Potential for Repowering Inland Coal-Fired Power Plants Using Nuclear Reactors According to the Coal-to-Nuclear Concept

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Abstract: The popularity of nuclear power as a high-availability energy source is increasing in countries that currently rely on coal-based energy. The growing use of renewable energy sources emphasizes the need for greater energy supply security and grid stability. However, nuclear reactors remain the most expensive commercially available power-generation technology, which limits investment in this field. This paper explores the feasibility of investing in Coal-to-Nuclear conversion at selected coal-fired power plant sites in Poland. By converting coal-fired infrastructure, it is possible to reduce the financial cost of constructing a nuclear power plant. The study included an analysis of hydrological conditions from 2010 to 2023 at selected locations, which determined the potential for siting high-power nuclear reactors. An analytical model was used to calculate the required water intake for cooling, and the results were compared with actual river flow measurements. The findings suggested that constructing an inland nuclear power plant in Poland is feasible while complying with legal standards regarding maximum cooling water temperature. The assessment of the four sites allowed appropriate recommendations to be made concerning further research into the implementation of Generation III reactors.

Keywords: Coal-to-Nuclear; energy transition; nuclear energy; coal-fired power plant; nuclear power plant

1. Introduction

The ongoing energy transition in Poland is resulting in significant changes in electricity production, as well as social and economic aspects. In 2014, power plants powered by hard coal had a total installed capacity of 19.4 GWe, representing about 54% of the National Power System (NPS) structure [1]. Lignite-based sources accounted for 8.4 GWe (23.5%). Renewable energy sources (RES) made up only around 11% of the NPS structure, with 3.8 GWe from wind capacity and 0.2 GWe from photovoltaic systems. By 2023, the share of RES in installed capacity had increased to 39.3%, with photovoltaic systems accounting for 14.3 GWe, and 9.6 GWe from wind turbines. The share of coal-fired sources decreased to 43.2%, with hard coal-fired power plants totaling 18.7 GW (30.7% of the NPS structure) and lignite-fired units at 7.6 GWe (12.5%). RES sources in 2023 produced 39.42 TWh of electricity, representing 25.3% of total production in Poland [1,2]. Further reductions in coal-fired capacity are expected in the coming years. Rusin and Wojaczek [3] showed that the structure of the Polish power system in 2035 does not ensure the country’s energy security. They calculated that in 2030, the maximum demand for electricity could reach 29.3 GWe, and the probability that the Polish power system will not be able to meet this demand is almost 13%. In 2035, when consumer demand will reach 30.3 GWe, the probability of this situation will be 100%. In 2040, the structure of the Polish power system, with over 72 GWe of installed capacity, is expected to be based on about 50% renewables and only about 19% conventional coal-fired generation [4]. The high share of RES in the national energy mix may
lead to grid instability due to their unpredictable operation [5]. Renewable energy sources affect the dynamic change of power distribution in the grid and the change of equipment operating points, as well as fluctuations in grid voltage and frequency [6]. Alhelou et al. [7] showed that it is necessary to maintain the contribution of conventional energy sources together with the implementation of large and micro energy storage systems to maintain grid stability. Lynch et al. [8] have shown, based on the author’s model, that nuclear power plants can operate successfully in a system deeply penetrated by renewable energy sources, especially with appropriate spent nuclear fuel replacement planning. Proper planning also reduces CO₂ emissions by reducing the operation of gas-fired power plants. Cany et al. [9], in 2018, discussed the prospect of a nuclear-based NSE and its development, focusing on the implementation of RES, using the French electricity system as an example. In 2023, nuclear and RES accounted for 67% and 26.2% of French electricity production, respectively [1]. The authors of the paper have analysed scenarios for 2030 and 2050 in which the share of nuclear power declines to less than 50% of total electricity generation. The main conclusion of the paper is to question the process of intensively increasing the share of renewables in the French electricity system due to the decrease in its flexibility. This in turn leads to an increase in greenhouse gas emissions caused by the operation of gas-fired peaking sources. The authors point out that it may be necessary to maintain the potential of nuclear power in France and to develop efficient energy storage and Power-to-X systems to increase the utilisation of nuclear units. Bartela et al. [10] investigated the possibility of integrating Kairos Power’s 320 MWth nuclear reactor system with a molten salt thermal storage system. The concept involves the use of an exchanger system and thermal energy storage (TES) between the reactor primary circuit and the steam generator and steam turbine circuits. The high-temperature heat-storage tank is designed to store salt at a temperature of approximately 600 °C, with the salt maintained in the liquid phase throughout the system. The authors showed that with the expected increase in the share of RES in the energy mix, energy storage of about 1200 MWh would be beneficial, allowing for increased plant flexibility while maintaining a stable operation of the nuclear reactors. The cost of the TES tank would represent only about 7.4% of the total investment for the nuclear unit. A similar concept has been proposed by Kosman et al. [11,12] as a way to retrofit existing coal-fired units. The research included the possibility of adapting the steam turbines to operate at minimum load, while the boiler is continuously operated at nominal parameters.

Figure 1 provides data on the net total electrical output of nuclear reactors in operation and under construction [13].

Figure 1. The total net active and built nuclear reactor capacity worldwide.

Figure 1 demonstrates that the most significant expansion of nuclear power capacity is occurring in Asia, with China at the forefront. As early as April 2024, China had 25 nuclear reactors under construction, with a total gross capacity of over 26 GWe. Of these, 23 were
PWRs and two were FBRs. In Japan, two nuclear reactors with a total capacity of 2.6 GWe are under construction, and the operation of 21 reactors with a capacity of almost 21 GWe remains suspended following the Fukushima nuclear disaster in 2011. Two reactors are also under construction in South Korea. India is the second country with the largest number of nuclear reactors under construction, with seven reactors under construction with a total capacity of 5.4 GWe. Four PWR VVER V-412 reactors are currently under construction at the Kudankulam nuclear power plant with a capacity of 1000 MWe. Russian reactors also form the basis for nuclear power construction in Turkey and Egypt. Four VVER V-509 reactors with a gross electrical output of 1200 MWe are currently under construction at Turkey’s Akkuyu power plant. The El Dabaa nuclear power plant in Egypt will be equipped with four VVER-1200-type reactors with a gross electrical capacity of 1200 MWe. Construction of these units commenced between 2022 and 2024. In Europe, the construction of nuclear power plants has commenced in Russia (four reactors with a total net capacity of 3.85 GWe), the United Kingdom (two reactors with a total capacity of 3.26 GWe), Ukraine (two reactors with a total capacity of 2.07 GWe), and Slovakia (one reactor with a capacity of 0.44 GWe).

In 2023, Lazard published a report outlining the financial expenditure for commercially available electricity sources [14]. The minimum Overnight Construction Costs (OCC) in new Generation III nuclear power plants is USD 8475/kW, and the maximum is USD 13,925/kW, which is in line with the planned investment values in Bulgaria. The construction of two AP-1000 reactors in Bulgaria has been announced. The second-most expensive source of electricity is coal-fired power, for which the upper limit of investment costs is USD 6775/kW. Nuclear power plants are characterised by a density of produced electricity ranging from 214 We/m$^2$ to 363.5 We/m$^2$ [15]. However, both fuel availability and cost must be considered—75% of the cost of generating electricity from gas-fired and gas-steam systems is a time-varying value [16] and depends on external factors. In the case of a nuclear power plant, only about 15% of the cost of generation is a variable value [17]. One of the proposed ways to reduce the financial outlay for the construction of a nuclear power plant is to implement the Coal-to-Nuclear (C2N) concept. The C2N strategy is technically based on the partial use of existing coal-fired power plant infrastructure and its integration into the resources of a future nuclear power plant. Due to stringent safety requirements, it is assumed that, in addition to the construction site, the power-generation infrastructure, cooling towers, internal and external rail and road networks, and nearby water sources for cooling can be reused. In 2022, the US Department of Energy published a report [18] focusing on the potential for converting existing coal-fired power plants to nuclear power. One hundred fifty-seven retired and 237 operating coal units were analysed. In an article [19], the authors point out that it is theoretically possible to continue using the existing 460 MW supercritical coal-fired steam turbine without modifying the steam generator. This would require permanent decommissioning of the high-pressure part of the turbine, where the fresh steam inlet pressure is around 27.5 MPa, significantly higher than typical PWR’s steam generators. One possible way of using the existing steam system is to couple the primary and secondary parts by using heat tanks, which will also allow the nuclear unit to be more flexible when faced with operating in an electricity system deeply penetrated by renewable energy sources [10,20]. The authors of the report [18] indicate that implementing the C2N pathway using existing ancillary infrastructure, power generation, and cooling systems could result in savings of 11% to 22% (including the cost of dismantling the replaced coal-fired power plant), assuming the construction of a nuclear unit with a high-capacity light-water reactor. It was also reported that the dismantling of the coal-fired plant would take approximately 1 year. The analysis results in a unit cost for a C2N type investment of between USD 3598/kW and USD 4066/kW, assuming the construction of a nuclear unit with an AP1000 reactor at USD 4572/kW.

The main novelty of this work is the use of an analytical model of the nuclear unit that considers the variable temperature of the cooling water of the steam turbine condenser. The implemented control system, by means of a variable river inlet flow and the increase of the temperature value of this water at each condenser, makes it possible to control
the temperature of the condenser outlet water. In this way, it is possible to plot the year-round characteristics of the electrical energy production as a function of the cooling water temperature. The resulting characteristics of the required water flow allow for an assessment of the feasibility of siting a nuclear reactor with an open cooling system at the inland site of an existing coal-fired power station. The third-generation high-power reactors utilised during the study were the AP1000, APR1400, and EPR1600. For each reactor, the nominal required cooling water flux was determined for average hydrological conditions at the selected locations. Based on this information, the ratio of replaced existing power was estimated for each reactor.

2. Methods

2.1. Coal-to-Nuclear Path

The implementation of the Coal-to-Nuclear pathway can be a source of savings in terms of the financial outlay for the construction of a nuclear power plant. The level of savings strongly depends on the degree of reuse of the existing coal plant infrastructure. In the case of third generation of reactors, it is not possible to reuse the turbine island due to significant differences in steam parameters. Therefore, savings can be made in terms of reuse of the infrastructure for power output to the transmission grid, car parks, heat extraction facilities, and auxiliary buildings, as well as land and water rights. The potential savings were estimated to be between 11% and 22% on the assumption of a conservative economic analysis. In addition, the decommissioning and demolition (D&D) costs for existing facilities were projected to be between 2% and 4% of the total financial outlay. However, it should be kept in mind that, from the perspective of a potential developer, it may be risky to use operational infrastructure. Nevertheless, any ancillary infrastructure and power derivation should not deviate in their standards from the newly built infrastructure. In [21], the authors first undertook analyses of the Coal-to-Nuclear pathway later classified in [18] as the direct pathway. This pathway assumes deep use for nuclear investment of infrastructure of the decommissioning coal-fired power unit, including the turbine island. Due to the requirements of steam turbines operating in coal-fired power plants, only fourth generation of reactors can be used here. Generation IV reactors constitute a large group of designs currently at various stages of development [22]. Among the IV generation reactors under development, SMR designs—small modular reactors—dominate, which, due to their smaller capacities and modular design, can be produced faster and may have wider applications, such as in district heating and industrial plants. Currently, two HTGR high-temperature reactors in China (HTR-PM) are in commercial operation, with a combined capacity of 500 MWth, driving a 210 MWe turbine [23]. In view of the maturity of the technology of these reactors and the direction of the transformation of the European market, which assumes a reduction in the number of investments in the coal power segment, the direct pathway should be classified as hypothetical.

The DOE report examined the locations of 157 decommissioned and 237 active coal units for their potential reuse in the construction of a nuclear power plant [18]. It demonstrated that 40% of the locations of active and 22% of the locations of decommissioned coal-fired power plants are conducive to the construction of high-capacity nuclear reactors. Abdussami et al. [24] also analysed the potential for C2N in the United States. The coal units were evaluated according to three main groups: (1) socio-economic target; (2) safety target; and (3) proximity target. A key outcome of their work was the identification of several locations conducive to pursuing a C2N pathway and the finding that there is no one-size-fits-all factor that determines the quality of a particular location. Consequently, future evaluations should be based on a multi-faceted assessment. In Poland, the DEsire project [25] is working on assessing the potential of the Coal-to-Nuclear pathway and developing a roadmap for future investment. Research in the first phase of the project focused on technical and safety assessments [26] of existing coal-fired power plants and their location. The current focus of work is on the implementation of third generation of
reactors, which is motivated by the imminent decommissioning of numerous coal-fired power plants in Poland.

In their article, Chmielewska-Śmietanko et al. [26] discuss in detail the legal and safety issues of siting an inland nuclear power plant following the Coal-to-Nuclear pathway as part of the DEsire project. The authors highlight that a key aspect of the implementation of a nuclear source investment is the assessment of the potential location of the future power plant. This assessment should be conducted according to three main criteria: (a) the characteristics of the location and surroundings in terms of their impact on the nuclear power plant and potential contribution to the proliferation of radioactive materials; (b) the effects of external hazards of natural and man-made origin; and (c) the population in the vicinity of the location and the identification of factors affecting the implementation of emergency management plans. The authors conducted a comprehensive analysis of 24 locations of existing coal-fired power plants for the construction of third- and fourth-generation reactors, according to their defined criteria. They also defined criteria that excluded a location, such as the risk of flooding, the presence of an airport within a 10 km radius, or mineral extraction within a 30 km radius of an existing coal site. The authors selected four locations for coal-fired power plants in Poland that met the safety criteria for the construction of a nuclear power plant equipped with a Generation III reactor. These locations were: (1) “Dolna Odra” Power Plant; (2) “Polaniec” Power Plant; (3) “Ostrołęka B” Power Plant; (4) “Kozienice” Power Plant. Furthermore, fourth-generation reactors have been proposed for locations where the available cooling water may be insufficient to cool high-capacity units. An important aspect of the DEsire project is the availability of cooling water at the sites of existing coal-fired power plants. The law in Poland also defines the cost of water intake according to the temperature of the discharged water. For temperatures between 26 and 32 °C, the charge is USD 0.17 per 1000 m³ of water. Above 35 °C, the fee rises to USD 1.08, which has a significant impact on the operating costs of power plants.

Qvist et al. [21] analysed the potential of the C2N concept in Poland. The authors identified 38 coal-fired units with a total electrical capacity of about 10 GWe (units of 200 MW and 360 MW) that are suitable for modernisation using SMR. The authors did not identify the specific SMR technology for which the analyses were conducted. Their conclusion was based on the size of the Polish electricity system, which is dominated by 200 MW coal-fired units. It has been shown that the investment cost can be reduced by up to 35% due to the potential use of the existing turbine section [27]. This level of cost savings identified by the authors was confirmed in the DOE’s 2022 report [17]. Haneklaus et al. [28] also indicated a high potential for C2N in Poland for both high-, small-, and medium-power reactor implementation.

In 2023, Poland had 18.7 GWe of installed capacity from stable coal-based sources, 7.6 GW from lignite-based sources, and 5.14 GWe from gas-based sources. Concurrently, 14.28 GW of capacity was installed in photovoltaic sources and 9.6 GWe in onshore wind. The data indicate that renewable energy sources accounted for 26% of total electricity generation in Poland in 2023 [1]. This figure is lower than the EU average of 43.6% but higher than that of countries with a similar energy sector. For example, the Czech Republic had a value of 14.9%, while Slovakia had 26.5%. As recently as 2017, the Polish electricity system was still largely based on coal, with 20.1 GWe installed in hard coal and 8.56 GWe in lignite sources. Photovoltaic panels accounted for only 0.23 GWe, while wind power accounted for 5.79 GWe. Renewable energy sources accounted for 11.7% of Poland’s electricity production in 2017. Poland is implementing an energy policy defined until 2040, which is divided into eight main directions [4]. These include the implementation of nuclear energy, the further development of renewable energy sources, and the optimal use of its own energy resources. According to the plans, the share of coal in electricity generation is to be reduced to below 56% by 2030. It is noteworthy that the document produced in 2021 assumed the development of photovoltaics to a level of 10–16 GWe by 2040, which was already achieved in 2023. This intensive penetration of renewables into the electricity system coincides with the near end of the life of existing coal-fired power
plants. The adopted strategy entails the permanent decommissioning of approximately 26.5 GWe of stable coal-fired capacity between 2016 and 2040. Consequently, it is evident that substantial investment in proven and stable sources of electricity is imperative, as evidenced by the outcomes of studies and the electricity system in Poland. Furthermore, Cho et al. [29] have demonstrated that over-generation of electricity by RES can result in increased costs and reduced environmental benefits. The planned shutdowns of key power plants in Poland, including “Kozienice” Power Plant, “Polaniec” Power Plant, and “Jaworzno” Power Plant, are scheduled to commence in 2030. Consequently, it is evident that there is a pressing need for a significant investment in proven and stable sources of electricity, as evidenced by the findings of various studies and the electricity system in Poland.

In China, coal is the primary energy source [30], resulting in increased greenhouse gas and particulate emissions and, consequently, a decrease in air quality [31]. China has committed to achieving total carbon neutrality by 2060 while being the largest emitter of carbon dioxide at 9899.33 Mt in 2020 [32]. This objective is to be achieved by redefining the structure of the country’s electricity system, in which renewable energy sources, supported by nuclear and biomass power, are to play a dominant role [33]. Xu et al. [34] considered the implementation of a Coal-to-Nuclear pathway in China. The authors planned the decarbonisation of China’s power industry using nuclear reactors in three stages: (1) the conversion of coastal power plants with an installed capacity of about 80 GWe, (2) the conversion of inland power plants in the coastal zone with an installed capacity of about 180 GWe, and (3) the conversion of power plants near inland cities with an installed capacity of about 640 GWe. This division is due to the limited experience of Chinese designers with closed-loop nuclear power plant-cooling circuits. It has been estimated that the total potential for implementing the C2N pathway in China is about USD 1200 billion, although the conversion of all existing coal-fired power plants may not be possible due to environmental conditions or local social acceptance. Luo et al. [35] also discussed the potential of the Coal-to-Nuclear pathway in China. The authors investigated the feasibility of converting a coal-fired power plant to a high-temperature gas-cooled reactor (HTGR). They demonstrated that this type of reactor is more compatible with Chinese coal-fired power plants compared to a PWR. The result of their work is a strategy for applying a steam turbine, steam heaters, and cooling water pumps.

In terms of socio-economic considerations, the C2N concept involves the absorption of existing coal unit personnel, which can form the basis of future employment in a nuclear power plant. A report by the United States Department of Energy [36], which discusses in detail the extent of similarities between coal and nuclear power plant positions, identifies the occupations of electrical and electronic mechanics or industrial machinery mechanics as being identical between the two units in terms of requirements, using the Standard Occupational Classification System (SOC). Nevertheless, the coincidence of the occupational identification does not imply that workers would be directly redirected to work in the nuclear power plant without prior training and extension of their certificates. At the same time, it was stated that some of the posts in the new unit could not be covered by existing staff, implying the need for external recruitment. These posts included primarily nuclear engineers. The prospect of a Coal-to-Nuclear pathway could lead to increased employment in the local economy. Furthermore, it could provide a favourable alternative to the closure of a coal-fired power plant with no further use of the remaining land. The 2024 E4 Carolinas report identified the economic impact of the nuclear power sector on the southeastern US states [37]. The region is home to 25 of the 93 operating reactors and 13 of the 55 active nuclear power plants in the United States. Nuclear power provides more than 150,000 jobs and more than USD 13.7 billion in revenue. In 2021, a survey of Polish respondents indicated that 44% believed that the development of nuclear power in Poland was necessary in the event of a shift away from coal power [38]. Concurrently, only 24% of respondents expressed support for the construction of a nuclear power plant in their vicinity. In 2022, 75% of respondents surveyed indicated their backing for the development
of a nuclear power plant in Poland [39]. The notable increase in support for nuclear energy is largely attributable to the unstable geopolitical situation in the region, which has led to a significant rise in energy prices in Poland due to the disruption of the energy fuel supply chain to EU countries from Russia [40]. Additionally, there has been a notable increase in public awareness of the country’s energy independence. It can, therefore, be concluded that Poland has the highest public support for nuclear energy among the countries surveyed. In comparison, support in the United Arab Emirates is 63%, 61% in India, 54.3% in Bulgaria, and 53.75% in Belgium [41].

2.2. Nuclear Power Reactors

The study considered three commercially operating Generation III high-power nuclear reactor technologies: AP1000, APR1400, and EPR1600. These technologies belong to the group of light water-pressurised reactors (PWRs). This is the most popular technology in the world with 307 reactors of this type currently in operation with a total installed capacity of 294.08 GWe [13]. The second technology, with 47 units and a total capacity of 24.76 GWe, is the Pressurised Heavy Water Reactor (PHWR). The selected reactor technologies are described below.

- **Advanced Passive PWR–AP1000 [42]**

  The AP1000 reactor (Westinghouse Electric Company LLC, Cranberry Township, PA, USA), is a pressurised light water reactor with a rated electrical output of 1200 MWe (gross), developed by the US company Westinghouse based on the earlier AP600 reactor technology. The reactor design ensures the use of a number of passive safety systems to minimise the risk of power loss or human error [43]. These systems include a Passive Core Cooling System (PXS) to remove residual heat or a Passive Containment Cooling System (PCS) based on natural air circulation and gravity cooling with water from the upper emergency vessels. Yu et al. [44] analysed the effectiveness of the PCS with respect to the potential location of the AP1000 reactor and, consequently, the different atmospheric conditions under which the safety system operates. The authors showed that the climatic conditions in a region with four distinct seasons significantly reduce the likelihood of a major accident compared to a subtropical region due to lower ambient temperatures and, consequently, better air circulation. Studies have also investigated the robustness of the reactor building to external actions or incidents. Wang et al. [45] investigated the durability of a reinforced concrete reactor building structure in the event of a direct impact by a civil aircraft. The study was characterised by parallel damage modelling in the concrete and reinforcement areas, as well as extensive sensitivity analysis including both aircraft speed and impact location. Xu et al. [46] analysed the effect of the water level in the PCS emergency tank on the behaviour of the reactor building structure during an earthquake. It was shown that a decreasing water level in the reservoir reduces the vibration damping of the building structure, which can lead to increased damage in the case of simultaneous PCS and aftershocks.

  To date, the AP1000 reactor at the Vogtle nuclear power plant (Unit 3) in the United States has started commercial operation in 2023, with construction of this unit starting in March 2013 [13]. The Vogtle-4 unit was placed in service on 6 March 2024, with construction beginning in November 2013. There are four AP1000 reactors in operation in China, as Units 1 and 2 of the Sanmen power plant have been in commercial operation since September and November 2018, respectively, and Units 1 and 2 of the Haiyang power plant have been in operation since October 2018 and January 2019, respectively. Based on this experience, the Chinese version of the reactor, CAP1000, has been developed and is currently under construction at Lianjiang and Haiyang power plants. The construction of Units 3 and 4 of the Sanmen power plant, which will be equipped with reactors of this type, is also underway.

- **Advanced Power Reactor–APR1400 [47]**

  The APR1400 reactor (KEPCO/KHNP, Naju, Republic of Korea) is a pressurised light water reactor with a nominal electrical output of 1455 MWe (gross) and a reactor thermal
output of 3983 MWt. The reactor was developed in South Korea in 2002 by Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power (KHNP). The reactor design is based on the experience gained from the construction and operation of Korea’s first light water-pressurised reactor design, the OPR1000. These reactors have been successfully operated at the Hanbit, Hanul, Shin–Kori, and Shin–Wolsong power plants. The aim of the design work was to develop a reactor with improved safety (achieved through the implementation of passive safety systems) and the ability to compete with other energy sources in terms of construction time and investment costs.

Amuda and Field [48] presented the concept of a Nuclear Heat Storage and Recovery (NHS&R) system for the APR1400 reactor. The aim of the study was to develop a system that would allow the reactor to operate at a constant thermal output while adapting the steam turbine operation to customer demand [49]. According to the concept, the heat exchange medium is thermal oil and the actual heat storage is a rock bed characterised by its resistance to high temperatures [50]. A major advantage of this solution is the easy scalability of the heat storage and the relatively low financial outlay.

APR1400 reactors are successfully operating at the Saeul nuclear power plant in South Korea, with two units having been commercially commissioned to date, in 2016 and 2019, and two more under construction [13]. One unit of this type has been in operation since 2022 at the Shin–Hanul plant, and the other has been under construction since 2013, with its first synchronisation with the electric grid in December 2023. In the United Arab Emirates, three APR1400 reactors have been commissioned for commercial operation at the Barakah nuclear power plant, with the fourth unit synchronised with the grid in March 2024.

• The Evolutionary Power Reactor–EPR1600 [51]

The EPR1600 (Orano, Paris, France) is a pressurised light water reactor with a nominal electrical power of 1770 MWe (gross). It is the result of a joint design effort between Framatome (Paris, France) and Siemens (Berlin, Germany) based on the experience gained from the construction of about 100 PWR units worldwide. The focus was on the development of multi-level systems to drastically reduce both the probability of a severe accident and its potential impact on the population and the environment. Four-tier redundancy has been applied to key safety systems, including the core cooling system. In the event of a severe accident with core meltdown and reactor vessel rupture, the use of a special safety chamber equipped with protective layers and cooling facilities into which the molten core components would enter was envisaged, as described in detail by Fischer [52]. Baumann and Terry [53] describe the design assumptions for the reactor construction and the objectives set, among which the issues of improving the safety of the system and of the personnel operating the nuclear power plant with the EPR1600 reactor were predominant. Among other things, measures were taken to reduce the formation of deposits in the piping due to dead zones, gaps, and bends. These deposits could have been a source of increased radiation.

The first reactor of this type was commissioned for commercial operation at the Taishan power plant in China in 2018, with a construction period of 108 months [13]. In Europe, construction of the first EPR1600 unit began in 2005 at the Olkiluoto nuclear power plant in Finland, and the unit will be commissioned in 2023. The design life of the EPR-1600 nuclear unit is 60 years with a fuel cycle of 24 months and a unit availability of 92%. The basic parameters of 3rd generation of nuclear reactors are presented in Table 1.

Table 1. Basic parameters of third generation nuclear reactors [13,42,47,54].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AP1000</th>
<th>APR1400</th>
<th>EPR1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross electrical power $N_{el}$, MWe</td>
<td>1200</td>
<td>1455</td>
<td>1770</td>
</tr>
<tr>
<td>Thermal reactor power $Q_{R}$, MWth</td>
<td>3400</td>
<td>3983</td>
<td>4590</td>
</tr>
<tr>
<td>Net electric efficiency $\eta_{N}$, %</td>
<td>32.0</td>
<td>35.1</td>
<td>36.0</td>
</tr>
<tr>
<td>Declared power availability, %</td>
<td>&gt;93</td>
<td>&gt;90</td>
<td>&gt;92</td>
</tr>
<tr>
<td>Planned lifetime, years</td>
<td>60</td>
<td>60</td>
<td>60</td>
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<tr>
<td>Fuel cycle, months</td>
<td>18</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Steam pressure, MPa</td>
<td>5.76</td>
<td>6.90</td>
<td>7.72</td>
</tr>
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</table>
2.3. Coal-Fired Power Plants

Based on the results of basic evaluation process of all Polish coal-fired power plants [21], which has been conducted within DEsire project, for an analysis of investments from the specific cooling water condition point of view four Polish coal-fired power plants were chosen:

- “Dolna Odra” Power Plant,
- “Kozienice” Power Plant,
- “Ostrołęka B” Power Plant,
- “Połaniec” Power Plant.

“Dolna Odra” Power Plant

“Dolna Odra” Power Plant is a division of PGE Górniczwo i Energetyka Konwencjonalna S.A. and is located in the northwestern part of Poland in the Gryfino, about 25 km from Szczecin. Additionally, the plant is situated approximately 5 km from Poland’s border with Germany, which may potentially pose challenges in the implementation of nuclear power at the site. Power plant consists of four power units (Units 5, 6, 7, and 8) with a total gross capacity of 900 MWe fired by hard coal and biomass. On 31 December, 2020, Units 1 and 2 with a total capacity of 454 MWe will be decommissioned, the former being an emergency source of heat and process steam. In 2022, 1,252,348 tonnes of hard coal and 1517 tonnes of biomass were used at Dolna Odra Power Plant, resulting in total gross electricity generation of 2,732,055 MWh with CO$_2$ emissions of 922.0 kg/MWh, with total emissions including greenhouse gas emissions (SO$_2$, NO$_x$, CO$_2$, dust) and their equivalent emissions expressed in kg CO$_2$ amounting to 923.09 kg/MWh [55]. The Dolna Odra plant has an open cooling system using water from a canal (the so-called Cold Canal) connecting the plant site to the Odra River. According to the data provided by PGE GiEK S.A. (Bełchatów, Poland) in the Environmental Statement, in 2022, the Dolna Odra Power Plant will use 562,389,000 m$^3$ of water for cooling purposes.

“Kozienice” Power Plant

The “Kozienice” Power Plant, operated by ENEA Wytwarzanie, is located in Świerże Górne in Mazovia Province, about 5 km from the town of Kozienice and about 35 km from Radom. It consists of 11 hard coal-fired units with a total installed capacity of 4071 MWe. Units B1-B8 with a capacity of 230 MWe and a total capacity of 1800 MWe are scheduled for decommissioning between 2030 and 2033 [56]. Units B9 and B10 of the 560 MWe class are scheduled for decommissioning in 2041 and 2042, respectively. The 1112 MWe unit B11 is scheduled for decommissioning in 2048. A preliminary multicriteria analysis recommended only 200 MWe class units with a total capacity of 1800 MWe for repowering using nuclear reactors. The “Kozienice” power plant’s coal requirements are met to 70% by Lubelski Węgiel “Bogdanka” S.A. (Puchaczów, Poland) deliveries by rail-PKP Cargo is responsible for about 55% of fuel deliveries [56]. In 2023, “Kozienice” emitted 12,796,315 tonnes of CO$_2$, a decrease of almost 18% compared to 2022, when 13,945 GWh and 17,118 GWh of electricity were produced. Units B1-B10 emitted 4801.2 tonnes of SO$_2$, 5325.6 tonnes of NO$_x$, and 345 tonnes of dust in 2023. As of 2019, ENEA is implementing a planning project to build gas-steam units using the existing infrastructure of the 200 MWe class units. Units B1-B10 have an open cooling system using water from the Vistula River. In addition, the system uses spray cooling towers to ensure that the environmental requirements regarding the temperature of the discharge water are met. Unit B11 has a closed cooling system with a cooling tower. From 2019, ENEA S.A. (Poznan, Poland) will report cooling water intake values for “Kozienice” and “Połaniec” Power Plants jointly. In 2023, 2,490,590,000 m$^3$ of water from the Vistula River. In 2018, Kozienice Power Plant used 1,486,197,962 m$^3$ of water [56].

“Ostrołęka B” Power Plant

“Ostrołęka B” Power Plant, owned by Energa Wytwarzanie SA, is located in Ostrołęka, Mazowieckie Province. It consists of three coal- and biomass-fired units with a capacity of 230 MWe. In 2023, “Ostrołęka B” was responsible for supplying 1575 GWh of electricity to
the National Electricity System, with a total capacity of 633 MWe from coal-fired sources and 57 MWe from biomass sources [57]. The equivalent carbon dioxide emissions of Energa Elektrownie Ostrołęka SA (Ostrołęka, Poland) associated with electricity generation in 2023 amount to 1,497,873 tonnes. Units 1–3 use an open cooling system fed by water from the Narew River. In 2023, power plant withdrew 326,758,899 m³ of water from the Narew River for cooling purposes and 4,345,984 m³ of water for non-cooling purposes.

- “Połaniec” Power Plant

The “Połaniec” power station, managed by ENEA Wytwarzanie, is located in the village of Zawada, which lies approximately 3.5 km from Połaniec (Świętokrzyskie Province) and 10 km from Mielec (Podkarpackie Province). The total installed capacity of the power station is 1899 MWe [56]. The “Połaniec” power station consists of eight energy units—unit B1 with an installed capacity of 200 MWe, which was taken out of ex-operation on 1 January, 2024, Units B2–B6, with a capacity of 242 MWe, Unit B7 with a capacity of 239 MWe, and Unit B9 with a capacity of 230 MWe, which is fully biomass-fired [56]. Units B2–B7 are scheduled for decommissioning in 2034 and the last unit, B9, in 2042. In 2023, “Połaniec” Power Plant was responsible for supplying 6628 GWh of electricity to the national power system, a decrease in production of 20.9% compared to 2022. Power plant uses an open cooling system, for which it draws water from the Vistula River. In 2018, ENEA last reported separate cooling water-intake data for “Kozienice” and “Połaniec” power plants, according to which “Połaniec” drew 1,410,373,066 m³ of water from the river [56].

### 2.4. Thermodynamic Model

The thermodynamic model used for the nuclear reactor and steam cycle system is described in detail in [19]. The model was extended to include the control of the cooling system of the low-pressure condenser parts of the steam turbine. The calculations considered the variable performance of the cooling water pump as a function of the water inlet flow for cooling purposes. The nominal parameters of the nuclear unit were determined using the producer data provided in Table 1. It was also assumed that the water temperature rise per condenser was 4.65 °C. Operational calculations were conducted with different water temperature increases in order to comply with the legal limits. In addition, the minimum temperature of the condenser cooling water was assumed to be 9.5 °C, since further reduction of the cooling temperature increases the losses in the low-pressure part of the turbine.

Based on Equations (1)–(3), the characteristic condenser parameters were determined:

\[
T_1 = T_{w1} + \frac{\dot{m}_1}{m_{1n}} \Delta T_n \tag{1}
\]

\[
\Delta T_n = T_{1n} - T_{w1} \tag{2}
\]

\[
p_{cond} = p_{sat}(T_1) \tag{3}
\]

where \(T_1\) and \(m_1\) are the inlet temperature and steam flow to the condenser, respectively, \(T_{w1}\) is the temperature of the cooling water feeding the condenser, \(\Delta T_n\) is the nominal difference between the nominal inlet steam temperature \(T_{1n}\) and \(T_{w1}\), \(m_{1n}\) is the nominal steam flow, and \(p_{cond}\) is the condensation pressure of the steam equal to the saturation pressure \(p_{sat}\) for temperature \(T_1\). The heat removed from the condenser \(Q_{cond}\) is calculated from the formula:

\[
Q_{cond} = \dot{m}_c \cdot \Delta T_c \cdot c_p \tag{4}
\]

where \(\dot{m}_c\) is the flux of the condenser cooling water, \(\Delta T_c\) is its temperature rise, and \(c_p\) is its average heat capacity at constant pressure.

The valves on the pipelines were treated as isentalpic throttling elements with the pressure drop factor \(\xi\), as shown in Equations (5)–(7):

\[
p_2 = p_1 \cdot (1 - \xi) \tag{5}
\]
where $p_1$ and $p_2$ are the pressure of the medium before and after the throttling valve, respectively, $h_1$ and $h_2$ are the enthalpy of the steam before and after the throttling valve, respectively, and $T_2$ is the temperature of the steam after the throttling valve. The steam flow in the turbine is determined by the fluxes required to feed the regenerative heat exchangers. For each group of turbine stages, the expansion process from the first group to the last is determined, according to Equations (8)–(12):

\[ s_{2s} = s_1 \]  
\[ T_{2s} = f(p_2, s_{2s}) \]  
\[ h_{2s} = f(p_2, s_{2s}) \]  
\[ h_2 = h_1 - \eta_i \cdot (h_1 - h_{2s}) \]  
\[ T_2 = f(p_2, h_2) \]

where $s_{2s}$ is the theoretical entropy of the steam after expansion, assuming an isentropic expansion process, $s_1$ and $h_1$ are the enthalpy and enthalpy of the steam before expansion, $T_{2s}$ and $h_{2s}$ are the theoretical steam temperature and theoretical enthalpy of the steam for pressure $p_2$ and entropy $s_{2s}$, and $h_2$ and $T_2$ are the enthalpy and temperature of the steam after expansion, respectively.

The numerical model uses a real gas model, and the functions used to calculate the thermodynamic quantities of the circulating medium comply with the International Association for the Properties of Water and Steam (IAPWS) standard. The model also includes variable steam turbine efficiency values that depend on steam parameters.

Basic indicators for assessing the performance of the nuclear unit were also defined. The gross electrical efficiency $\eta_B$ is described using Equation (13):

\[ \eta_B = \frac{N_{el,b}}{Q_R} \]  

where $N_{el,b}$ is the gross electrical power of the nuclear unit and $Q_R$ is the thermal power of the nuclear reactor. The net electrical efficiency $\eta_N$ is defined as:

\[ \eta_N = \frac{N_{el,n}}{Q_R} \]  

where $N_{el,n}$ is the net electrical power of the nuclear unit after considering the coverage of the nuclear power plant’s own needs. The calculation considers the variable power of the cooling water pump, which depends on the water flow directed to the condenser.

The rate of use of available river water for cooling purposes $m_{c/n}$ was determined using the formula:

\[ m_{c/n} = \frac{\dot{m}_c}{\dot{m}_n} \]  

where $\dot{m}_n$ is the flow of water in river.

The hydrological conditions at the indicated power plant sites in Poland were analysed on the basis of measured data from the Institute of Meteorology and Water Management (IMGW) [58]. The analysis period covered the years 2010 to 2023, with data from different monitoring stations—the temperature values were taken from the station located above the water intake for cooling purposes to avoid the influence of the discharge water on the temperature of the natural water in the river. For each month, the average value for the period under study was determined, along with the maximum and minimum limit values for that period. This allowed for the identification of the most unfavorable hydrological
conditions from the perspective of power plants with an open cooling system, defined as instances where the flow of flowing water was lowest or the water temperature was highest during the period under study.

The data on the electricity production of the power plants selected for repowering were obtained from the ENTSO-E Transparency Platform [1]. These data were obtained for the full year 2023 on a unit-by-unit basis. For each coal-fired power plant, power generation data were presented on a daily and cumulative basis to show the impact of the power plant on the Polish electricity system. The data on the emissivity of individual power plants, cooling water use, and other information on plant operations were obtained from the annual reports of the power plant operators.

3. Results

Figure 2 presents the characteristic temperatures of the water in the rivers, including the monthly average temperatures over the study period and the highest and lowest measured temperatures [58].

As illustrated in Figure 2, the temperature of rivers in Poland exhibits a cyclical pattern aligned with the seasons. The highest temperatures are observed during the summer months, from June to September, with a peak of 27 °C (for the location of “Dolna Odra” Power Plant, Figure 2a). It is noteworthy that the “Polaniec” Power Plant and the “Kozienice” Power Plant are owned by the same entity and utilize the same river as a source of cooling water and a discharge point for post-cooling water. However, the measurements did not demonstrate a discernible impact of post-cooling water from the
“Polaniec” Power Plant on the natural temperature rise of the “Kozienice” Power Plant. The length of the Vistula River between the power plants is approximately 190 km. The impact of hot discharge water on the environment is only locally recorded.

Flow data were analysed from the station closest to the plant unless there was a tributary of another river between the plant and the station. Figure 3 presents the characteristic volumetric flows of water in the rivers, including the average monthly flows of the study period and the highest and lowest measured flow [58].

![Figure 3](image-url)

**Figure 3.** Characteristic fluxes of water in the river above the cooling water intake: (a) “Dolina Odra” Power Plant; (b) “Kozienice” Power Plant; (c) “Ostrołęka B” Power Plant; (d) “Polaniec” Power Plant. The data presented have been compiled for the period between 2010 and 2023.

The data presented indicate a notable reduction in average river flows during the summer period. The Narew River, on which the Ostrołęka Power Plant is located, exhibits the lowest average flows, ranging from 61 to 170 m³/s. In contrast, the Vistula River in the vicinity of the Kozienice Power Plant exhibits almost twice the water flow observed in the vicinity of the Polaniec Power Plant. The Kozienice Power Plant is permitted to utilise a maximum of 100 m³/s of water from the river for cooling purposes. In 2022, the maximum water abstraction was 88 m³/s, with an active production capacity of 2397 MWe (2800 MWe gross maximum). This abstraction occurred on a day when the water flow in the river was 146 m³/s, and its temperature was 24.6 °C. Consequently, the utilisation of the available water for cooling purposes was approximately 60%, and the temperature of the water discharged into the river was 34 °C. Table 2 shows the characteristic parameters describing the hydrological conditions at the indicated sites.
The characteristic water temperatures are similar for all the power plants analysed and are within 1.34 °C for the average temperature, despite the very different locations of the plants. This is a direct result of the cyclical temperature changes associated with the seasons that are characteristic of Poland. Even smaller differences, within the limit of 0.80 °C, were recorded for the maximum water temperature at a particular location. The highest water temperatures were recorded in the summer months of June and July, which also coincides with reduced water flows in rivers. This phenomenon exacerbates the negative hydrological conditions for power plants using an open cooling system. Figure 4 shows the electricity production profiles in 2023 for the power plants selected for repowering [1].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average water temperature, °C</td>
<td>11.25</td>
<td>11.14</td>
<td>9.91</td>
<td>11.16</td>
</tr>
<tr>
<td>Average flow, m³/s</td>
<td>636.34</td>
<td>483.34</td>
<td>95.72</td>
<td>249.31</td>
</tr>
<tr>
<td>Maximum water temperature, °C</td>
<td>27.0</td>
<td>27.1</td>
<td>26.3</td>
<td>26.5</td>
</tr>
<tr>
<td>Minimum water flow, m³/s</td>
<td>284.0</td>
<td>132.0</td>
<td>20.5</td>
<td>72.0</td>
</tr>
</tbody>
</table>

Figure 4. Daily and total electricity production: (a) “Dolna Odra” Power Plant; (b) “Kozienice” Power Plant; (c) “Ostrołęka B” Power Plant; (d) “Polaniec” Power Plant.

In the case of “Dolna Odra” (Figure 4a), the average daily electricity production in 2023 was 5.78 GWh. The coal-fired units showed high availability—with an average availability of 297 days. However, the four units actually operated in alternating mode, resulting in
212, 224, 214, and 180 days of operation, respectively. The total electricity production of the “Dolna Odra” plant was 2.11 TWh. Figure 4b shows the electricity production at the “Kozienice” Power Plant of the 200 MWe class units, which are typical for repowering due to the nearest estimated outage date. The average daily production was 17.65 GWh, with a total annual production of 6.40 TWh. The total electricity production of “Ostrołęka B” Power Station was 1.58 TWh, and that of “Polaniec” Power Plant was 5.03 TWh.

Table 3 summarises the estimated cooling water intake rate per installed capacity of the coal and nuclear power plants studied.

Table 3. Cooling water demand per installed capacity.

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>Cooling Water Demand, m³/(s·MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolna Odra</td>
<td>0.0198</td>
</tr>
<tr>
<td>Kozienice + Polaniec</td>
<td>0.0163</td>
</tr>
<tr>
<td>Ostrołęka B</td>
<td>0.0150</td>
</tr>
<tr>
<td>AP1000</td>
<td>0.0272</td>
</tr>
<tr>
<td>APR1400</td>
<td>0.0269</td>
</tr>
<tr>
<td>EPR1600</td>
<td>0.0255</td>
</tr>
</tbody>
</table>

For “Kozienice” and “Polaniec” power plants, water intake data are aggregated due to common ownership. Due to the structure of the available data, all coal-fired units with open cooling systems were included. The estimation of water demand for nuclear reactor systems was performed using the thermodynamic model presented in Equations (1)–(12) for the reference cooling water temperature parameters provided in Table 2. The cooling water demand indicator provides only an estimate of the power plant’s water demand, as it is based on aggregated annual cooling water intake data. The average annual cooling water intake at the “Dolna Odra” Power Plant is 17.83 m³/s, which is 2.8% of the average flow and 6.2% of the minimum flow of the Odra River, as shown in Table 2. In the case of “Ostrołęka B” Power Plant, the average annual water withdrawal is 10.36 m³/s, which is 10.82% of the average flow and as much as 50.54% of the recorded minimum flow.

For the nuclear units, the cooling water temperature rise at each of the three condensers of the low-pressure parts of the steam turbine was assumed to be 4.65 ºC. In reality, the inlet water flow would have to be higher during the summer period in order to comply with the upper limit of the outlet water temperature set by Polish law. The required cooling water flows for the nuclear units $m_c$ are shown in Table 4. The use of the natural water available in the river $m_{c/n}$ was also estimated.

Table 4. Use of available water by nuclear units compared to average river flow.

<table>
<thead>
<tr>
<th>Water Flow Demand for Nuclear Power Units, m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power plant</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>Dolna Odra</td>
</tr>
<tr>
<td>Kozienice</td>
</tr>
<tr>
<td>Ostrołęka B</td>
</tr>
<tr>
<td>Polaniec</td>
</tr>
</tbody>
</table>

It has been shown that the estimated cooling water requirements for all nuclear units exceed the current water consumption of existing coal-fired power plants per installed capacity. This is a direct consequence of the lower energy efficiency of nuclear power plants. In addition, the existing units are not operated continuously and close to nominal capacity, as shown in Figure 4, so the water consumption of the power plants is correspondingly
lower. Based on the data presented in Tables 4 and 5, it was concluded that the location of the “Ostrołęka B” Power Plant does not allow for the construction of any of the available high-power nuclear reactors with an open cooling system. The water flow required to cool the condensers significantly exceeds the minimum river flow recorded during the study period.

Table 5. Use of available water by nuclear units compared to minimum river flow.

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Minimum river flow, m³/s</th>
<th>Degree of water use in the river for the needs of the nuclear power units, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolna Odra</td>
<td>284.00</td>
<td>12.62</td>
</tr>
<tr>
<td>Kozienice</td>
<td>132.00</td>
<td>27.14</td>
</tr>
<tr>
<td>Ostrołęka B</td>
<td>20.50</td>
<td>174.16</td>
</tr>
<tr>
<td>Połaniec</td>
<td>72.00</td>
<td>49.77</td>
</tr>
</tbody>
</table>

Table 6 shows the ratio of new capacity to replacement capacity for the construction of a nuclear unit of a particular type at the selected site of an existing power plant. The indicated gross capacity of the Kozienice Power Plant is contingent upon the assumption that 200 MWe class B1-B8 units with a total capacity of 1800 MWe were directed to repowering. The gross reactor powers have been obtained by averaging the results, assuming that the cooling water temperatures are the same as those provided in Table 2 for different locations. The nominal parameters of the reactors provided in Table 1 differ from the data provided in Table 6 due to the difference in the reference temperature of the cooling water.

Table 6. Power replacement ratio in the event of the construction of a nuclear power plant unit of a particular type.

<table>
<thead>
<tr>
<th>Nuclear Unit Gross Power Output, MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP1000</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>1312</td>
</tr>
</tbody>
</table>

The data in Table 6 show that the construction of one EPR unit will almost completely replace the installed capacity of the coal-fired units at the “Kozienice” and “Polaniec” power plants. The construction of two nuclear units will each exceed the current installed capacity of the power plants under consideration. The report shows [59] that the construction of a nuclear power plant with more than one reactor results in a lower unit capacity expenditure and leads to a faster return on investment.

As described above, the assumed nominal values for the nuclear reactors were obtained from the average cooling water temperature at the locations in question and from an assumed constant cooling water temperature increment. This increase was 4.65 °C at each of the three low-pressure condensers of the steam turbine section. In fact, the law in Poland requires that the temperature of the water discharged into the river be controlled and enforces a limitation by a significant increase in charges with the next temperature level. For this reason, it is necessary to use control systems that adjust the intake flow in
order to control the temperature of the discharge water according to the equation 4. On the basis of the numerical model, an analytical model has been developed for the AP1000 nuclear unit, which adjusts the intake water flow for cooling purposes according to the outlet temperature and the power plant parameters. Figure 5 shows the calculated flux of water taken from the river and the rate of use of the available water in the river.

![Figure 5. Average daily cooling water supply and use of available water for the AP1000 reactor at the “Kozienice” power plant site.](image)

For the calculations, the results of which are shown in Figure 5, the average daily values of the water flow in the river in the section of the water intake for cooling purposes of the “Kozienice” Power Plant were used. The course of the water intake values clearly shows the influence of the river water temperature on the performance of the power plant cooling process. In summer, an increase in water intake is necessary due to the high water temperature. The maximum calculated discharge temperature was 34 °C with an annual average of 24.4 °C. The average annual cooling water intake flow was 52.1 m³/s. The increase in water intake flow due to water temperature also had the effect of reducing net electrical power. The power required to drive the cooling water pump was included in the calculations. In addition, the inlet temperature of the cooling water affects the pressure in the condenser, which also affects the generated power according to Equations (1)–(3). The net electrical power of a nuclear power unit $N_{N,n}$ with an AP1000 reactor varies from 1143 MWe to 1225 MWe per year after considering these factors.

Calculations showed that the use of available water during the summer period reached almost 55%, which means that the construction of more than one nuclear unit at the “Kozienice” power plant site would require a reduction in the power of the plant or the use of a water cooling system before discharging it into the river. A similar solution is used at the inland Civaux Nuclear Power Plant, which is equipped with two 1561 MWe N-4 series reactors.

### 4. Conclusions

The research project analysed four sites in Poland for hydrological conditions and the possibility of building a nuclear power plant with an open cooling system. The analysis included three operating commercial Generation III high-power nuclear reactors: AP1000, APR 1400, and EPR 1600. The analysis is based on the implementation of the Coal-to-Nuclear concept, which assumes that the infrastructure of an existing coal-fired power plant can be used, at least in part, to reduce the financial outlay for the construction of...
a nuclear power plant. In countries with a high proportion of conventional coal-fired generation, such as Poland, China, and the US, this concept is gaining popularity in both research and business circles. An important aspect of the implementation of the Coal-to-Nuclear pathway is the recognition of the possibility of building nuclear power plants inland due to the need to ensure the stability of the transmission grid and the possibility of using existing coal-fired power plant personnel. On the basis of the analyses conducted, the following conclusions have been drawn:

- Preliminary analyses recommend four Polish coal-fired power plant sites – “Dolna Odra” (900 MWe), “Kozienice” (1800 MWe), “Ostrołęka B” (690 MWe), and “Polaniec” (1899 MWe) – for further investigation of repowering potential. The plants are located on three different rivers and use an open cooling system.
- The AP1000 nuclear reactor, with the lowest net electrical power among the nuclear technologies considered, appears to be the most suitable from the perspective of the Polish power system, which is dominated by coal-fired units of the 200 MWe class and an increasing penetration by renewable energy sources.
- Hydrological conditions at the investigated sites were estimated on the basis of measured data for the period from 2010–2023. The river used by the “Ostrołęka B” plant is characterised by low water flow, which excludes it from consideration for the construction of a high-capacity nuclear power plant. For this site, studies on the implementation of SMR technology are recommended.
- The largest amount of cooling water is available at the “Dolna Odra” site, which makes it possible to build more than one nuclear unit with an open cooling system. In fact, the Dolna Odra plant is located close to the German border, which could significantly hinder the implementation of the investment due to the need to obtain approval from neighbouring countries.
- Considering the variable temperature of the condenser cooling water and the legal restrictions on the maximum temperature of the discharge water, the potential operating characteristics of a nuclear power plant at the selected site are derived. It was shown that an AP1000 reactor built at the “Kozienice” power plant site would use up to 55% of the available river water during the summer period. The net electrical output per year would vary between 1143 MWe and 1225 MWe, assuming a constant nuclear reactor power output.

The estimated financial outlay for the construction of a new nuclear power plant from 2023, together with the potential savings from the Coal-to-Nuclear pathway, yielded a financial outlay at the lower bound of USD 6610/kWe–USD 7542/kWe and an upper bound of USD 10,861/kWe–USD 12,393/kWe. Consequently, the costs of implementing a nuclear power plant still exceed the estimated costs of new coal-fired power plants (USD 3200/kWe–USD 6775/kWe) and geothermal (USD 4700/kWe–USD 6075/kWe) [14]. However, it is important to remember that nuclear power provides stability and predictability of electricity generation regardless of weather conditions and the diurnal cycle. This ensures the stability of power systems and guarantees a reliable electricity supply to consumers. Further work should focus on demonstrating the economic viability of a Coal-to-Nuclear pathway in countries without indigenous nuclear technologies. It should also identify the main barriers to implementation and possible ways of overcoming them. In addition, analyses should include the use of Generation IV reactors and their interaction with evolving energy systems around the world.

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