ARCHIWUM ENERGETYKI tom XLI(2011), nr 3-4, 155–166

Tomasz Minkiewicz*
Andrzej Reński

Gdansk University of Technology
Faculty of Electrical and Control Engineering

Nuclear power plant as a source of electrical energy and heat

In this paper, certain the issues concerning usage of nuclear power plants as sources of not only electric power but also thermal energy will be discussed. For such a solution appeals most of all the need to limit harmful emissions of gases (including CO2) and ashes, which come from the process of burning fossil fuels, as well as the raising demand for network heat and chill. Additionally combined heat and power production brings measurable economic benefits and increases energy security in the given region. In particular, the possibility of operating a nuclear power plant (NPP) as a source of heat for the heating network system of an agglomeration and the most probable locations for this plant in Pomeranian Voivodeship are considered. Both technical and economic aspects of such an undertaking are taken into account.

1 Introduction – conditions of introducing large co-generation sources in Poland

Introducing nuclear power plants into the Polish power system (PPS) will enable using these units as sources of electrical energy, and in some urban heating systems also as sources of heat. This means that along with numerous classic combined heat and power (CHP) systems, cogeneration systems working on nuclear fuel would occur in PPS. An important advantage of these systems is providing considerable savings in primary energy consumption and reduction of harmful pollutants emission into the atmosphere. Therefore the development of cogeneration units is supported by the directive 2004/8/WE of the European Parliament and the Council of the European Union of 11 February 2004 on cogeneration development based on local heat demand. The existence of such demand is an essential condition of building new generation units using this technology. The directive concerns all cogeneration systems including those based on nuclear

*E-mail: a.renski@ely.pg.gda.pl

fuel. However, attention should be paid to the differences in reference to classic systems: the reduction of pollutants emission is a result of not only the considerable reduction of fuel consumption, but mostly of the fact that nuclear sources of energy hardly emit ashes, sulphur and nitrogen oxides and carbon dioxide. A low share of fuel costs in the final price of energy (electrical and thermal energy) is also of great importance. In case of a conventional power plant fuel costs account for about 50% of annual total costs, while in case of a nuclear power plant it is currently about 20% of total costs. It is also worth mentioning that the share of the cost of the uranium in the variable operating cost, i.e. fuel costs, is about 20%, so even if the cost of uranium rises by 100% the rise of electric power generation costs of a nuclear power plant will account for about 4%. As it was previously mentioned there are also explicit differences in the amount of burnt fuel – a 1000 MW nuclear power plant uses annually about 35 tonnes of uranium dioxide (UO_2) as a fuel, while a corresponding conventional power plant needs nearly 2 500 000 tonnes of hard coal [1].

The possibility to use a nuclear power plant as a source of heat occurs particularly in locations with high thermal power demand and developed heating networks, which are big cities and agglomerations. Thermal power demand and annual heat production by heating companies in Poland have gradually decreased in the last few years mainly due to the large-scale thermal modernization undertakings and energy saving by heat consumers. Changes in levels of installed thermal power in particular voivodeships (with marking of percentage shares of thermal power installed in Pomeranian Voivodeship) are shown in Fig. 1.

Given that thermal power installed by heating companies is close to 60 000 MJ/s and that total heat production accounts for about 400 PJ/a, Poland is in the forefront among European Union countries. Also total length of heating networks – over 19 000 km – is one of the greatest in Europe. Moreover, it is significant that over a half of heat sold from heating networks comes from cogeneration sources and that in a few biggest cities thermal power demand exceeds 1000 MJ/s [2]. Beside Warsaw, Silesia, Lodz, Krakow and Wroclaw agglomerations, the Tricity is one of such places where potentially it would be the most favourable to exploit heat from nuclear power plants. According to the document *Polish energetic policy until the year 2030* electrical energy demand in the year 2020 is supposed to rise from current level of 155 TWh to about 170 TWh. Considering that about 60% of generated power comes from sources which are at least 30 years old, construction of new energy sources of large total installed power will be essential.

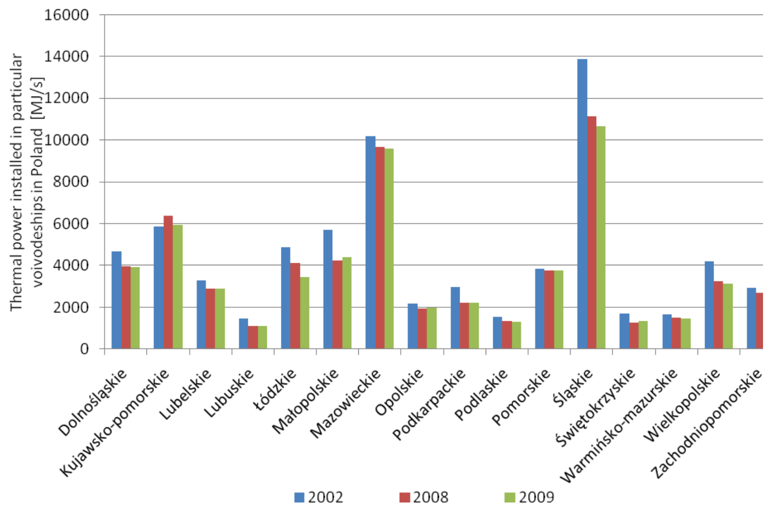

Figure 1. Thermal power installed in particular voivodeships in Poland [4]

Figure 2 illustrates Polish production of electrical energy and, as it is shown, the share of Pomeranian Voivodeship in national total electric power production is quite low. Therefore, in order to ensure an appropriate level of energy security, setting new generating units in this region will be vital. In agreement with national energetic policy assumptions producing energy in the process of cogeneration will be preferred. It is also planned to replace as many as possible urban heat generating plants with cogeneration sources. On the national scale, it is predicted that until the year 2020 the amount of electrical energy generated in high-performance cogeneration technology (i.e. technology assuring saving of primary energy by at least 10% and a proper level of energy generation efficiency – over 75%) will double in comparison with the year 2006 [3].

As it follows, there are appropriate reasons to place in Pomeranian Voivodeship a nuclear power plant which could be simultaneously exploited as a source of heat for the Tricity agglomeration. According to the assumptions of the Programme for the Development of Polish Nuclear Energy, running the first nuclear power plant in Poland is predicted after the year 2020. Its electric power is estimated at about 3000 MW [5]. It is very probable that the plant will be equipped with either two nuclear units with European pressurised water reactors (EPR) or two nuclear units with advanced boiling water reactors (ABWR) or else three nuclear units with AP-1000 pressurised water reactors. Each of these units could be exploited as a source of heat for an urban heating system. One of predicted locations is the region of Lake Żarnowiec in Pomeranian Voivodeship [6].

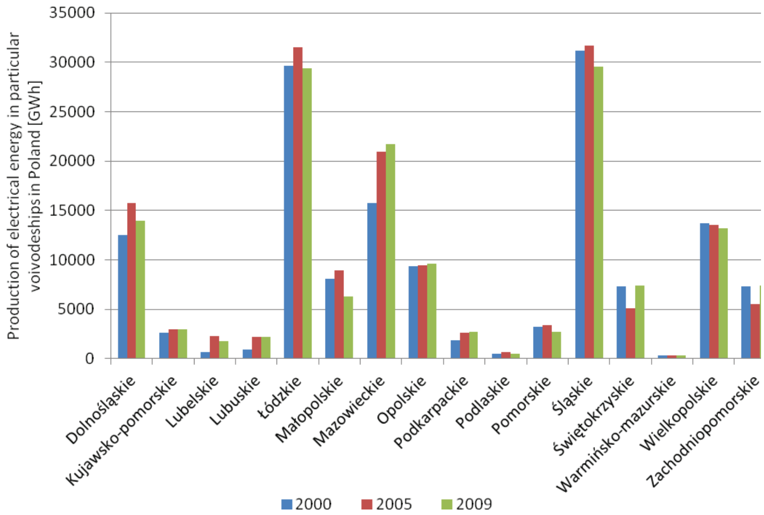

Figure 2. Production of electrical energy in particular voivodeships in Poland [4]

2 Cooperation of a nuclear power plant adapted for heat supply with the national power system and with the local heating system

Assuring the cooperation of the planned nuclear power plant adapted for heat supplies with external power systems requires fulfilling a broad range of conditions. These conditions are a result of numerous legislation regulations such as energy law and lately amended nuclear law. They concern the possibility of building new energy sources, especially those of high power, and extensive electrical energy and heat distribution networks as well as the possibility of joining these facilities into the currently exploited systems. It should be noted that usually these are long-term investments, whose preparation period is often much longer than its construction period. As an example high voltage power lines could be mentioned, where the construction of a 400 kV and 100 km power line may be performed in 1.5 years' time, whereas the planning and preparation of such an investment may last even 7–10 years [6]. It is similar with main heating pipelines and heating networks as well as with energy generating sources, particularly the nuclear ones. Therefore, it is of great importance to choose an appropriate location for the nuclear power plant, which on the one hand has a significant impact on securing appropriate radiation safety level and on the other hand influences total costs of the undertaking.

Nuclear power plant's cooperation with the power system mainly depends on the plant's control properties. These properties are determined by both the strength of primary circuit materials and the character of processes proceeding in the reactor core. Thermal stresses, which can arise in fuel elements of the reactor and in heavy-walled elements of the primary and secondary circuit (tanks, pipelines, the turbine), limit the plant's control properties due to the variable load of a nuclear unit, which has a disadvantageous effect on the power system. Variations in the electrical load of the nuclear unit cause changes in reactor power, which results in unbalancing the number of forming and disintegrating xenon nuclei in the core – xenon is the chemical element which along with samarium is mostly responsible for poisoning the reactor, which means parasitic neutron absorption. This provokes quite complex changes in reactor's reactivity, i.e. aberrations of the reactor's state from its critical state. Therefore, working by highest and possibly most stable load of the nuclear reactor and the whole unit is beneficial. Load changes are though unavoidable because of an advanced process of burning nuclear fuel.

From the operating side the most significant are reactivity changes during transient states caused by power reduction (decrease in density of the neutron flux) or switching off the reactor, because in these situations highest reactivity losses occur. Compensation of these losses and other reactivity effects is a responsibility of the control system and reactor safety devices. However in a stationary state samarium poisoning value depends on fuel enrichment and not on density of the neutron flux, as in case of xenon. This causes that during different reactor's power changes, except the switching off state, samarium concentration and reactivity loss begin and finish at the same stabilized level.

New solutions of nuclear reactors of III and III+ generations, in comparison with previous solutions, enable the nuclear power plant unit to work by much broader range of changes and changes of higher frequency in power variations. Current nuclear power plants are designed to follow changes in power system's load in a broad range, so they are characterized by appropriate manoeuvrability. Nuclear units of about 3.4 GW of thermal power and 1.1 GW of electric power enable discrete power changes by ±10% in the range of 15–100% of rated power, power reduction from 100% to 50% in 2 hours' time, maintaining power at the level of 50% for 2 to 10 hours and bringing it back to the level of 100% in 2 hours' time. Moreover it is possible to change power at the pace of 5%/min in the range of 15–100% of rated power (i.e. about 56 MW/min) [7].

In case of power plants adapted for delivering heat supplies, changes of electrical load may also be a result of changes in thermal power demand from the local heating system. Nevertheless, irrespective of the secondary circuit construction, thermal power consumption will generally cause the decrease in the amount of electric power generated by a nuclear power plant (CHP plant).

3 Secondary circuit of a nuclear combined heat and power plant

When deciding to use nuclear power plant as a source of network heat or process steam, special care should be taken to choose a proper turbine set and other parts of a secondary circuit. In classic CHP systems working on organic fuels backpressure turbines (bleeder backpressure turbines) or bleeder condensing turbines are used. In the first case, thermal power delivered from the turbine is distinctly higher (sometimes over twice) than electric power of the turbine set and, moreover, electric power is strictly dependent from thermal power demand.

Assuming that thermal power of the reactor in a nuclear unit proposed for Poland will amount to 3400–4500 MJ/s, using such a turbine would not be possible because the heat demand does not reach such a level. In Poland only the Warsaw heating system characterizes with similar thermal power level. The main problem is forced diversity of generated electric power resulting from seasonal heating demand change. A bleeder condensing turbine, whose bleedings could be used for supplying heating steam in the heating season, would be a definitely better solution. After the heating season this turbine could operate with entire condensation producing only electrical energy. Because of more complex construction allowing heat generation, costs of such a turbine are correspondingly higher in comparison with a condensing turbine. Chosen examples of turbine systems, presented in the literature [8,9], are shown in Fig. 3. A stage of modifications and changes within a condensing turbine depends on predicted thermal power for heating needs demand. A turbine with about 200 MJ/s of thermal power demand (in case of a 1600 MW nuclear unit) requires least changes. In such case steam can be taken from suitably enlarged bleeds in the high and low-pressure sections of the turbine – Fig. 3a. When thermal power consumption reaches about 500 MJ/s, it can be indispensable to place an additional low-pressure cylinder on the main turbine's shaft, devoted to heating operation – Fig. 3b. Greatest changes should be expected at the thermal power consumption over 1800 MJ/s. Then applying two or even three separate shafts with individual generators can be required – Fig. 3c. Currently there are no nuclear power plants in the world which would deliver higher amounts of heat to external consumers. Usually they are facilities which deliver heat to the nearest housing estates inhabited by the power

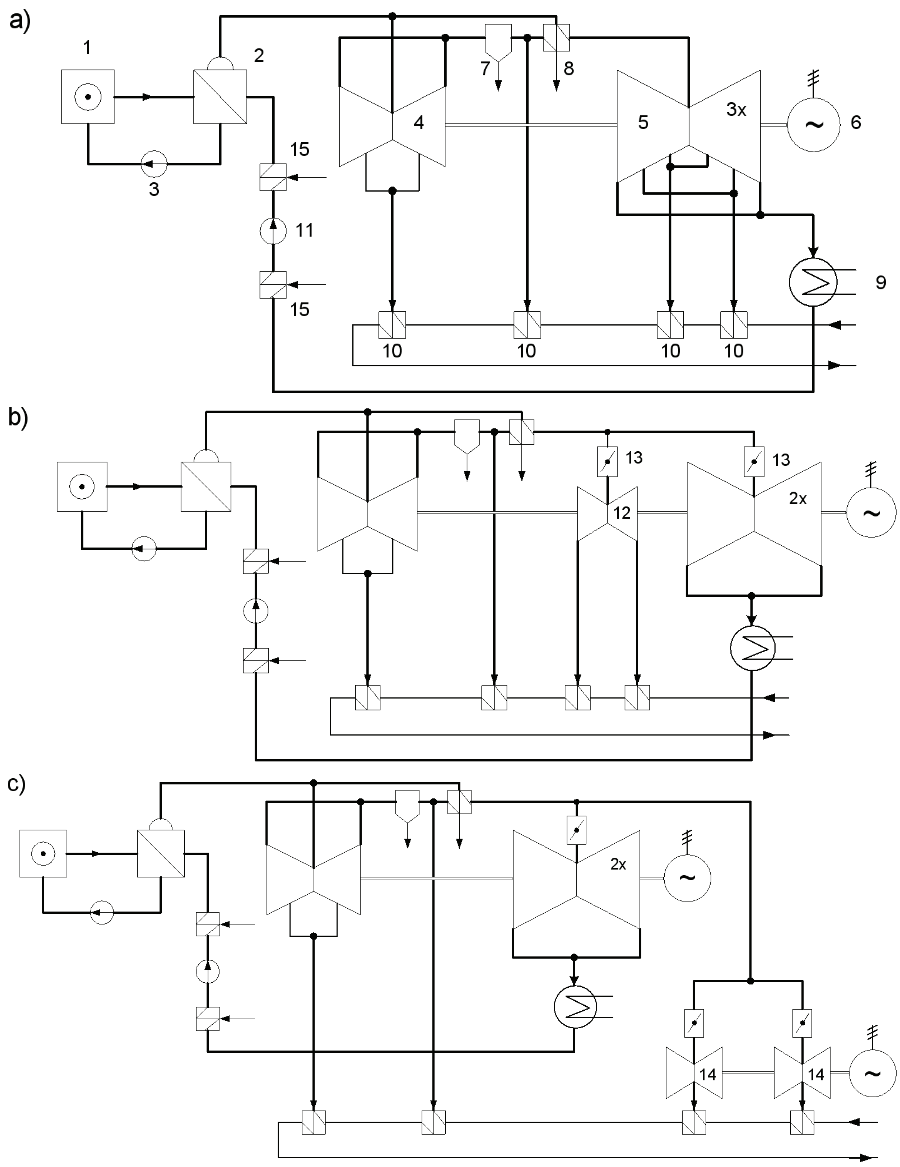

Figure 3. Simplified thermal diagrams of NPP systems adapted for district heating: 1 – nuclear reactor, 2 – steam generators, 3 – main circulation pumps, 4 – high-pressure cylinder of a turbine, 5 - low-pressure cylinder of a turbine, 6 – generator, 7 – steam separator, 8 – interstage steam superheater, 9 – condenser, 10 – network heat exchanger, 11 – feed-water pump, 12 – backpressure cylinder of a turbine, 13 – regulating valve, 14 – heating turbine on a separate shaft, 15 – regenerative heat exchanger.

plant's site personnel. Their power is rather low and reach several MJ/s. In the 1990's a great industrial nuclear heat and power plant operated in Canada. Its thermal power was 5350 MJ/s and it was based on the Bruce A nuclear power plant consisting of 4 nuclear units, which supplied a nearby heavy water production plant and a few other industrial consumers with process steam. Whereas an example of a currently working nuclear power plant delivering thermal power of peak value of 80 MJ/s to a quite complex heating network (130 km of total length) is a Swiss power plant named Beznau, which is equipped with two nuclear units with PWR reactors, each of 380 MW of gross electric power [10], [11].

Total electric power of Beznau nuclear power plant is practically at the same level as powers of classic steam units working in Polish power plants (for example Bełchatów, Opole). However due to the differences in generated steam parameters, their construction is very distinctive. The turbines installed in Polish power plants work on superheated steam (540 ^{0}C, 18 MPa), while the turbines in the Swiss nuclear power plant use dry saturated steam (5,5 MPa). Consequently, live steam flow in the nuclear unit is considerably higher (2160 t/h) than in Polish classic units (1150 t/h). Working medium flows in water-steam circuit are also clearly higher. Low parameter values and high steam moisture have a very disadvantageous impact on operating conditions of a saturated steam turbine. As a result of thermodynamic cycle's lower efficiency, the amount of heat emitted in the condenser is higher and therefore the cooling water demand in a nuclear power plant is also much higher (in comparison with a classic power plant of the same electric power). However exploiting nuclear power plants for heating operation enables limiting this demand. In case of Beznau nuclear unit the amount of cooling water is about 72 000 t/h (in Opole power plant unit it is about 40 000 t/h). For comparison, about 1150 t/h of network water circulates in the whole Refuna's heating system (supplied from Beznau nuclear power plant). It is significant that the Swiss power plant is equipped with an open cooling circuit of condensers, while Opole power plant uses cooling towers, despite the fact that the Aare river, by which the nuclear power plant is located, is poorer in water than the Oder river.

4 Nuclear combined heat and power plant in Pomeranian Voivodeship

Due to the preparation of "The Programme for the Development of Polish Nuclear Energy", an opportunity for reconsidering planned nuclear power plants utilization as sources of heat for existing heating systems has occurred. Therefore, it is possible to go back to previously made analyses and to base on gained at that time design experience. Warsaw society is particularly active in this field, as they are aware of the role of locating the nuclear CHP plant near the capital, which would improve natural environment's condition in Warsaw agglomeration. This CHP plant, introduced to the metropolitan heating system, could successfully replace existing sources of heat, working on hard coal, with a lot of pollutions. Very high thermal power demand appeals for such a solution, what positively impacts on economic effectiveness of heat cogenerating. A disadvantage of this solution would be a relatively distant heat transfer from the potential nuclear power plant (CHP plant) located in the region of Nowe Miasto to the Warsaw agglomeration's centre.

A separate issue is connecting a nuclear energy source with an existing heating system and their cooperation, which was analysed when the possibility of supplying Tricity agglomeration from potential nuclear power plants located in Pomeranian Voivodeship (proposed locations: Żarnowiec, Choczewo, Tczew, Lubiatowo-Kopalino) was considered [12]. In comparison with Warsaw agglomeration, this region characterises with significantly lower (over treble) thermal power demand. Distances between potential power plants adapted for delivering heat are similar, but good knowledge of main heating pipelines and availability of former thermal and hydraulic transfer system calculations results speak in favour of the Tricity region.

Recently performed analyses assumed parallel cooperation of heat sources supplying given consumption region, which is illustrated in Fig. 4. This configuration (in comparison with serial configuration) enables more effective exploitation of already existing classic sources of heat in the consumption region and gradual overtaking their role by a nuclear power plant (CHP plant). It also allows reducing heat transfer pipelines intersections, what is of great importance during long-distance heat transfer. Seasonal diversity of thermal energy for heating aims demand is a fundamental operating problem. Current solutions enable using network heat also in summer – network chill is produced then.

In case of a parallel system presented in Fig. 4, already existing sources of heat, located nearby the consumer region, would change their operating character to peak load sources, while basic thermal energy would be delivered from a distant nuclear power plant. A cogeneration factor, describing mentioned supply system, would be defined as (symbols as in Fig. 4):

$$\alpha_s = \frac{Q_{EJ}}{Q_{EJ} + Q_{ZS}} \, .$$

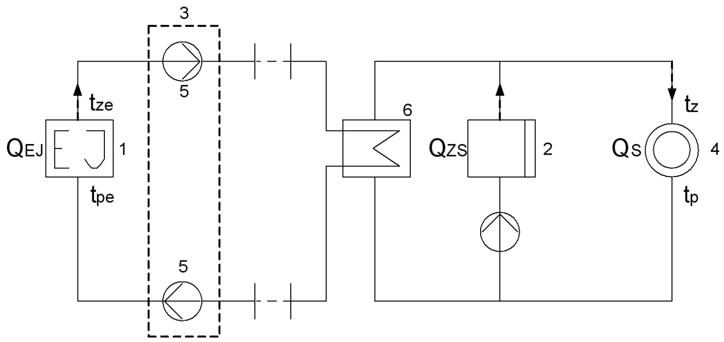

Figure 4. A pictorial scheme of a centralized heat supply system with a NPP cooperating in parallel with a local peak energy source: 1 – nuclear power plant, 2 – peak load heat source, 3 – network water pumping station with pumps 5, 4 – consumer region; 6 – intermediate exchanger station ; Q_{EJ}, Q_{ZS} – peak thermal capacity: of a nuclear power plant and of a local heat source, Q_s – maximum heat demand of a consumer region, t_{ze}, t_{pe}– supply and return network water temperatures at the nuclear power plant, t_z , t_p– supply and return network water temperatures at the consumer region inlet and outlet.

Costs of heat delivery from such a system have also been examined assuming that a nuclear power plant located by Lake Żarnowiec would be a base load source and that Wejherowo and Gdynia would be consumer regions. It was also presumed that in the first stage the nuclear power plant would fulfil a half of the peak heat demand of both regions, i.e. deliver about 300 MJ/s to the system, suitably cooperating with an existing local heating station and a CHP plant. This relatively modest heat demand from a nuclear power plant equipped with two EPR 1600 reactor units would enable supplying heat exchangers with steam coming from the last three slightly enlarged uncontrolled bleeds in the low-pressure section of the turbine.

The method used to estimate costs of heat delivery to consumer regions is described in the article [13] and its detailed algorithm is presented in the elaboration [14]. The main idea of this method is that fixed costs of generating heat in a nuclear power plant were enlarged by costs of electric power loss, while variable costs were enlarged by costs of electrical energy loss, arising in a nuclear power plant due to its adaptation for district heating. Moreover, the costs of heat delivery to consumer regions include costs of installing heating unit in a nuclear power plant and heat generation costs in local energy sources (in this case of a heating station in Wejherowo and of a CHP plant in Gdynia), as well as costs of heat transport from the NPP to both consumer regions. The costs of heat transport consist of main heating pipelines fixed costs, costs of the network water intermediate pumping station and costs of heat losses following this heat transport. The level of specific investment costs for generating and transport objects has a significant impact on total costs of heat delivery.

Preliminary calculations, assuming optimistic – i.e. relatively low – level of specific investment costs allowed to point out that considered supply system basing on extraction heat from the nuclear power plant has a chance to compete with existing classic heating systems, because it could provide heat delivery to consumers at the cost of 40 PLN/GJ. Performed analysis should be enriched with more detailed examination of levels of successive development of the supply system with a nuclear source of heat and with further examination of comparative analysis of supply systems' sensitivity on changes of different technical and economic indices.

5 Summary

As it arises from this analysis, implementation of the proclaimed Programme for the Development of Polish Nuclear Energy gives serious basis for considering purposefulness of using first nuclear power plants as cogeneration sources, which despite electrical energy would also produce heat for heating aims. Such a chance will be given to these power plants whose locations are predicted in the areas of high heat demand, so in the vicinity of urban agglomerations such as Warsaw and the Tricity agglomeration. For the nuclear power plant's location in the region of Lake Żarnowiec, preliminary technical and economic conditions of preparing a nuclear power plant to work as a base load heat source in the district heating system, which in the first stage would supply regions of Wejherowo and Gdynia, have been considered. The results of primary research indicate possible competitiveness of such a solution towards existing supply systems. It is also worth emphasizing that such utilization of a nuclear power plant would significantly limit waste heat and therefore improve total efficiency of a power plant.

Received in October 2011

References

[1] Niewodniczański J.: *Current view of nuclear power plants development in Poland*. In: Proc. Conference „The Influence of Nuclear Power Engineering on Environment and Inhabitants of Poland – Methods, Measurements, Evaluation", Institute of Nuclear Physics – Polish Academy of Sciences, Cracow 26.11.2007 (in Polish).

[2] President of the Energy Regulatory Office: *Thermal power in numbers – 2009,* Warsaw 2010 (in Polish).

[3] Ministry of Economy: *Polish Energy Policy until 2030*, Warsaw 10.11.2009 (in Polish).

[4] Central Statistical Office: *Concise Statistical Yearbook of Poland 2011.* Warsaw, July 2011.

[5] Ministry of Economy, Polish Government's Plenipotentiary for Nuclear Energy: *Program of nuclear energy development in Poland,* Warsaw, 16.08.2010 (in Polish).

[6] Kasprzyk S.: *Polish Nuclear Power Program. Most preferred locations, power capacity in these locations, development and modernization of lines and high voltage switchgears.* Energetyka **8**(2009) (in Polish).

[7] Kubowski J.: *Problems of co-operation between nuclear power plants and electric power system*, Energetyka **4**(2010) (in Polish).

[8] Mühlhäuser H.J.:, *Steam turbines for district heating in nuclear power plants.* Nuclear Technology **38**, April 1978.

[9] Reński A.: *Nuclear power plants as a source of network and process heat,* Energetyka **8**(2009) (in Polish).

[10] http://www.axpo.ch/axpo/de/kernenergie/wissen/ke 22.03.2011

[11] World Nuclear Association: *Nuclear Power in Switzerland*, 06/2011

[12] Patrycy A.: *Location of the first nuclear power plants in Poland.* 3rd Nuclear Power Academy, Gdansk, 11/2010 (in Polish).

[13] Reński A.: *How to reduce effectively the waste heat from nuclear power plant.* Rynek Energii **1**(2010) (in Polish).

[14] Kusto Z., Olszewski A., Reński A., Szafran R.: *Optimization of technical and economic parameters of heat delivered from a nuclear power plant.* Elaboration of Institute of Electrical Power and Control Engineering of Gdansk University of Technology within the framework CPBR 02.18, Stage 2, Gdansk 1987 (in Polish).

Wykorzystanie elektrowni jądrowej jako źródła energii elektrycznej i cieplnej

S t r e s z c z e n i e

Rozpatrzono wybrane problemy eksploatacji elektrowni jądrowych, wykorzystywanych nie tylko jako źródło energii elektrycznej, ale również i cieplnej. Za takim rozwiązaniem przemawia przede wszystkim konieczność ograniczenia emisji szkodliwych gazów (w tym CO_2)) i pyłów powstających w procesie spalania paliw kopalnych, a także rosnące zapotrzebowanie na ciepło czy też chłód sieciowy. Dodatkowo praca w skojarzeniu przynosi wymierne korzyści ekonomiczne, a także zwiększa bezpieczeństwo energetyczne w danym rejonie. W szczególności rozważono możliwość wykorzystania elektrowni jądrowej jako źródła ciepła dla systemu ciepłowniczego aglomeracji miejskiej, biorąc pod uwagę najbardziej prawdopodobne lokalizacje tej elektrowni w województwie pomorskim. Uwzględniono zarówno aspekty techniczne, jak i ekonomiczne tego przedsięwzięcia.