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Modeling of a nuclear combined heat and power station supplying heat to remote municipal customers—the case of Poland

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Abstract

Nuclear power is advocated as a cheap, clean and reliable source of electric power for both industry and the household sector. This paper focuses on technical issues relating to commissioning a cogeneration unit for use in combination with a typical Pressurized Water Reactor (PWR). Three heat extraction possibilities were analyzed and modeled in order to identify the most favorable option based on various criteria. The investigated possibilities of heat extraction were turbine bypass, steam bleeding and partial removal of heat from the network of regenerating heat exchangers.

The working conditions of a municipal heat network, such as pressure drop and heat losses, were calculated and adapted to the conurbation centered on Gdansk (Poland). Annual demand was analyzed in light of the current state of development of the heating network. The operating parameters of the power plant were based on the Asco Nuclear Power Station in Spain. It was observed that certain heat extraction methods could deliver a significant increase in the weighted utilization factor.

Keywords: Combined heat and power (CHP) technologies; District energy systems; Nuclear power; Energy production

1. Introduction

Cogeneration is widely applied in conventional coal-fired and gas-fired power stations in order to enhance useful output from the conversion of fuel chemical energy. These plants are known as combined heat and power plants (CHP). The alternative to conventional CHP processes is fission. In a nuclear power station large amounts of low temperature heat energy are produced as a by-product, most of which is currently wasted in condensers. It may make economic sense to apply this potential to a district heating system and create a nuclear combined heat and power plant (NCHP).

Work on NCHP was first carried out back in the 1950s. In 1957 construction started on the Ågesta nuclear power plant. After it went operational it produced 10 MWe and provided 100 MWt to the Stockholm suburb district heating network [1]. Small NCHP reactors were developed in the USSR and then Russia [2, 3, 4]. Similar research into new technologies took place in Japan [5], Canada [6] and other countries [7, 8].

Several research teams have produced economic and technical analyses. Safa described a system to transport heat from nuclear power over long distances [9]. Bergroth analyzed the application of large NCHP based on the Loviisa Nuclear Power plant [10]. The UK energy system has been analyzed in the context of nuclear heating [11]. Le Pierrès et al. described a system to transport heat from a nuclear power station over a distance of 35 km [12]. Preliminary analysis of the heating application of a new Polish nuclear power station has been performed [13]. Analysis in respect of inclusion of a nuclear power plant in the Polish energy mix was considered [14]. Other research has shown the possible positive environmental impact of NCHP on Warsaw [15]. Hanuszkiewicz et al. analyzed the application of gas-cooled nuclear as a source of heat for the cogenerating cycle [16].

Heat can be used for other purposes in addition to district heating [17]. Nuclear generated steam was proposed as part of a scheme to produce ethanol [18]. Konishi suggested harnessing nuclear heat for water desalination purposes [19], which was dealt with in more detail in an IAEA report [20]. High temperature heat can find applications in the chemical and oil industries [21]. Chen et al. suggested integrating a nuclear source of heat and power with an electrolysis device [22]. The use of nuclear power for purposes other than electric energy production poses several problems connected with reactor dynamics [23], similar in nature to the integration of nuclear and renewable power [24, 25]. Hong et al. analyzed the optimal share of renewable and nuclear power in a power system [26]. Nian et al. analyzed total

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carbon emissions during the life cycle of a nuclear power plant [27].

Polish efforts to build a nuclear power station date back to 1971 when the then Polish government decided to start a nuclear energy program. The location next to Lake Żarnowieckie was selected in 1979. This paper investigates the application of a planned power plant as the source of heat for the Gdansk-Gdynia-Sopot conurbation (Tricity) regional heat network.

2. Methods

2.1. Location

For the purpose of this paper NCHP is assumed to be located on the site of the existing Żarnowiec Power Station. Żarnowiec was considered optimal in a report appraising possible Polish nuclear power plant locations [28]. The site is in close proximity to large natural expanses of water (Baltic Sea and Lake Żarnowieckie) and existing energy storage infrastructure (Żarnowiec Pumped Storage Power Station).

The area which will be supplied with heat by the proposed NCHP has a population of approximately 800,000. This area includes Gdansk, Sopot, Gdynia, Wejherowo and Rumia, the major urban areas in the region. The proposed pipeline starts at the power station and ends in Gdansk, passing through each of the localities listed above. The route was chosen to minimize impact in respect of existing structures and the protected Tricity Landscape Park. The site and proposed route of the pipeline are shown in Fig. 1.

The distance from the power station site to Gdansk city center is approximately 62 km. This translates into a total pipeline length of 68.2 km order once the compensators are added. A U-shaped compensator with displacement of 10 m is placed every 200 m, giving a total of 310 compensators.

2.2. Heat demand

The assumptions of heat usage per person are based on current data for Gdansk (total pop. 460,000). The annual usage of heat according to [29] in 2010 was ca. 2.22 TWh (8000 TJ of heat). According to the same report, heat consumption will have increased 15% by 2030 (planned date of connection of NPP to the power grid). Therefore 2.56 TWh is the anticipated value at the scheduled time of commissioning. Assuming a steady structure of heating systems and consumer preferences in other locations, a heat demand indicator of 5.53 MWh per capita per year was adopted. This value has to be multiplied to include the remaining population of the region, as shown in Table 1, yielding an annual heat demand of 4.82 TWh (17.4 PJ).

Heat consumption varies over the year, as shown in Fig. 2. In this Fig. aggregated heat demand is compared with several scenarios of available heat production of the power plant. This layout makes it easier to assess the need to source additional peak heating power from other plants to meet demand.

The availability of 8016 hours was assumed (31 days of NPP down time). Every refueling stage of nuclear reactor should be launched by summertime, when heat demand is low. In order to achieve good operating parameters (low heat losses, high efficiency of auxiliaries) the heat network should work under a steady thermal load the whole year round. Calculating demand and supply for heat power, it was assessed that 250 MW_{th} could be an optimal power value. It covers 41.5% of annual heat demand. The operational needs of a nuclear power plant require the operating parameters of heat network to be as steady as possible.

2.3. Power station model

The models of cycles were developed in Aspen Hysys. They are based on the operating parameters of the Asco Nuclear Power Station with two PWR reactors. Only a single reactor loop was modeled as the heat source of the district heating system. Peng-Robinson is the equation of state employed.

The power cycle of the modeled power plant consists of two thermally connected loops. The primary loop receives heat from the reactor and moves it to a steam generator. The working fluid of the primary loop is water pressurized to 15.7 MPa. Pressure losses occurring in the loop are included in the steam generator model and were assumed at 0.5 MPa. They are countered with a coolant pump. The major issue connected with this loop is keeping the working fluid in liquid state during the whole operation. This is done by adjusting the coolant mass flow and pressure appropriately. Failure to meet this requirement might result in water vaporization on the reactor rods. This leads to an uncontrolled heat release and the danger of rod melting and safety layer perforation. The use of a modern reactor means that no Chernobyl-class accident would occur [30].

The secondary loop is a Rankine cycle with a steam generator serving as heat source. In the case of the modeled plant steam expansion is performed in a 2-stage high pressure turbine and a 6-stage low pressure turbine. Part of the flow from each stage is rerouted to the network of heat exchangers including a reheater and series of regenerators. The normal operating pressure of the steam generator is 66.5 MPa and of the condenser is 7 kPa. The steam in the steam generator and in the reheater is superheated to approximately 281°C. The total mass flow of steam entering the steam generator is approximately 5850 t/h. 1.4% of initial steam flow is used to provide power to the turbopumps. The expected electric power produced by the power station is 1013 MW. Reactor heat duty is 3088 MW.

The model includes adiabatic pressure drop blocks to account for pressure losses occurring in the piping of the plant. Multistream heat exchangers were modeled as a combination of the mixer and heat exchanger blocks. In similar fashion to the actual power station, some of the steam was al-

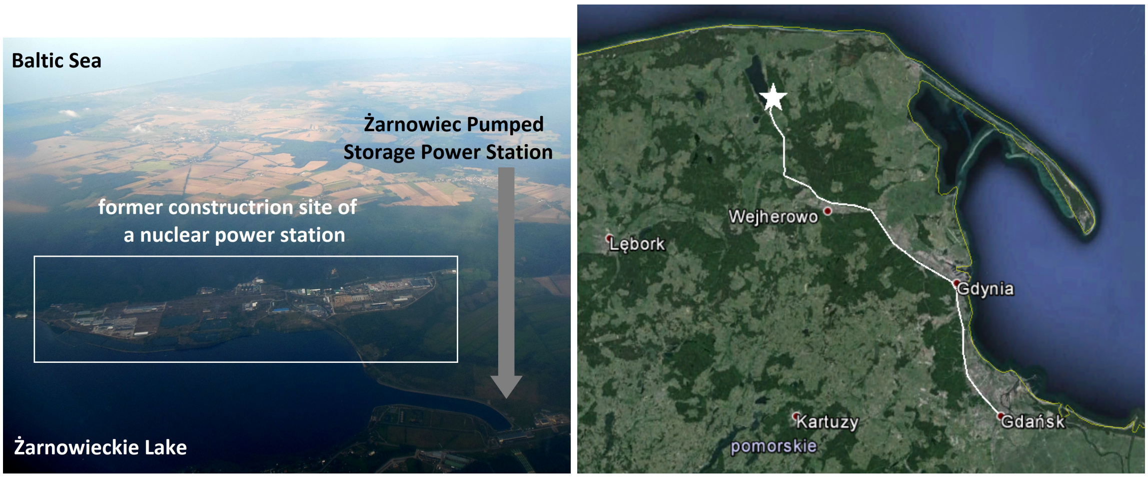

Figure 1: Location of the plant. Left—aerial photo of the proposed plant and its surroundings. Right—map showing the proposed route of the heat pipeline

Table 1: Calculated heat demand in cities

City	Population	Estimated heat demand in 2030	% of a total heat network load	Instantaneous heat flow
–	–	MWh p.a.	%	MJ/s
Wejherowo & Reda	75 967	420 212	8.7	28.3
Rumia	47 500	262 747	5.5	76.4
Gdynia	248 000	1 371 813	28.5	76.4
Sopot	38 000	210 197	4.3	11.8
Gdansk	462 000	2 555 556	53.0	143.2

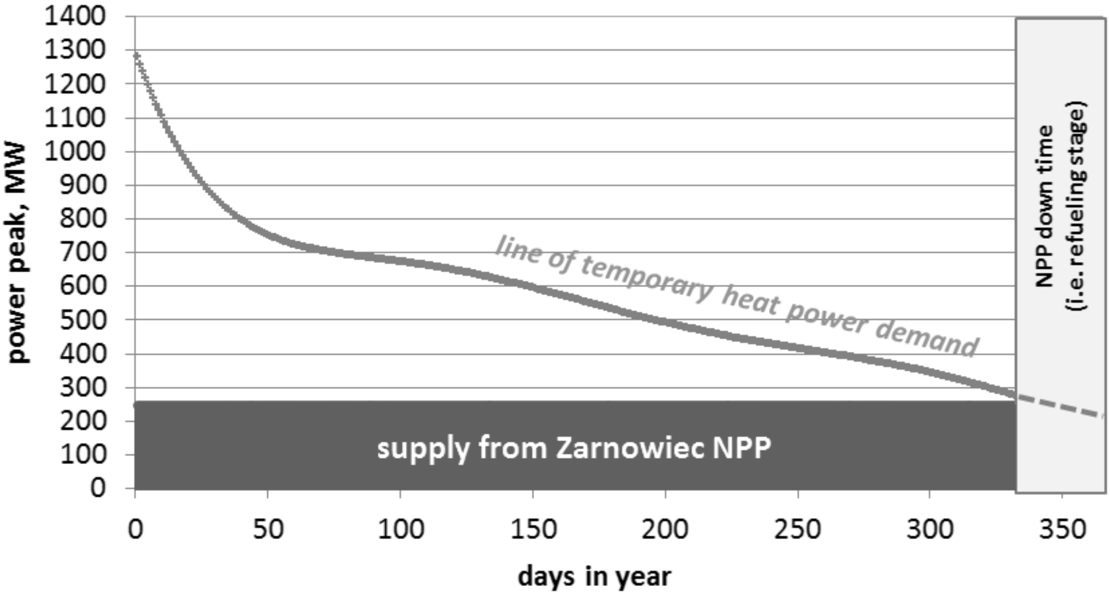

Figure 2: Heat demand and proposed power load of heat network

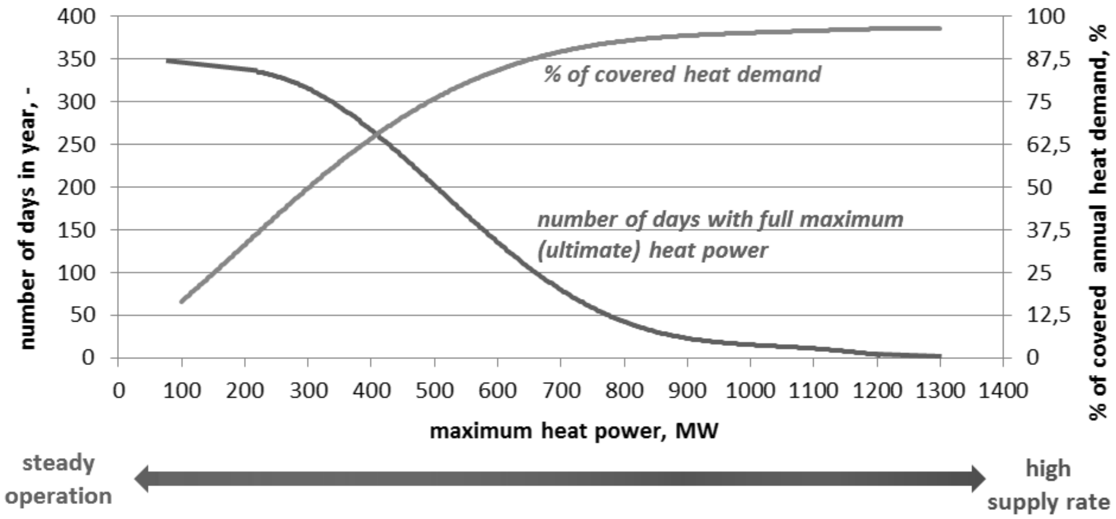

Figure 3: Diagram of heat demand showing assumed load of the heat network

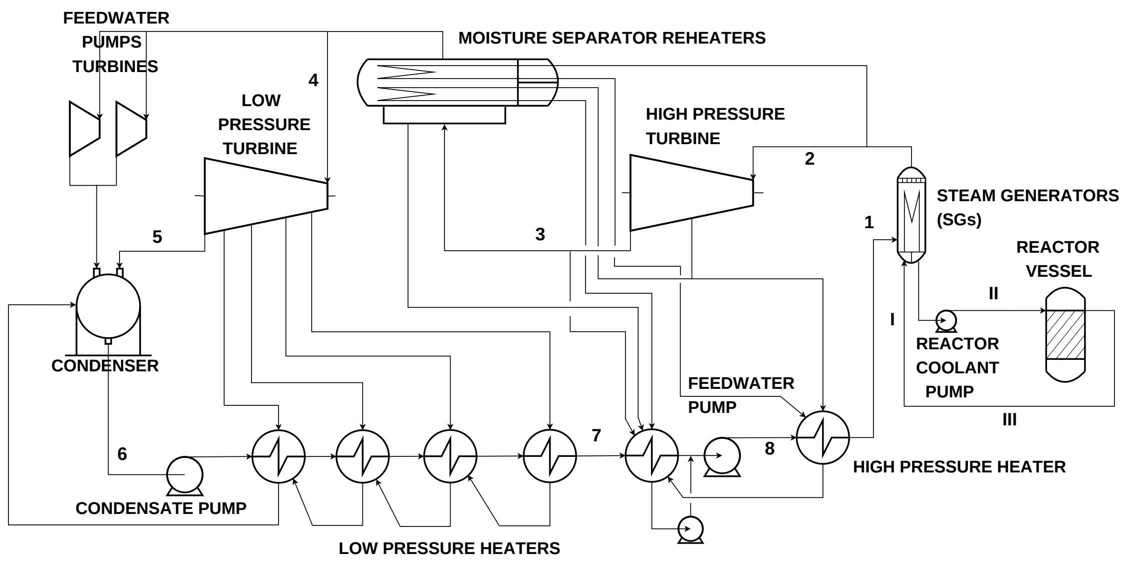

Figure 4: Diagram of the power station without modifications

lowed to condense in the turbines. A schematic diagram of the power station is shown in Fig. 4. Its operating parameters are presented in table 2.3. p is the pressure at given point, T—temperature, $\dot{m}$—mass flow and x—vapor fraction.

2.4. Modeling of the district heating system

In the case of models with heat extraction for a district heating system a third loop representing the heat pipeline was added. It connects the power station with a metropolitan area. Series of heat exchangers representing every major locality included in this loop and connected with pipelines were modeled as a pipe block. Since the district heat system was modeled in parallel, the pipeline consists of supply and return pipes. To provide heat for customers, part of the flow is routed from the supply pipe to an exchanger and then moved to the return pipe. The flow through each exchanger was adjusted so the removal of heat causes a similar temperature drop. Pumps were included to counter pressure losses. A diagram of the network is shown in Fig. 5.The details on the calculation of heat and pressure losses are presented in subsection 2.5. This paper presents three mechanisms of heat supply to the district heating system. The goal of each of them is to provide the required heat while minimizing interference with normal operating parameters of the power station.

2.4.1. Bypass of a single turbine stage

A common solution to extract heat for a district heating system is to add a back pressure turbine. While this reduces the electric power output, it increases the condensation temperature and pressure. In the case of the modeled power station, the amount of extracted heat is small when compared to the enthalpy carried by the flow of working fluid through the turbine. Therefore it would be unjustified to remove the entire turbine section down to a condenser. We proposed bypassing only the single stage of the turbine, in which the working temperature is sufficient to supply the district heat exchanger.

In light of these assumptions it was decided to bypass stage 4 of the turbine, located in its low pressure section. During the normal operation of the power station dry steam entering this stage has a temperature of 162°C and a pressure of approximately 0.51 MPa. It is expanded to approximately 0.2 MPa obtaining a temperature of approximately 121°C and a vapor fraction of 0.97. These parameters are optimal to supply the district heat exchanger with heat. We assumed that the district heat exchanger which replaces the turbine stage will cause a pressure loss of 0.12 MPa and remove the amount of heat required to supply the previously assumed part of demand. Intermediate expansion pressures p_{ex} of subsequent stages were calculated so that a criterion described with formula 1 was met. In this formula n is a stage number.

$$p_{ex_n} = \sqrt{p_{ex_{n-1}} \cdot p_{ex_{n+1}}} \quad (1)$$

The entire steam flow which would normally enter the turbine stage is passed through the district heat exchanger. Except for the difference in pressure of the exiting working fluid and the further expansion pressures, the rest of the system remains the same.

2.4.2. Steam bleeding

The next proposed solution is steam bleeding. In this case only part of the working fluid flow (known as bleed steam) is rerouted to a district heat exchanger, after exiting the high pressure section of the turbine. Bleed steam gives away heat at the heat exchanger and experiences a pressure loss and partial condensation. Alternatively, in the case of low heat demand it can be moved to a pressure reduction station. After heat removal it is injected to a further stage of the low pressure section of the turbine and expanded again.

The major difference between normal and cogenerating operation is the lower steam flow to some stages of the turbine. This leads to lower electric power production and a lower heat input into the regeneration heat exchangers. Expansion pressures and other operating parameters remain the same. We assumed that the bleed steam, after it is mixed with expanded steam coming from turbine stage 6, will be injected into turbine stage 7. We expect that the condensing pressure in the district heat exchanger will be similar to the inlet pressure of this stage.

2.4.3. Regeneration heat utilization

Our final proposal is to obtain part of the heat from the network of regenerating heat exchangers and use it to supply the district heating network. In this case a smaller amount of heat will be supplied to the steam generator. The operating parameters of the turbines will remain the same. However, the thermal efficiency of electricity production will still suffer, as either more heat would have to be supplied by the reactor or less working fluid would have to flow in the secondary loop in order to maintain good outlet parameters from the steam generator. To reduce interference with reactor operation the latter option was chosen.

The amount of heat the regenerating heat exchangers deliver is limited by the amount of heat supplied by streams extracted from the turbines and their parameters, especially temperature. In the case of our solution, heat is removed from the line of return streams connecting regenerating heat exchangers. In each heat exchanger the flow from a previous one mixes with steam extracted from the next stage of the turbine. Therefore the flow and the available amount of heat increases with each heat exchanger, at the cost of falling temperature. A large amount of low-temperature heat can be efficiently used to preheat the stream coming from district heating network.

2.5. Heat pipeline model

Calculations of a heat pipeline were performed on the basis of the standard PN-EN 13941+A1:2010: *Design and installation of preinsulated bonded pipe systems for district heating*. The pipeline is constructed in non-canal technology of pre-insulated distribution lines. A cross-section of it is

Table 2: Operating parameters of the power station

Point	p	T	$\dot{m}$	x	Point	p	T	$\dot{m}$	x
-	kg/cm^2	$^\circ C$	$tonne/h$	-	-	kg/cm^2	$^\circ C$	$tonne/h$	-
I	152	289.5	43000	0	4	15.1	261	4190	1
II	152	325	43000	0	5	0.07	41.7	3195	0.87
1	83.1	227	5857	0	6	0.07	41.7	4190	0
2	66.5	281	5857	1	7	83.1	145.9	4190	0
3	16.1	201	5042	0.91	8	83.1	197.6	5857	0

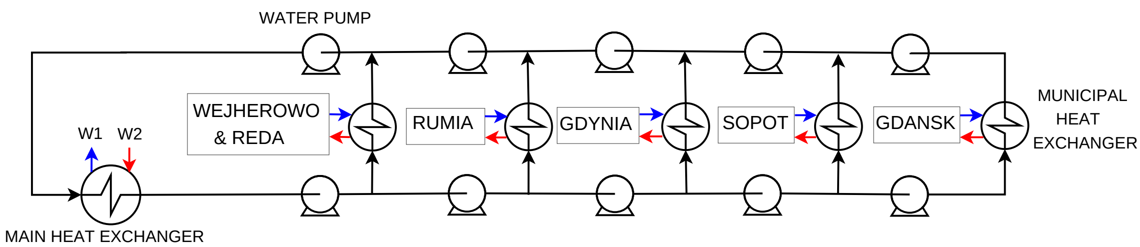

Figure 5: Diagram of the district heating network

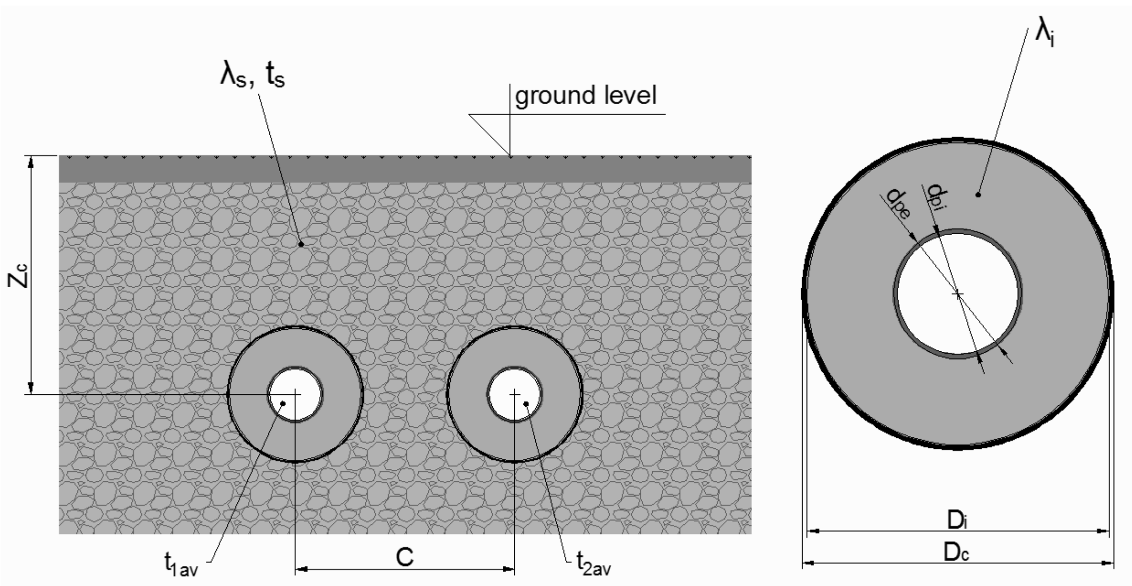

Figure 6: Model of pipeline heat loss calculations

shown in Fig. 6. This pipeline technology was chosen in order to minimize heat losses during pipeline operation [31]. Heat power in a calculated heat network was chosen in order to obtain rated conditions during all seasons of the year. It guarantees the steady mass flows and reduces additional heat losses during summertime when heat demand is low [32]. The dimensions of the lines were matched to obey local recommendations (average water velocity of 2 to 3 m/s).

Thermal conductivity of insulation (per length unit) R_i is calculated using formula 2.

$$R_i = \frac{1}{2 \cdot \pi \cdot \lambda_i} \cdot \ln \frac{D_i}{d_{pe}} \tag{2}$$

D_i is the external diameter of insulation, m, λ_i—thermal conductivity coefficient of insulation material, equal to 0.028 W/mK , d_{pe} is the external diameter of the steel pipe in meters. To compute the thermal conductivity of soil (per length unit) R_g formula 3 is used.

$$R_s = \frac{1}{2 \cdot \pi \cdot \lambda_s} \cdot \ln \frac{4 \cdot Z_c}{D_c} \tag{3}$$

D_c is the external diameter of the shell in meters, λ_s—thermal conductivity coefficient of soil, estimated for wet ground as 2 W/mK , Z_c is the depth of the pipeline foundation equal to 2 m.

The thermal conductivity between the two lines (interaction between supply and return) of the pipeline (per length unit) R_h is found with formula 4.

$$R_h = \frac{1}{4 \cdot \pi \cdot \lambda_s} \cdot \ln\left(1 + \left(\frac{2 \cdot Z_c}{C}\right)^2\right) \tag{4}$$

C is the distance between line axles given in meters.

Heat loss coefficients were calculated for the supply line (formula 5) and the return line (formula 6).

$$U_1 = \frac{R_s + R_i}{(R_s + R_i)^2 - R_h^2} \tag{5}$$

$$U_2 = \frac{R_h}{(R_s + R_i)^2 - R_h^2} \tag{6}$$

Heat losses of the pipeline q (per length unit) were calculated using equation 8.

$$q = (U_1 - U_2) \cdot (t_{1av} + t_{2av} - 2 \cdot t_s) \tag{7}$$

t_{1av} is the average temperature of a medium in the supply line estimated as 135°C, t_{2av}—average temperature of a medium in the return line expected as 70°C and t_s—average temperature of soil, assumed as 8°C.

Geometric parameters of the pipes are shown in Table 2.5. In the table d_{pi} is the internal diameter of the steel pipe. Parameters for the supply and return lines are equal. The pipeline section to Gdynia was divided into 3 DN200 lines to follow the guidelines suggesting the ratio between the inner dimension of a branch and the main one (close to 1:3). Heat transfer parameters are presented in Table 2.5.

The Darcy-Weisbach model was used to calculate the pressure drop in the pipe. The Darcy equation is also used to compute the friction factor 8.

$$\frac{\Delta p}{L} = f_d \cdot \frac{\rho}{2} \cdot \frac{w^2}{d_{pi}} \tag{8}$$

$\Delta p/L$ is the pressure drop per length unit given in Pa/m, f_d—Darcy friction factor, ρ is the density of water in kg/m^3, w—average flow velocity of water in a cross-sectional area in m/s.

2.6. Comparison criteria

The performance of each proposed NCHP solution was rated according to several criteria. The first is reactor thermal power P_{reac} marking the amount of nuclear fuel used. The second is the net amount of electric power P_{el} produced by the power station. The next two criteria are related—Q_{hn} is the amount of heat supplied to the district heating network and $\%D$ is the percentage of supplied annual demand. η_{el} is electrical efficiency of the plant found by using the formula 9.

$$\eta_{el} = \frac{P_{el}}{P_{reac}} \tag{9}$$

The next criterion is fuel utilization factor η_{us} calculated using the equation 10.

$$\eta_{us} = \frac{P_{el} + Q_{hn}}{P_{reac}} \tag{10}$$

In order to take into consideration the fact that electric power is more highly valued – thermodynamically and economically – than heat, the coal equivalent of useful product m_{coal} was chosen as the final criterion and is calculated with the formula 11.

$$m_{coal} = \frac{P_{el} \cdot r_{el} + Q_{hn} \cdot r_h}{P_{reac}} \tag{11}$$

r_{el} and r_h are weighting factors based on the coal use of a typical CHP. They are equal to 1 and 0.673 respectively. The result obtained gives the amount of coal in tonnes which is saved for each MWh of heat produced by a nuclear reactor.

3. Results

Fig. 7 shows the diagram of NCHP using heat from a partially bypassed low pressure turbine. The differences in operating parameters are minor, except for the fall in electrical power output. The mass flow of steam flowing through the district heat exchanger on the cold side is 3800 t/h. The temperature of district heating water increases from 70°C to 135°C. The mass flow of working fluid on the hot side is 3724 t/h. The temperature at point W1 is 161°C, then after passing through district heat exchangers it drops to 121°C. During the process most of the heat exchange occurs in a condensing regime.

Table 3: Geometry and flow velocity of pipelines

Line	Pipeline type	D_c	D_i	d_{pi}	C	w
	-	m	m	m	m	m/s
NPP ⇔ Wejherowo	DN700	1	0.976	0.695	1.5	2.52
→ Wejherowo	DN200	0.355	0.347	0.2101	0.855	2.40
Wejherowo ⇔ Rumia	DN650	1	0.976	0.6458	1.5	2.67
→ Rumia	DN150	0.28	0.272	0.1603	0.78	2.58
Rumia ⇔ Gdynia	DN650	1	0.976	0.6458	1.5	2.51
→ Gdynia	3 x DN200	0.355	0.347	0.2101	0.855	2.61
Gdynia ⇔ Sopot	DN550	0.8	0.778	0.5462	1.3	2.34
→ Sopot	DN150	0.28	0.274	0.1603	0.78	2.06
Sopot ⇔ Gdansk	DN500	0.71	0.688	0.4954	1.21	2.62
→ Gdansk	DN500	0.71	0.688	0.4954	1.21	2.63

Table 4: Heat transfer parameters of pipelines

line	R_s	R_i	R_h	U_1	U_2	q
-	$m \cdot K/W$	$m \cdot K/W$	$m \cdot K/W$	$m \cdot K/W$	$m \cdot K/W$	W/m
NPP ⇔ Wejherowo	0.11	1.930	0.041	0.490	0.010	90.82
→ Wejherowo	0.193	2.852	0.074	0.329	0.008	60.60
Wejherowo ⇔ Rumia	0.110	2.347	0.041	0.407	0.007	75.65
→ Rumia	0.212	3.005	0.081	0.311	0.008	57.31
Rumia ⇔ Gdynia	0.110	2.347	0.041	0.407	0.007	75.65
→ Gdynia	0.193	2.852	0.074	0.329	0.008	60.60
Gdynia ⇔ Sopot	0.128	2.011	0.048	0.468	0.011	86.42
→ Sopot	0.212	3.047	0.081	0.307	0.008	56.60
Sopot ⇔ Gdansk	0.138	1.867	0.052	0.499	0.013	91.89
→ Gdansk	0.138	1.867	0.052	0.499	0.013	91.89

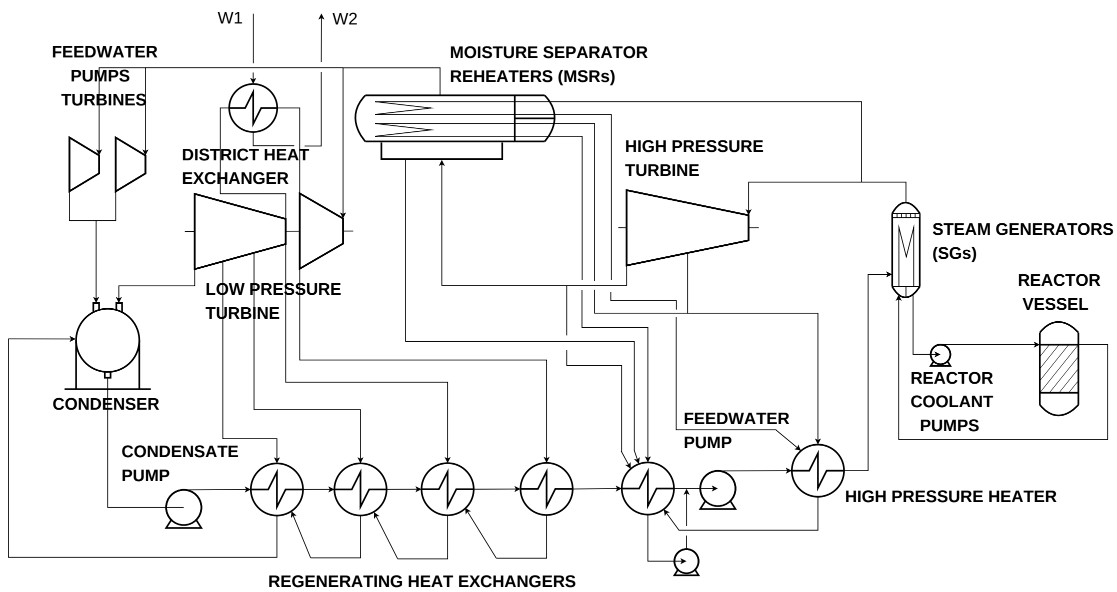

Figure 7: Diagram of NCHP using heat from the bypassed turbine

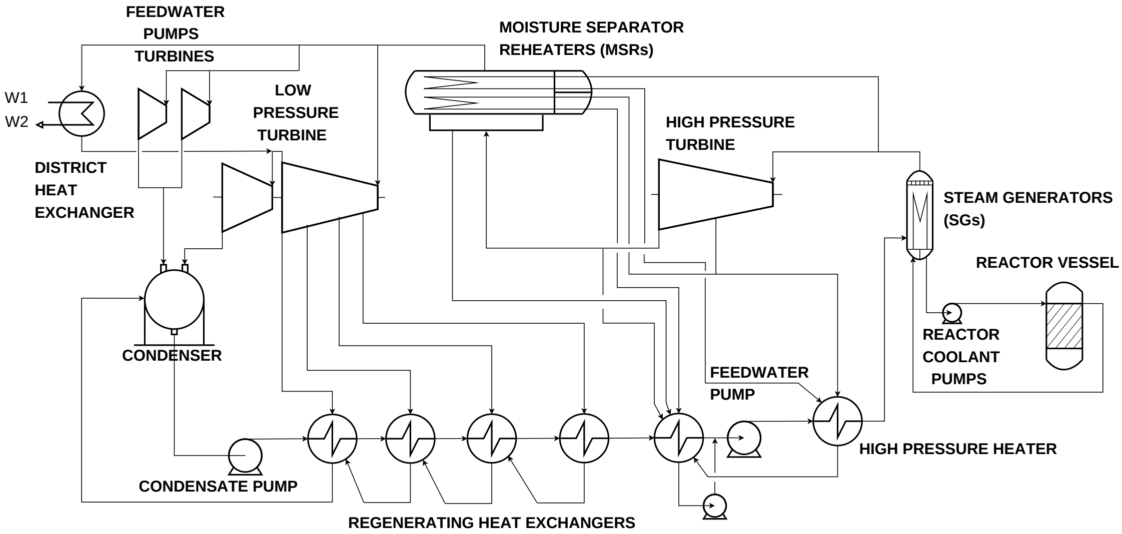

Figure 8: Diagram of NCHP using heat from the bleed steam

The diagram of NCHP using heat from bleed steam is shown in Fig. 8. The mass flow of heating medium on the hot side of the district heat exchanger is 1468 t/h. The temperature drops between 261°C at point W1 and 78°C at point W2. The parameters on the cold side remain the same. The parameters of the water entering the steam generator also do not change. Similarly to the previous solution, a large part of the heat transferred to the district heating water comes from the steam condensation process.

The schematic diagram of NCHP using heat extracted from the network of the regenerating heat exchanger network is shown in Fig. 9. The mass flow of district water entering the network of heat exchangers on the cold side is 3240 t/h. The temperature at the inlet is 70°C (point D1 on the diagram), at the outlet—122°C (point D2). The increase in temperature is lower than in the case of the two previous methods. The parameters of flow on the hot side differ between individual exchangers.

The major operational parameter which changes when compared to the based model is the temperature of water entering the steam generator. It drops from 227°C to 205°C. In order to maintain constant operating parameters of the reactor the mass flow at point A was decreased from 5857 t/h to 5334 t/h. Other flows in the secondary loop were decreased proportionally.

Table 3 shows a comparison of the analyzed heat extraction variants based on the criteria described earlier.

4. Discussion

The results show that NCHP can deliver environmentally and economically beneficial effects. The reduction in electric power output which accompanies every proposed solution can correspond with an increased utilization factor. It is generally assumed that 1 kWh_e is an acceptable loss for 6 kWh_t. There are advantages and drawbacks to all analyzed methods of heat extraction.

Turbine bypass leads to a significant drop in electric power output and electrical efficiency. Supplied heat demand concurs with the assumptions. The system meets 44.9% of the annual heat demand, the assumed share was 41.5%. The coal equivalent is marginally higher than in the case of normal operation. Removal of the turbine stage leads to changes in working pressures of the remaining turbines and in the parameters of the regenerating heat exchangers. Nevertheless, the regenerating network is able to provide working fluid with unchanged parameters to the steam generator.

The primary loop can therefore operate with the same parameters. Implementation of this solution may require the introduction of a pressure reducing station in order to avoid excessive condensation of working fluid leaving the district heat exchanger. Since the turbine stage chosen to be bypassed was selected based on the similarity of outlet and inlet parameters of the turbine stage and the district heat exchanger, exergy losses are smaller than in the case of the next solution.
Bleed steam extracted right behind the reheater has high parameters and exergy. It is mostly lost, even though after heat extraction it is further expanded in the low pressure turbine. This causes very high losses of electric power output and efficiency. The coal equivalent is actually lower than in the normal operation mode. The main advantage of this solution is the minimal interference with the existing design. Operating pressures remain unchanged and the thermodynamics of the regenerating network is affected only slightly. This solution allows the assumed part of demand to be fully supplied.

The extraction of heat from the network of regenerating heat exchangers leads to the best electrical efficiency of all the proposed solutions. The coal equivalent is significantly higher than in normal operation. The utilization factor is also the highest. These advantages come at a cost. The amount of heat which can be reasonably extracted from the regenerating network is insufficient to cover the assumed heating

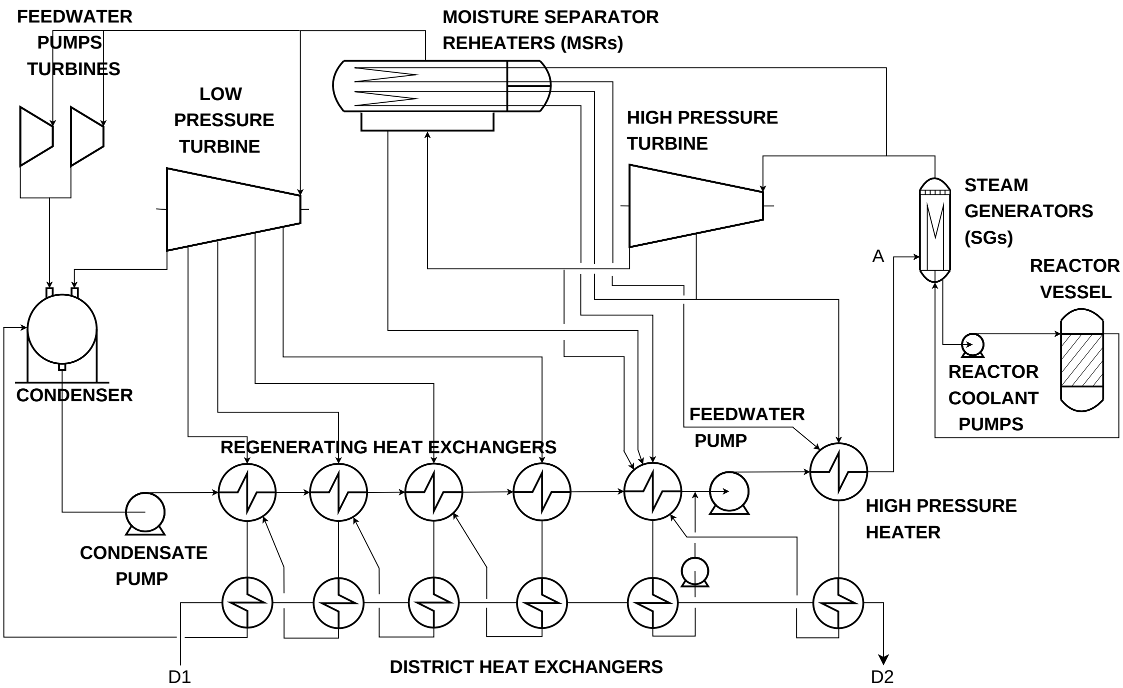

Figure 9: Diagram of NCHP using heat from the regenerating heat exchangers

Table 5: Comparison of NCHP variants

Variant	P_{reac}	P_{el}	Q_{hn}	$\%D$	η_{el}	η_{us}	m_{coal}
-	MW	MW	MW	$\%$	-	-	t/MWh
No modification	3088	1012	0	0	0.328	0.328	0.138
Turbine removal	3088	840	270	44.9	0.272	0.359	0.139
Bleed	3091	817	270	44.9	0.264	0.352	0.136
Regeneration	2982	915	219	36.4	0.307	0.38	0.149

target: only 36.4%. An additional problem is the change in temperature of the working fluid entering the steam generator. It is 25°C lower than in the unmodified power station. This may require changes to the design of the steam generator to ensure good heat transfer and to avoid mechanical stresses.

In terms of thermodynamical efficiency alone, the best solution seems to be the extraction of heat from the network of regenerating heat exchangers. However, this method causes large changes in the operating parameters of the primary loop. The other methods do not offer significant gains in the weighted utilization factor.

Interference with the existing operating parameters may prolong the process of licensing the power station. It would also require a costly redesign of power station components. However, the observed gain of almost 8% of coal equivalent in the case of extraction of heat from the regenerating network may justify these actions. Since heat is a commonly needed commodity, this profit would also be obtained when commissioning new power stations without any need to redesign components.

It was assumed that the power station would supply only base demand for heat, connected mostly with meeting domestic hot water requirements. Therefore operating parameters would be steady, without seasonal variations. Using a nuclear reactor as a heat source for the district heating system offers the advantage of high availability. However, if the system is to cover a larger share of annual demand, problems with waste heat would arise and the utilization factor would deteriorate.

The proposed method of long range heat distribution is straightforward and does not cause large heat losses. Heat leakage could be cut further by using costlier, high specification pipelines with additional insulation. The major part of the operating expenditures of the system relates to the energy needed to pump water through the long network. This was factored into the simulations. As was demonstrated, even with this additional energy burden it is still possible to achieve positive effects.

The proposed system is environmentally-friendly. The presented coal equivalent is based wholly on energy considerations. Saving coal leads to a reduction in emissions of carbon dioxide and other gases implicated in climate change or otherwise harmful. The environmental premium is even more pronounced, as many domestic and local heat sources in Poland are extremely inefficient and burn fuels that are more harmful than coal. They also lack any emission control systems. Replacing these sources with clean heat from NCHP may significantly improve air quality. Another issue is the reduction in waste heat released to the environment and related impact on local water bodies.

There is no significant increase in radiation risk. Heat exchange in the district heat exchanger takes place with non-irradiated working medium from the secondary loop. Any irradiated contaminants present in the water from the primary loop are separated off. In the extremely unlikely event of a simultaneous leak in both the steam generator and the district heat exchanger, the consumers of heat are far away enough for the short-life products to decay. The risk would be greater if a boiling water reactor were constructed, which would require an intermediate loop.

5. Conclusions

This study shows that it is technically feasible to install a cogeneration unit in a PWR nuclear power plants. By reducing the electric power of the nuclear power plant, district water can be warmed up to network supply conditions and piped to remote individual recipients. The possible locations for heat extraction were identified and assessed. The best solution seems to be to extract heat from the network of regenerating heat exchangers. To do so would require significant changes to the operating parameters of the power station.

In order to identify appropriate working parameters, a feasibility study of local heat demands is necessary with a view to ensuring steady operation of NCHP. Long distance water heat networks can achieve high efficiencies when pipelines are installed underground and rated operating conditions (such as mass flow and temperature profile) are met during the year, regardless of season or weather. NCHP can lead to lower environmental impact and lower emissions. Moreover, the radiation risk is extremely low in the case of PWR technology.

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