

Review

Selected Legal and Safety Aspects of the “Coal-To-Nuclear” Strategy in Poland

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Abstract: Poland is actively exploring the application of nuclear power as a substitute for its present reliance on fossil fuels for the generation of heat and electricity. This change reflects a calculated attempt to reduce carbon emissions, diversify the nation’s energy sources, and enhance the sustainability of its energy infrastructure. However, the implementation of nuclear technology faces many challenges, such as radiation exposure, the production of radioactive waste, the off-site effects of nuclear accidents, and high capital costs. Addressing such nuclear-safety-related issues is crucial for nuclear technology’s successful deployment. An extended analysis of the “coal-to-nuclear” process in terms of its safety has to be performed. Therefore, this review paper covers multidisciplinary studies related to the rollout of nuclear energy in Poland. The first stage of this study was the identification of the key areas of analysis, which included (i) formal requirements and recommendations imposed by international and national organizations on the process of designing and operating nuclear power systems; (ii) potential nuclear hazards for the personnel working at a nuclear reactor unit and the local population; (iii) the applied solutions of the security systems of a reactor itself, the steam turbine cycle, and the auxiliary infrastructure; and (iv) the management of spent nuclear fuel and radioactive waste. This methodology, developed based on a review of the literature and international standards, was tested for the selected country—Poland.

Keywords: small modular reactors (SMRs); coal-to-nuclear; site assessment; site selection



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1. Introduction

Coal played a crucial role in the industrial revolution and continues to play such a role in economic growth worldwide. Even though coal remains a significant contributor to the modern economy, it is also the dominant cause of global climate warming. Coal combustion is responsible for 44% of global CO₂ emissions from fuel combustion, while coal-fired power stations emit around 73% of CO₂ in the power sector [1]. Even though the economies of developing countries rely on coal, there is enormous political and financial pressure to substitute this fuel with clean energy technologies. Therefore, many countries have undertaken initiatives to reach net zero emissions in recent years. Moreover, the Russian invasion of Ukraine disrupted fossil fuel supplies, which impacted the energy market. In response to the energy crisis, several nations have revised their strategies for energy security, emphasizing the creation of a wide array of energy sources from national resources. All these factors contribute to the perception of nuclear power as a strategic source of energy. The source is projected to be important to the decarbonization process and the accomplishment of the 2050 zero net emission target while maintaining energy security.

Currently, the nuclear energy produced by 436 power reactors provides around 10% of the world’s electricity, while 59 new nuclear reactors are under construction [2]. Nevertheless, among the most important issues that should be taken into consideration in the nuclear power plant (NPP) construction process are safety, site selection, and public opinion. It is

important to prevent environmental contamination, protect workers, and mitigate potential hazards, ensuring the reliable and safe operation of a facility. Additionally, proper site selection has to be performed. This process is complex since it involves the assessment of many different environmental, economic, social, and political factors. Moreover, society at large has to be considered because negative public perceptions of nuclear power can become a hurdle for its realization [3].

An increasing interest in small modular reactors (SMRs) has been observed in recent years. These technologies, involving simplification and standardization, can be easier and more economic to deploy than conventional large units. Their use is a promising alternative for the process of decarbonizing coal-fired power stations [4,5]. According to the recommendation from the International Atomic Energy Agency (IAEA), the site selection procedure for SMRs should cover all aspects included in the Environmental Impact Assessment (EIA) for large reactors [6]. Therefore, the site preferred for NPP construction should be selected after the evaluation of all factors related to radiation accidents and the installation of NPPs. To reach this goal, a procedure for the multi-parametric analysis of many aspects related to environmental and legal issues needs to be developed. Such spatial analysis is a crucial step that should validate the construction of NPPs and their operational safety for the selected location.

2. Energy Market from the Perspective of Reducing CO₂ Emissions—Polish Case

The Polish power sector heavily relies on fossil fuel combustion, with over 70% consisting of brown and hard coals. Around 70% of such hard coal is mined in Poland. At the current level of consumption, Poland's coal resources are projected to be enough to meet its needs for hundreds of years. However, coal is buried deep underground, making its mining more complex and less economically viable [7]. Other fuels used in Poland are mainly imported because natural gas production constitutes approximately 22% of the national demand, while crude oil production only accounts for ~3.7% of this demand [8]. According to a report from the Polish Transmission System Operator (PSE) issued in June 2023, electric power production in Poland amounted to 11,811 GWh, while consumption reached 12,704 GWh. The largest market share corresponds to commercial power plants based on hard coal (44.07%) or lignite (22.90%). Wind power plants produced 7.02% of green energy, and 15.83% was generated from other renewable resources (Figure 1) [9].

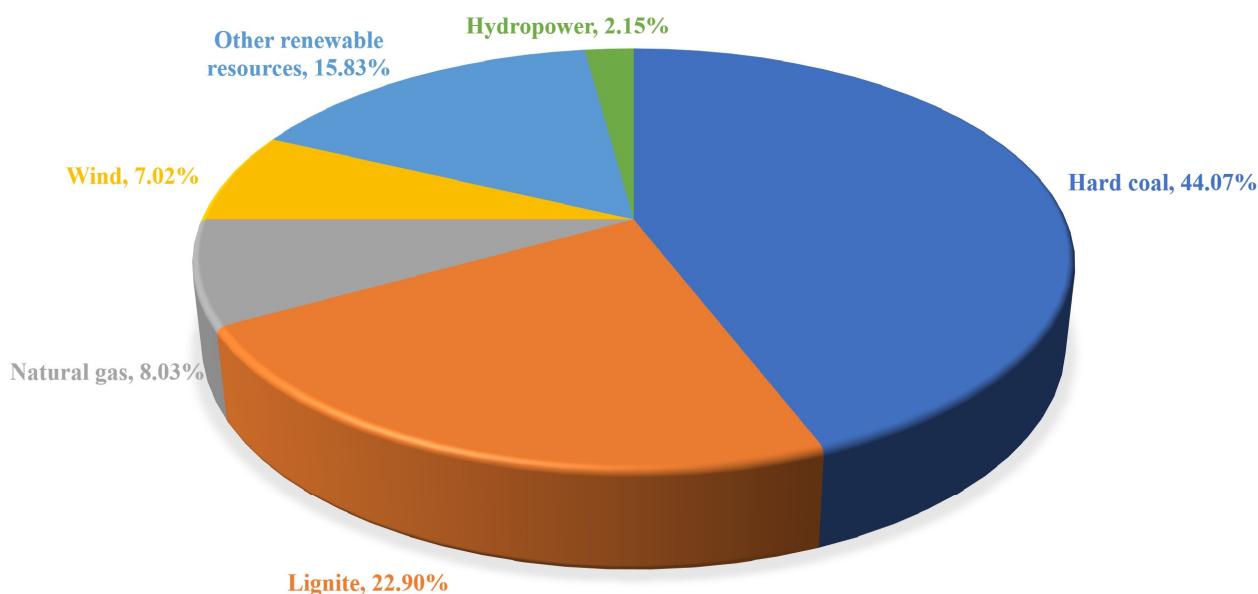


Figure 1. Breakdown of electric power production in Poland in June 2023.

The production of electric power from coal harms the environment. Poland was ranked second amongst the International Energy Agency member countries for CO₂ emission intensity for energy supply and fourth for CO₂ emission intensity for the economy in 2022 [10]. Therefore, the energy sector is responsible for the greatest proportion of CO₂ emissions (Figure 2).

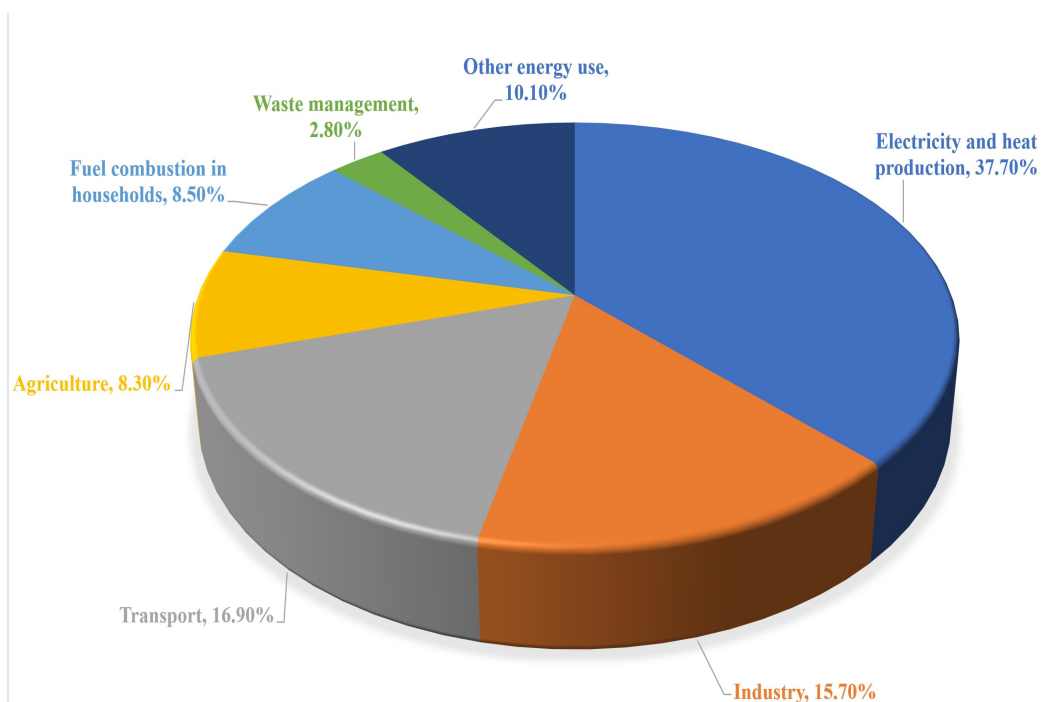


Figure 2. Breakdown of greenhouse gas emissions in Poland in 2021.

The CO₂ emission intensity (kg CO₂/MWh), calculated as the share of CO₂ emissions from electricity production, in Poland was found to be 750 kg of CO₂/MWh in 2021. This value was the second highest in the EU [11]. This indicates that reducing CO₂ emissions in the energy sector is essential and inevitable. Fulfilling the obligations mandated by the EU will also be important. The Paris Agreement signed by Poland in 2016 highlights the regional steps for mitigating climate change, including continuously reducing emissions to net zero by the middle of the 21st century [12]. Long before this treaty was adopted, the United Nations Framework Convention on Climate Change (UNFCCC) was established to combat climate change, which resulted in the adoption of the Kyoto Protocol. This initiative obliged developed countries to reduce their greenhouse gas emissions [13]. Poland ratified the protocol together with the EU member states in May 2002. Besides the environmental aspects, the decarbonization process is also driven by economic factors. This is because the cost of carbon emissions increased dramatically from EUR 31 at the start of 2021 to around EUR 100 in 2023 [14]. However, it should be emphasized that the decarbonization of the electric power sector is an indispensable requirement for reducing CO₂ emissions. Nevertheless, the decarbonization of industries, transport, and heating at large can be effective.

Coal-Fired Units in Poland

The current Polish power and heat sector analyzed in this study consists of around 300 larger coal units with a combined installed capacity of 32.9 GWe [15]. Most of these coal-fired power plants contain several units. It is worth noting that not all of them are suitable for decarbonization. According to the Polish Economic Institute, the average time for operating a coal-fired power plant is 47 years, while the average for the EU is 35 years.

The time limit for new units in service no longer than 20 years is one of the relevant criteria in this field. Older units equipped with depleted and outdated infrastructure are difficult to modernize. By applying this condition to the data from Polish coal power plants, only 55 units, totaling 16.9 GWe of capacity, were found to meet the requirements for the decarbonization process. The rest of the coal-fired power stations will be shut down gradually. More than half of the units applicable for retrofit decarbonization are units with a capacity of 200 to 400 MWe. More than 75% of them operate with steam cycles with peak temperatures in the range of 530 to 570 °C. Additionally, four units operate with steam temperatures exceeding 600 °C. About two-thirds of the applicable Polish coal power plants operate using subcritical (<22.1 MPa) steam cycles [4]. These data were taken as the starting point for choosing a coal-fired power plant, which was further analyzed for preliminary site selection.

3. Energy Sector Decarbonization Pathways

The integration of NPPs in the decarbonization process is a response to the impending need to replace aging coal-fired power plants. It will also increase the stability and flexibility of energy generation and supply. The following standards should be met by coal-fired power stations after adopting different carbon reduction technologies:

- The life cycle of greenhouse gas emissions should be below 50 g of CO_{2eq}/kWh. This represents the average emission level for electricity production systems that must be accomplished by 2050 in compliance with the terms of the Paris Agreement.
- Annual energy production (electricity and/or heat) should be maintained at a level of at least 50% of the reference value of a coal-fired unit. This corresponds to an aerial energy generation capacity of ~1 MWh/m²/y [4].

Due to climatic conditions, energy production from renewable energy sources (RESs) cannot satisfy the demand in Poland. The main obstacles preventing the more efficient exploitation of RESs include prolonged periods of low wind and reduced sunlight during the autumn and winter. The fluctuation in electricity from RESs can be partially offset by enhancing the balancing of energy sources, advancements in energy storage, and the more efficient recycling of surplus power. Another important consideration is the selection of sites and infrastructure ideal for the decarbonization process, with the retrofit application being accessible and representing a minimum of 5% of the original plant's capital expenditure [4]. Several carbon reduction techniques, including the use of solar photovoltaic (PV) panels, carbon capture systems (CCS), wind turbines, geothermal power, biomass conversion, and NPPs, are being evaluated. NPPs, in particular, are emphasized for their small area footprint, requiring around 3.4 square km per 1000 MW of energy. This means they produce more power with less land occupation compared to renewable sources (31 times less than solar facilities and 173 times less than wind farms) [16]. Moreover, nuclear energy is a clean source of energy that is independent of climatic conditions.

Nevertheless, nuclear energy faces many challenges, such as radiation exposure, the generation of radioactive waste, the off-site effects of nuclear accidents, and high capital costs. In regard to this aspect, nuclear-safety-related issues regarding decarbonizing the power sector are crucial for the effective implementation of nuclear energy. Therefore, in this work, an extended analysis of the "coal-to-nuclear" process was performed regarding its safety. The first stage consisted of the identification of the main important areas for analysis, which include the following:

- Formal requirements and recommendations imposed by international and national organizations on the process of designing and operating nuclear power systems;
- Potential nuclear hazards posed to the personnel of a nuclear reactor unit and the local population;
- The applied solutions of the security systems of a reactor, the heat cycle of a steam turbine, and the auxiliary infrastructure;
- The management of spent nuclear fuel and radioactive waste.

Afterward, critical criteria that may be an obstacle to the modernization of existing coal-boiler units in different locations in Poland were identified. This approach enabled the compilation of a list of locations where the carbon reduction process should be applied, prioritizing the ones that are paramount for nuclear safety.

4. Legal Aspects of the “Coal-to-Nuclear” Implementation Process

Preparation for the NPP construction process, further operation, and finally decommissioning must meet the highest safety standards due to an NPP’s environmental impact. International and national legal acts regulate all these safety aspects. The basic effective legal clause is the Atomic Law Act, which constitutes laws governing all nuclear activities in Poland [17]. The second important legal document act on the preparation and execution of investments in nuclear power facilities and associated investments was amended in 2023 to accelerate the construction of the first Polish NPP [18]. Moreover, other applicable complementary provisions include executive acts, acts of European Union law, and international law [19–23].

The evaluation of a site’s suitability for nuclear installation is the most crucial part of the preparatory stage. This process can significantly affect the construction time (and related costs) and safety of an NPP over its operating lifetime, translating into the level of public acceptance for the installation. Comprehensive analyses of different site parameters and external factors influencing the NPP construction process and safe NPP operation contribute to the success of a project.

The site selection process should be guided by an established set of criteria consistent with relevant regulatory requirements. Generally, the IAEA safety standards are applied as guidance for the proper selection of parameters, which should be analyzed in the process of evaluating potential sites for an NPP [22,24]. There are three main aspects that should be considered in the selection process:

1. The characteristics of a site and its environment could affect installation and further contribute to the spread of radioactive material in a situation wherein its release takes place;
2. The effects of external hazards that may occur at the selected site, including both natural risks and those induced by human activity;
3. The density and distribution of a population, together with other features of the external zone, may affect the enactment of emergency management planning and further lead to risks for individuals and the whole population.

There is a long list of natural hazards and site parameters that have to be carefully studied in the site selection process. The specifics of evaluating a potential site for the installation of an NPP are clearly outlined in Polish law (Figure 3) [19]. All the areas included in the assessment of a potential NPP site selection cover a wide spectrum of studies and data precisely described by Polish legal regulations.

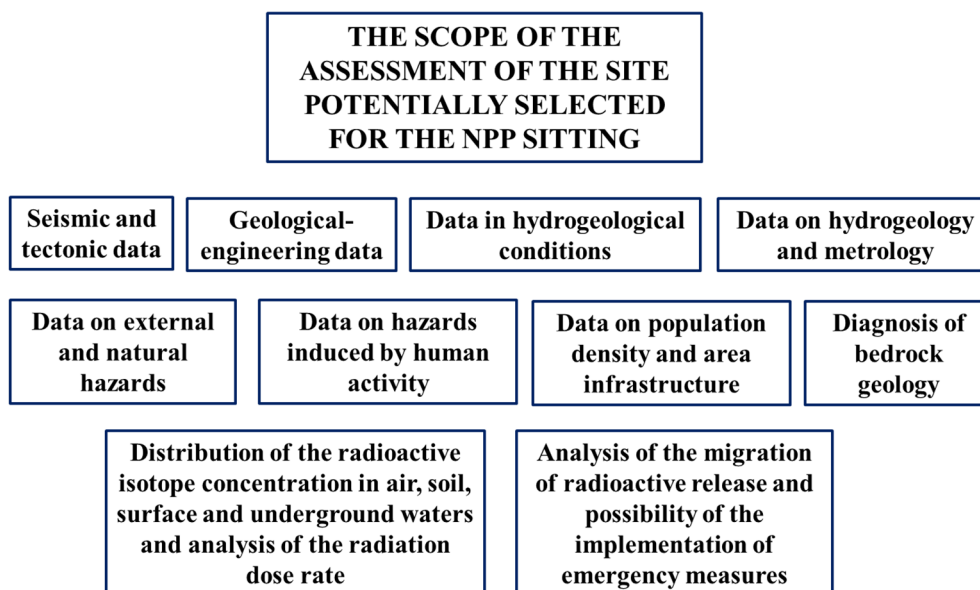


Figure 3. Components of the site assessment process used to select a site at which to situate an NPP specified by Polish legal regulations.

4.1. Seismic and Tectonic Data

The great East Japan earthquake, with a magnitude of 9.0, and the corresponding tsunami that struck a wide area of coastal Japan occurred on 11 March 2011. Several nuclear plants located in this region were affected by this disaster. The majority of them were shut down safely. However, the catastrophe happened at the Fukushima Daiichi NPP, where nearby operational and safety equipment was severely damaged by the tsunami. The earthquake also destroyed the electric power supply line for the site [25]. As a result of the disruption in cooling water circulation, the reactor cores in three units overheated, leading to core melt accidents and the explosions, leading to the release of radionuclides into the atmosphere and their deposition in soil and seawater.

Standards for the design of an NPP meant to prevent the harmful influence of natural disasters have been employed. Power plants are sometimes installed in areas affected by earthquakes. The case of the Fukushima Daiichi nuclear power only confirmed the importance of seismic and tectonic data in the site selection process [26].

According to Polish law, not only natural but also human-induced seismic activity should be analyzed. The presence of fault and land stability should be taken into account. Moreover, if an earthquake with an intensity level of VIII or higher on the European macro seismic scale (EMS-98) has been observed in the last 10,000 years or there is a probability that such an earthquake may happen more than once over 10,000 years, the corresponding area should be excluded from the list of potential NPP sites. Additionally, even if an earthquake below an EMS-98 intensity level of VIII may occur with a probability lower than once in 10,000 years, this natural disaster may influence the safe operation of an NPP, so the area should be excluded as well. The presence of an active fault line within 20 km of the site is another exclusion parameter.

4.2. Geological-Engineering Data

The building housing the reactor, turbines, steam generators, and auxiliary infrastructure needs stable ground due to its heavy construction. The containment building's average ground stress is typically about 0.5 MPa, while the other plant structures experience stresses of about 0.25 MPa on average [27]. Soil–structure interactions, groundwater conditions, liquefaction potential, bearing capacity, potential settlement and swelling, soil piping, heave, and construction settlement are all important factors to take into account when analyzing geological and engineering data. Additionally, data on surface faulting or

landslides and ground stability during earthquakes and meteorological and hydrological natural events should be provided. Moreover, a site with geological conditions that could affect the safety of an NPP and that cannot be corrected using a geotechnical treatment or compensated for by constructive measures is unacceptable [27]. If there is a risk of geological phenomena such as soil piping and landslides occurring or karst within 30 km below the site that cannot be compensated for in the installation design, the site should also be excluded.

4.3. Data on Hydrogeological Conditions

Groundwater systems should be characterized within a radius of 30 km from a planned NPP. The analyzed characteristics should include groundwater's physicochemical parameters, groundwater migration dynamics, and changes in groundwater after an NPP has been erected. The permeability of different soil layers and the influence of groundwater characteristics on concrete and steel corrosion should be also analyzed.

4.4. Data on Hydrology and Meteorology

It is important to address meteorological phenomena, including strong winds, flooding, intense precipitation, and low-temperature extremes like hoarfrost, ice floes, or frazil ice production. The characteristics of an NPP's cooling systems and how they affect the balance of surface water must be addressed. The effect of drought on the surface water and groundwater systems in relation to the effectiveness of an NPP's cooling system should be analyzed. The influence of meteorological conditions on surface water and groundwater systems, ground stability, and an NPP's cooling system must also be studied [28]. Finally, the site exclusion criterion is the risk of flooding that cannot be compensated for in the installation design.

4.5. Data on External Natural Hazards

Areas at risk of fire or other natural hazards ought to be scrutinized to confirm the safety of the planned installation. The effect of natural events such as clogging by leaves, ice floes, or other materials on the flow in cooling systems should be taken into account. The possible adverse effects of aerosols and particulate matter on nuclear installation must be examined.

4.6. Data on Hazards Induced by Human Activity

The distance from the planned and existing military facilities, such as airports or training zones has to be taken into account. Also, the presence of industrial plants that may affect the NPP through mechanical, chemical, and biological means (especially if there is a risk of a serious accident) necessitates their inclusion in the evaluation. Potential risks related to the damage of water facilities and telecommunication facilities existing in the planned NPP vicinity need to be evaluated. The presence of the listed above facilities in the vicinity of NPP that can affect negatively nuclear infrastructure and cannot be compensated in the installation design requires an exclusion criterion. In this part, it is essential to consider terrorist threats and the available transport infrastructure.

4.7. Analysis of the Migration of Radioactive Release and the Possibility of the Implementation of Emergency Measures

Population density and distribution, public utility facilities, industrial plants, rural and cattle-breeding areas, woodlands, and transport infrastructure should be characterized. Moreover, future employment levels and land development over the entirety of the operating and decommissioning periods should be determined. The condition of the population, including regarding the presence of diseases related to radiation exposure, should be monitored. One of the most important factors that may jeopardize even the best-planned investment (because of the attitude of the local population and ecological organizations)

is the presence of protected landscape areas near the scheduled NPP; therefore, this issue should also be analyzed very carefully.

4.8. Distribution of the Radioactive Isotope Concentrations in Air, Soil, and Surface and Underground Waters and Analysis of the Ionizing Radiation Dose Rate

Radionuclide concentrations and migration rates and paths outside nuclear installations need to be studied [29]. The distribution of radioactive isotope concentrations in air, soil, and surface and underground waters should be determined. Ionizing radiation dose rates ought to be provided. All these factors must be included in the assessment of the possibility of implementing effective intervention measures in the case of a radiological emergency during regular operations or with respect to anticipated radiological conditions or emergency conditions.

4.9. Diagnosis of Bedrock Geology

The presence of mineral and ore deposits should also be considered. Moreover, if ore or minerals were excavated in the area 30 km below the planned NPP in the last 60 years, the site should also be excluded.

5. Approaches in Site Selection: Large-Scale NPP Units vs. SMRs

The various requirements introduced by national law and international organizations stipulate that multicriteria analysis must be employed in the process of NPP site selection. In addition to helping to cut down on building time and expenses, this will guarantee the safety of a site. This analysis includes decision-making procedures, such as figuring out how important each criterion is for the location under study.

Different approaches have been applied for site selection in various countries. A multicriteria decision-making model (MCDM), including a fuzzy analytic network process (FANP) and the technique for order preference by similarity of ideal solution (TOPSIS), was proposed for NPP site selection in Vietnam [30]. The disadvantage of the FANP model is its limitation in the number of site selections due to the number of pairwise comparisons that need to be made. Moreover, in the FANP approach, the baseline data depend on the experience of decision makers and thus involve subjectivity. A common approach is the application of spatial-weighted multicriteria analysis. A geographic information system (GIS) can be applied alone or in combination with analytical hierarchical processes (AHPs) to determine the preferred NPP site [31–36]. Recently, this approach was additionally supported by Weighted Linear Combination (WLC), which provides more flexible and reliable results for site selection [37,38]. A Korean example confirmed that the AHP model can also be implemented to analyze items of strategic importance, urgency, and business feasibility for four significant fields related to nuclear energy: nuclear safety, decommissioning, radioactive waste management, and strengthening industrial competitiveness [39]. A quantitative model was developed to analyze optimal locations and scales for power plants, considering CO₂ reduction targets and several demand scenarios [40]. Another method, the Fuzzy Decision-Making Trial and Evaluation Laboratory (DAMATEL), which helps to create a structural model and visualizes relationship by providing a cause-and-effect diagram, was studied as a tool for NPP selection in Bushehr, Iran [41]. Twenty-two factors related to safety, the environment, economy, and local society were analyzed and scored using GIS, MCDM, and AHP methods to select suitable sites for an NPP in Egypt [42]. A combined fuzzy MCDM model that includes Interval type-2 fuzzy AHP for the determination of the weights of criteria and an interval type-2 fuzzy TOPSIS model for ranking the sites were applied to select the most suitable site for NPP construction in Turkey [43]. A preliminary analysis of the energy demand for different provinces in Turkey resulted in the recommendation of the Bursa region as a potential area for developing an NPP. Then, GIS was integrated with MCDM to evaluate nine potential locations and choose two priority sites [44]. A multi-criteria evaluation (MCE) based on GIS was applied to select potential NPP sites in Ghana [45]. Gray theory designed for handling situations

in which only limited data are available was applied to choose an NPP site in the inland part of China [46,47]. A feasibility study on NPP siting in El-Dabaa, Egypt, was carried out with the technical assistance of the IAEA in the period of 1999–2001. This survey also included an investigation of the possibility of water desalination on site. Natural freshwater resources that are fit for industrial use are mainly limited to isolated and distant locations [48]. This problem is explicitly present in the Middle East region [49]. SMRs were also considered for use for electricity generation and water desalination in the Middle East and North Africa [50,51]. Such an analysis must be supported by the environmental assessment of radioactivity levels and radiation hazards in soil [52].

Even though SMRs have not yet left the concept and design phase, more and more studies on SMR site selection are being published [53–56]. However, different approaches have been proposed. The SMR-induced environmental input–output model (SEIOM) was presented to simulate the environmental consequences of SMR development and provide suggested schemes for SMR deployment in Saskatchewan, Canada [57]. Nevertheless, the application of IAEA guidance and national provisions valid for large-scale NPPs constitute a widely recommended pattern for site selection in the case of SMRs [58,59]. However, the cited study was conducted to determine the potential of reducing the size of emergency-planning zones (EPZs) for SMRs when lower risks for these units are expected [60,61].

The idea of employing nuclear power in decarbonizing power production in Poland reflects both the need to replace aging coal-fired power plants and the necessity of increasing the stability and flexibility of energy generation and supply. The smaller footprints and higher safety margins of SMRs make them more likely to be installed in place of older coal-fired boilers in conventional power plants. However, the switch from coal to nuclear power should happen as smoothly as possible to avoid long-term power plant exclusion from the energy supply [62]. Therefore, after a nuclear reactor replaces a coal-fired power plant, the more existing infrastructure (cooling towers, grid lines, turbines, etc.) that can be used, the easier and more affordable the retrofitting process. More than 80 SMR designs are under development and being deployed at different stages [63]. The III/III+ generation SMRs, in which water is the heat carrier in the primary circuit, are based on well-developed and well-understood technologies previously applied in large-scale units. However, these nuclear reactors use relatively low temperatures and high pressures [64]. Using steam characterized by such parameters in a steam turbine would be challenging, requiring different designs compared to the those of steam turbines used in supercritical coal-fired units. A more promising idea is using IV-generation nuclear reactors, which are cooled with gas, salt, or liquid metal to generate steam with a temperature of up to 600 °C. This is because the turbines applied in supercritical coal-fired units can be maintained. Moreover, the application of IV-generation nuclear reactors enables heat production apart from electricity [65]. However, these advanced reactors employing non-conventional cooling mediums and new materials dedicated to operation in very high temperatures can pose challenges to regulators [66]. In any case, technologies that will be selected for retrofitting current coal-fired units in each separate site should be selected based on an in-depth technical and economic analysis, considering environmental and social aspects as well.

The U.S. Department of Energy (DOE) released a report demonstrating that 157 retired coal plant sites and 237 operating coal plant sites are potential candidates for a coal-to-nuclear transition. The corresponding study indicated that 80% of analyzed plants are good candidates for hosting advanced reactors operating under the gigawatt scale [67]. Analyses of the technical and economic effects of the integration of nuclear units based on a fluoride-salt-cooled high-temperature reactor, KP-FHR, on repowering an existing coal plant in Poland have already been presented [68]. A similar approach was applied to analyze the same coal-fired plant repowered with a pressurized water-reactor-type small modular nuclear system (PWR SMR) [69]. A study examining the factors affecting site readiness for different energy technologies, including SMRs within Poland, was published recently [70].

6. Safety of Nuclear Reactors

Globally, there is a fundamental principle of running an NPP: the operator is responsible for safety [71]. The national regulatory authority is accountable for assuring the safe operation of plants by the licensee and the approval of their design. Another crucial rule states that the primary objective of a regulator is to safeguard individuals and the environment. National regulators are also responsible for the design certification of reactors. International collaboration exists among these entities to different extents, and there are multiple sets of mechanical rules and standards on quality and safety [71–73].

Since the 1990s, establishing new reactor designs on an international scale has prompted the industry and regulators to pursue increased standardization in design and regulatory harmonization. A 2010 report by the OECD-NEA [74] highlighted that the calculated frequency of a significant release of radioactivity resulting from a severe NPP accident decreased by a factor of 1600 from the early Generation I reactors to the current Generation III/III+ plants under construction. On the other hand, previous designs have undergone continuous improvements throughout their lifespan.

A required safety indication is the estimated likelihood of core degradation or core meltdown events. The US Nuclear Regulatory Commission (NRC) mandates that reactor designs must adhere to a core damage frequency of 1 in 10,000 years [75]. However, contemporary designs surpass this requirement. The recent values are set at a frequency of once per 100,000 years. The existing plants with the highest level of performance now achieve a frequency of almost one occurrence in one million years [76]. The plants expected to be constructed in the next ten years are projected to achieve a frequency of nearly one occurrence probability in 10 million years. Although the calculated probability of core damage frequency has traditionally been a key measure for evaluating reactor safety, European safety authorities prioritize a deterministic approach emphasizing backup hardware's physical availability. However, they also conduct probabilistic safety analysis (PSA) to assess core damage frequency and mandate a 1 in 1 million core damage frequency requirement for new designs [77]. The primary safety issue has consistently been the potential for an uncontrolled discharge of radioactive substances, resulting in contamination and subsequent exposure to radiation outside a facility. Previously, it was hypothesized that this outcome would be probable in the case of a significant cooling failure incident (LOCA) leading to the melting of the reactor core [78,79]. With a deeper comprehension of the physics and chemistry of the materials within a reactor core during extreme circumstances, it became clear that a severe core meltdown combined with a breach of containments would probably not result in a significant radiological catastrophe in most Western reactor designs. Current licensing regulations mandate that in the event of a core melt catastrophe, the consequences must be limited to the plant's premises, eliminating the necessity of evacuating neighboring residents [80].

Nuclear reactor accidents have consistently been seen as prime examples of danger characterized by a low chance of occurrence but a great potential for severe consequences. Naturally, considering this, certain individuals are reluctant to embrace this risk, regardless of how minimal the likelihood is. Nevertheless, the intricate interplay between the physics and chemistry of a reactor core, which is partially influenced by engineering, implies that the potential repercussions of an accident are expected to be considerably less severe compared to accidents arising from other industrial and energy sources [74].

Philosophy of the Defense-In-Depth Strategy

To ensure maximum safety, NPP operators in the Western world employ a 'defense-in-depth' strategy. This involves utilizing numerous safety measures in addition to the inherent characteristics of a reactor core [81,82]. This technique encompasses several crucial elements, which can be summed up as prevention, monitoring, and action to mitigate the consequences of failures; the details are provided below:

- Superior design and construction, ensuring excellent quality;

- The use of equipment that effectively stops operational disturbances, human failures, and errors from escalating into problems;
- Using comprehensive monitoring and testing to detect equipment or operator failures;
- Implementing redundant and diverse systems to control damage to the fuel and prevent significant radioactive release;
- The implementation of measures to contain the consequences of significant fuel damage (or any other issues) within the boundaries of the power plant.

The safety safeguards encompass a range of physical barriers that separate the radioactive reactor core from the surrounding environment [82,83]. Additionally, various safety systems are in place, each equipped with backup mechanisms and designed to account for potential human errors. In addition to the physical components of safety, institutional factors are just as significant. The primary obstacles in an NPP are twofold: Firstly, the fuel is composed of compacted ceramic pellets made of uranium dioxide (UO_2). Secondly, the radioactive byproducts of fission reactions are predominantly contained within these pellets during the combustion process. The pellets are enclosed within hermetically sealed tubes made of zirconium alloy, thus creating fuel rods. The mentioned objects are enclosed within a sizable steel pressure container, including walls that can reach a thickness of 30 cm. The accompanying principal water-cooling pipes are also of significant size. The building mentioned above is further encased within a sturdy container made of reinforced concrete, with walls with a minimum thickness of one meter. Three key barriers surround the fuel, which remains stable even at very high temperatures. These barriers are constantly monitored. The level of radioactivity in the cooling water is measured to monitor the condition of the fuel cladding. The high-pressure cooling system is monitored by detecting the rate at which water leaks. However, the containment structure is periodically assessed by measuring the rate at which air leaks at approximately five times the atmospheric pressure. From a functional perspective, a nuclear reactor's three fundamental safety functions are the regulation of reactivity, fuel cooling, and the confinement of radioactive materials [84–86].

The primary safety characteristics of the majority of reactors are inherent, namely, the negative temperature coefficient and negative void coefficient [87]. The former indicates that beyond an optimal threshold, the effectiveness of a reaction diminishes as the temperature rises. This phenomenon is utilized in specific modern designs to regulate power levels. The latter implies that the presence of steam in the cooling water leads to a reduction in the moderating effect, resulting in a decreased ability of neutrons to induce fission [88]. Consequently, the reaction naturally decelerates.

Beyond the control rods, which are inserted to absorb neutrons and regulate the fission process, the main engineered safety provisions are the back-up emergency core-cooling system (ECCS) designed to remove excess heat and the containment [89]. Conventional nuclear reactor safety systems are considered 'active' since they rely on electrical or mechanical operation when instructed. Certain engineering systems function in a passive manner, such as pressure relief valves. Both necessitate the integration of parallel redundancy systems [90,91]. The inherent or full passive safety design relies solely on physical phenomena, such as convection, gravity, or resistance to high temperatures, rather than the operation of manufactured components [92,93]. All reactors possess certain inherent safety characteristics, as previously indicated. However, passive or inherent features are employed in more contemporary designs to replace active systems for cooling and other functions. Such a design can prevent accidents by mitigating the loss of electrical power, which leads to the loss of cooling function [94,95]. The basis of this design presupposes a scenario in which there is a risk of core melting and a breach of containment, either as a result of an accident or malicious intent, such as terrorism [96,97]. The dual potential of this situation has been thoroughly studied and provides the basis for exclusion zones and contingency plans. In addition, NPPs use seismic sensors that trigger automatic shutdown mechanisms in the event of an earthquake, making this a crucial factor in numerous regions worldwide [98,99].

The highest safety standards characterize primarily modern-generation III/III+ reactors and emerging modern SMR designs. Many of the benefits of SMRs are inherently linked to the nature of their design—small and modular [63]. Due to their compact size, SMRs can be placed in areas that are unsuitable for larger NPPs. SMRs can be produced as pre-made modules and subsequently transported and installed at the desired place, resulting in lower construction costs compared to larger power reactors. The latter are sometimes tailored to specific sites, which can cause delays in the construction process [100]. Small modular reactors provide cost and time savings as well as the ability to be implemented gradually to meet growing energy needs. Compared to current large-scale reactors, the suggested designs for small modular reactors are typically less complex [101]. The safety approach for SMRs often depends more on passive systems and the inherent safety features of the reactor, such as its low-power and operating pressure [102]. In these circumstances, passive systems operate without the need for human interaction or external power sources to shut down systems. They rely on physical processes, such as natural circulation, convection, gravity, and self-pressurization. These enhanced safety margins, in certain instances, eradicate or substantially reduce the possibility of the release of hazardous emissions of radioactivity into the environment and the general population in the event of an accident. Moreover, SMR designs benefit from incorporating existing safeguards and security prerequisites [103].

The engineering process for designing new SMRs includes integrating facility protection systems, which consist of barriers that can withstand potential aircraft crashes and other specific threats. Most small modular reactors are built underground to enhance safety and security protocols, effectively mitigating possible hazards arising from deliberate sabotage and natural calamities [100].

Furthermore, there has been a reduction in the fuel consumption of small modular reactors. SMR power plants require less-frequent refueling, often needing to be refueled every 3 to 7 years, in contrast to the refueling cycles of standard plants, which must be refueled every 1 to 2 years [104]. Certain SMRs will be engineered to function for prolonged durations without refueling. These SMRs have the potential to be manufactured and powered in a controlled environment, securely transported to designated locations for electricity production or heat generation, and subsequently brought back to the factory for the safe removal of fuel at the end of their operational lifespans. This technology has the potential to reduce the transportation and handling of radioactive material. Light water-based small modular reactors SMRs are anticipated to utilize low-enriched uranium as fuel, which is comparable to the fuel used in current large-scale NPPs [105,106]. Further, IV-generation SMRs based on non-light water reactor coolants could be more effective at dispositioning plutonium while minimizing the amount of waste requiring disposal and offering high operating temperatures suitable for the industry and the direct retrofitting of conventional power plants [63,107,108].

Because of SMRs' safety advantages, there are considerations regarding the shrinking the size of the emergency planning zone (EPZ) surrounding an SMR plant from the current standard of 30 km to as little as 400 m, making it easier to site the plants near population centers and in convenient locations such as former coal plants and military bases [109,110]. On the other hand, safety and security improvements are critical to establishing the viability of nuclear power as an energy source for the future, so the nuclear industry and regulators should focus on developing safer reactor designs rather than weakening regulations. Ultimately, the national regulator is responsible for ensuring the plants are operated safely by the licensee and that the design is approved. This means that safety considerations play a key role. In the Polish "coal to nuclear" program, all of the technological safety measures have been taken into account. All of the examined reactor designs fulfill the safety and licensing standards. The main differences between the technologies are the results of the offered parameters, such as the temperature of the coolant for electricity production [4,62,68]. Some of the technologies are better scored because they are already in operation, produce less nuclear waste, or have a lower demand for cooling water. The first

stage of the concept aimed at exchanging the existing coal power plants with NPPs is site assessment for existing Polish coal-fired plants.

7. Proposed Methodology for Assessing Nuclear Safety of “Coal-To-Nuclear” Process in Poland

This work presents the site assessments for 24 existing Polish coal-fired plants slated to be retrofitted with various types of nuclear reactors. This study includes the assessment of 23 sites dedicated to being repowered with a Gen III/III+ nuclear reactor and 9 sites expected to be retrofitted with a Gen IV nuclear reactor. Based on formal requirements and recommendations imposed by international and national organizations on the process of designing and operating nuclear power systems, the following aspects for site assessment and selection were developed:

- Potential nuclear hazards regarding the personnel of a nuclear reactor unit and the local population;
- The applied solutions of the security systems of the reactor itself; the heat cycle of the steam turbine and the auxiliary infrastructure;
- The management of spent nuclear fuel and radioactive waste,

The regulations described above and included in Polish legal acts were the starting point for developing a list of the hazards excluding an area from being considered a potential nuclear plant site (Table 1).

Table 1. List of the hazards excluding an area from being considered a potential nuclear plant site.

No	Hazards Excluding an Area from being Considered a Potential Nuclear Plant Site
1.	Geological conditions that could affect the safety of a nuclear power plant and that cannot be corrected through a geotechnical treatment or compensated for by constructive measures.
2.	The presence of an active fault line within 20 km below the site.
3.	An earthquake of an intensity level of VIII or higher according to the European macro-seismic scale (EMS-98) observed in the last 10,000 years or a probability that such an earthquake may happen more than once in 10,000 years in the area 30 km below the site.
4.	The possibility of an earthquake below the intensity level of VIII according to EMS-98 happening with a probability lower than once in 10,000 years but which may influence the safe operation of the NPP.
5.	A risk of a geological phenomenon, such as soil piping, landslides, or karst, occurring within 30 km below a site that cannot be compensated for in the installation design
6.	A risk of flood or flooding occurrence that cannot be compensated in the installation design in the area within 5 km from the site.
7.	Excavation of ores or minerals within 30 km from the site in the last 60 years.
8.	The implementation of effective intervention measures in the case of a radiological emergency will not be possible.
9.	The presence of military facilities or military zones; industrial plants that may affect the NPP by mechanical, chemical, and/or biological means; and water facilities that can negatively affect nuclear infrastructure if this negative impact cannot be compensated for in the installation design.
10.	The presence of a civilian airport within 10 km from the site, unless the probability of an airliner crashing into the nuclear facility is lower than once in 10,000,000 years.

The population density 30 km from a site is one of the most important criteria. It is even more crucial if we consider societal exposure to ionizing radiation in the case of a radiological emergency. Additionally, it is essential to develop transport infrastructure, which enables efficient evacuation and rescue operations in case of an emergency. If analyzing the migration of released radioactive material outside an NPP, hydrological and wind conditions within 30 km from the site should be taken into account. The presence of protected landscape areas around the planned NPP has been selected as one of the most decisive factors in the process of site selection. Such criteria are of particular importance in the assessment of sites that can be excluded.

Results

To assess the nuclear safety of power units planned to be modernized through the installation of nuclear reactors, a catalogue of basic organizational and design solutions was developed. As part of the preparation of the catalogue, the following areas, important from the point of view of the safety of the entire modernization process (licensing, design, commissioning, operation, and decommissioning processes) were analyzed:

1. Formal requirements and recommendations imposed by international and national organizations on the process of designing and operating nuclear power systems;
2. Potential nuclear hazards posed to the personnel of the nuclear reactor unit and the local population;
3. The applied solutions of the security systems of the reactor itself, the heat cycle of the steam turbine, and the auxiliary infrastructure;
4. Management of spent nuclear fuel and radioactive waste.

In each of these areas, a set of criteria has been identified (Table 2), which must be considered when assessing the safety of the entire modernization process of existing coal units.

Table 2. Lists of parameters identified for each safety area and weights of these parameters given in brackets: (x/y), separately for Gen III/III+ (x) and Gen IV (y) nuclear reactors.

No	Area of Analyses	Criteria and Their Weight for Third- and Fourth-Gen Reactors
1.	Formal requirements and recommendations imposed by international and national organizations on the process of designing and operating nuclear power systems	<ul style="list-style-type: none"> • Mechanical parameters of soils (5/5); • Occurrence of natural seismic activity (5/5); • Occurrence of floods or inundations potentially threatening the safety of the nuclear facility in the area (5/5); • The presence of mineral deposits in the region or the existence of a mine or mining activity in the last 60 years (5/5); • The existence of a military facility or military restricted area (5/5); • The existence of a facility that may affect the nuclear facility chemically, biologically, or mechanically (5/5); • The presence of a water facility fitting the definition of the Act of July 18, 2001—Water Law (5/5); • The existence of a civil airport less than 10 km from a nuclear facility (5/5); • The existence of naturally and culturally protected areas (2/2).
2.	The applied solutions of the security systems of the reactor itself, the heat cycle of the steam turbine, and the auxiliary infrastructure.	<ul style="list-style-type: none"> • Number of security systems (5/5); • Cooling systems' redundancy (4/4); • Access to local water sources sufficient for cooling the nuclear facility (4/2); • Consequences of a severe reactor accidents (2/2); • The degree of technology advancement (4/2).
3.	Potential nuclear threats to the personnel of the nuclear reactor unit and local population.	<ul style="list-style-type: none"> • Population density (5/4); • The degree of development of communication infrastructure (3/3); • Hydrogeological conditions (3/2); • Windiness of the region where the nuclear facility is located (3/2).
4.	Management of spent nuclear fuel and radioactive waste.	<ul style="list-style-type: none"> • Availability of RW management technology (4/4); • Availability of SF management technology (4/4); • Quantity of SF and RW (3/3); • RW from decommissioning (3/3).

Measurable and quantifiable parameters were assigned to individual evaluation criteria. A six-point grading system was adopted for each area, ranging from zero to five points, where five points meant that very favorable features were found for a given criterion, and zero points means that no promising characteristics were noted. Moreover, weights (ranging from one to five) were proposed for these parameters, which were intended to

reflect the importance of a given guideline in the context of nuclear safety. A weight of “5” means that a given measure was considered very important for the overall assessment. A weight of “1” means that a given parameter was considered to be of little importance for the overall assessment. The weights of individual criteria were considered separately for III/III+ generation nuclear reactors and separately for IV-generation reactors.

Based on this method, 23 coal blocks were examined, taking into account the parameters of areas number (No) 1 and 3, as they are site-specific and allow a rough assessment of coal blocks considered for modernization using nuclear reactors. All of the criteria sets for the four areas (Nos. 1 to No. 4) were then used, and only a small subset of the coal-fired units that were chosen for this preliminary rough assessment were subjected to more thorough examinations. The results of the evaluation of the 23 coal blocks are presented in Figure 4.

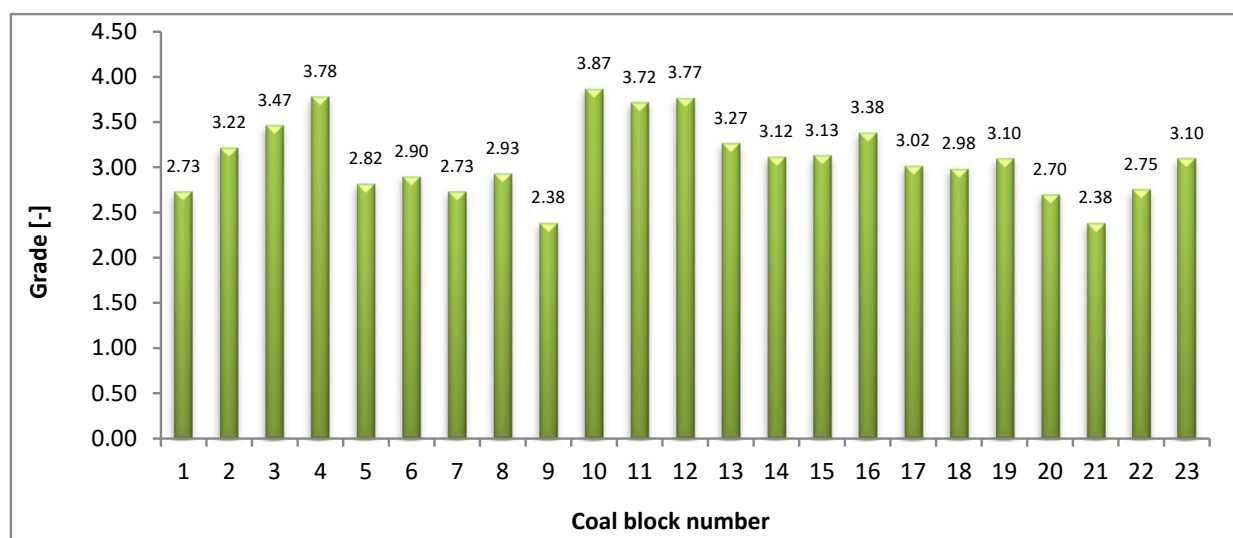


Figure 4. Results of the assessment of the 23 coal blocks considering site-specific parameters (Area No 1 and No 3).

Moreover, experts from Energoprojekt-Katowice assessed the technical aspects of the infrastructure of the coal assets of these 23 coal blocks. They took into account the location and ease of access to cooling water, the features and state of the power output system, the layout and accessibility of the cooling water unit, the space needed to organize the construction site and develop the reactor system, and the local demand for decarbonized heat. A common ranking of coal blocks was established as a result of these two simultaneous assessments.

Based on this ranking, four coal blocks (ST1–ST4) were selected for further analysis, considering the use of generation III/III+ reactors. In the case of generation IV reactors, the two coal-fired units (ST5 and ST6) were chosen for deeper examination. The locations of the individual coal blocks are shown in Figure 5.

Detailed analyses of key requirements and recommendations regarding nuclear safety were carried out for the units mentioned above. The assessment covered all four areas, vital for the safety of the whole modernization process. It concentrated on commissioning, licensing, design, operation, and decommissioning. The evaluation followed a prepared catalogue of important design and organizational solutions regarding nuclear safety for a modernized power unit. The results of the assessment are given in Table 3.



Figure 5. Location of the assessed coal blocks.

Table 3. Ranking of coal blocks regarding the safety of their modernization with nuclear reactors (a) for Gen III/III+ nuclear reactors and (b) Gen IV nuclear reactors.

(a)									
Number of points in each area:	ST1		ST2		ST3		ST4		
Area No 1	186		147		177		147		
Area No 2	87		83		87		87		
Area No 3	41		64		29		56		
Area No 4	60		60		60		60		
Total	374		354		353		350		
(b)									
Type of reactor	HTR-PM		IMSR400		KP-FHR		Xe-100		
Number of points in each area:	ST5	ST6	ST5	ST6	ST5	ST6	ST5	ST6	
Area No 1	152	122	152	122	152	122	152	122	
Area No 2	64	64	62	62	61	61	60	60	
Area No 3	30	33	30	33	30	33	30	33	
Area No 4	25	25	21	21	21	21	25	25	
Total	271	244	265	238	264	237	267	240	

The adopted evaluation criteria showed that the key safety aspects are related mainly to the location where the planned modernization was slated to take place. Due to the high standards and nuclear safety requirements, all the assessed technologies are comparable (Table 3b).

It should be emphasized that in the current legal system, SMR structures are assessed in a manner exactly like that applied to large-scale reactors (LNR). This results in a lack of an undoubted advantage of SMRs, namely, the ability to limit exclusion zones around reactors. Therefore, the main differences between the individual reactors assessed result from the type of coolant (Gen IV reactors are cooled with gas or molten salts), the type of fuel used, and the level of technological advancement in developing a specific reactor. In the second criterion, known and operational third-generation designs and the HTR-PM reactor have a significant advantage.

8. Conclusions

The Polish decarbonization program needs nuclear reactors and safety site assessment, constituting some of the first stages of coal-fired boilers' replacement with nuclear reactors. Site selection is a complex procedure that involves the assessment of many different environmental, economic, and political factors. The various requirements introduced by national law and international organizations stipulate that multicriteria analysis must be employed in the NPP site selection process to ensure the location's maximal safety. The analysis carried out in this study was based on the national and international requirements and allowed us to analyze many factors grouped into four different areas essential for the safe construction, operation, and decommissioning of NPPs. It is important to underline that all the SMR designs that meet licensing and safety requirements were evaluated as potential technologies that can be used to retrofit coal-fired boilers. Starting from the comprehensive analysis of a large number of sites located in all parts of Poland where coal-fired power plants currently operate and that fulfill the criteria for being retrofitted with nuclear reactors, six of the most promising sites were selected for further, more detailed analysis. Taking into account different criteria that were assessed for Gen III/III+ and Gen IV reactors, four preferential locations for retrofitting with Gen III/III+ nuclear reactors were evaluated, and the two most promising locations for replacing coal-boilers with IV Gen reactors were determined.

This complex analysis resulted in a ranking list, which gives directions regarding the sites for which the implementation of the "coal-to-nuclear" approach would be the most economical and problem-free. No industry is immune from accidents, including nuclear power. The enormous energy density of nuclear power makes the potential danger evident, and this has always been taken into account when designing nuclear power facilities. Nevertheless, the safety of nuclear power relies on meticulous planning, conservative design with ample margins and backup systems, top-notch components, and a well-established safety culture in operation. The longevity of reactors is contingent upon preserving their safety margin, rendering the utilization of nuclear energy for electricity generation exceedingly secure.

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