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Repowering a coal-fired power plant according to the coal-to-nuclear pathway - analysis of nuclear unit development from the perspective of cooling water availability

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Abstract

Changes in energy fuel markets, the rise of renewables and the aging of existing coal-fired units are leading to increased popularization of research on potential pathways for restructuring power systems. One proposed concept is the Coal-to-Nuclear path, which involves the partial use of existing coal-fired power plant infrastructure in favor of the construction of nuclear units, which can reduce investment costs. An additional benefit is the ability to manage the workforce competencies identified within the coal-fired power unit, and which are also required for the effective operation of the nuclear unit. The article considers the possibility of repowering the Kozienice power plant in Poland from the perspective of the availability of water used to cool the power units. Three different nuclear reactor technologies that are potentially being considered for the construction of the first nuclear units in Poland were analyzed. The study showed that the lowest water flows in the Vistula river recorded in 2022, equal to 146 m^3/s, make it impossible to simultaneously cool the nuclear units and ensure sufficiently low water temperatures from an environmental perspective. Nuclear units were shown to require about 1.55−1.67 times more water for cooling than typical coal-fired units.

Keywords: Coal-to-nuclear; Nuclear power plant performance; Repowering; Cooling water; Efficiency/power output

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1. Introduction

The shift in the global hydrocarbon trade market, particularly due to the sanctioning of Russian exports, has resulted in increased public awareness of the effects of fossil fuel shortages and increased support for investment in renewable energy sources, and a renewed interest in nuclear energy. In Poland, which is the largest hard coal producer in Europe, the number of people employed in the mining industry between 2009 and 2017 fell from 183 000 employees to 138 000, respectively. Between 2020 and 2021 there was a 2.2% decrease in employment [1]. The country's coal production fell from 144 million tons to 100 million tons (hard and lignite) between 2012 and 2020 [2]. Although China, which is the world's largest coal producer, reported a decline in production in those years from 3 945 to 3 902 million tons, the trend shows a significant increase in coal production relative to the lowest point in 2016 when China produced 3 410 million tons of coal. According to a report pub

Nomenclature

$c_{p,cond}$ – water heat capacity at constant pressure, kJ/(kg·K)
h – steam enthalpy, kJ/kg
h_s – steam enthalpy for ideal expansion, kJ/kg
$\dot{m}_1$ – steam mass flow in condenser, kg/s
$\dot{m}_{cond}$ – cooling water flow in the condenser, kg/s
N_{el} – net electric power of power plant, W
$N_{el\ b}$ – gross electric power of power plant, W
p – steam pressure, Pa
$\dot{Q}_{cond}$ – heat flux in the condenser, W
$\dot{Q}_{SG}$ – heat flux in the steam generator, W
T_{cond1} – cooling water inlet temperature, K
T_{cond} – cooling water temperature, K

Greek symbols

β – cooling water requirements for installed megawatt installed, kg/(s·MW)
Δ – difference
η_g – gross power plant electric efficiency
η_i – isentropic efficiency of steam turbine
$\eta_{i,k}$ – isentropic efficiency of each k-stage group of steam turbine

Subscripts and Superscripts

$cond$ – condensate
el – net electric
$el\ b$ – gross electric
k – k-stage
s – isentropic
SG – steam generator

Abbreviations and Acronyms

FEM – finite element method
LCOE – levelized cost of energy
SMR – small and medium reactors / small modular reactor
TES – thermal energy storage

lished by the International Energy Agency [3], in 2019 China added approximately 60 GW of renewable energy capacity, half of which was solar PV. In 2021, there was an increase of nearly 130 GW of capacity, with more than 50 GW coming from PV, 40 GW from wind sources, and 30 GW from hydropower. In addition, in 2023, China had 22 nuclear reactors under construction with a total capacity of 22.72 GW$_e$. However, a similar trend of nuclear power development is not observed in Europe. In 2023, there were two nuclear units under construction in Ukraine, two in the UK and one in France. Figure 1 presents the structure of energy production in European Union countries in (a) 2019 and (b) 2023 [4].

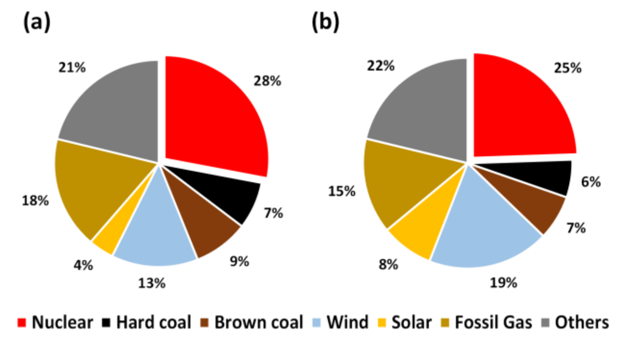


Fig. 1. Share of energy sources in total electricity production in the European Union countries in the years: (a) 2019, (b) 2023 [4].

In 2019, total electricity production in the European Union countries was 2 606 TWh, and in 2023 – 2 408 TWh. During this period, the share of nuclear power in total electricity production fell from 28% to 25%. This decline is mainly due to the implementation of Germany's plan to move away from this energy source, which resulted in the shutdown of 4 nuclear power units with a total electrical capacity of 5.46 GW. In addition, a 907 MW nuclear unit was permanently shut down in Sweden in 2019 and an 881 MW unit in 2020, as well as in Belgium, where a 1 006 MW unit ceased operation in 2022. No new nuclear unit commissioning was reported in the European Union countries during the period under review. Only in 2023 was one 440 MW nuclear unit launched at the Mochovce power plant in Slovakia [5].

Nuclear power, due to the restrictive safety conditions that must be ensured by a series of construction and safety barriers, requires significant financial investment. Figure 2 summarizes the financial expenditures for various power generation technologies [6].

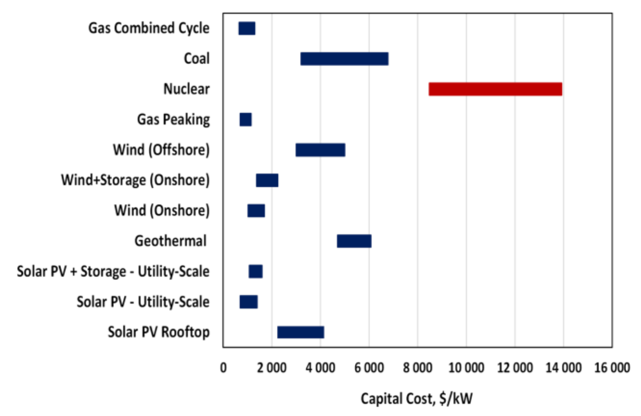


Fig. 2. Financial outlay for different types of energy producers.

Financial expenditures for the construction of a nuclear power plant range from 8 475 $/kW to 13 925 $/kW, which significantly exceeds the expenditures required to build coal and geothermal units. Considering the Levelized Cost of Energy (LCOE) index, since 2009 the value of nuclear power has increased from 1 230 $/MWh to 1 290 $/MWh. The biggest changes have been for photovoltaic power plants, for which the value of the LCOE index has dropped from 359 $/MWh to 60 $/MWh. On the other hand, according to Noland et al. [7] nuclear power has the highest value of energy generated relative to the area occupied 6 703 TWh/km^2. This compares with a value of 3 280 TWh/km^2 for gas-fired power plants and 0.087 TWh/km^2 for solar photovoltaic (PV) plants, which corresponds with studies by Smil [8] and Van Zalk and Bahrens [9].

One of the potential ways to reduce financial outlays for the implementation of investments in nuclear sources is the coal-to-nuclear path [10]. It assumes at least partial use of the existing infrastructure used in the operation of coal-fired units [11]. Generation IV nuclear reactor technology opens up the possibility of using the existing turbine island due to the similar parameters of live steam obtained from the primary circuit steam generator to the reference parameters of the turbines [12]. In recent years, small and medium reactors (or small modular reactor (SMR)) technologies developed in the group of Generation IV reactors (including those with fully passive safety systems and increased gross efficiency) have become particularly popular, especially in countries with medium or small electricity systems [13,14]. In these countries, the construction of high-power units is problematic, as the possible failure of a large generating unit causes a significant loss of power in the system [15]. Research is also being carried out to increase the flexibility of nuclear units while maintaining a uniform pattern of change in nuclear reactor thermal power. One concept involves the use of high-temperature Thermal Energy Storage (TES) using molten salts [16]. The construction of heat storage tanks allows for short-term storage of heat and its use in a steam generator during periods of higher electricity demand [17]. This concept is also proposed as part of classic coal-fired circuits [18].

This study analyzed a selected location of a coal-fired power plant in Poland in terms of its feasibility as a site for the potential construction of a high-power Generation III nuclear unit. The actual operating parameters of nuclear reactors from three different suppliers were also taken into account.

2. Methods

The analysis of the repowering potential of selected coal- and lignite-fired power plants included the evaluation and ranking of individual units according to six defined categories, which were identified as key from the perspective of restrictive techno-economic requirements for the implementation of nuclear units. These categories were defined as:

1) the area of power units with their supporting infrastructure, their operating parameters and technical considerations for the installation of nuclear reactors, in particular, the CO_2 emissions of the replaced power plant,
2) the area of electricity infrastructure, including power derivation and the technical condition and capacity of electricity transmission networks,
3) the area of associated infrastructure, for example, railroads and roads, in terms of the modernization under consideration and the necessary engineering work associated with the investment process,
4) the area of availability of cooling water and the possibility of building additional water reservoirs,
5) the area of availability of the land required for the development of energy systems and the organization of investment works because of the dates provided for the retirement of coal units,
6) the area of the demand for district heating in the analyzed locations and the possibility of heating the modernized power units.

A separate evaluation criterion is the nuclear safety criterion, which takes into account factors that are not necessarily relevant to the possibility of building a coal-fired power plant at a given location. Certain factors in this category, such as proximity to an airport, proximity to a mine, seismic activity, may be those that would exclude a particular location from the aspect of including it in a nuclear investment. Evaluation of locations according to the security criterion is subject of analyses in this article.

Based on the evaluation conducted according to the mentioned six techno-economic categories, the Kozienice Power Plant located in Świerże Górne, Poland, was selected for further analysis [19]. The power plant is located in the middle part of the Vistula River and consists of 11 coal-fired units – 8 with a capacity of 230 MW, 2 with a capacity of 560 MW, and 1 with a capacity of 1 112 MW. The lower-capacity coal units have an open cooling system using water drawn from the river. The 1 112 MW unit has a closed cooling system equipped with a cooling tower. According to plans, the first 4 (230 MW) units are to be decommissioned in 2025 and the remaining units in 2027. The 560 MW units have been scheduled for operation until 2041 and 2042. The last 1 112 MW unit of the power plant is to be disconnected from the power grid in 2048. Coal supplies to the power plant are carried out entirely by rail transport. In 2022, total CO_2 emissions from Kozienice Power Plant amounted to 15.85 Mt and 7 499 t of SO_2.

Due to Poland's location in the temperate climate zone, cyclical changes in temperature and water flow in rivers are observed due to changes in air temperature levels, as well as the intensity of precipitation. Figure 3 shows the average, minimum, and maximum water temperatures obtained at the Dęblin measuring station in 2022, located 15 km above the water intake for the cooling needs of the Kozienice power plant [20].

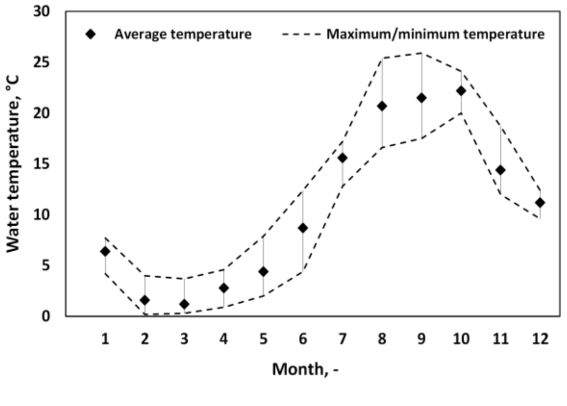


Fig. 3. Water temperature in the Vistula river in 2022.

According to the data presented in Fig. 3, the highest average water temperature was recorded in the month of October and was 22.2°C. The highest water temperature before the water intake for the cooling of the Kozienice power plant was recorded in September and was 25.9°C. The lowest water temperature was recorded in February and was 0.2°C. The lowest average monthly water temperature was recorded in March and was 1.2°C. Cooling water temperature is crucial from the perspective of Kozienice power plant operation also due to environmental and economic aspects. Environmental law in Poland precisely regulates monetary rates for water withdrawal for power plant cooling depending on the temperature of water emitted into the river. The currently applicable rates are presented in Table 1.

Table 1. Water withdrawal fee depending on the temperature of the discharge water.

Water temperature, °C	Mandatory payment, \$/1000 m^3 [21]
26 – 32	0.17
32 – 35	0.35
>35	1.08

As indicated in Table 1, exceeding the threshold of 35°C of the temperature used to cool the power plant results in a threefold increase in the fee relative to the lower temperature level of the water. The 2019 study indicated that the temperature of the water discharged from the power plant was 10.7°C higher than the temperature of the water taken from the river [22]. A measurement taken 1 km downstream of the water discharge indicated an increase of 3.2°C in the river water temperature. The temperature of the mixed water at each measurement section is also affected by the flow of water in the river. Figure 4 shows the average, minimum, and maximum water flow in the Vistula river monitored at the same measuring station.

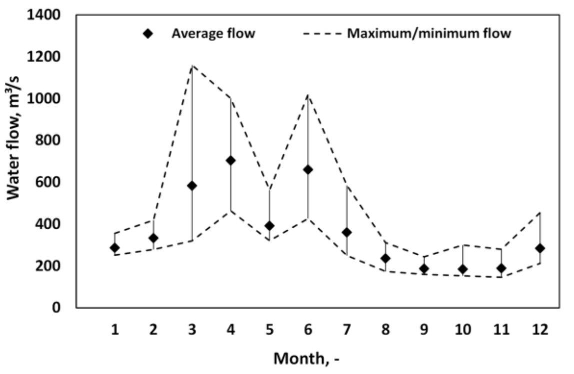


Fig. 4. Water flow in the Vistula river in 2022 [20].

As shown in Fig. 4, the lowest average water flow in 2022 was recorded in October and was 184 m^3/s. The Kozienice power plant uses an average of about 52 m^3/s, which is about 30% of the locally flowing water. The lowest average monthly water flow also corresponds with the maximum average water temperature, which may result in an increased negative impact of discharge water on the environment [23−25].

Pressurized Water Reactor (PWR) high-power (Generation III) technology was selected for thermodynamic analysis [26]. PWR technology is widely used in the world nuclear power industry [27]. As of 2023, 303 reactors of this type, with a total net capacity of 289 GWe, were operating or under temporary suspension of operation. In addition, 49 PWR reactors with a total net capacity of 53 GWe were under construction. In comparison, the second most popular nuclear reactor technology is the Pressurized Heavy-Water Moderated and Cooled Reactor (PHWR) with 46 operating or suspended reactors [5]. The following technologies were selected for analysis [5,28]:

Westinghouse Advanced Passive PWR (AP-1000) - reactor technology based on the earlier AP-600 type. The unit has a gross electrical output of 1 250 MW$_e$ and a thermal output of 3 600 MW$_{th}$, with both moderator and coolant being light water. The operating pressure of the reactor is 15 513 MPa. The inlet temperature of the reactor coolant is 279.4°C and its temperature rise is 45.2°C. The coolant directed to the two steam generators is used to produce live steam at a rate of 1 889 kg/s with a pressure of 5.76 MPa and a temperature of 272.8°C. The planned lifetime of the reactor is 60 years, assuming operational availability above 93% of the time and a fuel cycle length of 18 months. The reactor requires enrichment of the nuclear fuel to between 2.35% and 4.8% U235 level. A distinctive feature of the AP-1000 reactor is the design of the external safety shield, which uses the natural stack draft to act as one of the passive cooling systems of the internal safety shield. In addition, the roof section of the outer containment has gravity water reservoirs, which can also be used if the need for passive reactor cooling arises.

KEPCO's Advanced Power Reactor 1 400 MWe (APR-1400) - a technology based on the experience developed with OPR1000 technology, which was the first PWR unit in South Korea. The unit has a gross electrical output of 1455 MW$_e$ and a thermal output of 3 983 MW$_{th}$, with both moderator and coolant being light water. The operating pressure of the reactor is 15.5 MPa. The inlet temperature of the reactor coolant is 290.6°C and its temperature rise is 34.66°C. The coolant directed to the two steam generators is used to produce live steam at a rate of 1 889 kg/s with a pressure of 6.84 MPa and a temperature of 284.3°C. The planned lifetime of the reactor is 60 years, assuming operational availability above 90% of the time and a fuel cycle length of 18 months. The APR-1400 reactor has a passive system to limit the hydrogen concentration to 10% in the reactor building in the event of an accident resulting in damage to the reactor core.

EDF's The Evolutionary Power Reactor (EPR-1600), a technology being developed through Franco-German cooperation. The unit has a gross electrical output of 1 720 MW$_e$ and a thermal output of 4 530 MW$_{th}$, with both moderator and coolant being light water. The operating pressure of the reactor is 15.5 MPa. The inlet temperature of the reactor coolant is 295.2°C and its temperature rise is 34.8°C. The coolant directed to the four steam generators is used to produce live steam at a rate of 2 443 kg/s with a pressure of 7.8 MPa and a temperature of 284.3°C. The planned lifetime of the reactor is 60 years, assuming operational availability above 92% of the time and a fuel cycle length of 24 months. The reactor requires nuclear fuel enrichment to 5% U235 content. The EPR-1600 nuclear unit can be continuously operated in the range of 25−100% of rated power.

Basic information on the nuclear reactors analysed along with the steam parts is summarized in Table 2 and Table 3.

Figure 5 presents a simplified circuit diagram of the nuclear unit. Saturated steam from the steam generator flows to the high-pressure part of the turbine after which it is directed to the moisture separator and the two-section steam superheater. The first section is fed with steam from the turbine bleed, while the sec-

Table 2. Characteristic data of the studied reactors [5].

Provider	Designation	Reactor type	Electrical power gross/net, MW	Gross efficiency, %
Westinghouse (USA)	AP-1000	PWR	1250/1150	34
KEPCO (South Korea)	APR-1400	PWR	1420/1350	36
EDF (France)	EPR-1600	PWR	1720/1600	38

Table 3. Characteristic parameters of the studied reactors [5].

Parameter	Unit	AP-1000	APR-1400	EPR-1600
Steam pressure at outlet of the steam generator	MPa	5.76	6.84	7.8
Steam temperature/humidity at outlet of the steam generator	°C/%	272.8/2.5	284.3/2.5	293
Steam mass flow at outlet of the steam generator	kg/s	1889	2261	2443
Supply water temperature at inlet of the steam generator	°C	226.7	232	230

ond section is fed with live steam from the steam generator. The condensate from the condensers is heated in a condensate cooler and four low-pressure heaters then flows to a deaerator and is routed via a feedwater pump through two high-pressure heaters to the steam generator.

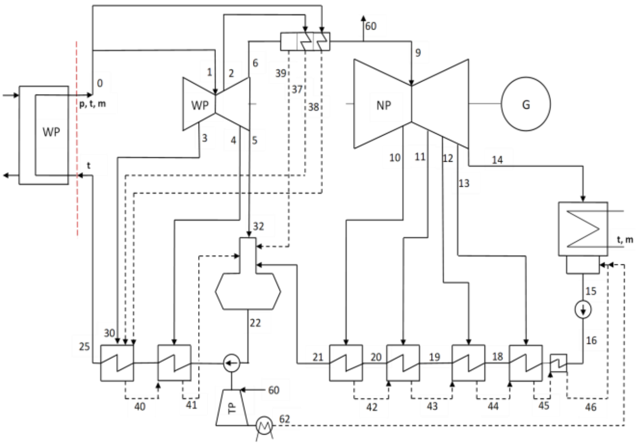


Fig. 5. Diagram of the nuclear system under analysis.

The feedwater pump can be driven by electric motors or an auxiliary steam turbine. For simplicity, only one low-pressure NP part is shown in the diagram, while all low-pressure parts are included in the calculations. In the analysis of the circuit with the APR-1400 reactor, a turbine drive of the feedwater pump was assumed, while with the AP-1000 and EPR-1600 reactor, an electric motor drive was assumed.

The calculations in the mathematical model are carried out iteratively: successive machines and equipment that make up the thermal circuit are modeled until the desired convergence is obtained. The thermodynamic calculations used the mass-energy balance method on the individual elements of the thermodynamic system, and used sets of equations describing the thermodynamic transformations occurring in the machines and equipment that make up the thermal cycle. The characteristic parameters at given points in the system were defined on the basis of the available documentation for each of the reactors studied [5]. The parameters of the working medium at the inlets and outlets are the connections between the objects. The simulation module uses thermodynamic quantities (enthalpy, entropy) comply with the international standard of the International Association for the Properties of Water and Steam (IAPWS).

The isentropic efficiency η_i of a selected group of steam turbine stages is defined as the ratio of the actual steam enthalpy drop in the stage (Δh) to the enthalpy drop for ideal expansion (at constant entropy – Δh_s):

$$\eta_i = \frac{\Delta h}{\Delta h_s}. \tag{1}$$

The isentropic efficiency of the stage groups $\eta_{i,k}$ varies with the load. The study considers a characteristic that relates the efficiency of each k-stage group to the steam flow $\dot{m}_k$ through that group:

$$\eta_{i,k} = f(\dot{m}_k). \tag{2}$$

The isentropic efficiency η_i calculated according to equation 1 is simple to determine for turbine parts operating in the superheated steam region. Measurements of the steam parameters in the pipelines located upstream and downstream of the stage group make it possible to determine the enthalpy and entropy of the steam unambiguously. The difficulty in determining the efficiency characteristics arises for low-pressure turbine parts. The expansion process in the last stage groups occurs in the wet steam region. In this situation, the measurement of temperature and pressure is not sufficient to clearly determine the thermodynamic properties of the steam. The solution to the problem is the simultaneous balancing of the entire thermal cycle and the determination of the enthalpy of the steam in the updrafts through heat exchanger balances. This approach was used in the conducted research.

The condenser is the component of the power unit whose operation remains the most sensitive to ambient conditions. The operation of the condenser, the vacuum that can be created, directly affects the efficiency of power generation in a condensing steam unit. The pressure in the condenser depends on two factors:

- the temperature of the condenser cooling water,
- the steam load of the condenser.

The minimum temperature of the condenser cooling water is determined by the design and operation of the cooling system. Possible solutions, such as cooling towers or the use of natural water reservoirs, vary depending on the location of the power unit. In the framework of the study, to create a universal system for evaluating the degradation of characteristics, the power unit was closed with a control volume that separates the condenser from the cooling system. For this reason, the characteristics of the condenser were used in the analyses in the form of a relationship:

$$p_1 = p_1 = f(T_{cond1}, \dot{m}_1). \tag{3}$$

It was assumed that the wet vapor pressure at the condenser inlet and the condensate pressure at the bottom of the condenser are equal. This assumption makes sense in view of the limited number of measurement sensors installed in condensers. For a circuit with a given reactor, parallel and series connections of turbine condensers were analyzed. The diagram of condenser connections is presented in Fig. 6.

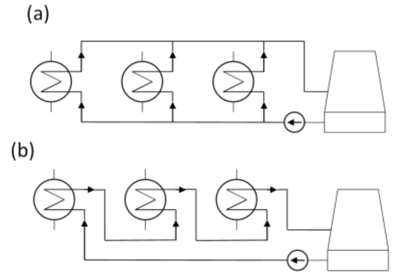


Fig. 6. Diagram of condenser connections: (a) parallel; (b) series.

For a series connection of condensers, a constant cooling water temperature rise in each condenser of 4.65°C was assumed, while for a parallel connection it is 9°C.

To evaluate nuclear technology, the gross electrical efficiency of a nuclear power plant η_g was defined as:

$$\eta_g = \frac{N_{el\,b}}{\dot{Q}_{SG}}, \tag{4}$$

where $N_{el\,b}$ is the gross electric power of power plant and $\dot{Q}_{SG}$ is heat flux in steam generator.

In addition, it was assumed that the net electrical efficiency is due to the use of part of the generated energy for the power plant's own needs. Gross electric power $N_{el\,b}$ was also used to assess the cooling water requirements for each megawatt of power plant installed β according to the equation:

$$\beta = \frac{\dot{m}_{cond}}{N_{el\,b}}, \tag{5}$$

where $\dot{m}_{cond}$ is cooling water mass flow.

The heat flux $\dot{Q}_{cond}$ taken up by the cooling water in the condenser is proportional to the amount of cooling water $\dot{m}_{cond}$ and the increase in its temperature ΔT_{cond} in the condenser:

$$\dot{Q}_{cond} = \dot{m}_{cond} \cdot \Delta T_{cond} \cdot c_{p,cond} \tag{6}$$

3. Results

The thermodynamic model was used to determine the fluxes of water supplied to the condenser depending on the condenser connection variant. Table 4 presents the results obtained for an assumed cooling water temperature of 10.9°C, which is the average annual water temperature from the Vistula River in 2022 above the water intake for the Kozienice power plant.

Table 4. Cooling water flow depending on the type of reactor and connection method.

Nuclear reactor	Parallel connection	Series connection
	Cooling water flow, m³/s	Cooling water flow, m³/s
EPR-1600	68.25	43.94
APR-1400	66.42	41.74
AP-1000	55.40	35.80

As shown in Table 4, the parallel connection of the condensers in each variant exceeds the current water intake for the cooling of the active units of the Kozienice power plant, which in the case of the EPR-1600 reactor on an annual basis would indicate the need to increase water intake by 512 460 000 m^3. It should also be noted that the calculations were carried out for relatively low intake water temperatures. During summer periods, as indicated in Fig. 3, the water temperature in the river reaches as high as 26°C, which, in the case of an assumed increase in water temperature of 9°C, would put one on the verge of having to significantly increase the cost of water intake (Table 1). In the case of a series connection, a decrease in the amount of water required was noted in every variant considered. Therefore, the turbine island variant with a series connection of condensers was selected for further analysis. Figure 7 presents the necessary flow of cooling water taken from the river depending on the temperature of this water.

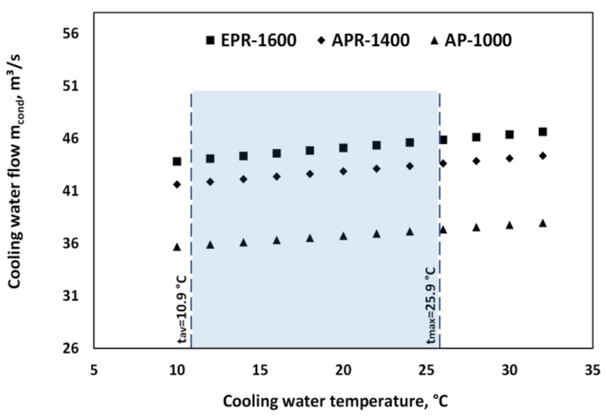
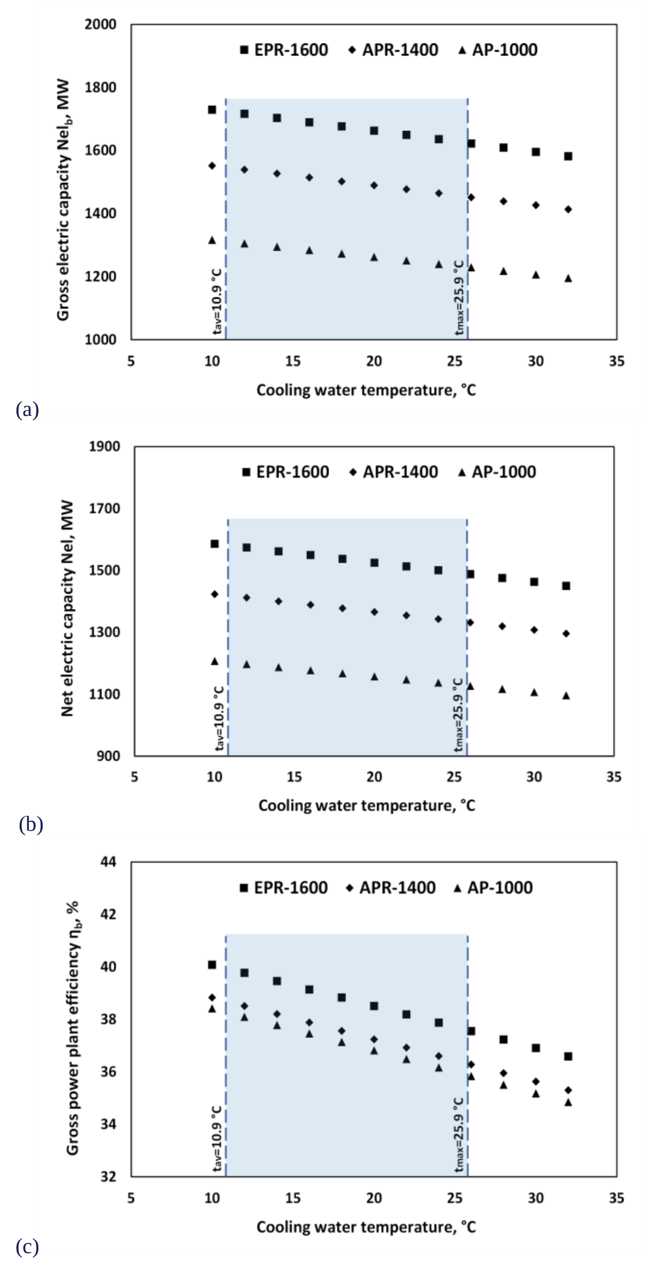


Fig. 7. Cooling water flow depending on its temperature.

Figure 7 indicates the area of average and maximum annual water temperature in the year 2022. It should be noted that the assumed water temperature increment of 4.65°C at each of the three condensers connected in series will result in the maximum allowable temperature of water taken from the river, which could be 21.05°C, in the event of a desire to avoid significant financial outlays for taking water to cool the nuclear power plant. The data presented in Fig. 3 suggest that situations of potentially reaching the limit temperature of river discharge water may occur during the months of August through October, i.e. during periods of higher air temperature and reduced precipitation. Figure 8a shows the gross electrical power of the nuclear units under consideration as a function of the temperature of the condenser cooling water. Figure 8b shows the net electrical power of the considered nuclear units depending on the temperature of the condensers' cooling water. Figure 8c shows the gross efficiency of the nuclear power plants under consideration as a function of the cooling water temperature.

From the perspective of nuclear unit operation, the fact that electrical power changes due to cooling water temperature is crucial. Figures 8a and 8b include the gross and net electrical power of the selected units, respectively. As the study showed, the electrical power for all analyzed units was reduced to about 94% of the power obtained at a nominal average cooling water temperature of about 11°C. It should also be noted that during periods of reduced water flow in the river and a simultaneous increase in its temperature to about 26°C, it may be impossible from the perspective of the environmental impact of the power plant to use the full available power.



(a)

(b)

(c)

Fig. 8. Dependence: (a) gross electrical capacity of nuclear units; (b) net electrical capacity of nuclear units; (c) gross power plant efficiency on the temperature of the cooling water.

According to the 2 022 data, almost three months are characterized by an increased probability of a forced reduction in generated power due to exceeding the allowable maximum discharge water temperature. This is an additional factor that, in addition to increasing the steam expansion pressure, affects the generated power and, consequently, the reimbursement of the costs incurred for the construction of the nuclear power plant.

The data shown in Fig. 8c directly depicts the decrease in gross efficiency of the nuclear unit resulting from changes in condenser pressure and possible steam expansion in the low-pressure part of the turbine. For the most efficient EPR-1600 unit, there was a decrease from 39.95% for a cooling water temperature of 10.9°C to 37.56% for a water temperature of 25.9°C.

The purpose of the retrofit of a coal-fired power plant using nuclear reactors is also to fill the gap in available capacity after the coal units are extinguished. In the case of the retrofitting of the Kozienice power plant, due to the age of the units and their planned retirement, all units (8×230 MW, 2×560 MW) using river cooling water were considered. The total capacity loss of 2 960 MW would require the construction of more than one nuclear unit at this location. Table 5 presents the water demand per nominal 1 MW installed.

Table 5. Cooling water demand.

Unit	Cooling water demand, $m^3/(s \cdot MW)$
Kozienice Power Plant	0.0175
EPR-1600	0.0273
APR-1400	0.0290
AP-1000	0.0293

As shown in Table 5 for nuclear units, the required cooling water flux per MW of installed capacity is 1.55–1.67 times higher than for coal units. Installing two EPR-1600 units covering the replaced installed capacity would result in a required river water intake flux of about 90.5 m^3/s. The minimum recorded water flux in the Vistula River in 2020 was 146 m^3/s, so the withdrawn water flux would be more than 60% of this value. This could therefore result in a significant increase in the temperature of mixed water, and consequently disrupt the local ecosystem. The installation of two AP-1000-type nuclear units, despite the incomplete coverage of the gap after the coal units are shut down, would result in keeping the river water intake at 73.5 m^3/s, which would be about half of the minimum river water flow.

4. Discussion

The study considered the retrofit of the Kozienice power plant (Poland) through the construction of a nuclear unit. The analyses included the three most popular third-generation PWR reactor technologies – EPR-1600, APR-1400, and AP-1000. The main objective of the work was to analyze the availability of water and hydrological conditions at the considered location and to study the possibility of a possible increase in the stream of water withdrawn for the cooling of future nuclear units. Based on the work carried out, the following conclusions were made:

1) The 230 MW and 560 MW class coal-fired units of the Kozienice power plant meet the defined criteria for evaluating recommendations for repowering using nuclear techniques due to the level of emissions, planned shutdown time and adequate transport facilities.
2) Nuclear power is the most expensive source of energy from the perspective of financial outlays for the construction of generating units while having the most favorable density of energy produced per unit area occupied by the unit. The Coal-to-Nuclear path potentially allows for a reduction in the financial outlay for the construction of a nuclear power plant due to the potential use of some of the existing components of coal units.
3) The Vistula river in the area of water intake for the cooling of the Kozienice power plant is characterized by significant variability in flow rate and temperature. The average water temperature in 2022 was 10.9°C, and the maximum in the months of August, September, and October was about 26°C. Restrictive laws in Poland regarding the maximum temperature of discharge water force the temperature of discharge water to be kept below 35°C.
4) Nuclear units have an average of 1.55 to 1.67 times the cooling water flux per MW installed compared to coal units. This therefore makes it impossible to maintain water intake at current levels while covering the units' replaced installed capacity.

Future research work should focus on assessing the potential for using the existing power derivation infrastructure at the plant site. In addition, the ongoing work should include an economic analysis qualifying the costs incurred during the construction of the nuclear unit and at the retrofit stage. Possible modifications to nuclear units to make them more compatible with existing coal unit infrastructure should also be recognized.

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References

[1] Statistics Poland. Average employment in mining and extraction (in Polish). https://stat.gov.pl/ [accessed 20 Feb. 2024].

[2] CEIC Data. Poland Coal Production. https://www.ceicdata.com/ [accessed 20 Feb. 2024].

[3] International Energy Agency. (2022). *Renewable Energy Market Update - May 2022: Outlook for 2022 and 2023 [Full Report]*. https://www.iea.org/reports/renewable-energy-market-update-may-2022 [accessed 20 Feb. 2024].

[4] European Network of Transmission System Operators for Electricity. https://www.entsoe.eu/ [accessed 20 Feb. 2024].

[5] International Atomic Energy Agency. https://www.iaea.org/ [accessed 20 Fe. 2024].

[6] Lazard. (2023). *Lazard's Levelized Cost of Energy Analysis*. https://www.lazard.com/media/typdgxmm/lazards-lcoeplus-april-2023.pdf [accessed 20 Feb. 2024].

[7] Noland, J.K., Auxepaules, J., Rousset, A., Perney, B., & Falletti, G. (2022). Spatial energy density of large-scale electricity generation from power sources worldwide. *Scientific Reports*, 12(1), 21280. doi: 0.1038/s41598-022-25341-9

[8] Smil, V. (2016). *Power Density: A key to understanding energy sources and uses*. MIT Press.

[9] Van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the US. *Energy Policy*, 123, 83-91. doi: 10.1016/j.enpol.2018.08.023

[10] Bartela, Ł., Gładysz, P., Andreades, C., Qvist, S., & Zdeb, J. (2021). Tech-no-Economic Assessment of Coal-Fired Power Unit Decarbonization Retrofit with KP-FHR Small Modular Reactors. *Energies*, 14, 2557. doi: 10.3390/en14092557

[11] Qvist, S., Gładysz, P., Bartela, Ł., & Sowiżdżał, A. (2021). Retrofit Decarbonization of Coal Power Plants-A Case Study for Poland. *Energies*, 14(1). doi: 10.3390/en14010120 Łukowicz, H., Bartela, Ł., Gładysz, P., & Qvist, S. (2023). Repowering a Coal Power Plant Steam Cycle Using Modular Light-Water Reactor Technology. *Energies*, 16, 3083. doi: 10.3390/ en16073083

[13] Miśkiewicz, A., Chmielewska-Śmietanko, D., & Smoliński, T. (2023). Decarbonization of coal-based energy production in Poland by application of modular nuclear reactors. *Bezpieczeństwo Jądrowe i Ochrona Radiologiczna: Biuletyn Informacyjny Państwowej Agencji Atomistyki*, 1(127), 47–55 (in Polish).

[14] Chmielewska-Śmietanko, D., Miśkiewicz, A., & Smoliński, T. (2023). Dynamic development of small modular reactors (SMR) – situation in the world and in Poland. *Bezpieczeństwo Jądrowe i Ochrona Radiologiczna: Biuletyn Informacyjny Państwowej Agencji Atomistyki*, 3(129), 10–20 (in Polish).

[15] Haneklaus, N., Qvist, S., Gładysz, P., & Bartela, Ł. (2023). Why coal-fired power plants should get nuclear-ready. *Energy*, 280, 128169. doi: 10.1016/j.energy.2023.128169

[16] Bartela, Ł., Gładysz, P., Ochmann, J., Qvist, S., & Martinez Sancho, L. (2022). Repowering a Coal Power Unit with Small Modular Reactors and Thermal Energy Storage. *Energies*, 16(5830). doi: 10.3390/en15165830

[17] Ochmann, J., Rusin, K., & Bartela, Ł. (2023). Comprehensive analytical model of energy and exergy performance of the thermal energy storage. *Energy*, 283, 128783. doi: 10.1016/j.energy. 2023.128783

[18] Kosman, W., & Rusin, A. (2020). The Application of Molten Salt Energy Storage to Advance the Transition from Coal to Green Energy Power Systems. *Energies*, 9, 2222. doi: 10.3390/ en13092222

[19] Enea. (2019). *Consolidated Annual Report for 2019* (in Polish). https://ir.enea.pl/ [accessed 20 Feb. 2024].

[20] Institute of Meteorology and Water Management. https://www.imgw.pl/ [accessed 20 Feb. 2024].

[21] Dziennik Ustaw. (2017). Act of *20 July 2017 - Water law act*. https://isap.sejm.gov.pl/ (in Polish) [accessed 20 Feb. 2024].

[22] Cebula, M., Ciężak, K., Mikołajczyk, Ł., Mikołajczyk, T., Nowak, M., Skowronek, D., Wawręty, R., & Żurek, R. (2021). *The impact of the discharge of hot cooling water from power plants into rivers.* Stowarzyszenie Pracownia na Rzecz Wszystkich Istot, Towarzystwo na Rzecz Ziemi, Oświęcim (in Polish).

[23] Latif, S., Souaissi, Z., Ouarda, T., & St-Hilaire, A. (2023). Copula-based joint modelling of extreme river temperature and low flow characteristics in the risk assessment of aquatic life. *Weather and Climate Extremes*, 41, 100586. doi: 10.1016/j.wace. 2023.100586

[24] Hannah, D., Webb, B., & Nobilis, F. (2008). River and stream temperature: dynamics, processes, models and implications. *Hydrological Processes*, 22(7), 899-901. doi: 10.1002/hyp.6997

[25] Ficklin, D., Stewart, I., & Maurer, E. (2013). Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California. *Water Resources Research*, 49(5), 2765-2782. doi: 10.1002/wrcr.20248

[26] Laskowski, R., Smyk, A., Jurkowski, R., Ance, J., Wołowicz, M., & Uzunow, N. (2022). Selected aspects of the choice of live steam pressure in PWR nuclear power plant. *Archives of Thermodynamics,* 43(3), 85-109. doi: 10.24425/ather.2022.143173

[27] Dudek, M., Jaszczur, M., & Kolenda, Z. (2019). Thermodynamic analysis of modular high-temperature nuclear reactor coupled with the steam cycle for power generation. *Archives of Thermodynamics*, 40(4), 49-66. doi: 10.24425/ather.2019.130007

[28] Leverenz, R., & Gerhard, L. (2004). The European Pressurized Water Reactor: A Safe and Competitive Solution for Future Energy Needs. In *International Conference Nuclear Energy for New Europe*. September 6−9, Portoroz, Slovenia.