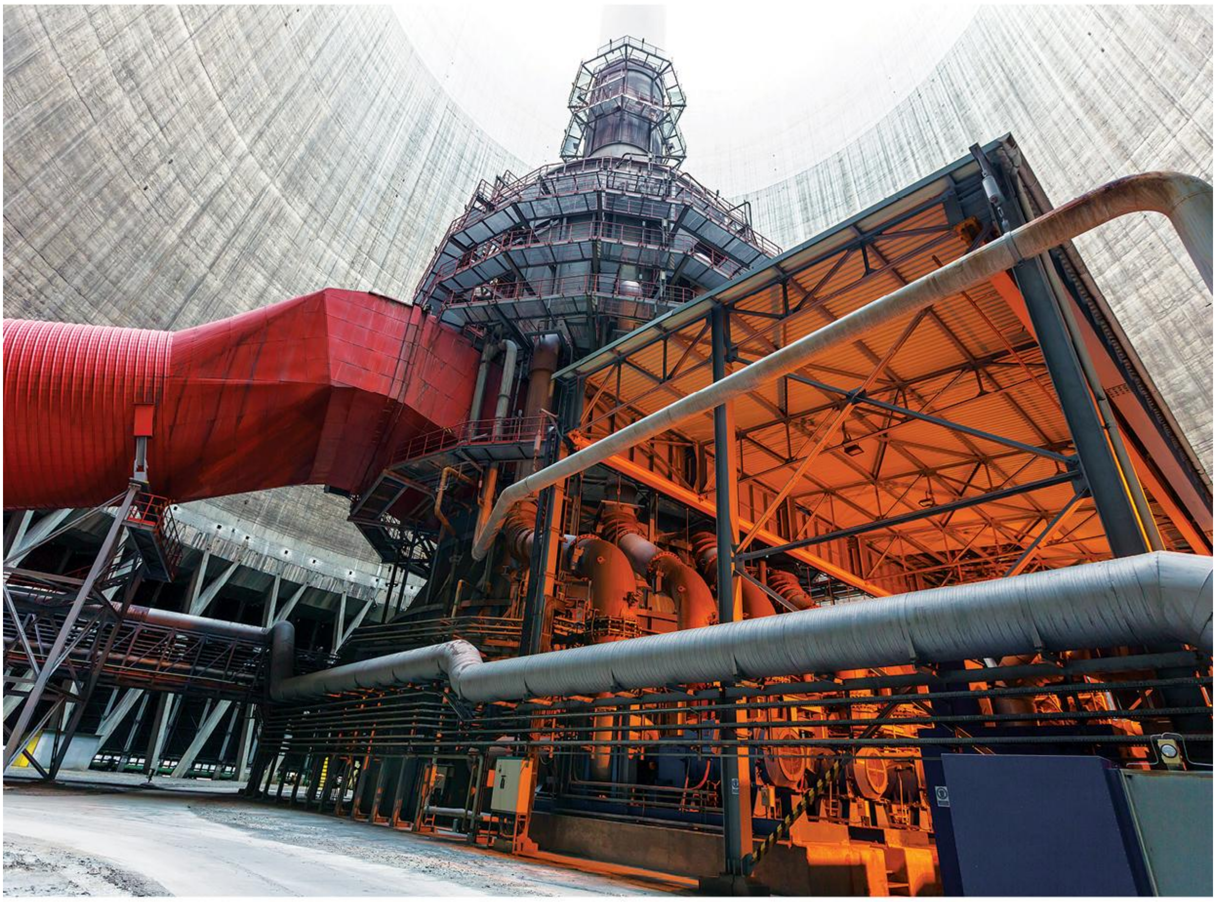
Nuclear power value chain in Poland

Report summary



Report under the direction of dr. Grzegorz Tchorek, Prof. IEn

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I – Purpose, content and research philosophy used in the report

The purpose of the report on the *Nuclear power value chain in Poland* is to define key factors for the success of nuclear power development in Poland and to assess the capabilities and define conditions that must be met by domestic companies in order to participate in this process in an optimal manner. The conclusions of the report include the assessment of several scenarios of nuclear power development, including the changes in the structure of use of various fuels and energy sources and the role of small nuclear reactors and large nuclear power plants. The report also contains recommendations allowing to plan market and institutional support instruments for the development of this power sector in Poland.

Chapter II – Global nuclear energy market, plans and development areas

Development of nuclear power in the world. Currently, there is an increase in interest in nuclear power sector and the largest number of new investments is implemented in China, Russia, South Korea and India. At the end of 2021, nuclear power generation capacity was 389.5 GWe[1], which means that it increased by just over 20% worldwide in 1990-2021. At that time, there were 437 nuclear power reactors operating worldwide in 33 countries, 17 of which are European countries, including 13 EU Member States. The largest number of reactors is operated in the USA – 93 reactors with a total power capacity of 95.5 GWe. The second is France, which has 56 operating utility nuclear reactors with a total capacity of approx. 61.4 GWe. It should be also pointed out that electricity generation in nuclear power plants increased by approx. 40% in 1990-2021.

Current projects and project duration. 56 reactors were under construction at the end of 2021, and they were located in 19 countries and had a total capacity of 58.1 GW(e)[2]. The largest power increase from NPPs is observed in Asia, where 70 new reactors with a total capacity of 63.6 GWe have been connected to the grid since 2005. The largest number of reactors is currently built in China (16 pcs), India (8 pcs), South Korea and Russia (4 pcs each). Four new reactors are being built in EU Member States (Finland, France, Slovakia). 34 reactors were commissioned in 2016-21 and the median construction time was 91 months.

Small modular reactors. In addition to the currently widely used “large” nuclear power plant sector, the vision of widespread use of *small modular reactors* (SMR) is increasingly popular. SMRs are defined as new generation advanced nuclear reactors distinguished by: (a) size – up to approx. 300/400 MWe and (b) modularity, making it possible for most components to be manufactured and assembled in factories, and then transport the

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[1] https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx

[2] https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/three-mile-island-accident.aspx

structure modules to the final place of installation. At the end of 2021, the number of documented SMR development projects was over 80[3]. Three small modular reactors are also currently in operation and located in Russia, China and Japan. At present, 5 main types of small modular nuclear reactors can be distinguished according to the International Atomic Energy Agency (IAEA): 1) water-cooled reactors; 2) high temperature gas-cooled reactors; 3) liquid metal-cooled fast reactors; 4) molten salt reactors; 5) microreactors.

Chapter III – Nuclear power position in EU climate policy

EU climate policy as part of energy transition. What is an important component in the timeline of the global energy transition is the Paris Agreement of 2016. It resulted in an EU policy that, three years later, adopted a policy of achieving climate neutrality in 2050 under the name of the "European Green Deal". The role of nuclear power in EU climate policy has so far not been above average and the European Commission has not referred to the nuclear power in subsequent regulations promulgated as part of Fit for 55. **The COVID-19 pandemic and then the war in Ukraine brought a fundamental shift in the strategic transition vision, leading to a significant destabilization of the raw material market.**

Approach to energy sources in the European Green Deal. The European Green Deal has basically affected all policies on the use of energy technologies and individual raw materials. This impact can be described as follows:

- **Coal** – it is a raw material that has a clear phase-out trajectory. Profitability of coal-fired power plants is significantly decreasing due to, among others, an increase in the prices of emission allowances on the EU ETS market and low quality of mined coal in relation to increasing purchase cost. However, the role of coal in the EU energy mix could be extended, partly replacing the potential role of natural gas as a transitional fuel.
- **Natural gas** – ultimately included as a fuel in line with EU climate policy in the EU taxonomy delegated act. However, its role remains unclear due to: high dependence on imports, involved emissions, as well as sensitivity of LCOE of gas plants to raw material prices. However, importing gas plants only as stabilizing ones seems less likely today than before the war and the pandemic.
- **RES** – due to climate and regulatory aspects, a dynamic development of RES in the EU can undoubtedly be expected. However, the basic challenge for RES development will be to ensure stability of the power system operation with an increase in the number of non-controllable facilities. In this context, it seems necessary to simultaneously develop technologies underlying the power system, as well as relatively fast reacting energy storage facilities.

[3] Advances in Small Modular Reactor Technology Developments, A supplement to: IAEA Advanced Reactors Information System (ARIS), 2022 Edition

- **Nuclear power – just like gas, nuclear power has finally been included in the EU taxonomy. It is therefore classified as a sustainable technology in line with the EU's climate policy. In the context of the EU's climate policy, it should be pointed out that nuclear power plants have three main advantages: stability of operation, zero emissions, very high efficiency of operation.** In addition, sector data indicate high controllability of nuclear plants compared to coal and gas plants. Minimizing the cost of capital by creating an optimal funding structure remains key strategic issues for nuclear plants. However, higher costs of construction of nuclear power sources may be compensated for by lower final system costs;
- **Other** – biomethane, which is referred to as a partial substitute for natural gas, also has an important potential to supplement the energy mix. Additionally, hydrogen is an important gas of the future, and its development will directly depend on the development of the RES market. Demand for hydrogen will come mainly from sectors difficult to electrify, such as refineries, chemical plants, steel industry and heavy transport. It should also be noted that hydrogen management can be additionally supported by the development of nuclear power, as stable operating nuclear plants (e.g. SMRs) can ensure predictable hydrogen production.

Nuclear power and EU climate policy. In view of the above, it can be seen that the nuclear power sector has become more and more pronounced in recent years and has begun to affect the shaping of the EU's climate policy. This significance is revealed in particular as a power system source that stabilizes RES and causes zero emissions. In accordance with the assumptions of the European Commission (as part of REPowerEU), the RES share in the energy mix is to reach 45% in 2030. Ambitious targets for the development of RES sources in the EU cause natural challenges related to the significant level of necessary balancing and stabilization of the power system. In this market situation, nuclear power is generally the only long-term solution that ensures simultaneous achievement of two strategic objectives: virtually zero CO2 emission in the life cycle and stabilization of the power system operation. The destabilization of raw material markets, in particular natural gas, has shown Russia's significant impact on the economic situation of the EU as a whole, including Poland. It should also be pointed out that the requirements implemented under regulations such as: EU taxonomy, the CEEAG state aid guidelines and the EED are ambitious requirements for new gas plants.

Nuclear power as stabilizer of the EU energy system. In view of the above factors of the market and regulatory environment, it seems that nuclear power sector may gain additional strategic importance. Firstly, it will stabilize the power system and fill the power gap with gradual phase-out from coal-fired plants and due to uncertainty as to the construction of gas plants assumed so far and the perspective of long-term prices of this raw material.

Development of nuclear power in Poland as a response to the challenges of the EU climate policy. Undoubtedly, the EU's climate policy and Russia's aggression on Ukraine causing disturbances in the functioning of the energy market are two important factors affecting the perspective of the transformation of domestic electricity generation. Poland faces the challenge of a significant transformation of the electricity generation mix because the average emission level for electricity generation is still approx. 700-750 kg of CO_2/MWh, which is one of the highest values in the European Union. High carbon intensity of the domestic power sector translates into a high exposure to emission costs related to the EU ETS, which in consequence affects the level of electricity prices at end customers and products produced in Poland with electricity.

Chapter IV – Global nuclear fuel market

Use of uranium ore. Due to its importance, nuclear fuel may constitute a separate part of the description of the value chain for nuclear power. Uranium ore is not a common raw material and its resources are not only limited, but also unevenly distributed. The extraction of uranium ore is the first stage in the preparation of nuclear fuel. The bottleneck is the availability of enriched uranium. This process can have dual applications and lead to the production of civilian fuel for nuclear reactors but also for military purposes. Even a country interested exclusively in the development of nuclear energy for civilian purposes must bear in mind that it will have to import fuel in the form of enriched uranium. If Poland does not make a decision on the construction of uranium enrichment plants or equipment is not available in the process of construction of energy production capacity from nuclear power, it must also take into account the accompanying availability of enriched uranium as a key factor affecting the energy security of Poland.

Uranium ore mining and milling. The first important component of nuclear fuel generation is the extraction of ore and its transformation into U_3O_8, referred to as “yellowcake”. The next step is to convert U_3O_8 to UF_6. UF_6 is then supplied to enUF_6 (enriched UF_6) in the enrichment process using gas diffusion technology in equipment called centrifuges (often in a cascade process). Civilian nuclear fuel is generally enriched to 3-5% U-235. The final stage in the production of usable nuclear fuel is the production of fuel. In production plants, enriched uranium is converted to uranium oxide powder (UO_2) and then formed into small ceramic pellets. Pellets are loaded into cylindrical fuel rods and then combined into reactor-specific fuel assemblies. The exact enrichment level and the types of fuel rods and assemblies are specific to each reactor.

Availability of nuclear fuel production technology. Each component of the fuel generation process (extraction, milling, conversion, enrichment, fuel production) requires access to separate technologies. Provided that there are no problems with the availability of technologies for mining or extraction from natural sources, milling, conversion or production of fuel (rods or fuel pellets). Then, the only barrier is the cost and the scale-related profitability of production. However, uranium enrichment technologies are restricted due to dual use and due to the non-proliferation of nuclear weapons and technologies related to their production, where enriched uranium is a key component. Consequently, the decision to make the aforementioned technologies available is a decision of the State providing other nuclear technologies (reactors).

Sources of uranium. Access to uranium sources is one of the cornerstones of nuclear independence. These sources can be divided into primary sources (natural resources, including conventional and non-conventional ones – with low uranium content) and secondary sources (unconventional ones – including copper industry waste, fly ash and others). Unconventional resources, i.e. rocks and materials with very low uranium content, in which it occurs mostly alongside other valuable components and is obtained as a by-product when extracting the main raw material.

Conventional uranium resources. The world's conventional uranium resources are estimated at 5.7-6.148 million tonnes. Extending the scope of geological surveys using satellite means, more precise assessments of the identified deposits changing the assessment of the economic efficiency of their use and shifting individual deposits (of uranium) from speculative to certain categories, as well as technological progress lead to an increase in the available uranium deposits. However, even if a country has large deposits, this does not mean that they are currently economically viable for industrial use. As of today, this depends on the content of uranium in the ore. Currently, Australia is the country with the largest uranium ore deposits, controlling more than 28% of the world's uranium resources. Another major player on the market is Kazakhstan in 15% of the controlled resources. Important players in the market controlling at least 5% of global resources each include: Canada, Russia, Namibia, South Africa and Brazil. Against this background, the uranium deposits located in Poland are not significant and estimates indicate their size between 7267 and 9072 tons of explored resources.

Uranium supply side. The primary supply of uranium results from the use of previously described deposits of this raw material. It is no surprise, therefore, that the main role is played by countries with high uranium resources. The main players on the market include Kazakhstan, Russia, Canada, Uzbekistan, but also France, China and the USA. In general, they come from countries that are the main producers of uranium (Kazakhstan, Canada, Uzbekistan or Russia and China), but are also based on controlled foreign deposits. First of all, Orano in France should be mentioned here.

Selection of the uranium supplier. When selecting a partner supplying uranium, it is worth knowing where it will come from, whether the supplier has the possibility to diversify the place of production from the point of view of political risk, as well as what key business partners it has. Meanwhile, production from primary sources currently accounts for only 75-76% of the global demand for uranium for civilian purposes. Increasing international tensions, plus the observed return to nuclear power or the upcoming revolution associated with the emergence of small modular reactors, may change the trends described earlier and either increase uranium production or significant price pressure associated with temporary problems with the availability of uranium from both primary and secondary sources.

Uranium conversion. Another important step in the uranium processing value chain is its conversion (before enrichment). In the EU, uranium conversion is carried out by the following plants: (1) Comurhex in France (Malvesi plant with conversion to UF4 and Pierrelatte plant with further conversion to UF6) – AREVA; (2) BNFL in Great Britain (Springfield plant in Lancashire county); (3) UKEM in Germany, but with relatively low production capacity; (4) Pitesti in Romania (its own uranium is processed there for CANDU type reactors).

Uranium conversion plants. Conversion plants operate commercially in Canada, France, Russia and China. Plants in the USA are closed, but are expected to resume operations in 2023. Production capacity in China is projected to increase significantly by 2025 and beyond to keep pace with the expected increase in domestic demand. Demand for converted uranium will significantly increase in the context of return to nuclear power, geopolitical changes or final reorientation of some countries in terms of nuclear fuel suppliers. This may lead to a dangerous demand gap for just before the planned start-up of the first reactors in Poland. However, although it seems that the nominal capacity of Western countries or the European Union will be sufficient in this context, the actual capacity will no longer be sufficient.

Uranium enrichment. Another important component of the nuclear fuel value chain is the uranium enrichment stage. Therefore, it is crucial to take into account access to opportunities for own enrichment of fissionable material or to ensure supplies from sources that are safe and secure from the point of view of political risk. Having its own enrichment capacity is particularly important in view of the planned use of SMRs, where more enriched fuel is needed. Additionally, a return to nuclear power for political reasons and climate policy favoring zero-emission energy sources or the aforementioned revolution related to the implementation of the SMRs increase demand for enriched uranium and burden on the existing plants? The current global demand for enriched uranium is approx. 51.2 million SWU/year[4]. Currently (after 2021 and the energy crisis), it can be seen clearly that there is a return to nuclear power as more economically efficient and safe source and with stable price levels, and, what is equally important, and perhaps even more important in Europe and in the future in the USA, Canada or Japan and Korea – a zero-emission energy source.

Uranium enrichment in the European Union is carried out by the following plants:

- French Georges Besse II, owned by the Societe d'Enrichissement du Tricastin (SET), a company controlled by AREVA
- and Urenco, English-Dutch-German company with sites in Capenhurst, Almelo and Gronau.

On the other hand, the world's largest player in the market is Russian TVEL controlled by Rosatom, with a production capacity of 28 million SWU/year.

Nuclear fuel production. With access to enriched uranium, nuclear fuel production can be started. It is usually concentrated in countries with suitable technologies and nuclear power plants. Fuel production is the last step in transforming uranium into nuclear fuel rods. Grouped in fuel rod assemblies, fuel rods make up most of the reactor core structure. This conversion of the replacement material – the uranium – to high-tech reactor components is conceptually different from refining and preparing fossil fuels. Nuclear fuel assemblies are specifically designed for specific reactor types (e.g. LWR,

[4] MacDonald, 2021, NPEC

PHWR) and are manufactured according to strict standards. In the case of LWR fuel, its production capacity, and thus its availability, is relatively high.

Re-enrichment of uranium. One important source of nuclear fuel is its re-enrichment. It is carried out by the same entities that provide primary uranium enrichment, and the data relating to that activity are included in their production of enriched uranium. This is an increasingly important component of the nuclear fuel value chain. Therefore, attention should be paid to where the fuel for reuse comes from, particularly since there is a phenomenon known as uranium washing, that is concealing the actual source of uranium, both on the primary and secondary markets.

Conclusions from the analysis. To sum up the assessments carried out in this part of the report, the following recommendations can be presented:

1. To develop a separate strategy for the nuclear fuel cycle with decisions whether to import ready fuel or to build capacities in part or in whole of the nuclear fuel chain, using the opportunities for outsourcing individual, especially less valuable intermediate goods on provided primary material.
2. To carry out a full political risk analysis of countries supplying not only nuclear energy production technologies, but also fuel suppliers or individual components of the cycle.
3. To assess economic viability in terms of safety of having production capacities in Poland throughout the entire fuel cycle (without obtaining ore and yellowcake). Capacities for conversion and, to a lesser extent, for uranium enrichment and nuclear fuel production appear to be crucial, especially in view of the wide use of small modular reactors (SMRs).
4. To obtain rights to or interests in uranium deposits in friendly countries – industry practice shows that this is possible. Rights to deposit may also apply to neutral countries, but then access to deposits from friendly countries should also be obtained due to risk diversification.
5. Consideration should be given to entering into a mining joint venture, but if it is not decided to acquire your own capacities, the joint venture should also cover the conversion and enrichment of uranium and the production of nuclear fuel.
6. Irrespective of whether own capabilities in the nuclear fuel chain are acquired as part of diversification, it would be advisable to obtain long-term contracts for the acquisition of yellowcake, converted and enriched uranium and nuclear fuel (to have at least two independent sources), in addition to building a strategic partnership, and to make their reserves.

Chapter V – Development areas for the Polish industry related to safe management and transport of radioactive waste

Types of radioactive waste. Radioactive waste generated from AP1000 reactor nuclear power units is solid, liquid and gaseous waste. Solid waste may include: ion exchange resins, metal components, dry granulated charcoal from filters, compactable waste (clothes, lignin, rags, etc.), plastic components, glass components, etc. Gaseous radioactive waste contains radioactive isotopes of hydrogen, nitrogen and gaseous fission products (mainly iodine, noble gases and aerosols). Liquid radioactive waste is mostly reactor coolant with boric acid, coolant from the secondary circuit of the reactor, demineralized water with solid components, liquid waste generated after decontamination, etc. Liquid radioactive waste will be processed at the place of its generation and solidified in the next step with cement mortars, and only in this form will it be transferred to radioactive waste repository. It is estimated that the total amount of solid radioactive waste generated (but not yet processed) in one AP1000 plant will be approx. 195 m^3, i.e. one nuclear power plant consisting of 3 power units, will be approx. 585 m^3/year.

Radioactive waste processing. The selection of radioactive waste solidification and processing methods depends on their physical and chemical properties and on the category of radioactive waste in question. Further preparation of the Radioactive Waste Disposal Plant State Company and Polskie Elektrownie Jądrowe Sp. z o.o. (PEJ) for optimal processing and solidification of radioactive waste will depend on the decision of the regulator on the change of classification of radioactive waste.

Radioactive waste acceptance criteria. An important aspect of spent fuel management is its initial enrichment and burn-out rate. The higher the burn-out rate, the longer the fuel should be cooled down. All processed, solidified and packaged radioactive waste must meet the waste acceptance criteria (WAC) prior to final placement in a radioactive waste repository. These criteria will be defined by the operator and approved by the regulator.

National Plan for Radioactive Waste and Spent Fuel Management. The National Plan for Radioactive Waste and Spent Fuel Management (NPRWSFM) assumes the construction of two new repositories:

- near surface repository of short-lived low and intermediate level waste, referred to as New Radioactive Waste Repository – NRWR,
- deep radioactive waste repository – DRWR, preceded by the construction of a Polish Underground Research Laboratory (PURL).

NPRWSFM assumes that by 2152, the amount of short-lived low and intermediate level radioactive waste will amount to 153,500 m^3, of which respectively:

- 54,000 m^3 from the operation of nuclear power plants (including 9,000 m^3 of intermediate level waste);
- 67,500 m^3 from decommissioning of nuclear power plants (including 6,000 m^3 of intermediate level waste);
- 12,000 m^3 from medical, industrial (non-nuclear) and scientific research applications, including the operation of the MARIA reactor and 20,000 m^3 from the decommissioning of the MARIA reactor and isotopic laboratories of the National Nuclear Research Center (NNRC).

Together with the planned reserve, 16,500 m^3, the total capacity of NRWR will be planned for the collection of 170,000 m^3 of waste. The construction of new radioactive waste repositories will largely depend on the regulator's decision on the change of the classification of radioactive waste – bringing Polish law into line with the International Atomic Energy Agency (IAEA) guidelines. If such a change were to take place, it would be worth considering to build a new third repository for very low waste – a near surface earth repository, the construction and operation of which would be much cheaper than the development of NRWR.

Radioactive waste transport. The transport of radioactive waste carried out outside of the area of the organizational unit, carried out on public roads, must be carried out in accordance with the regulations specified in the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) for materials classified in category 7 and national regulations.

Increased demand for qualified personnel. It is worth considering that the list of sites important for ensuring nuclear safety and radiological protection, as defined by the Ordinance,[5] should be extended to include additional sites strictly related to the safe storage and warehousing of radioactive waste. It is also worth noting that the number of persons with the license of the radiation protection officer of IOR-2 type is also small and access to specialist training is very limited.

Update of the NPRWSFM. One of the main challenges related to the management of radioactive waste and spent fuel will be the update of the NPRWSFM. This document should update the schedule of works related to the construction of NRWR, PURL and DRWR, as well as the current estimates related to the amount of generated radioactive waste. In Poland, it should also be aimed at amending the regulations related to the change of the radioactive waste categorization in which the category – very low lived waste – will appear.

Clearances level. Another issue that should be included in the amended law is the introduction of the “clearance level”, i.e. the level below which materials contaminated by radioactive isotopes in a trace manner that do not pose a threat to human health and the environment may be transferred to municipal waste landfills.

Preparation of the WAC. WAC should be developed in the near future for all radioactive waste repositories in Poland. These criteria should be developed by the operator of the future repository and agreed with the operator of the NPP and approved by the regulator.

Chapter VI – Business models in the nuclear power sector

Challenges related to the economics of nuclear power plants. The implementation of new nuclear projects has been facing a number of difficulties for at least 20 years: organizational, human resources and competence, market and financial ones. One of the most important disincentives to start new investments is the problem of economics of

[5] ORDINANCE OF THE COUNCIL OF MINISTERS of March 5, 2021 on the location important for ensuring nuclear safety and radiological protection.

nuclear power plants, i.e. high capital expenditures related to high costs of construction financing, often also difficulties in locating a new nuclear power plant on the broadly understood energy market.

Share of the financing costs in the total costs of a nuclear power plant. The main component of the cost of generation of a megawatt hour (MWh) of electricity in a nuclear power plant is formed by the financing costs. Financing costs include the cost of: interest payments on investment loans as well as the cost of capital, which is a combination of the cost of debt and the cost of capital provided by owners. The financing costs with the repayment of physical construction costs (including the EPC contract, i.e. Engineering, Procurement and Construction) account for up to 80% of the total cost.

Capital expenditure. The range of capital expenditure in the implemented projects is huge: from approx. 2.2 million USD/MW[6] for Korean APR-1400 units at Shin-Kori NPP in Korea up to approx. USD 15.2 million/MW[7] for US AP1000 prototype units at Vogtle NPP in USA. At this stage, it is not possible to determine credibly and responsibly the capital expenditures for Polish nuclear power plants. There was information in the media that the construction of six AP1000 power units of the Westinghouse and Bechtel consortium is initially valued at USD 40 billion, i.e. approx. USD 5,70 million/MW net[8].

The cost of financing and the cost of energy generation. Financing, in the form of equity and foreign capital, is provided by investors expecting a certain rate of return. In principle, the higher the level of risk attributed to the investment, the higher the return expected by investors. Therefore, lowering the financing costs is an extremely important aspect, as it will directly translate into lower costs of energy generation. A properly selected financing structure, diversified and reliable sources of low-cost equity and foreign capital allow to obtain a relatively low Weighted Average Cost of Capital (WACC). In most cases, both domestic and foreign financial institutions require government guarantees and the assumption by the State (taxpayers) of ultimate financial responsibility for any investment problems.

Customized investment financing model. The business model covers not only financing issues, but also ownership structure, legal form of the company, method of investment risk allocation and method of ensuring revenues (i.e. sale of energy). The latter is the most important component. This is exactly what determines most of the other aspects and ultimately determines the chosen business model. No business model identifies sources of financing, at least not for foreign capital[9]. Financing always applies to a

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[6] *Projected Costs of Generating Electricity. 2020 Edition*, NEA-OECD, Paris 2020, p. 49.

[7] https://www.powermag.com/vogtle-nuclear-expansion-price-tag-tops-30-billion/

[8] https://www.green-news.pl/3080-miroslaw-kowalik-westinghouse-polska-atom-elektrownia-jadrowa ; https://energia.rp.pl/atom/art37325621-amerykanie-wybuduja-atom-w-polsce-morawiecki-potwierdzamy-decyzje

[9] An exception is the Czech model for the Dukovany-5 power unit, in which, due to its specific nature, the authors considered some constituents of financing to be model features.

specific investment and is created only for it. The same business model used in various investment projects may have different sources of financing.

SaHo business model. The report presents the SaHo model[10], which is a new Polish business model developed for nuclear power sector, although it can also be used for other large infrastructure projects. It is a semi-cooperative model. The main idea of the SaHo model is that the State builds a nuclear power plant and then sells it to final consumers of electricity (industry, transport, trade, indirectly households). Afterwards, as owners of the power plant, they acquire the right and obligation to collect the generated energy at the cost of its generation, without a profit margin. In principle, energy should be used to cover the own needs of customer-shareholders. This is a semi-cooperative initiated (and possibly controlled) by the State in the final consumer group. Trading companies are acceptable as a complement and as a last resort.

State as primary investor. In this model, the State appoints a SaHo NPP, which it is the sole owner referred to as *primary investor*. Its statutory purpose is not to generate profit, but to construct a nuclear power plant and then to produce energy and sell it to shareholders at production cost. Upon completion of the investment project, at the latest at the time of connecting to the power grid, the State sells the shares of SaHo NPP to energy consumers, i.e. *final investors*. The sale price of energy depends on the production costs. SaHo NPP shares are sold by the State using market mechanisms (e.g. auctions), on a non-discriminatory basis, albeit under possible defined boundary conditions (e.g. minimum volumes of consumed energy). *Final investors* have the right to sell shares in the SaHo NPP, and the State, using existing regulations, can ensure supervision of these transactions. This provides *final investors* with business flexibility as they can purchase at a convenient time a number of shares that will give them the right to receive the necessary amount of energy, while at the same time they will be able to sell these shares at any time, with certain technical limitations. The report presents several possible versions for the functioning of the SaHo model. In the original version, the State sells all its shares on a single date just before connecting to the grid.

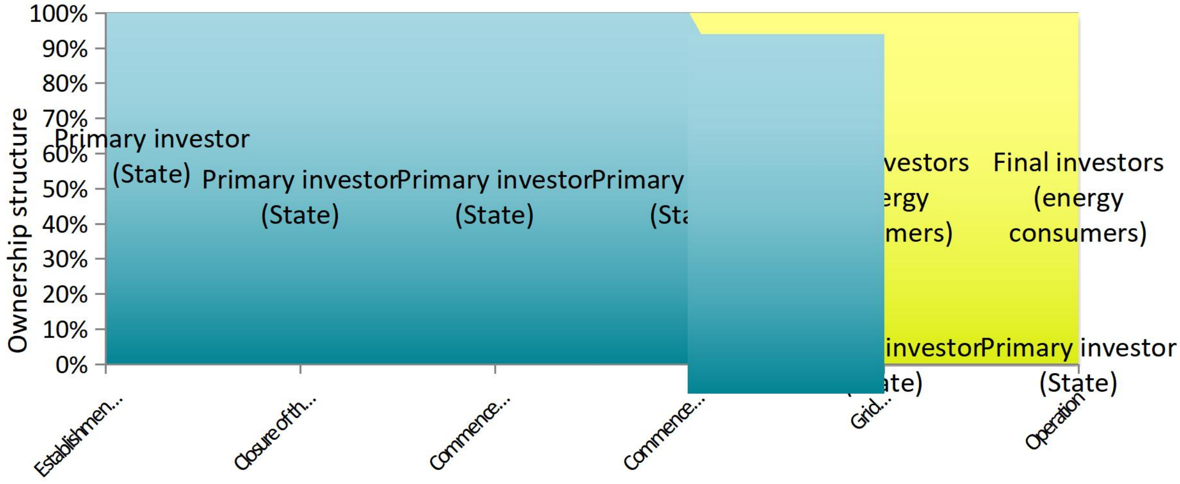


Diagram 2. Changes in the ownership structure in the SaHo model – output version

[10] The name is an acronym derived from the authors' names (Sawicki-Horbaczewska).

SaHo model variants. However, the SaHo model can also be modified through the gradual sale of shares in the SaHo NPP. Final investors acquire the right to receive energy in the future, after connection to the grid, but assume the risk and gain an impact on the investment process. In addition, the earlier the shares in the SaHo NPP are bought from the original investor, the lower their price will certainly be. The early sale of shares in SaHo NPP to final investors also benefits the original investor, the State. The funds thus obtained may be used to finance the construction of subsequent nuclear power units ("cash recycling") or used to finance other needs of the State. However, in the extended version of the SaHo model, the list of potential final investors is developed, including but not limited to local governments, state institutions or households. It is also possible to use the SaHo model with indirect investors as well as with the involvement of the technology provider.

Chapter VII – Nuclear power development scenarios in Poland

This report presents the following forecasts of the electricity generation structure in Poland until 2040, taking into account the role of nuclear power as a stabilizing and complementary source for RES:

- **Zero scenario (without detailed description)** – relating to the abandonment of nuclear power development, without the construction of nuclear reactors – currently the least probable and the least advantageous scenario,
- **Baseline scenario** (**PEP 2040/PNPP + slow SMR commercialization**) – assumes the relatively lowest share of nuclear power (both large power units and SMRs) in the structure of electricity generation in Poland at a level of approx. 7.65 GW, which will require the relatively slowest shutdown of gas (-0.5 GW) and coal (-1.5 GW) plants from the power system after 2040 in order to maintain energy security and RES balancing. The level of installed power in RES remains unchanged.

Forecast investments in large nuclear power units in 2035-2045 (*baseline scenario;* PEP 2040/PNPP + slow SMR commercialization*)*

Year	Investment	Total installed power	Accumulated number of reactors
2035	• 2 WEC-PEJ 1.1 GW nuclear power units (2 x 1.1 GW)	**2,2 GW**	**2**
2040	• 1 WEC-PEJ 1.1 GW nuclear power units (1 x 1.1 GW) • 1 nuclear unit by selected investor with a capacity of 1.1-1.65 GW (2 x 1.1 – 1.65 GW)	**4,4 – 5,5 GW**	**4**

2045	• 2 nuclear units by selected investor, each unit with a capacity of 1.1-1.65 GW (2 x 1.1 – 1.65 GW)	**6,6 – 8,8 GW**	**6**
SMR			
2035	• 1 GE Hitachi BWRX-300 SMR built by Orlen Group (1 x 300 MW)	**300 MW**	**1**
2040	• 1 NuScale six-pack built by KGHM (6 x 77 MW)	**762 MW**	**2**
2045	• 1 GE Hitachi BWRX-300 SMR built by Orlen Group (1 x 300 MW)	**1062 MW**	**3**

Source: own study based on: PEP 2040, NECP, PNPP, industry sources

- **Extended scenario** (**PEP 2040/PNPP + private investors + gradual SMR commercialization**) – assumes the participation of nuclear power (both large power units and SMRs) in the electricity generation structure in Poland at a level of approx. 12.75 GW, allows for potential additional shutdown of connection capacities in gas-fired (-2 GW) and coal-fired (-3 GW) sources after 2040. The level of installed power in RES remains unchanged. **The extended scenario was assumed as the most probable scenario**

Forecast investments in large nuclear power units in 2035-2045 (*extended scenario*; PEP 2040/PNPP + private investors + gradual SMR commercialization)

Year	Investment	Total installed power	Accumulated number of reactors
2035	• 2 WEC-PEJ 1.1 GW nuclear power units (2 x 1.1 GW) • 1 ZE PAK/PGE 1.35 GW nuclear power unit (1 x 1.35 GW)	**3,55 GW**	**3**
2040	• 1 WEC-PEJ 1.1 GW nuclear power unit (1 x 1.1 GW) • 1 nuclear unit by selected investor, unit with a capacity of 1.1-1.65 GW (1 x 1.1 – 1.65 GW) • 1 ZE PAK/PGE 1.35 GW nuclear power unit (1 x 1.35 GW)	**7,1 – 7,65 GW**	**6**
2045	• 2 nuclear units by selected investor, each unit with a capacity of 1.1-1.65 GW (2 x 1.1 – 1.65 GW) • 1 ZE PAK/PGE 1.35 GW nuclear power unit (1	**10,65 – 12,3 GW**	**9**

	x 1.35 GW)		
SMR			
2035	• 1 GE Hitachi BWRX-300 SMR built by Orlen Group (1 x 300 MW) • 1 NuScale six-pack built by KGHM (6 x 77 MW)	**762 MW**	**2**
2040	• 1 GE Hitachi BWRX-300 SMR built by Orlen Group (1 x 300 MW) • 1 NuScale six-pack built by KGHM (6 x 77 MW)	**1524 MW**	**4**
2045	• 2 GE Hitachi BWRX-300 SMRs built by Orlen Group (2 x 300 MW)	**2124 MW**	**6**

Source: own study based on: PEP 2040, NECP, PNPP, industry sources

- **Comprehensive scenario** (**PEP 2040/PNPP + private investors + quick SMR commercialization**) assumes the relatively highest share of nuclear power (both large power units and SMRs) in the structure of electricity generation in Poland at a level of approx. 17.4 GW, allows for potential additional shutdowns of connection capacities in gas-fired (-4 GW) and coal-fired (-6 GW) sources after 2040. The level of installed power in RES remains unchanged. The scenario also assumes development in other elements of the value chain, i.a. in the field of nuclear fuel (construction of own uranium conversion, uranium enrichment and nuclear fuel production plants).

Forecast investments in large nuclear power units in 2035-2045 (*comprehensive scenario;* PEP 2040/PNPP + private investors + quick SMR commercialization)

Year	Investment	Total installed power	Accumulated number of reactors
2035	• 1 WEC-PEJ 1.1 GW nuclear power unit (1 x 1.1 GW) • 1 ZE PAK/PGE 1.35 GW nuclear power unit (1 x 1.35 GW)	**2,45GW**	**2**
2040	• 2 WEC-PEJ 1.1 GW nuclear power units (2 x 1.1 GW) • 1 ZE PAK/PGE 1.35 GW nuclear power unit (1 x 1.35 GW)	**6 GW**	**5**
2045	• 4 nuclear units by selected investor, each unit with	**13,1 – 15,3**	**11**

	a capacity of 1.1-1.65 GW (4 x 1.1 – 1.65 GW) • 2 ZE PAK/PGE 1.35 GW nuclear power units (2 x 1.35 GW)	**GW**	
	SMR		
2030	• 2 GE Hitachi BWRX-300 SMRs built by Orlen Group (2 x 300 MW)	**600 MW**	**2**
2035	• 2 GE Hitachi BWRX-300 SMRs built by Orlen Group (2 x 300 MW) • 1 NuScale six-pack built by KGHM (6 x 77 MW)	**1662 MW**	**5**
2040	• 2 GE Hitachi BWRX-300 SMRs built by Orlen Group (2 x 300 MW) • 1 NuScale six-pack built by KGHM (6 x 77 MW)	**2724 MW**	**8**
2045	• 2 GE Hitachi BWRX-300 SMRs built by Orlen Group (2 x 300 MW) • Several 1 GW SMRs built by selected industry investors (i.a. offered by EDF[11])	**4324 MW**	**15+**

The above scenario analysis indicates that the share of nuclear power (both large power units and SMRs) in the structure of electricity generation may amount to 7.6-11.9% in 2035, 13.4%-20.7% in 2040 and 17.8-35.8% in 2045, respectively. In all the described scenarios, nuclear power is the basis for the operation of the national power system.

Chapter VIII – Building the supply chain and local added value – Research results

The construction of nuclear power plants in Poland poses a huge organizational and financial challenge. A very important aspect is the involvement of Polish companies and R&D institutions in the implementation of the investment projects as much as possible, so that a significant part of the incurred capital expenditures remains in Poland. During the conference "Energetyka jądrowa – rozwiązania dla Polski" [Nuclear Power – solutions for Poland] held at the Faculty of Management, University of Warsaw, in September 2022, technology suppliers applying for the contract for the construction of the power plant declared the potential participation of Polish entities in the project at a level from 40 to even 70%[12]. However, in order to achieve the above-mentioned estimates, it is necessary to mobilize all stakeholders, including Polish companies and state institutions. The key to success is not only efficient communication between all entities interested in the

[11] Respect Energy and EDF will jointly erect SMRs in Poland (wnp.pl)

[12] https://wysokienapiecie.pl/krotkie-spiecie/firmy-staraj-ce-si-o-kontrakt-na-elektrowni-atom-szacuj-udzia-polskich-firm-na-40-70/

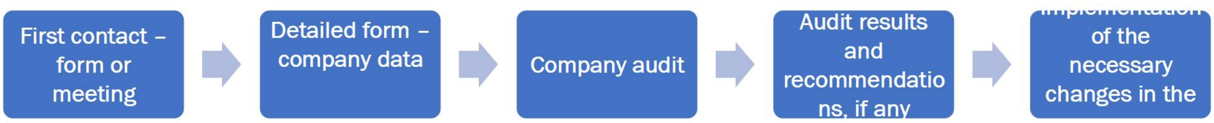
implementation of the investment project, but also quick actions, transparent guidelines for companies wishing to actively participate in the project and proper management of the project risk on the part of state institutions, including the main investor/contracting entity.

Qualification of companies by technology suppliers

Starting with companies, it is very important that they show an initiative in contact with technology suppliers, ensuring that they are seen, and demonstrate their competences. The largest number of companies with technological potential to build nuclear power in Poland should actively seek entry into the supply chain of the main technology suppliers. Qualification of a company as a potential sub-supplier, including compliance with organizational, technical and certification requirements, is the first step towards being among the narrow group of companies accepted as a potential supplier of technology or services and participating in the Polish nuclear program. At this point, it should be noted that not all companies have to meet very strict requirements of standards dedicated to nuclear power – this depends on the nature and subject of their business activity and the place of application of the product or service in the nuclear power plant. Therefore, the previously indicated communication between the company concerned and the main technology supplier is crucial, including the completion of the qualification process, which will specify detailed process requirements and other guidelines to be met by a particular company.

According to the information obtained in the completed survey of companies and technology suppliers, the process of qualification of companies wishing to participate in the project consisting in the construction of nuclear power plants can be divided into 5 stages (figure below).

Process of qualification of companies by technology suppliers in the nuclear power sector



Source: Own study

Local content **management during the construction of nuclear power plants in Poland – conclusions**

When analyzing the involvement of domestic companies in the process of development of nuclear power in Poland, it should be stated that the domestic potential for construction of the power plants themselves is large, but there are equally important barriers relating to nuclear competences in all areas of the value chain (design, construction, operation, decommissioning of power plants), resulting from the failure to implement nuclear programs and low priority of nuclear research in the last few decades. With the increasing public debate about the Polish nuclear program and the implementation of studies and market research, the main elements of the so-called local content management are visible. Based on the conducted research, the following areas can be distinguished:

1. Management of the process of qualification of companies by technology suppliers and involvement of Polish entities in the supply chains of key technology leaders.
2. Management of the process of implementation of new quality management systems, adaptation of infrastructure and purchase of equipment, obtaining certificates and accreditation in the field of nuclear power, in particular by companies which have not had any experience in working on nuclear projects so far. Implementation of investment risk mitigation mechanisms for business entities which, even after meeting technical and organizational requirements, may not be selected as sub-suppliers of services and products for the project.
3. Management and central coordination of business contacts between all stakeholders (including state institutions, technology suppliers, R&D companies and institutions). Minimization of the information chaos and the large number of contradictory media information, as well as barriers to involving many actors from different countries using different measurement systems or different quality standards in the program.
4. Organization of training courses and information meetings as well as media campaigns aimed at encouraging as many entities as possible to audit the company and identify individual possibilities of participation in the nuclear program. Development of simple and transparent catalogs of technical and certification requirements for products and services in all areas of construction of a nuclear power plant, so as to enable each interested entity to know as early as possible the scale of challenges, necessary time and financial expenditures needed to prepare for participation in the project. This will be particularly important at an early stage where contracts with the EPC Contractor have not yet been officially signed and detailed information on technical and certification requirements for individual products and services is not available.
5. Adaptation of training programs and conditions for young staff to the demand reported by both the nuclear and conventional power sector market. Promoting and giving higher priority to technical majors at universities, including in relation to nuclear power, nuclear physics, nuclear chemistry, radioisotopes and other nuclear fields, as well as education programs at technical secondary schools, in order to significantly increase the number of technical graduates, including for the needs of industry in general – e.g. welders and mechanics. Establishing cooperation with leading scientific centers in the world, specializing in nuclear technologies, including the launching of new training courses for staff, ensuring the possibility of foreign exchange and internship in foreign nuclear power plants and research laboratories.
6. Ensuring staff replacement in research institutes and R&D units with competence in nuclear technologies. Ensuring an adequate level of research funding and conditions for the reconstruction of larger research teams, including the involvement of young staff in institutes, in order to prevent the loss of competence resulting from generational change. Exploiting the existing potential in particular nuclear specializations, including the consolidation of domestic competences in the field of

radiopharmaceuticals and using the opportunities arising from new EU programs for this specialization.

7. Ensuring that appropriate provisions are included in contracts with technology suppliers and EPC Contractors for the construction of nuclear power plants in Poland and implementation of other activities which will secure the minimum share of the use of equipment and services manufactured in Poland in individual areas of the investment project. Implementation of actions aimed at equalization of the opportunities for participation in the project of Polish entities that are only entering the nuclear power market and have to compete with foreign entities that have been operating in these markets for years and are significantly stronger in terms of capital or come from countries where labor costs and costs of materials and energy are much lower than in Poland.