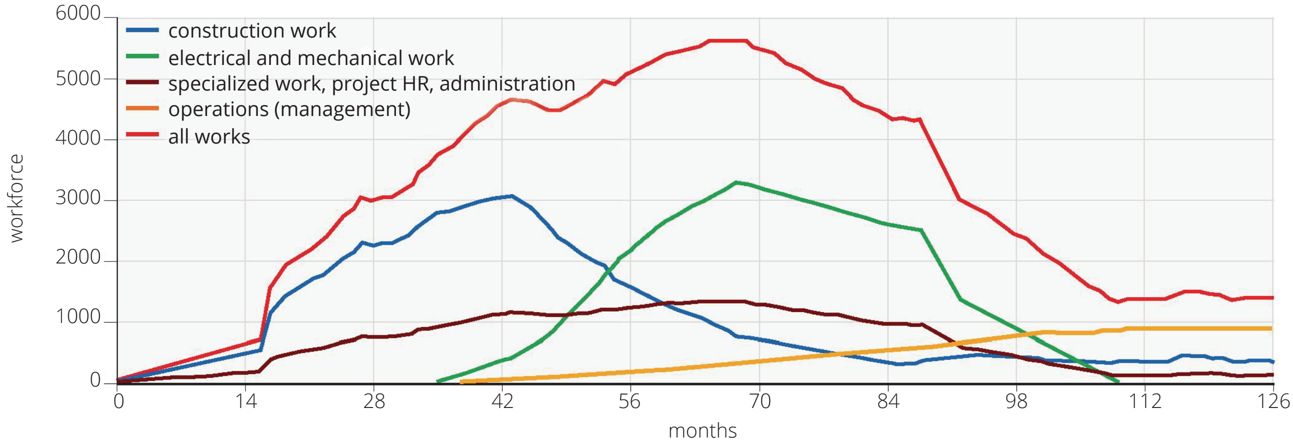
This regularity has been confirmed by analyses carried out as a part of the UK nuclear program (21), where the closest to the Polish program is the 10 GWe capacity option and the participation of domestic industry at an overall level of 44% for the first two units and 63% for subsequent units, which are realistic to achieve. It was estimated that about 33,000 jobs would be created during the construction phase.

TABLE 5. **THE IMPACT OF THE PROGRAM OF CONSTRUCTION OF 10 GW OF NUCLEAR POWER CAPACITY ON THE BRITISH ECONOMY IN 2012-2030** (21)

Type of impact	Value of production sold (EUR billion$_{2019}$)	Gross added value (EUR billion$_{2019}$)	Employment (person-years)
Direct	25.482	11.196	106,200
Indirect	20.076	9.009	121,400
Induced	14.156	7.207	104,900
Total	59.586	27.412	332,500

The scale of the forecast is confirmed by more recent analyses of the construction of the Hinkely Point C plant (3.2 GWe) in a 2018 UK government's report (22), where this project alone is expected to create about 25,000 jobs in the construction, civil engineering, electrical systems, project management, administrative and accounting services, retail, hospitality and catering, logistics, security services, and other sectors.

FIG. 10. **THE BASIC WORKFORCE SECTORS INVOLVED DURING THE NUCLEAR PROJECT (22)**



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In Poland, there are about 70 companies that have competencies and newly acquired experience in construction of nuclear facilities abroad and several hundred more Polish companies are in a position to acquire such competencies in a short time once the Polish Nuclear Power Program (PNPP) is launched. Additionally, in some areas, despite the generally greater industrialization of the United Kingdom, our companies are more competent than British companies, e.g. we manufacture steam turbine components for NPPs.

Each worker directly employed in the construction of a nuclear power plant, through his or her increased consumer spending, will contribute to the creation of additional new jobs (84 per 100 workers) in the service industries in the region where the construction will take place.

TABLE 6. **THE MULTIPLIER EFFECTS OF EMPLOYMENT AT THE CONSTRUCTION SITE OF ONE NUCLEAR POWER UNIT AND AT PRODUCTION PLANTS, AND FOR THE ADDED VALUE - INDUCED AND TOTAL** (30)

Area of the project	Multiplier for induced impact		Multiplier for total impact (induced + indirect)	
	Employment	Added value	Employment	Added value
Construction	0.84	1.17	2.17	2.70
Manufacture of materials and equipment	1.79	1.23	4.15	3.45
Total (average)	1.36	1.20	3.27	3.11

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The implementation of other megaprojects in the energy sector in Poland in recent years confirms the scale of employment during the construction phase. Coal power units 5 and 6 at the Opole power plant (PGE), with the total capacity of 1,800 MWe, under construction between 2014 and 2019, required about 5,500 people (23) at the peak of the work, with Polish companies involved at 70%. A similar scale of engagement is required for the construction of the 910 MWe New Jaworzno coal-fired power plant (TAURON). In 2018, an average of 2,190 people worked there each day. The maximum number of people who worked on the site on a single day was as many as 3,030 (24).

Regardless of the technology and type of the project, foreign contractors prefer to hire local laborers and engineers, and select local companies as subcontractors due to lower labor and logistics costs. For construction and erection works that do not require specialized knowledge and experience related to the conventional (turbine) island, the vast majority of construction crews will be employees of Polish companies.

The operation stage

Regardless of the positive macroeconomic impact of nuclear power achieved by ensuring, with the right business model, stable and relatively low energy prices, operation of nuclear power plants as large industrial facilities also brings microeconomic benefits.

As is the case with the construction phase, the creation of new jobs during the operation period is also noticeable. Not only are jobs created that are directly related to provision of support and services for the nuclear power plant (fuel cycle, repairs and overhauls, consulting services, testing, data processing, insurance, etc.), but they are also induced through increased purchasing power at the local level and greater demand for goods and services related to everyday consumer spending.

In 2013, the commercial nuclear industry in the USA directly employed 62,170 people at power plants with 104 nuclear power units. Such a large sample was used to estimate the statistical employment according to unit size and job.

TABLE 7. **EMPLOYMENT AT NPPS IN THE USA DEPENDING ON THE NUMBER OF POWER UNITS** (25)

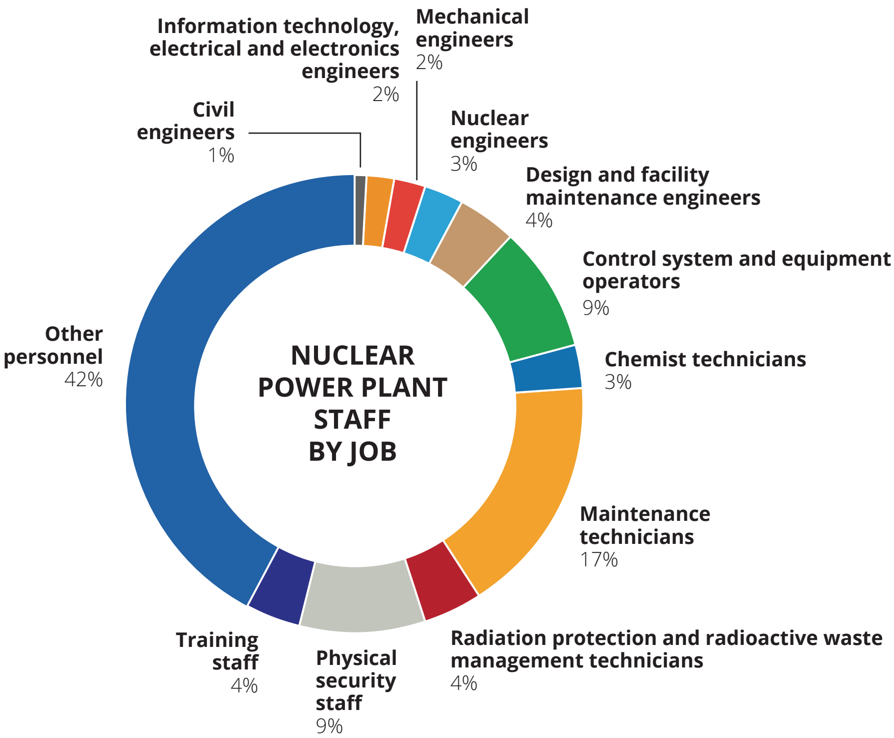
	1 power unit	2 power units	3 power units
	Employment [persons]		
Average	700	960	1,640
Minimum	460	640	1,130
Maximum	1,040	1,520	2,260

TABLE 8. **THE MULTIPLIER EFFECTS OF OPERATION OF ONE NUCLEAR POWER UNIT ACCORDING TO OXFORD ECONOMICS (AMERICAN CONDITIONS)** (34)

	Indirect	**Induced**	**Total**
Jobs	0.17	0.62	1.79
Added value	0.13	0.30	1.42

The power plant itself can employ personnel with a wide range of education backgrounds, not only strictly nuclear, since much of the equipment is similar in purpose to that used in conventional power plants or other large industrial plants.

FIG. 11. **THE DIVISION OF A NUCLEAR POWER PLANT CREW ACCORDING TO JOBS** (18)



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According to a 2011 publication by Oxford Economics (19), the operation of 6 nuclear power units, with the total capacity of 6,000 MWe, could generate about 3,200 direct jobs in the power plants themselves and further 23,000 jobs in the economy. All jobs in Polish nuclear power plants will eventually be filled by local staff. During the first few years of operation, a part of the operating crew may be duplicated with employees of the foreign technology supplier, whose task will be to train the Polish crew to work in the new environment and to get them acquainted with the specific characteristics of all equipment and facilities, which is a worldwide practice regardless of the type of technology used.

The above figures do not include jobs created by the power plant operator at the owner's premises, which are typical of power companies and corporate organizations - an additional 150-400 people.

Eventually, based on the above information, it can be estimated that operation of only the first two power units (2-3 GWe) will result in the employment of 0.9-1.2 thousand people per 1 GWe for operation and management of the power plant. In addition, approximately 0.15-0.21 thousand jobs per 1 GWe of installed capacity will be generated in the industry associated with providing adequate support for nuclear power plant operations (including waste handling). On the other hand, the induced impact can be estimated at another 0.5-0.8 thousand jobs. The estimates of the employment level are confirmed by the calculations performed for the Hinkley Point C project. During the operation phase, the plant will have a workforce of 900 persons, of whom about half can be recruited locally (26). The investor wants to increase the share of local workers by educating technicians at local schools, through a scholarship program, assigning about GBP 10 million to special education programs at local colleges combined with apprenticeships. The graduates will have the opportunity to find work at other nuclear power plants due to the insufficient supply of specialists to work in power plants in Europe, which is due, among other things, to the ageing of the European population and, consequently, of the workforce. **After the launch of the PNPP, Poland will also have the chance to cooperate internationally with the technology provider to train and prepare staff for future nuclear facilities. The educational process takes from several to over ten years and requires intensive targeted development of universities and research institutions, but also vocational schools, to satisfy the market's demand for skilled manual workers.**

Also at the level of the regional economy, the positive impact of such a large facility as a nuclear power plant will be clearly noticeable. For example, the richest commune in Poland is Kleszczów in the Łódzkie Province, which is home to two large industrial plants: a lignite coal mine and a lignite-fired power plant, which in 2013 paid the municipality a total of about PLN 200 million in taxes and local fees. Both Kleszczów and the second richest commune, Polkowice (where the main taxpayer is a copper mine owned by KGHM S.A.) use the tax revenue, among other things, to improve the standard of living of their residents.

The communes closest to the nuclear power plant, i.e. Krokowa and Gniewino, would benefit most from the construction of the NPP, with slightly smaller benefits for the town of Wejherowo and other surrounding communes. The scale of the revenues is large, but does not include direct subsidies to the local community from the investor. As a part of the development of Hinkley Point C, EDF committed GBP 20 million for local needs (social, economic, and environmental) (27). It should be assumed that **construction of nuclear power plants in Poland will have a clearly noticeable positive impact on the local economy, e.g. thanks to projects financed from taxes or directly by the investor**[1].

[1] In the case of wind and photovoltaic power projects, the tax revenues for communes are lower. The main part of the tax - the tax on building structures - is levied on the surface area in contact with the ground. For wind farms, it is mainly the surface of turbine foundations and transformer station buildings. In the case of ground-mounted solar PV farms, the tax is paid on the mounting systems, which account for a few percent of the farm's surface area (34). The investment project process itself, depending on the size of the PV and wind installations, takes 12 to 36 months, and the operation lasts for 25 years

TABLE 9. **THE ANNUAL TAX REVENUE FOR LOCAL GOVERNMENT UNITS (LGU) IN THE CONSTRUCTION AND OPERATION PHASES OF THE POSSIBLE NEW NUCLEAR POWER PLANT IN ŻARNOWIEC** (15)

LGU	Tax (amounts in PLN_{2015})				
	Property tax (including redistribution)	CIT (only from THE NPP)	PIT		Total tax revenue during THE operation phase of the NPP
			NPP construction phase	NPP operation phase	
Krokowa commune	192,350,450.00	17,261,452.45	8,922,312.00	1,784,462.40	211,396,364.85
Władysławowo municipality	38,470,090.00	–	4,639,602.24	927,920.45	39,398,010.45
Puck commune	38,470,090.00	–	4,282,709.76	856,541.95	39,326,631.95
Gniewino commune	38,470,090.00	–	8,922,312.00	1,784,462.40	40,254,552.40
Wejherowo commune	38,470,090.00	–	3,568,924.80	713,784.96	39,183,874.96
Town of Wejherowo	–	–	5,353,387.20	1,070,677.44	1,070,677.44
Choczewo commune	38,470,090.00	–	–	–	38,470,090.00
Puck district	–	3,601,495.30	4,649,400.00	929,880.00	4,531,375.30
Wejherowo district	–	–	4,649,400.00	929,880.00	929,880.00
Pomorskie Province	–	36,014,952.96	1,451,520.00	290,304.00	36,305,256.96
TOTAL					**450,866,714.31**

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(More information on the impact of the nuclear power plant on public perception and tourism is provided in Chapter 9.)

The impact on the industry

The Polish economy can benefit from the new industry and its interactions with those currently present in the country. This is particularly important in view of the retreat of heavy industry from Europe and especially the need to rebuild and strengthen an economy weakened by the COVID-19 pandemic.

At this point, it is worth pointing again to South Korea as a model example of development of the nuclear industry. At the time of construction of the first nuclear power plant, the country had a low level of industrialization and relied mainly on cheap labor - the participation of domestic companies in the construction of the first three units was small and consisted only in preparation of the site and construction work on ancillary facilities. With the gradual industrialization of the country and construction of subsequent nuclear units, the participation of Korean companies began to increase, but it still consisted mainly in construction work on the non-nuclear parts of the NPP - this is similar to the current level of Poland's preparations. The technology acquisition program has been successful, as high technological autonomy (95%) was achieved within 16 years of the completion of the first unit. The latest APR+ reactor (1,500 MWe), which is based on Combustion Engineering (now Westinghouse) reactors, is now based mostly on Korean technology. Korean engineers and scientists have been actively involved in the construction of the power plant from the beginning, thus gaining knowledge and experience. Today, the Korean nuclear industry comprises about 600 companies of different sizes, of which 250 specialize in production of materials and equipment for NPP operation and the remaining 350 are mainly involved in construction and erection work. The quality standards and requirements applicable to the nuclear industry started to be used also in other industries, which resulted in increased competitiveness of the whole national economy, mainly in metal production, shipbuilding, heavy industry, and machinery industry.

Implementation of the PNPP can have a positive impact on the Polish economy, which is still partly based on heavy industry. The indisputable advantages of the new branch of the economy will be the stabilization of others, since supply and service contracts in the nuclear industry are long-term contracts, which allows for sustainable development of companies in various industries. In addition, the high standards and the technology transfer will accelerate Poland's transformation into a modern country and will be a sign of stability and development potential for foreign investment not only in the energy sector.

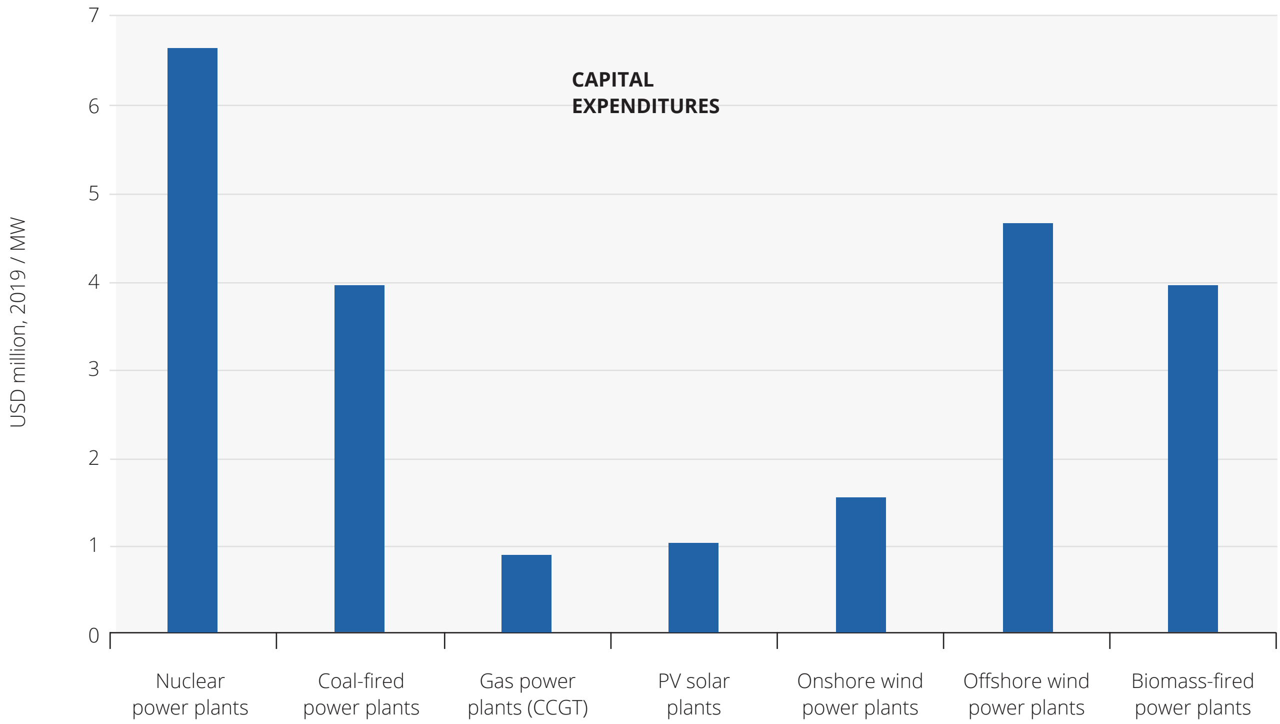
THE BUSINESS PERSPECTIVE OF THE PNPP 4

Łukasz Sawicki

4.1. Investment environment in Western countries

Nuclear power plants, like e.g. offshore wind farms, are characterized by relatively high capital expenditures, high fixed costs of operation and maintenance (O&M), high investment risk (long construction time, complicated administrative procedures, and risk of delays and increase of construction costs) and long return on investment.

FIG. 12. **THE AVERAGE CAPITAL EXPENDITURES (CAPEX) FOR VARIOUS ENERGY SOURCES IN MILLIONS USD FOR 2019 (AMERICAN CONDITIONS)** (28)



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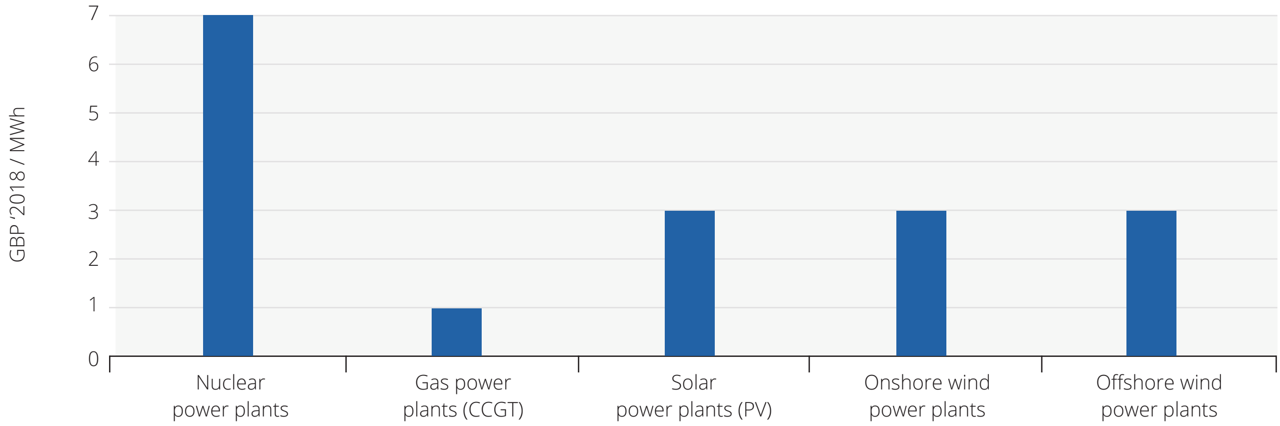
The project pre-development costs are also high. As a result of the above factors, all nuclear projects currently underway globally require more or less active participation of national governments, just as is the case with RES (state aid programs), natural gas and "future technologies" such as hydrogen.

FIG. 13. **A COMPARISON OF PROJECT PRE-DEVELOPMENT COSTS IN THE COST OF ELECTRICITY PRODUCTION FOR DIFFERENT TYPES OF POWER PLANTS. BRITISH CONDITIONS, PRICES IN GBP/MWh FOR 2018** (29)**,** (30)



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The success of historical nuclear programs of most Western European countries (France, Sweden, Germany, United Kingdom, Belgium, Spain, Italy, etc.) was the result of clear and stable energy policies and energy markets that provided incentives for investments in the energy sector. Today, the market conditions are not conducive to any investment without guarantees for investors, although the extent of these guarantees may be more or less explicit and broad. The EU countries that are implementing new investment projects in the nuclear sector have decided to create appropriate conditions for the implementation of such projects, each time obtaining the approval of the European Commission (on a case-by-case basis). However, each of these mechanisms is different and tailored to the conditions of a particular project, which means that **there is no universal and certain business formula for the PNPP at the moment, so the government should consider developing its own concept**, which is discussed in more detail in the next subchapter.

4.2. The business models for Polish nuclear power

The business model of nuclear power plants is one of the most important elements of a nuclear power project, as it determines not only its profitability, but also whether and to what extent its low production costs will translate into customers' bills. Although a poorly chosen model can result in low capital expenditures and low cost of capital, which may enable low energy production costs compared to other sources, but this will not reduce the electricity bills of companies and households, and may even increase them.

The latest version of the PNPP does not specify what the complete business model of the planned NPPs will be, although certain elements have been indicated, including a foreign co-investor who would buy up to 49% of the shares in the SPV. The nature of this investor - whether it will be an energy sector company, an investment fund, or another entity - has not been specified. Such a framing may be a good move, as it leaves the government with a lot of room for maneuver and strengthens its negotiating position. However, regardless of the type of investor, it is likely that the co-investor will require guarantees from the Polish state, especially an offtake agreement, in terms of both volume and price. Other elements of the target model will need to take this into account accordingly.

There are a number of business models in use globally for implementationof nuclear power projects. Most of them consist of several elements:

- participation of the state (to a greater or lesser extent), similarly to RES, coal, and gas power plant projects;
- a defined ownership structure of the project and sources of financing for capital expenditures;
- an offtake guarantee for the electricity produced; and
- a guarantee of a stable selling price for the electricity produced.

In the case of RES, the participation of the state consists in creating conditions for private investments and/or state-owned companies by establishing priority of energy offtake from RES (a dispatch priority) by the distribution system operator (DSO) and by energy trading companies, establishing fixed prices for sales of energy from RES (Feed-in-Tariff) or subsidies (Feed-in-Premium), as well as an obligation to purchase energy from RES. In the case of investments in gas- and coal-fired power plants, the government creates and guarantees capacity mechanisms, e.g. a capacity market, which serves mainly to cover the fixed costs incurred by generating units. In the case of nuclear power projects, the minimum state involvement is to ensure a stable and predictable long-term energy policy and a stable, transparent, and non-discriminatory legal framework for the development of the nuclear industry. Further tools for investment support are participation of state-owned companies, loan guarantees (including political guarantees and guarantees for export credits and insurance), followed by the guarantees for energy production in an NPP described above (offtake). The range of tools can be much wider.

As a rule, the greater the state's participation, the lower the investment risk and the lower the energy production costs, which should ultimately translate into benefits for citizens. However, this is not so obvious as it depends largely on the business model adopted. The low production costs of NPPs do not always translate into low energy bills - sometimes the investor makes excessive profits, which is also a problem in other industries. Such projects meet with public criticism and do not win support for nuclear energy. Therefore, **it is extremely important that the business models adopted for Polish NPPs take into account the interests of both investors and energy consumers**. As mentioned in subchapter 6.3, the government has an obligation to balance the interests of all groups of the society, particularly if the nuclear power projects are to be supported by taxpayers' money (e.g. in the form of loan guarantees). An additional requirement in the case of Poland **is the requirement for the planned models to comply with EU legislation** (directives on the energy market, competitiveness, and other relevant areas) and long-term policies, especially the policy towards the energy sector, since Polish NPPs will be in operation between 2033 and 2143 (even 100-year operation periods can be expected, given the recent experience of other countries, including the USA). Any forecasts for such a long period of time are very risky; nevertheless, no radical changes should be expected in the future in the EU's present directions for the development of the European energy sector.

Given the aforementioned provisional nature of the models used in recent years in the EU, their local specific characteristics, the lengthiness of the procedure for obtaining approval from the European Commission, the social controversies, as well as the non-prospective nature of most models (e.g. taking into account the direction of EU regulations), the government should develop a new model taking into account Polish and EU conditions. **Such a model must meet all of the following criteria**:

- investment certainty (stability) and attractiveness for investors;
- an offtake for the electricity produced;
- a guarantee of a stable selling price for the electricity produced;
- low energy costs for consumers and security of supply (a significant reduction of electricity bills compared to their current levels);
- compliance with EU legislation and strategies, and the highest possible degree of resistance to possible obstructionist actions by the EC;
- simple and fast implementation;
- comprehensiveness and replicability - possibility to apply to the entire PNPP and not only the first NPP or one power unit (this is very important for negotiations with technology suppliers);
- minimizing the burden on the state budget and public finances (this is important among others due to the economic crisis caused by the COVID-19 pandemic);
- flexibility; and
- social acceptability.

It would also be desirable for the model created to contribute to the reconstruction of the Polish economy after the crisis related to the COVID-19 pandemic and to provide real support for the reindustrialization of the country and the development of Polish companies. It seems reasonable to use Polish capital as much as possible and to avoid increasing the foreign debt and the trade deficit, although some of the capital expenditures will certainly have to be covered by imports of key equipment for the NPP.

The business model for Polish NPPs will be one of the most important economic decisions of the government made in the 2020s. It will have a major impact on most sectors of the Polish economy (more information on this issue can be found in chapter 6) and will determine their development over the next 100 years. If it is well designed, it will not only enable implementation of the largest industrial program in Poland after 1990, but it will also protect the country from the starting economic and social crisis and the loosing of a large number of jobs in Poland. Subsequently it will enable a fast economic growth and dealing with industrial competition (both in traditional sectors, such as metallurgy and cement plants, but also in new ones, such as robotics and IT) from other EU countries, as well as from countries outside the EU.

The government’s decision must be carefully considered and balanced, because its consequences will be much more serious than just the question of whether or not to build an NPP.

THE IMPACT OF NUCLEAR POWER PLANTS ON THE ENVIRONMENT

5

Wojciech Gałosz

5.1. General information on impacts.

Modern civilization is based on electricity and is more and more dependent on it: we have to supply electricity regardless of the weather or time of day.

Virtually every human undertaking has an impact on the environment: indirect, direct, and complex. Sometimes the impact is minimal and visible only in the long run and sometimes it is significant and visible immediately.

In the case of most projects, usually only the impact of the project itself is determined: when building a road, the impact of the road is discussed, not the impact of the bituminous mass production plants; when building a dam, the impact of cement production plants is not assessed; when building a coal-fired power plant, the plant itself is assessed in the environmental procedure, without considering the mine or the means of transport that deliver the coal.

Public discussion of nuclear power has taken a different turn. In this case, the impacts of the various stages of acquisition of the fuel, construction of the power plant itself, its operation, and waste handling are meticulously calculated and considered.

This is the right approach, but one should be aware that other electricity production methods should also be assessed in a similar way. For example, cement, polymers, copper, steel, and rare earths are used in production of wind turbines, in quantities greater than those used in a nuclear power plant for the same amount of electricity produced. The same is true for solar power plants.

5.2. The impact at the stages of extraction, processing, and enrichment.

In Poland uranium ore was mined in the 1950s. Relatively small quantities of ore were mined for the former Soviet Union. Today, the country, like the rest of Europe, no longer mines uranium ore as a primary mineral. The last European mine, located in the Czech Republic, was closed in 1917 (31).

Uranium for the energy sector is mined using three methods: open pit, deep pit, and borehole, also known as in-situ recovery (in-situ leaching).

For the first two methods, uranium mining is no different from mining other minerals. The main threats are emission of particulate matter that contains radioactive substances (mainly uranium compounds) and accompanying minerals containing e.g. heavy metals. Mine workers are most exposed to particulate, so personal protective equipment is used and in areas of high ore concentration, in extreme cases, mining is done with remotely controlled equipment. At these sites, gamma radiation and radon - a radioactive inert gas that is constantly released from the earth's interior but is found in significantly higher concentrations in deposits of uranium and other minerals (including phosphate, coal, and non-ferrous metal ores) - are also significant hazards to workers (32). Radon in various concentrations is also present in our environment. As it migrates from the interior of the earth, it appears, for example, in basements of buildings.

Various methods are used to prevent the spread of particulate matter outside the mine site. Routine monitoring of the air and of the surface contamination is carried out during mining operations in the surrounding area (33). The next stage involves crushing, grinding, and leaching the extracted uranium ore to obtain uraninite (a radioactive mineral from the oxide cluster, which is the main source of uranium and contains 86% U, radium, as well as many other elements) in enclosed spaces so as to keep particulate matter emission to a minimum.

In the case of the borehole method, the surface of the ground is preserved intact, while through the boreholes liquids are pumped into the deposit, such as hydrogen peroxide (i.e. the popular "oxidized water"), acids (e.g. sulfuric acid), or carbonates (sodium bicarbonate, ammonium carbonate, or dissolved carbon dioxide), which dissolve the uranium ore contained in the deposit. The solution is pumped out through another borehole and a concentrate is obtained for further processing. In this case, the principal hazard is not the injected chemical compounds (which are quickly bound by minerals contained in rocks) but a possible leakage or seepage of the solution containing leached uranium compounds into the groundwater. **With well-designed and executed projects of this type, there are virtually no significant releases of these substances.**

Although this is the dominant method of uranium ore extraction today, the reclamation of such mined deposits is difficult and, as a relatively young technology, it still poses some challenges. They are the result of exacting environmental standards, which of course are a positive phenomenon and are in line with the assumptions of ideal reclamation. Using the United States as an example: reclamation requires the water quality in the deposit to be the same as it was before mining began, which means that very high environmental standards are maintained and even small changes in the water quality in the deposit do not allow for the termination of the extraction process. One must be aware of the fact that these problems are not unique to uranium mining, but are typical of the entire mining sector, which besides coal, oil, and gas extraction, also supplies raw large amounts of materials for renewable energy sources (34).

It is also worth noting that some of the problems with old mines that have already been closed are due to the very low environmental standards and primitive technologies used at the time of their construction, operation, and closure (35). Discussions often portray uranium mining sites as completely contaminated and uninhabitable. In order to see what such areas can look like after several dozen years after the end of extraction, one can go for example to the Polish Sudetes. There are hiking trails in the tunnels left after uranium mining operations, healthy plants and animals live in their immediate vicinity, and the radiation levels in most cases do not differ from the background radiation (36).

5.3. The impact during the nuclear power plant operation stage

Nuclear power plants in normal operating modes do not increase ionizing radiation. Studies conducted over the years at various nuclear power plant sites around the world show that radiation levels do not exceed background radiation levels (37).

The basic impact of nuclear power plants is similar to other thermal power plants. In the case of open system operation - the operation of the plant affects the river or water reservoir from which it draws water. It is important to note that the water from the nuclear part (partially activated by processes taking place in the reactor) never mixes with the water used to generate steam to power the turbines or with river (or sea) water. Therefore, the primary impact of a water-cooled nuclear power plant is the thermal impact on a river, lake, or body of water from which it draws water and into which it releases clean heated water. In the case of any thermal power plant (e.g. coal-fired), the threat to the environment can be significant in the case of smaller rivers, when at times of low water level there is so little water in the river that the plant's intake disturbs its flow and the returned heated water significantly raises the water temperature in the river downstream of the power plant site. Such impact negatively affects aquatic organisms mainly by reducing the availability of dissolved oxygen in the water. However, one must keep in mind that as early as at the stage of design and environmental impact assessment procedures, such locations are selected and such installations are designed so that such negative phenomena do not occur. In the case of coastal power plants using seawater, this problem usually does not exist because of the size of the body of water (sea).

A nuclear power plant is not only a power unit, but also a storage site for radioactive materials and spent nuclear fuel. **The nuclear power plant to be built in the near future will meet all stringent requirements and its impact will be no greater than that of the nuclear power plants currently in operation, or even smaller due to the implementation of a modern Generation III+ reactor technology** (more information on this topic can be found in chapter 5).

5.4. The impact at the storage stage.

Depending on their chemical composition and level of radioactivity, radioactive materials are classified and then stored in appropriate types of repositories. Currently, the nuclear power industry globally produces about 10,000 m^3 high-level waste per year (38). This data should be compared with the operations of the Bełchatów power plant, for example. One part of the energy system of one medium-sized country produces annually more than 1,300,000 m^3 of ash alone.

Opponents of nuclear power often raise arguments about allegedly leaking repositories and lack of experience with such long-term storage of radioactive materials. However, it turns out that nature has already conducted similar experiments and we know their results and can see them at Oklo in Gabon (see below). Low- and intermediate-level waste can be safely stored in a variety of surface facilities. In Poland there is one such repository - in Różan on the Narew River. It was located in a suitably prepared old fort. The repository has been in operation since 1961 and is continuously monitored by environmental protection authorities. During this time, no elevated levels of radiation have been observed in the vicinity or in the waters of the Narew River flowing nearby. In this respect, the quality of the river's waters is exactly the same upstream and downstream of the repository and corresponds to the background level (natural radiation of the surrounding environment). Poland has experience in radioactive waste management and will be able to deal with the challenge of waste management also for nuclear power plants.

5.5. The natural reactor and repository in Oklo.

Discussions on nuclear power often include arguments against it that refer to permanent environmental pollution with radioactive waste, leaks, repositories that are not leak-tight, contamination that threatens not only people but also the nature as a whole, and negative effects lasting for thousands or even millions of years. Another argument is contamination with elements that do not occur naturally, such as plutonium, and that we do not know how this will affect ecosystems and how chemical compounds containing these new or rare elements will spread.

An interesting case showing what can happen to spent fuel from nuclear power plants is the Oklo uranium mine (Gabon, Africa). In 1972, in the course of mining operations, during examinations of successive samples of uranium ore it turned out that within some batches of freshly extracted material a considerable amount of uranium itself was missing and other elements appeared that should not naturally occur in the deposit. Instead of typical ore, material resembling spent fuel from a nuclear reactor was extracted from a part of the deposit. Upon further investigation, it was determined that this was indeed the case.

In Oklo, within a single deposit, in 16 uranium concentration zones, elements and their isotopes were found that indicated the occurrence of similar physical processes as in man-made reactors. Based on studies and simulations, it was determined that natural, self-regulating nuclear reactors formed at this site 2 billion years ago. Within them, a chain reaction raised the temperature by several hundred degrees and the calculated capacity (about 100 kW) corresponds to that of a small research reactor. These reactions took place over several hundred thousand years and the total energy released is estimated at 1,000 GWh.

But the most interesting thing - from the point of view of waste disposal - happened later. For almost 2 billion years, the products of decay stayed in sandstone rocks. These are highly porous rocks, penetrated by water. The migration and dispersion of chemicals over such a long period of time can be measured in meters. This is an important testimony that safe storage of such substances is possible, also on a geological time scale.

Consequently, we can assess how radioactive substances left in the rock mass behave in specific conditions, which allows us to design effective repositories that will last for centuries.

5.6. The substitution effect

Due to the significant negative impact of burning of fossil fuels on the environment and, consequently, on the climate, abandonment of fossil fuels (coal, oil, and gas) as well as of large-scale burning of wood biomass becomes an urgent necessity, which is reflected in the actions taken by the international community, including the European Union. However, in order to maintain our current standard of living, we need to have efficient and stable energy sources that do not cause greenhouse gas emissions - ones that will replace those used today. In this respect, there are different approaches, ranging from extreme promotion of RES (a vision of an energy system based 100% on RES) to a whole range of systems that combine renewable energy sources with nuclear energy. Technologically, there is no incompatibility between the nuclear power sector and the RES sector, as both sectors can efficiently cooperate and complement each other. Nevertheless, nuclear power is fully rejected by proponents of 100% RES.

How do both forms of energy production affect the environment? The impact on birds and bats is well known. In the case of nuclear power plants, there are incidental collisions of birds with electrical cables and with walls of cooling towers or other structures that are a part of the power plant. In the case of wind energy - both for individual turbines and entire farms, numerous collisions of birds and bats are observed. A significant negative impact of wind turbines on birds of prey (eagles, hawks, ospreys, etc.) and some wetland birds has been confirmed (39).

Hydroelectric power plants are always an important partition that divides river ecosystems. Despite the existence of fish ladders (structures that allow fish to migrate upstream), they are an insurmountable barrier for a significant number of aquatic organisms. Another negative effect is the impact on the river downstream of the dam, caused by the discharge of oxygen-deprived water from deeper parts of the reservoir and thus - sometimes drastic - change of the living conditions in the river. The most important is the disturbance of the regime of natural floods, which negatively affects many species inhabiting rivers (40).

It would seem that photovoltaic systems have the least destructive effect on the environment, but their poor efficiency and operation only for a part of the day make it difficult to even consider them as a substitute for a basic source of electricity.

Their biggest disadvantages are occupation of huge areas for relatively inefficient production of electricity and consumption of large quantities of materials, disproportionate to the amount of energy produced.

Another energy source that is still rated as renewable is biomass. In most cases, however, this means wood used for combustion in power plant, combined heat and power plant, and heating plant boilers. Wood harvested from forests causes a significant loss of biodiversity and its burning contributes to additional greenhouse gas emissions into the atmosphere.

It is estimated that if the pressure on uncontrolled development of RES is maintained, the number of protected areas threatened by this form of energy may increase by about 60% in the nearest future. If the world continues its rapid transition to renewable energy alone, these areas will come under increasing pressure to accommodate the expansion of energy harvesting infrastructure (41).

The impact of different types of energy sources on the environment caused by the use of available resources is also important. The following comparison shows how many tons of what type of material are used in a power plant of a given type to produce one terawatt-hour of electricity. The conclusions are obvious.

TABLE 10. **THE SCOPE OF MATERIAL REQUIREMENTS FOR DIFFERENT FORMS OF ELECTRICITY PRODUCTION** (42)

Material (ton/TWh)	Coal	Gas cogeneration	Nuclear power (PWR)	Biomass	Hydropower	Wind energy	Photovoltaics (silicon cells)	Geothermal (high-temperature, ORC)
Aluminum	3	1	0	6	0	35	680	100
Binders	0	0	0	0	0	0	3,700	750
Concrete	870	400	760	760	14,000	8,000	350	1,100
Copper	1	0	3	0	1	23	850	2
Glass	0	0	0	0	0	92	2,700	0
Iron	1	1	5	4	0	120	0	9
Lead	0	0	2	0	0	0	0	0
Plastics	0	0	0	0	0	190	210	0
Silicon	0	0	0	0	0	0	57	0
Steel	310	170	160	310	67	1,800	7,900	3,300

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It should be emphasized that the above considerations apply to large energy systems that cover entire countries. In the case of small systems (small towns) located in specific conditions (e.g. no extensive distribution network), renewable energy sources may be the only reasonable alternative without negative impact on the climate.

In conclusion - nuclear power affects nature incomparably less than most of us imagine. It is a complex technology that requires great care, but it is advanced and safe enough to be a reasonable alternative to current fossil fuels, and given the threats of climate change, in the near future it could be a key factor in preserving the diversity of life on Earth while maintaining human comfort and continued development of our civilization.

6 THE IMPACT OF NUCLEAR POWER ON THE SOCIETY

Urszula Kuczyńska

6.1. The social aspects of the use of nuclear power

The social aspects of the use of nuclear power in the national energy mix go far beyond economic issues. Access to electricity, which is a critical resource today, determines access to a range of other goods and services: from the very basic, related to survival and existence, to the ability to participate in social, economic, and cultural life.

According to forecasts, net final energy consumption in Poland will increase by 2040. Only by implementing available energy efficiency tools will it be possible to achieve some reduction in this consumption (43). Poland needs a deep energy transition, but it cannot repeat the mistakes made by our neighbors. The German Energiewende, which uses only one group of zero-emission technologies, i.e. renewable energy sources, has disproportionately burdened households with the lowest incomes with its costs, which lead to a decline in public support for the changes (44). Meanwhile, the participation of nuclear power in the energy transition guarantees a lower cost of transition to a zero-emission energy system (44) and ensures a rapid increase of stable and zero-emission capacity in the system (45), thus ensuring its quickest decarbonization (46) (more information on this topic can be found in chapter 6)..

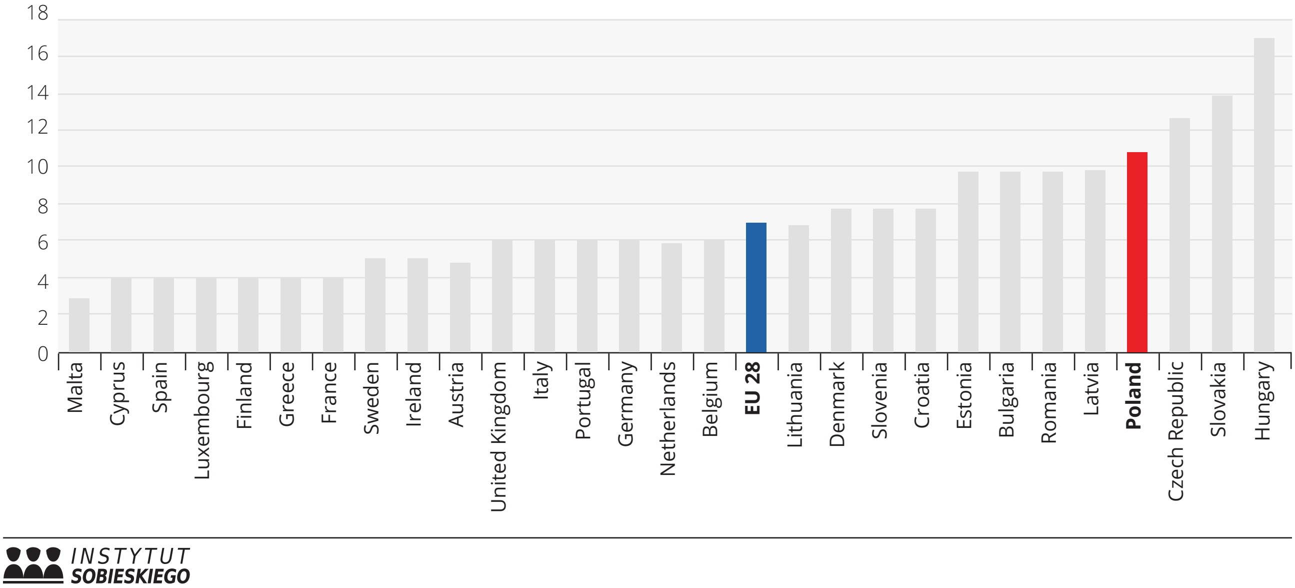
Nuclear power can be seen as a tool to help ensure that social stability is maintained and to enhance social cohesion, thus ensuring public acceptance of the energy transition.

6.2. Social stability and cohesion

Social cohesion is a multidimensional concept. Its essence is to improve the quality of life in the society by creating a sense of community (47). The prospect of social cohesion and stability requires active participation of state structures in the process of guaranteeing universal access to electricity.

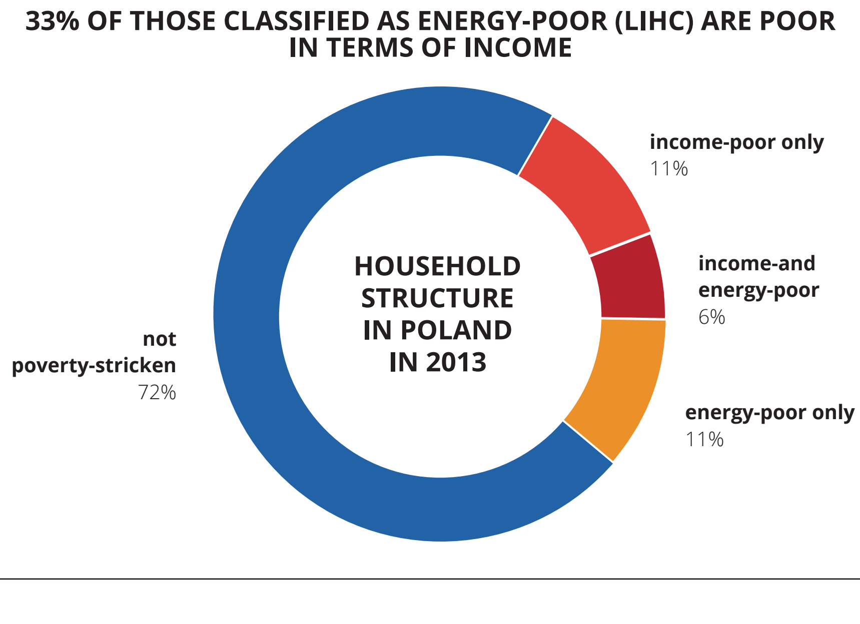
The system of fees for CO_2 emissions into the atmosphere is the key factor that increases the wholesale energy price in Poland to almost the highest level in the EU (48). This affects the price of electricity for individual consumers and, therefore, their purchasing power. According to Statistics Poland (SP), in 2013 as much as 12.2% of all expenditures incurred by households were expenditures for energy (49) - two thirds of them were the costs of heating in the autumn and winter season (50). Polish households are more burdened with energy expenses than the EU average.

FIG. 14. **THE SHARE OF EXPENDITURES ON ENERGY IN TOTAL HOUSEHOLD EXPENDITURES IN SELECTED EU COUNTRIES IN 2010 [%]**



According to the absolute definition of the so-called 13% threshold, as many as 34% of Poles were energy-poor in 2013. The relative definition of LIHC (*Low-Income-High Cost*) narrows this group down to 17% of the Polish population, i.e. about 6.4 million people, mainly living in the countryside and single-family houses. However, as many as 28% of Poles declared difficulties in maintaining thermal comfort at home. This difficulty is only moderately correlated with income poverty (51).

FIG. 15. **ENERGY POVERTY AND INCOME POVERTY** (51)



As a report by the Institute for Structural Research indicates, the autumn-winter peak in energy demand is increasingly joined by the summer peak, associated with the need to cool rooms (57).

6.3. Public health and transport exclusion

Public health and transport exclusion can also be considered from the standpoint of social stability and cohesion. Every energy source has an impact on the environment and the people who inhabit it. Impact on humans can be considered in three categories: (a) the number of fatalities and accidents occurring along the production and supply chain for a given source; (b) the air pollution generated by a given source; and (c) the carbon dioxide emitted that increases the risk of uncontrolled climate change.

Safety

An analysis of WHO data (52) shows that nuclear power is the safest source of energy (see subchapter 5.2), as confirmed by numerous scientific studies, including an update of the 2020 estimates for Statista.

TABLE 11. **MORTALITY DEPENDING ON THE ENERGY SOURCE** (52)

Energy source	Mortality rate (deaths/billion kWh)
Coal – world average	**100** (50% of global electricity production)
Coal – China	**160** (75% of electricity production in China)
Coal – USA	**15** (44% of electricity production in the USA)
Crude oil	**36** (36% of world global production, 8% of global electricity production, nobody in the USA)
Natural gas	**4** (20% of global electricity production)
Biofuels/biomass	**24** (21% of global energy production)
Photovoltaic (roof-mounted)	**0.44** (<1% of global electricity production)
Wind power	**0.15** (approx. 1% of global electricity production)
Hydropower – global average	**1.4** (15% of global electricity production, 171,000 deaths - Banqiao dam disaster)
Nuclear power – global average	**0.04** (17% of global electricity production, including the Chernobyl disaster and the Fukushima accident, nobody in the USA)

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More and more studies confirm the disastrous impact of air pollution on public health. PM2.5 alone contributed to 43,000 premature deaths in Poland in 2019 (53). The target levels of carcinogenic benzo(a)pyrene are regularly and repeatedly exceeded in Poland.

FIG. 16. **SMOG IN POLAND AND ITS CONSEQUENCES** (53)

KEY NUMBERS	
43,000	premature deaths reported in Poland in 2019 due to PM2.5
1st place	Poland's rank in 2017 in terms of exceeding the EU average annual benzo(a)pyrene air concentrations
4.8 ng/m^3	concentration of benzo(a)pyrene in air in the EU (the target level is 1 ng.m^3)
96%	zones in Poland subject to air quality assessment in 2018 where the permissible concentrations of benzo(a)pyrene were exceeded
4th place	Poland's rank among all EU countries in 2017 in terms of the average annual concentration of PM2.5 in the air, which was equal to 23 µg/m^3 (the permissible level is 25 µg/m^3)
85%	zones in Poland subject to air quality assessment in 2018 where the permissible concentrations of PM10 were exceeded

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Poland stands out negatively in terms of air quality compared to other European countries and, as a result, incurs costs estimated at PLN 111 billion annually (53). These costs take the form of additional respiratory and nervous system diseases, which lead to lower productivity and an associated burden on the healthcare and social insurance systems.

FIG. 17. **THE SHARE OF IMPORTANT SECTORS IN PM10 EMISSIONS IN 2017 (IN %)** (53)

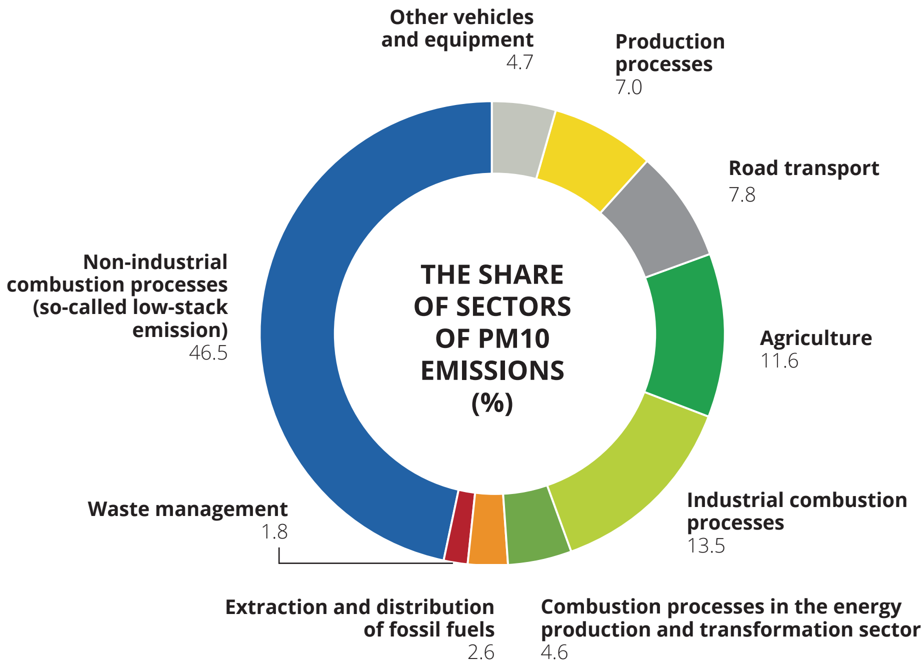
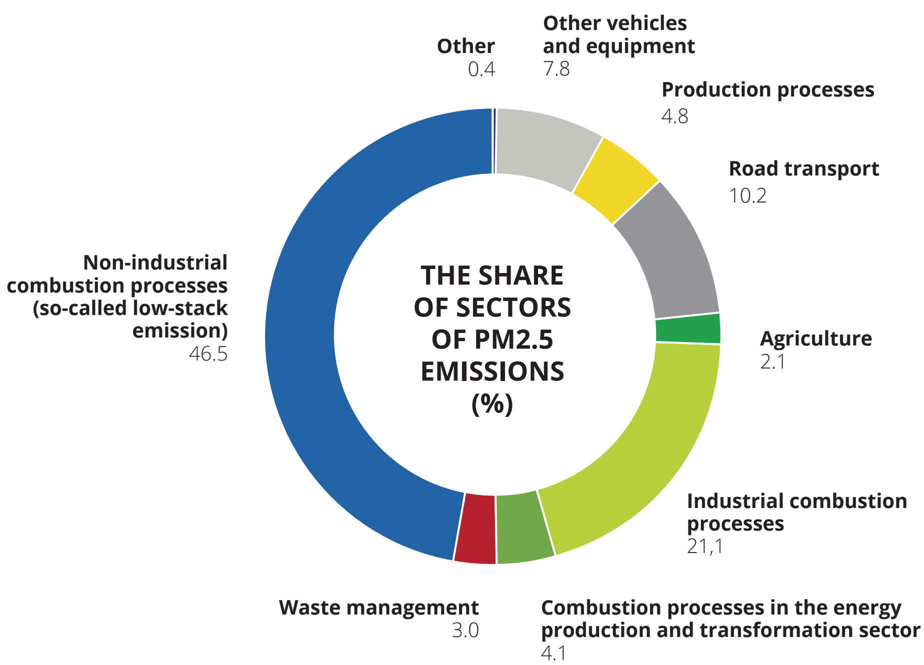


FIG. 18. **THE SHARE OF IMPORTANT SECTORS IN PM2.5 EMISSIONS IN 2017 (IN %)** (53)



Since as much as 84% of emitted benzo(a)pyrene and 46% of PM2.5 and PM10 originate from households (53), **the problem of air pollution associated with heating is one of the manifestations of energy poverty**. Efforts to eliminate this phenomenon (low-stack emission), among others by expanding access to cheap electricity for space heating, will mean progress in the fight against pollution.

Transport emissions can be significantly reduced by its electrification, including increasing the share of rail transport in goods and freight transport.

6.4. Social stability and cohesion in the context of the so-called collapse

Extreme, life-threatening heat waves occur 11 times more frequently in New York City today than in the 19th century (54). Climate change is bringing record droughts and rising food prices in Poland, as well as floods of the century in China. They contributed to the landmark communiqué of the UN Human Rights Committee that recognized the existence of the climate refugee category as persons under international protection (55).

The objective of the Paris Agreements, and the target cited by the UN's International Panel on Climate Change, is to keep global warming to 1.5°C relative to the pre-industrial era. The pressures of climate change on individual societies and humanity as a whole will increase as the global warming reaches higher levels.

Recent studies of the human temperature niche show that failure to act to decarbonize the global economy will mean that 3.5 billion people will have to migrate to other parts of the world even before 2070 (56).

Poland should work towards achieving climate neutrality and adapting to the ongoing changes. It should also actively engage in the international community's efforts to halt global warming at 1.5 °C and to support the populations of the most vulnerable areas in implementing adaptation tools to improve their livelihoods. A part of the answer should be nuclear power as a zero-emission source of electricity that supports the principle of social justice more than others.

6.5. A nuclear power plant as a driving force for development of the regional and the local community

A nuclear power plant is practically permanently inscribed in the landscape of the place where it is built.

The assessments, conducted by the American Nuclear Energy Institute (NEI), of the impact of nuclear power plants on the economies of Florida and Texas were so positive that their presence was considered to be a **stable driving force, independent of the economic situation, for the local economies**: every dollar generated directly by the St. Lucie and Turkey Point facilities in Florida translated into USD 1.27 generated by the economies of the local municipalities and USD 1.50 generated by the state's economy (57) (see chapter 6 for more on this economic impact).

Infrastructure development and improvement

Construction of a nuclear facility requires an upgrade and development of the region's infrastructure. The construction of the never completed Żarnowiec Nuclear Power Plant changed the profile of this agricultural part of the Kaszuby region. The 230a railway line, built for the project, connected Żarnowiec with the Tri-City and facilitated the inhabitants' access to education and healthcare. Until 2002 the Nadole hotel was in operation which, originally intended for the construction workers, gave rise to a thriving tourist industry. The road infrastructure built for the construction works is still used by the Żarnowiec region to this day.

The elements needed for the implementation of the project and its subsequent efficient functioning vary depending on the facility and its location.

On the occasion of the construction of the Czech nuclear power plant in Temelín, two additional wastewater treatment plants were built, which solved a real environmental and social problem in the region. Their operation is still mentioned by the local residents as one of the greatest benefits of the operation of the nuclear power plant in their area.

In Turkey, it was necessary to expand the road network and to provide equipment to local hospitals so that they could handle more patients (58). The enlargement of the staff of the local healthcare facilities, together with the modernization and expansion of the hospital infrastructure, translated into improved access to healthcare services and a better public health status in the region.

A good example of the positive impact of nuclear infrastructure on public life is also the National Radioactive Waste Repository (NRWR) in Różan in the Mazowsze region of Poland. Due to its operation in the municipality, the residents have some of the lowest water and sewage charges in Poland, and children and young people enjoy free summer holidays every year that are financed by the NRWR operation fee.

The impact of nuclear power plants on tourism

The presence of a nuclear power plant in a region that is attractive to tourists does not diminish its attractiveness - it may even increase it. This is illustrated by the examples of the Tihange nuclear power plant in Belgium, located near the historic town of Huy, and the Czech Temelin plant, located in a region of great historical and natural beauty. (For more on the economic impact of a nuclear power plant, see chapter 6.)

Cooperation with and involvement in the life of local community

The power plant operator's support for projects carried out by local governments and for initiatives taken by communities is an important part of nuclear power plants' operation in the social environment. However, it is also important **to create channels of communication that give the community insight into the life and operation of the facility, thus increasing its sense of empowerment and safety**.

In Olkiluoto, Finland, representatives of the municipality form a social committee together with the operator's representatives. Residents are invited to participate in measurements of cleanliness of the environment around the power plant and of the level of radiation. Their opinion on many matters is binding.

TEIT, an association set up by 13 neighboring communes and the operator, is active at the Hungarian Paks power plant and exercises social control over the plant. It has the right to enter its premises and operates its own radiation and water purity monitoring network. It serves as a bridge between the Hungarian society and the power plant. Thanks to such a model of cooperation, **public support for nuclear power in the vicinity of the facilities is higher than nationwide**. In the vicinity of the Dukovany power plant in the Czech Republic, as many as 90% of respondents support its continued operation and presence in the region (58). Polish regulations also provide for extensive rights for the local community to control the performance of the project and operation of the nuclear power plant.

6.6. Support for nuclear power

Regular polls show that development of nuclear power in Poland enjoys high public support. According to the results of a 2020 survey cited by the Ministry of Climate in the Polish Nuclear Power Program, **57% of the country's population is in favor of nuclear power in Poland**.

In possible site areas, the number of supporters of construction of a nuclear power plant is even higher and equal to 71%.

90% of respondents see the need to launch a broad information campaign on nuclear power. Eurostat data show that **the more informed the public feels about nuclear power, the higher the level of support for its operation in a given country (59). In Poland, too, the support for nuclear power may further increase as a result of educational activities**.

Foratom (Forum Atomique European, a non-profit non-governmental organization of European nuclear power and nuclear industry actors) emphasizes the impossibility of calculating a "European average" of support for nuclear power. This is due to a deep polarization of attitudes and the fact that on the European continent the countries positively disposed towards nuclear energy (e.g. Finland - 61% support, the Czech Republic - 64% support) are neighbors with countries that are openly and ideologically hostile to it (e.g. Norway, Austria, and Germany) (59).

6.7. Nuclear power opponents in Poland and the world

The natural opponents of nuclear power are miners who see it as the only source of energy that can realistically compete with coal. In Australia, the mining community has lobbied for a ban on the development of nuclear power (60). Polish miners in Bełchatów (61) have also protested against construction of a nuclear power plant. The issue of nuclear energy polarizes the environmental and climate protection movements. It is an identity issue for them: western organizations (e.g. Greenpeace) were established in the 1970s by a generation of people who grew up in fear of a global nuclear armed conflict.

Anti-nuclear protests took place in Poland after the Chernobyl disaster and torpedoed the construction of the Żarnowiec Nuclear Power Plant. Members of the "Freedom and Peace" movement organized protests throughout the country. Some of them continue to be active in public and political life as a loud, albeit marginal, voice of opposition to the construction of a nuclear power plant in Poland.

Active opposition to nuclear power, including on the EU level, is currently concentrated in the political stances of Germany, Austria, and Luxembourg, where the voices of the European Green Party dominate the energy debate. Despite the fact that nuclear power today provides a half of the EU's low-emission energy and that many member states are using nuclear sources and intend to develop them (62), the European Green Deal was designed according to the logic of the German Energiewende, i.e. to support non-dispatchable renewable energy sources at the expense of zero-emission sources operating in the base (63). Renewable energy sources require a reserve to be installed in the system, which is most often provided by gas-fired power plants, and even the French Ministry for the Green Transition, which is planning to increase the share of renewable energy in the national mix that has so far been based on nuclear energy, is preparing to increase purchases of this raw material (64). Natural gas will soon flow from Russia through the Nord Stream 2 pipeline, putting Germany in the privileged position of a country that, by actively fighting nuclear power as a stable source of zero-emission energy, is creating a market for natural gas that it imports and resells (65). Basing Poland's national energy mix on only one zero-emission energy generation technology, i.e. RES, may thus pose a real threat of losing its energy independence and, consequently, its energy security.

Polish public opinion remains very sensitive to arguments related to economy, safety, and energy independence, as well as to the argument related to the prestige resulting from possible development of the nuclear power sector. The effort put into educating and informing the public about the benefits of nuclear power will ensure that the decision to build a nuclear power plant in Poland will enjoy a stable and high public support.

7 ENERGY SECURITY IN THE CONTEXT OF NUCLEAR ENERGY

Anna Przybyszewska

There are currently several similar definitions of energy security. The most popular one is the one in which it is defined as a state of the economy that makes it possible to satisfy the current and prospective demand of consumers for fuels and energy in a technically and economically reasonable manner, while maintaining the requirements of environmental protection. It has several dimensions, which can be described as (66):

- The environmental dimension, which takes into account the aspiration to supply energy in compliance with environmental standards, as well as with limited negative impact on the environment.
- The technical dimension, which describes the state of the generation and transmission infrastructure and the efficiency of the energy facilities and the energy distribution system.
- The political dimension, which is strongly linked to foreign policy. The idea is to ensure and plan investment projects that will guarantee continuity and reliability of energy supplies from the coal, gas, oil, nuclear, and renewable sources to individual, municipal, and industrial consumers, which may not be possible to achieve only based on the country's own resources. In such a case, international cooperation in terms of supply of technologies, machinery and equipment, fuels, and specialized service contracts is crucial.
- The institutional dimension, created by the state and institutions whose aim is to take action to strengthen energy security and implement its principles, and to stimulate the investment environment to strengthen critical infrastructure, including the construction of energy production facilities.
- The economic dimension, which seeks to ensure energy supply at competitive costs and prices acceptable to the economy and society.

7.1. The environmental and technical dimension

Given the increasing CO_2 emissions and the pursuit of climate neutrality, as well as the declaration of improved access to modern energy sources, Poland faces the necessity of implementing a broad investment program related to the modernization or replacement of its coal-fired power generation units that are approaching the end of their service life. The aim is not only to comply with the BAT (best available technology[1]) conclusions, but also to increase energy security.

[1] On 17 August 2017, the executive decision of the European Commission establishing BAT conclusions for large combustion plants (LCP), i.e. with the capacity greater than or equal to 50 MW, was published in the Official Journal of the European Union. The conclusions summarize the best available techniques and provide descriptions of each technique, data to assess their applicability, and the emission levels and consumption levels associated with the best available techniques. The requirements apply to both existing and new installations. In the case of existing installations, a derogation could be granted if action to achieve the emission limit values requires costs disproportionate to the possible environmental benefits.

TABLE 12. **THE VOLUME OF PRODUCTION CAPACITY OF THE FOUR LARGEST ENERGY PRODUCERS IN 2017 AND PLANNED CHANGES IN THE PERSPECTIVE UNTIL 2032 [MW]** (69)

Group	Installed capacity at the end of 2017	Planned to be phased out by 2032	Under construction and planned UNTIL 2032 (gas + coal)	Balance
ENEA	6,257	2,095	(1,000)[2]	4,162 (5,162)[2]
ENERGA (currently ORLEN Group)	1,313	0	1,050	2,363
PGE	10,766	2,704	2,290	10,352
TAURON	4,291	3,385	1,310	2,216
Total	**22,627**	**8,184**	**4,650 (5,650)[2]**	**19,063 (20,093)[2]**

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As indicated in a report of the Polish Supreme Audit Office (67), the advanced age of power units and the high level of pollutant emissions require withdrawal of some units from operation or their modernization. In the perspective until 2035, there may be a risk of a serious shortage of the required surplus capacity and subsequently also of a shortage of the capacity available from the domestic generation resources (Centrally Dispatched Generation Units). The planned decommissioning of units with the total capacity of 8 GWe will result in the generation capacity remaining at 19-20 GWe[2], which is 2.5-3.5 GWe less than in 2017. In the coming decades, the demand for electricity is expected to grow and, therefore, the deepening decline of the capacity that is the basis of the power system in Poland is alarming. **It is necessary to make a decision to build new generating capacity.**

Basing the energy system in Poland solely on weather-dependent RES installations (wind power and photovoltaic systems) is not possible in the perspective until 2050. Increasing the installed capacity of PV (photovoltaic panels) and WF (wind farms) sources indefinitely without any real safeguards in the form of energy storage facilities (e.g. pumped storage) or gas units (acting as back-up sources) has a destabilizing effect on the operation of the power grid. Currently, the largest battery energy storage system is the Hornsdale Power Reserve (68) in Australia, which can deliver a maximum of 193.5 MWh. In the case of pumped storage power plants, the maximum energy accumulated in Polish installations is about 8 GWh and further development potential is small. **In terms of energy supply guarantees, the construction of nuclear power plants, based on the latest proven technologies, appears to be the most sensible choice to secure future electricity needs.**

7.2. The political dimension

The question of self-sufficiency in energy supply, taking into account the dimensions listed above, is very important: only a few countries in the world are able to achieve true energy independence (69). However, most countries, including Poland, have to shape their energy sovereignty by diversifying the directions of energy imports. Limiting the impact of foreign purchases of raw materials on energy security relies on the so-called integrated approach: a guarantee of stable and long-term supplies of energy carriers from countries with which good relations have been established, often supported by mutual economic dependence.

[2] In February 2020 ENEA and ENERGA made a joint decision to suspend financing of the Ostrołęka C project - a 1,000 MWe coal-fired power unit. Currently works are being conducted related to the change of the project from coal-fired to gas-fired, arranged by PKN ORLEN - the partner of the project and the owner of Energa.

One way is to integrate the energy market with the EU. In terms of import dependency, the key issue is the level of risk involved in particular types of supply in relation to a particular supplier or energy carrier.

Poland, due to its small own resources of natural gas and crude oil, covers its demand mainly with imported raw materials. Poland's heavy dependence on natural gas supplies from Russia (imports by PGNiG at 60% in 2019) (70) requires diversification efforts. To this end, projects such as the Baltic Pipe, the expansion of the LNG (liquefied natural gas) terminal, and the expansion of gas connections in the south of the country (71) are being and will be performed. However, funding for gas projects over the next two decades is severely limited. The European Investment Bank has stopped financing gas projects from 2021 by setting an emission standard of 250 g of CO_2/kWh (72). As a result, financing construction of new capacities of gas-steam power units with the emission factor of 300-350 g of CO_2/kWh will not be possible using preferential financing instruments and will force Polish investors to seek funds in commercial banks. In addition, the European Green Deal, touted as Europe's roadmap for a green transition that should help it reduce CO_2 emissions, create jobs, and open up new opportunities, also does not favor gas technologies, as it assumes a shift away from hydrocarbon fossil fuels. To implement this plan, EU member states should achieve a 40% reduction in greenhouse gas emissions (relative to 1990) by 2030. The recovery package agreed in July 2020 and the EU budget for 2021-2027 intended to help the EU recover from the COVID-19 pandemic and to support investment in green and digital transition are insufficient for Poland's ambitious energy transition as they do not provide the right environment for gas projects (73).

In this context, **the right solution is to turn towards nuclear energy**. Some European Union member states are aware that in order to meet the climate neutrality targets it is necessary to maintain the use of nuclear energy. Nuclear projects are currently excluded from funds supporting zero- and low-emission projects, contrary to the obligations of the Euratom Treaty to promote the development of the nuclear sector in the EU. Nuclear power facilities supply electricity regardless of the weather and with zero emissions in the course of energy production on such a large scale, and the carbon footprint (according to the cradle-to-grave approach) that will soon be factored into investment project appraisals is still lower than for most renewables.

Poland[3] does not currently have uranium resources whose extraction would be profitable (more information on this topic can be found in chapter 5).

[3] Indirect emissions from co-firing are based on the relative proportions of biomass fuels from crops and energy-rich residues (5-20%) and from coal (80-95%), so the carbon content of coal and the relative proportion of biomass fuel must be taken into account. For this reason, each installation has its own specific emissions.

TABLE 13. **CO_2 EMISSIONS FROM ELECTRICITY PRODUCTION FROM DIFFERENT SOURCES ($PC0_2$ EQ/KWh)** (74)

Technology	Direct emissions min./median/max.	Emissions from construction and supply chain	Methane emissions	Carbon footprint in entire life cycle min./median/max.
Coal	670/760/870	9.6	47	740/**820**/910
Gas – combined heat and power	350/370/490	1.6	91	410/**490**/650
Biomass – co-firing[3]	n/a	–	–	620/**740**/890
Geothermal	0	45	0	6/**38**/79
Hydropower	0	19	88	1/**24**/2200
Nuclear power	0	18	0	3.7/**12**/110
Photovoltaics – roof-mounted	0	42	0	3.7/**12**/110
Photovoltaics – ground-mounted	0	66	0	18/**48**/180
Wind energy – onshore	0	15	0	7.0/**11**/56
Wind energy – offshore	0	17	0	8/**12**/35

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If a nuclear power plant is built, the fuel will have to be imported. Uranium enrichment and fuel production facilities are located in countries such as France, Germany, Netherlands, Belgium, Spain, United Kingdom, and United States. **Gathering an annual fuel stockpile for a 1,000 MWe class LWR-based nuclear power unit will not be a problem not only technically[4], but also in terms of the ability to ensure continuity of supply due to a competitive market and good relations with the above-mentioned countries.**

7.3. The institutional dimension

The COVID-19 pandemic, which forced the lockdown of many economies, including Poland, is making us rethink the importance of energy security in emergency situations. Electricity consumption has fallen by around 7% in recent months (compared to 2019, Poland recorded a decline of 5% and Italy a record 11.5%) (75). The number of extremely hot days has tripled since 1950 (76). In addition, the pandemic has forced a large part of the population to work remotely and has made the European economy even more dependent on electricity and the Internet. This prompts a reconsideration of energy security in the context of securing energy and fuel supplies in a crisis situation towards solutions that are more resilient, secure, competitive, and sustainable, and above all that create economic growth for years to come (more information on this topic can be found in chapter 6).

[4] 1,000 MWe class gas-steam power units require gas supplies of 1-1.3 billion m^3 per year; only one gas storage facility in Poland - PMG Wierzchowice (80) - is capable of storing such an amount. On the other hand, storing "green energy" produced from RES, due to the state of maturity of energy storage methods (including P2G and P2H), is practically impossible on a large scale.

The significant increase in the share of RES in electricity production recorded in the recent months coincided with a reduction in electricity generation in the dispatched power plants and took place in the months of photovoltaic systems' "production season."

The OECD's Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA) have called for nuclear projects to be included in broad recovery and economic stimulus plans (77) (78). This is supported by the following arguments which also apply to Polish plans for implementation of nuclear power:

- Nuclear power plants supply large amounts of zero-emission electricity while creating large numbers of high-value jobs locally and nationally in the long term and boosting research and development;
- Nuclear power plants generate electricity reliably around the clock (more information on this issue can be found in chapter 5) and guarantee supply even in the face of the global health crisis, while maintaining social stability. Their operation is flexible: they respond to current load and supplement supply from weather-dependent RES. In the face of the COVID-19 pandemic, no nuclear power plant has had its generating operations curtailed because of concerns about staff health and the need to maintain social distancing. The standard operating procedures of nuclear power plants were partly in line with epidemiological recommendations, which protects such installations from similar events in the future;
- Financing of nuclear projects can be a barrier in markets where investors are looking for returns in short-term projects such as RES. In contrast, in a period focused on economic recovery, large-scale and long-term infrastructure projects supported by the state, such as construction of a nuclear power plant, stimulate social cohesion (high quality of life, elimination of social inequalities - more on this issue can be found in chapter 9) and encourage investors seeking safer investments for their capital.

By implementing the PNPP, Poland has a chance to revive its economy and build resilience to similar crises that may take place in the future.

7.4. The economic dimension

The zero-emission nature of nuclear power, despite the obvious facts, continues to be discussed in most countries' clean electricity policies and as part of financing for sustainable energy sources (79). Achieving the goal of climate neutrality and limiting global warming in a vast majority of countries will not be possible with wind and photovoltaic power alone. In the strategic scenario, the PNPP provides for a significant share of both RES and nuclear energy. This scenario ensures the optimal average annual external cost of electricity generation in the national power system and limits the increase in system and environmental costs the most (more information on this issue can be found in chapter 6).

In a perspective of several decades, commissioning more nuclear power units will contribute to a stabilization of energy prices in Poland.

7.5. The role of nuclear power in the energy transition

In May 2019, the International Energy Agency (IEA) published its report entitled "Nuclear Power in a Clean Energy System" (80) which concludes that without a significant contribution from nuclear power, it is not possible to meet the climate goals of global sustainable development with increased security of energy supply. The IAEA assumes that in order to meet its forecast of more than a 2-fold increase in installed capacity under the "optimistic" scenario and thus to contribute to limiting climate change (81), significant investments would have to be made in countries with existing power plants and dynamic introduction of nuclear power would be required in more than 20 other countries, including Poland. To this end, it is planned to build nuclear power plants with the total capacity of 6-9 GWe, which will make it possible to achieve ambitious targets for reduction of CO_2 emissions and to transform the energy sector towards a sustainable and zero-emission energy mix (with the expected share of nuclear energy equal to approx. 20%).

The European Commission has proposed to revise the current emissions reduction pathway to achieve climate neutrality by 2050 and to reflect this in a proposal for a European climate law. The proposed EU-wide target is to reduce greenhouse gas emissions across the EU economy by at least 55% by 2030 compared to 1990, including emissions and removals (82).

A significant reduction of emissions is assumed as a result of closure of coal-fired power plants and decarbonization of energy-intensive sectors, as well as intensive electrification of transport and agriculture, and improved efficiency in buildings. Particular emphasis is placed on extensive investments in RES, with the omission of nuclear and gas power plants, which are treated by Poland as transitional technologies.

Intensive decarbonization is necessary to meet new climate targets and reduce the greenhouse effect. However, the power sector will implement at least 40% of the planned reduction. Despite declaration of ambitious RES investment targets of the major players in the Polish power sector, i.e. PGE, ORLEN, and TAURON (83) (84) (85), full and fast decarbonization may not be possible based on RES alone. The pace of decarbonization of the energy sector should reflect the technical, organizational, and financial capacity of each member state. One should keep in mind that while significantly changing the energy mix in the "green" direction, investments should be made in parallel in energy sources that ensure security of supply and provide a backup for RES, e.g. in natural gas projects Large-scale (electric) energy storage (86) and hydrogen power (87), which are expected to contribute to secure back-up of RES, are likely to reach full commercial maturity and make a significant contribution to a climate-neutral economy after 2030, despite ambitious deployment plans. **Until then, in order to achieve sustainable decarbonization, other investments are needed in zero-emission sources, such as nuclear power, which can be a solution for rapid and efficient CO_2 emission reduction.**

In the context of the announced (82) changes in emissions trading (ETS)[5], it is necessary to act as soon as possible to reduce the costs incurred in this respect. While an energy mix based predominantly on RES and a smaller proportion of coal and gas could be sufficient to meet climate targets (assuming that ambitions are not increased soon), it would be a costly solution (88). Regardless of the energy efficiency programs implemented, electricity consumption in Poland will continue to grow. This will be driven, for example, by the large-scale digital transition and electrification of transport and heating throughout Europe and Poland. **Therefore, it is not possible to reconcile Poland's development and meeting the EU's climate policy goals without implementing nuclear power.**

[5] European Emissions Trading System or community carbon dioxide emission allowance market

8 REFERENCES

1. US Nuclear Regulatory Commission. *Risk Metrics for Operating New Reactors*. 2009. https://www.nrc.gov/docs/ML0909/ML090910608.pdf.
2. Markandya, Anil and Wilkinson, Paul. *Electricity generation and health*. 2007. pages 979-990, vol. 30. ISSUE 9591.
3. Sovacool, Benjamin K., Andersen, Rasmus and Sorensen, Steven. Balancing safety with sustainability: assessing the risk of accidents for modern low-carbon energy systems. *Journal of Cleaner Production*. Volume 112, 2016, Volume Part 5, pages 3952-3965.
4. Lokhov, Alexey. *Nuclear Energy Agency*. 2011. NEA News 2011 - No. 29.2.
5. NUCLEAR ENERGY AGENCY. *Technical and Economic Aspects of Load Following with Nuclear Power Plants*. 2011.
6. Sepulveda, Nestor A., Jenkins, Jesse D. and Sisternes de, Fernando J. The Role of Firm Low-Carbon Electricity resources in Deep Decarbonization of Power Generation. *Joule*. 2018, Tom Vol. II, 11, pages 2403-2420.
7. Nuclear Energy Agency & International Atomic Energy Agency. *Uranium 2018: Resources, Production and Demand*. 2018. NEA no. 7413.
8. Cameco. Uranium Price. [Online] [Cited: 31 August 2020.] https://www.cameco.com/invest/markets/uranium-price.
9. Hedin, Allan. *Spent nuclear fuel - how dangerous it is?* Stockholm: Swedish Nuclear Fuel and Waste Management Co., 1997. Technical Report 97-13.
10. International Atomic Energy Agency. *Status and Trends in Spent Fuel and Radioactive Waste Management*. 2018. IAEA nuclear Energy Series no. NW-T-1.14.
11. Ministry of Energy. *Explanatory Memorandum to the draft Regulation of the Minister of Energy amending the Regulation on specific principles of shaping and calculating tariffs and settlements in electricity trade (draft dated 31 July 2018)*. 2018. p. 11.
12. wnp.pl. Przyszłość 1,3 mln Polaków pod znakiem zapytania. Wszystko przez drogi prąd [The future of 1.3 million Poles in question. All because of expensive electricity]. [Online] [Cited: 21 August 2020.] https://www.wnp.pl/wiadomosci/przyszlosc-1-3-mln-polakow-pod-znakiem- zapytania-wszystko-przez-drogi-prad,323421.html.
13. —. Jerzy Kozicz, CMC Poland: Przemysł energochłonny w Polsce ma potencjał wzrostu [Energy-intensive industry in Poland has no potential for growth]. [Online] [Cited: 21 August 2020.] https://www.wnp.pl/wiadomosci/316239.html.
14. Office of the Government Plenipotentiary for Strategic Energy Infrastructure, in essential and analytical cooperation with the Polish Power Grid, commissioned by the Ministry of Climate. *Appendix 5 to the "Polish Nuclear Power Program."* Ministry of Climate, 2020.
15. Department of Nuclear Energy of the Ministry of Economy. *Wpływ programu jądrowego na polską gospodarkę. Korzyści na poziomie lokalnym [Impact of the nuclear program on the Polish economy. Benefits on the local level]*. 2017. https://www.gov.pl/web/aktywa-panstwowe/publikacja-wplyw-programu-jadrowego-na- polska-gospodarke-korzysci-na-poziomie-lokalnym-3.
16. Department of Nuclear Energy of the Ministry of Economy. *Wpływ programu jądrowego na polską gospodarkę. Korzyści dla gospodarki narodowej [Impact of the nuclear program on the Polish economy.*

Benefits for the national economy]. 2017. https://www.gov.pl/web/aktywa-panstwowe/publikacja-wplyw-programu-jadrowego-na- polska-gospodarke-korzysci-dla-gospodarki-narodowej-3.

17. Department of Nuclear Energy of the Ministry of Economy. *Wpływ programu jądrowego na polską gospodarkę. Udział polskiego przemysłu [Impact of the nuclear program on the Polish Economy. Participation of Poland's industry]*. 2017. https://www.gov.pl/web/aktywa-panstwowe/publikacja-wplyw-programu-jadrowego-na- polska-gospodarke-udzial-polskiego-przemyslu-3. 6.
18. —. *Wpływ programu jądrowego na polską gospodarkę. Zatrudnienie [Impact of the nuclear program on the Polish economy. Employment]*. 2017. https://www.gov.pl/web/aktywa- panstwowe/publikacja-wplyw-programu-jadrowego-na-polska-gospodarke-zatrudnienie-3.
19. Nuclear Energy Agency & International Atomic Energy Agency. *Measuring Employment Generated by the Nuclear Power Sector*. 2018. no. 7204.
20. International Atomic Energy Agency. *Nuclear Technology and Economic Development in the Republic of Korea.* Vienna : International Atomic Energy Agency, 2009. 09-14371.
21. Oxford Economics. *Economic Benefit of Improving the UK's Nuclear Supply Chain Capabilities*. 2013. https://www.gov.uk/government/publications/economic-benefit-of-improving-the-uks-nuclear-supply-chain-capabilities. BIS/13/633.
22. UK Department for Business, Innovation and Skills. *Hinkley Point C Wider Benefits Realisation Plan*. 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/725960/HPC_Benefits_Realisation_Plan.pdf.ver. 3.
23. PGE zakończyła największą w Polsce megainwestycję energetyczną po 1989 roku [PGE completed the largest energy megaproject after 1989 in Poland]. PGE GiEK S.A. [Online] [Cited: 27 August 2020.] https://elopole.pgegiek.pl/Aktualnosci/pge-zakonczyla-najwieksza-w-polsce- megainwestycje-energetyczna-po-1989-roku.
24. Nowe Jaworzno TAURON Group. [Online] [Cited: 27 August 2020.] https://www.nowejaworzno-grupatauron.pl/.
25. Oxford Economics. *Economic, Employment and Environmental Benefits of Renewed U.S. Investment in Nuclear Energy*. 2008. https://d2rpq8wtqka5kg.cloudfront.net/128895/open20080105120000.pdf?Expires=1601240580&Signature=X7hK7a~A1BZLrWBLkZTMkuw-xlxANQ13XTnpdjjH~r29eXYXme4fsxFz4YLFRat24AzLaKmeqLU0x8XCIRmbQHmALTBLjUnwRAcBFQ0890tZnq PP4V730FCArF4qb2vGExx4GntqarjabsyDldGHbi3fj4QI7j.
26. EDF. Hinkley Point C - Jobs & Training. [Online] [Cited: 31 August 2020.] https://www.edfenergy.com/energy/nuclear-new-build-projects/hinkley-point-c/jobs-and-training.
27. —. Community Fund. [Online] [Cited: 31 August 2020.] https://www.edfenergy.com/energy/nuclear-new- build-projects/hinkley-point-c/local-community/being-part-of-the-community/community-fund.
28. National Renewable Energy Laboratory, NREL. *Annual Technology Baseline*. U.S. Department of Energy, 2019.
29. UK Department for Business, Energy & Industrial Strategy. *Electricity generation costs*. UK Department for Business, Energy & Industrial Strategy, 2016. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/566567/BEIS_Electricity_Generation_Cost_Report.pdf.
30. —. *Electricity generation costs*. UK Department for Business, Energy & Industrial Strategy, 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/911817/electricity-generation-cost-report-2020.pdf.

31. WnP.pl. *Czesi zamykają ostatnią kopalnię uranu w Europie [Czechs are closing the last Uranium mine in Europe]*. [Online] [Cited: 27 August 2020.] https://www.wnp.pl/energetyka/czesi-zamykaja-ostatnia-kopalnie-uranu-w-europie,297008.html.
32. Olszewski, Jerzy, Kacprzyk, Janusz and Kamiński, Zbigniew. Ocena narażenia radiacyjnego górników w wybranych kopalniach metali nieżelaznych na radon i produkty jego rozpadu [Assessment of radiation exposure of miners in selected non-ferrous metal mines to radon and its decay products]. *Medycyna Pracy*. 2010, Vol. 6, 61, pages 653-639.
33. Uranium Mining Overview. World Nuclear Association. [Online] [Cited: 27 August 2020.] https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.aspx.
34. *Problem ochrony środowiska w górnictwie otworowym na przykładzie Kopalni i Zakładów Chemicznych Siarki „Siarkopol" S.A. - kopalnia „Osiek" [The problem of environmental protection in well mining using the example of the Kopalnia i Zakłady Chemiczne Siarki "Siarkopol" S.A. - "Osiek" mine]*. Kowalik, Stanisław, Gajdowska, Maria and Herczakowska, Joanna. 2, 2009, Budownictwo Górnicze i Tunelowe, pages 23-27. ISSN 1234-5342.
35. Nuclear Energy Agency & International Atomic Energy Agency. *Uranium 2016: Resources, Production and Demand*. 2016. NEA no. 7301.
36. Krysiński, W. Pomiary hałdy po byłej kopalni uranu „Grzmiąca" w Grzmiącej, gm. Głuszyca woj. dolnośląskie [Measurements of the spoil tip of the former "Grzmiąca" uranium mine in Grzmiąca, Głuszyca commune, Dolnośląskie Province]. *Bezpieczeństwo Jądrowe i Ochrona Radiologiczna*. 2014, no. 4, pages 15-21.
37. Lee, UkJae, Lee, Chanki and Kim, Minji. Analysis of the influence of nuclear facilities on environmental radiation by monitoring the highest nuclear power plant density region. *Nuclear Engineering and Technology*. 2019, Vol. 51, 6, pages 1626-1632.
38. Waste from Nuclear Power. [Online] [Cited: 27 August 2020.] https://web.archive.org/web/20200216080147/http://nuclearinfo.net/Nuclearpower/WebHomeWasteFromNuclearPower.
39. Thaxter, Chris B., Buchanan, Graeme M. and Carr, Jamie. Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society of London. Series B*. 2017.
40. Wawręty, Robert and Żelaziński, Janusz. *Zapory a powodzie [Dams vs. floods]*. Oświęcim - Kraków: Towarzystwo na Rzecz Ziemii & Polska Zielona Sieć, 2005. http://www.ratujmyrzeki.pl/dysk_KRR/biblioteka_koalicji/ZAPORY.pdf.
41. Rehbein, Jose A., Watson, James E. M. and Lane, Joe L. Renewable energy development threatens many globally important biodiversity areas. *Global Change Biology*. 26, 2020, 5, pages 3040-3051.
42. U.S. Department of Energy. *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities*. September. U.S. Department of Energy, 2015. https://www.energy.gov/sites/prod/ files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf.
43. Ministry of Energy. *Polityka energetyczna Polski do 2040 r. - strategia rozwoju sektora paliwowo-energetycznego, Zał. 2 Wnioski z analiz prognostycznych [Poland's energy policy until 2040 - strategy for the development of the fuel and energy sector. Annex 2. Conclusions from forecasting analyses]*. 2019. draft of 8 November 2019.
44. EU Energy Poverty. Energy Poverty in Germany - Highlights of a Beginning Debate. [Online] [Cited: 31 08 2020.] https://www.energypoverty.eu/news/energy-poverty-germany-highlights-beginning-debate.

45. Partanen, Rauli and Korhonen, Janne M. *Klimatyczna ruletka: czy zwalczając energetykę jądrową, zagrażamy naszej przyszłości? [Climate roulette: do we put our future in danger by fighting against nuclear power?]* Fundacja Instytut Zrównoważonej Energetyki. Wydawnictwo, 2018. ISBN 8394425488.
46. Cao, Junji, Cohen, Armond and Hansen, James. China-U.S. cooperation to advance nuclear power. *Science*. Vol. 353, 2016, Tom Issue 6299, pages 547-548.
47. Jastrzębska, Ewa. Spójność społeczna w kontekście społecznej odpowiedzialności przedsiębiorstw. Definiowanie, pomiar i dobre praktyki biznesu [Social cohesion in the context of corporate social responsibility. Defining, measuring, and good business practices]. *OPTIMUM. ECONOMIC STUDIES.* 2018, Vol. 88, 4.
48. EMBER. *Global Electricity Review*. 2020. https://ember-climate.org/project/global-power-2020/.
49. Statistics Poland. *Budżety gospodarstw domowych w 2013 r. [Household budgets in 2013]*. Warsaw: SP, 2014. ISSN 0208-9793.
50. Owczarek, Dominik; Miazga, Agata. *Ubóstwo energetyczne - definicja i charakterystyka społeczna grupy [Energy poverty - definition and social characteristics of the group]*. Instytut na Rzecz Ekorozwoju, 2015. ISBN: 978-83-89495-44-0.
51. Miazga, Agata and Owczarek, Dominik. *Dom zimny, dom ciemny - czyli ubóstwo energetyczne w Polsce [Cold house, dark house - energy poverty in Poland]*. IBS Working Paper, 2015. https://ibs.org.pl/publications/dom-zimny-dom-ciemny-czyli-ubostwo-energetyczne-w-polsce/.
52. Brook, Barry W., Alonso, Agustin and Meneley, Daniel A. Why nuclear energy is sustainable and has to be part of the energy mix. *Sustainable Materials and Technologies*. 1-2, 2014, pages 8-16.
53. Adamkiewicz, Łukasz and Matyasik, Natalia. *Smog w Polsce i jego konsekwencje [Smog in Poland and its consequences]*. Warsaw: Polski Instytut Ekonomiczny, 2019. ISBN 978-83-66306-59-2.
54. Raymond, Colin, Matthews, Tom and Horton, Radley M. The emergence of heat and humidity too severe for human tolerance. *Science Advances*. Vol. 16, 2020, no. 19.
55. Human Rights Committee. *Views adopted by the Committee under article 5 (4) of the Optional Protocol, concerning communication*. The Office of the High Commissioner for Human Rights (UN Human Rights), 2015. https://tbinternet.ohchr.org/_layouts/15/treatybodyexternal/Download.aspx?symbolno=CCPR%2fC%2f127%2fD%2f2728%2f2016&Lang=en. No. 2728/2016.
56. Xu, Chi, et al. Future of the human climate niche. *Proceedings of the National Academy of Sciences*. Vol. 117, 2020, no. 21, pages 11350-11355.
57. Nuclear Energy Institute. *The Economic Benefits of Texas' Nuclear Power Plants*. 2015. 202.739.8000.
58. SENATE CHANCELLERY, OFFICE OF ANALYSIS AND DOCUMENTATION, Department of Analysis and Subject-Specific Studies. *Stosunek lokalnych społeczności krajów europejskich do lokalizacji w ich sąsiedztwie elektrowni atomowych [The attitude of local communities of European countries to the location of nuclear power plants in their vicinity]*. Polish Senate, 2009. OT-575.
59. Foratom. What People Really Think about Nuclear Energy. *Energy Policy, Economy and Law*. Vol. 62, 2017, No. 3, pages 157-163. https://www.kernd.de/kernd-wAssets/docs/fachzeitschrift-atw/2017/atw2017_03_157_What_People_Really_Think.pdf.
60. Bradish, David. Australia's Big Coal Ad Against Nuclear Power. *NEI NUCLEAR NOTES*. [Online] [Cited: 31 August 2020.] http://neinuclearnotes.blogspot.com/2008/08/australias-big-coal-ad-against-nuclear.html.

61. Łódź Radio. Związkowcy Kopalni i Elektrowni Bełchatów żądają koncesji i budowy odkrywki w Złoczewie [Trade unions of the Bełchatów Mine and Power Plant demand a license for and construction of an open pit mine in Złoczew]. [Online] [Cited: 31 August 2020.] https://www.radiolodz.pl/posts/62389-zwiazkowcy-kopalni-i-elektrowni-belchatow-zadaja-koncesji-i-budowy-odkrywki-w -zloczewie.
62. World Nuclear Association. Nuclear Power in the European Union. [Online] [Cited: 31 August 2020.] https://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx.
63. Kuczyńska, Urszula. Europejski Zielony Ład do remontu [European Green Deal for an overhaul]. *biznesalert.pl.* [Online] [Cited: 31 August 2020.] https://biznesalert.pl/europejski-zielony-lad-atom-oze-energetyka-klimat/.
64. Ministere de la Transition ecologique. Strategie Nationale Bas-Carbone (SNBC). [Online] [Cited: 31 August 2020.] https://www.ecologie.gouv.fr/strategie-nationale-bas-carbone-snbc.
65. Wiech, Jakub. *Energiewende. Nowe niemieckie imperium [Energiewende. A new German empire]*. TS Wydawnictwo Tomasz Szukała, 2019. ISBN: 978-83-65960-13-9.
66. Sroka, Paweł. *Bezpieczeństwo energetyczne: między teorią a praktyką [Energy security: between theory and practice]*. Elipsa, 2015. str. R.2. ISBN 978-83-8017-060-5.
67. Supreme Audit Office. *Inwestycje w Moce Wytwórcze Energii Elektrycznej w Latach 2012-2018 [Investments in electricity production capacity in 2012-2018]*. Warsaw: Supreme Audit Office, 2019. Ref. no. 26/2019/P/18/018/KGP.
68. Hornsdale Power Reserve-South Australia's Big Battery. [Online] [Cited: 31 August 2020.] https://hornsdalepowerreserve.com.au/.
69. Radovanović, Mirjana, Filipović, Sanja and Pavlović, Dejan. Energy security measurement - A sustainable approach. *Renewable and Sustainable Energy Reviews*. Vol. 68, 2017, Vol. Pt. 2, pages 1020-1032.
70. PGNiG. Aktualności PGNiG: mniej gazu z Rosji, rośnie import LNG [PGNiG news: less gas from Russia, LNG imports on the rise]. [Online] [Cited: 31 August 2020.] http://pgnig.pl/aktualnosci/-/news-list/id/pgnig-mniej-gazu-z-rosji-rosnie-import-lng/newsGroupId/10184?c hangeYear=2020&currentPage=1.
71. Ministerstwo Energii. *Polityka energetyczna Polski do 2040 r. - strategia rozwoju sektora paliwowo-energetycznego [Poland's energy policy until 2040 - strategy for the development of the fuel and energy sector]*. 2019. draft of 8 November 2019.
72. European Investment Bank. *EIB energy lending policy: Supporting the energy transformation*. 2019. https://www.eib.org/en/publications/eib-energy-lending-policy.htm.
73. European Council. Meeting results: Extraordinary European Council meeting, 17-21 July 2020. [Online] [Cited: 31 August 2020.] https://www.consilium.europa.eu/pl/meetings/european-council/2020/07/17-21/.
74. IPCC. *Climate Change 2014: Mitigation of Climate Change - Annex III: Technology-specific cost and performance parameters*. Cambridge University Press, 2014. https://www.ipcc.ch/report/ar5/wg3/.
75. Kolasa, Michał. Zużycie energii elektrycznej jako przybliżona miara aktywności gospodarczej (tydzień 32) [Electricity consumption as an approximate measure of economic activity]. *Polish Development Fund Group*. [Online] [Cited: 15 August 2020.] https://pfr.pl/analizy-ekonomiczne/ zuzycie-energii-elektrycznej-jako-przyblizona-miara-aktywnosci-gospodarczej-tydzien-32.html.
76. PAP - Science in Poland. Badanie: Europa ogrzewa się szybciej, niż zakładano [Study: Europe is warming

faster than assumed]. [Online] [Cited: 31 August 2020.] https://naukawpolsce.pap.pl/aktualnosci/news%2C78421%2Cbadanie-europa-ogrzewa-sie-szybciej-niz-zakladano.html.

77. OECD Nuclear Energy Agency. Post Covid-19 Recovery Plan. [Online] [Cited: 31 August 2020.] http://www.oecd-nea.org/news/2020/covid-19/post-covid-19-recovery/index.html.
78. International Energy Agency. The Covid-19 crisis is undermining nuclear power's important role in clean energy transitions. [Online] [Cited: 31 August 2020.] https://www.iea.org/commentaries/the-covid-19-crisis-is-undermining-nuclear-power-s-important-role-in-clean-energy-tr ansitions.
79. CIRE. URE: moc zainstalowana większych OZE sięgnęła w połowie roku 9,5 GW [ERO: the installed capacity of larger RES reached 9.5 GW in the middle of the year]. [Online] [Cited: 31 August 2020.] https://www.cire.pl/item,202602,1,0,0,0,0,0,ure-moc-zainstalowana-wiekszych-oze-siegnela-w-polowie-roku-95-gw.html.
80. International Energy Agency. *Nuclear Power in a Clean Energy System*. Paris: IEA, 2019. https://www.iea.org/ reports/nuclear-power-in-a-clean-energy-system.
81. International Atomic Energy Agency. *Climate Change and Nuclear Power*. IAEA, 2020. 978-92-0-115020-2.
82. European Commission. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS*. 2020. https://ec.europa.eu/transparency/regdoc/rep/1/2020/PL/ COM-2020-562-F1-PL-MAIN-PART-1.PDF. COM(2020)562 final.
83. PGE chce być w 100 proc. zielona. Jak to osiągnie zużywając węgiel? [PGE wants to be 100% green. How will it achieve by using coal?]. Online] [Cited: 16 September 2020.] https://www.green-news.pl/1260-PGE-100-proc-zielona-oze.
84. PKN ORLEN neutralny emisyjnie do 2050 [PKN ORLEN carbon-neutral by 2050]. [Online] [Cited: 9 September 2020.] https://www.orlen.pl/PL/BiuroPrasowe/Strony/PKN-ORLEN-neutralny-emisyjnie-do-2050.aspx.
85. Finansowe porozumienie przyspieszy Zielony Zwrot TAURONA [The financial agreement will accelerate TAURON's Green Turn]. [Online] [Cited: 8 July 2020.] https:// media.tauron.pl/pr/537707/finansowe-porozumienie-przyspieszy-zielony-zwrot-taurona.
86. European Commission. *Study on energy storage -contribution to the security of the electricity supply in Europe* Publications Office of the European Union, 2020. ISBN 978-92-76-03377-6.
87. Fuel Cells and Hydrogen 2 Joint Undertaking. *Hydrogen Roadmap Europe*. Publications Office of the European Union, 2019. ISBN 978-92-9246-331-1 .
88. Ministry of Climate. *Program polskiej energetyki jądrowej [Polish nuclear power program]*. Warsaw: 2020. draft dated 6 August 2020.
89. International Atomic Energy Agency. Power Reactor Information System. [Online] [Cited: 2 August 2020.] https://pris.iaea.org/PRIS/home.aspx.
90. World nuclear Association. *World Nuclear Performance Report*. 2019. Report No. 2019/007.
91. Nian, Victor. Technology perspectives from 1950 to 2100 and policy implications for the global nuclear power industry. *Progress in Nuclear Energy*. 105, 2018, pages 83-98.
92. Roh, Seungkook, Choi, Jae Young and Chang, Soon Heung. Modeling of nuclear power plant export competitiveness and its implications: The case of Korea. *Energy*. 166, 2019, pages 157-169.
93. Schneider, Mycle and Froggatt, Antony. The Current Status of the World Nuclear Industry. *The Technological and Economic Future of Nuclear Power*. 2019, pages 35-73.

94. National Skills Academy for Nuclear. About NSAN. [Online] [Cited: 31 August 2020.] https://www.nsan.co.uk/page/AboutNSAN.
95. French Embassy in London. France-UK agreement signed for training in nuclear industry. [Online] [Cited: 31 August 2020.] https://uk.ambafrance.org/France-UK-agreement-signed-for-training-in-nuclear-industry.
96. Statistics Poland. *Zatrudnienie i wynagrodzenia w gospodarce narodowej w 2016 r.* [Employment and wages in the national economy in 2016]. Warsaw: SP, 2017. https://stat.gov.pl/obszary-tematyczne/rynek-pracy/pracujacy-zatrudnieni-wynagrodzenia-koszty-pracy/zatrudnienie-i-wynagrodzenia-w-gospodarce-narodowej-w-2016-r-,1,25.html. ISSN 1509-8443.
97. Statistica. Global mortality rate by energy source 2012. [Online] [Cited: 31 August 2020.] https://www.statista.com/statistics/494425/death-rate-worldwide-by-energy-source/.
98. World Nuclear News. Second US plant licensed for 80-year operation. [Online] [Cited: 31 August 2020.] https://world-nuclear-news.org/Articles/Second-US-plant-licensed-for-80-year-operation.
99. PGE EJ1. Nastawienie mieszkańców gmin lokalizacyjnych do budowy elektrowni jądrowej [The attitude of the inhabitants of the location municipalities towards the construction of a nuclear power plant]. [Online] [Cited: 31 August 2020.] https://pgeej1.pl/Aktualnosci/nastawienie-mieszkancow-gmin-lokalizacyjnych-do-budowy-elektrowni-jadrowej2.
100. Su, Weihua, Ye, Yujing and Zhang, Chonghui. Sustainable energy development in the major power-generating countries of the European Union: The Pinch Analysis. *Journal of Cleaner Production*. Vol. 256, 2020.
101. Kiegiel, Katarzynaandi Zakrzewska-Kołtuniewicz, Grażyna. Zasoby uranu w Polsce - możliwości pozyskiwania uranu ze źródeł niekonwencjonalnych [Uranium resources in Poland - possibilities to obtain uranium from unconventional sources]. *Postępy Techniki Jądrowej*. VOL. 61, 2018, Vol. Z.2, pages 17-22.
102. IAEA Low Enriched Uranium (LEU) Bank. [Online] [Cited: 31 August 2020.] https://www.iaea.org/topics/iaea-low-enriched-uranium-bank.
103. World Nuclear Association. Nuclear Fuel Cycle Overview. [Online] [Cited: 31 August 2020.] https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/nuclear-fuel-cycle-overview.aspx.
104. PGNiG. TPGNiG Podziemne Magazyny Gazu [PGNiG Underground Gas Storage Facilities]. [Online] [Cited: 31 August 2020.] http://pgnig.pl/podziemne-magazyny-gazu.
105. Blasio, Nicola de and Nephew, Richard. *The geopolitics of nuclear power and technology*. Columbia University - Center on Global Energy Policy, 2017. https://energypolicy.columbia.edu/sites/default/files/The%20 Geopolitics%20of%20Nuclear%20Power%20and%20Technology%20033017.pdf.
106. International Atomic Energy Agency. Safeguards legal framework. [Online] [Cited: 31 August 2020.] https://www.iaea.org/topics/safeguards-legal-framework.
107. Relacje Dwustronne RP - Informator ekonomiczny [Poland's bilateral relations - Economic information source]. *Website of the Republic of Poland*. [Online] [Cited: 31 August 2020.] https://www.gov.pl /relacje-dwustronne.
108. International Renewable Energy Agency. *Renewable Energy and Jobs - Annual Review 2020*. IRENA, 2020. ISBN: 978-92-9260-266-6.

109. Photovoltaic Industry Association. *Polski rynek fotowoltaiczny w liczbach - dane 31.12.2019*. [Polish photovoltaic market in numbers - data as of 31 December 2019]. SBF, 2020. http://polskapv.pl/wp-content/uploads/2020/05/Raport_PV_2019_SBF.pdf.
110. Joint Research Centre - European Commission. *Employment in the Energy Sector - Status Report 202*0. Publications Office of the European Union, 2020. ISBN 978-92-76-18206-1.
111. rp.pl. Elektrownie słoneczne bez podatku - wyrok NSA [Photovoltaic power plants without a tax - judgment of the Supreme Administrative Court]. [Online] Rzeczpospolita. [Cited: 31 August 2020.] https://www.rp.pl/Podatki-lokalne/304159994-Elektrownie-sloneczne-bez-podatku---wyrok-NSA.html.

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Poland's decarbonization and energy transition is a challenge for the coming decades that will require a change of approach in many aspects: planning, organization of businesses, providing funds for the project and, most importantly, a coherent and sustainable strategy aimed at building a modern, competitive, and climate-neutral economy. Development of the nuclear power industry in synergy with RES is the only viable pathway to achieve climate neutrality quickly and efficiently. A half of the member states of the European Union (including Poland) use, or intend to develop, nuclear power as a part of a faster and more efficient decarbonization program. In early October 2020, Poland's Council of Ministers adopted a resolution on the update of the Polish Nuclear Power Program. The objective of the program is to build and commission nuclear power plants with the total installed capacity between 6 and approx. 9 GW. This Report, divided into 6 parts, reflects individual aspects of implementation and operation of the nuclear power sector, including with reference to the conditions prevailing in Poland.

The report contains references to the debate on whether nuclear energy should be treated in the same way as "dirty" technologies or whether it is a source of clean energy with a much lower environmental impact. Misunderstanding of nuclear power, including the concerns related to it, stems from the complexity of the issues, which simultaneously raise many issues: technical, economic, political, social, environmental, and others.

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