Assessment of district heating needs and technical possibilities in the vicinity of a future polish nuclear power station

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Abstract: *Nuclear power plants can be a reliable source of heat supplying district heating systems. Importantly, thermal and flow parameters of a secondary loop in pressurized water reactor technologies are sufficient to supply a district heating networks. Therefore, NCHP (Nuclear Combined Heat and Power) systems seem to be a viable replacement for traditional coal-fired cogeneration units located in big cities and may contribute to environmental protection in both local and international scale. In this paper working conditions of a municipal heat network, such as a pressure drop and the heat loses, were calculated and adapted to expected Poland's first nuclear power plant located in Pomerania Province. Cumulative probability distribution model of heat generation power in metropolitan area and future heat demand have been created and used to identify optimal size of NCHP heat output. Main parameters of heating network were presented and discussed. The positive effects on environment were assessed and summarized as well.*

Keywords: *nuclear power plant, cogeneration, district heating system, pressurised water reactor, heat demand*

1. Introduction

Sustainable development, basically derived in 1987 by World Commission on Environment and Development, focuses on the development of civilization with a full respect of the environment (natural resources, ecosystem services) – to ensure the present community a high quality of life without the decreasing the chances of covering mentioned needs for future generations. This idea refers to almost all human activities, among others agriculture, economics, energy generation, manufacturing processes, transport, architecture, industrial technologies, habits and preferences, business goals, and might be considered to be an idealised picture of future, in particular when the tough economy rules (i.e. Thomas Malthus demands) are at the core of functioning market.

One of the most important activities within the area of the sustainable development is power generation. In order to cover electricity, heat and coolness demands in a controlled, safe and, just as important, sustainable way, eco-friendly, high-efficient, readily available with high rangeability power technologies must be introduced. While finite energy resources such as coal, oil, gas are located only in selected areas and very often seem to be subjects to dispute in international deliberations between governments, most of modern nuclear technologies base on the fissile materials imported from politically stable countries. Moreover, fossil fuels emit CO_2, SO_2, NO_x, dusts when burned, that leads to climate changes and progressing degradation of the environment, while the operation of nuclear power plants merely requires adaptation of safe utilization technologies (storage technologies will be soon out of date) of radioactive wastes and coping with the indirect emissions. The implementation of renewable energy technologies – solar, wind, hydro, biomass, tidal, geothermal, wave units – is relevant as well, however, due to different limitations in power capacities, economic factors, annual availability, controllability, supply control or sensitivity to weather conditions, they are still recognised only as a technical supplement in large scale power systems (national or international). Therefore, to achieve a clean, available over a long period of time (40-60 years in the case of new III and III+ generation nuclear stations) energy (electricity, heat), save fossil fuels (coal, oil, natural gas), protect ecosystems (by obtaining low emissions per unit of generated energy) and avoid several problems of having unpredictable availability of renewable energy sources, integration of nuclear power units, while radioactive wastes are managed with the highest degree of safety, is crucial to promote the idea of the sustainable development. Equally significantly, according to many experts, nuclear energy, also in relation to renewable ones, meet the economic sustainability in a field of national security (even without a financial subsidy) as well.

1.1. Nuclear power as a vital element of a Polish energy sector in future

Nowadays, when the implementation of an low-emissions power plants is becoming increasingly favourable, the nuclear power units (with different levels of capacities and in miscellaneous systems) might be an economically justified technologies that can easily meet stringent standards of a progressing environmental policy. With regard to the entire lifecycle, their application offers many advantages over the majority of both conventional (fossil fuels) and renewable energy sources (i.e. wind turbines, solar plants). Furthermore, the development of a new types of reactors (generation III+ and IV) and radioactive waste processing technologies enhances the prospective technical capacity of a nuclear sector and significantly reduces the scale of a final storage of dangerous materials. Nuclear power sector allow governments to introduce the diversification of energy sources, provide the reliable electricity and heat at competitive prices and rely on a relatively common fuels from politically stable suppliers. Most importantly, it is virtually emission-free, therefore its application may be necessary to obtain a significant CO_2 emission reductions and support the idea of a sustainable development.

In Poland, where the energy sector is currently in a restructuring phase, the construction of first 2-3 nuclear power reactors is approved. In general, new national programmes (Energy Policy of Poland until 2030, Polish Nuclear Power Programme), corresponding to the expected international regulations (different EU Directives concerning industrial emissions and emissions trading market), suppose that the Polish nuclear sector will cover 21.1-31.6 TWh of electricity until the 2030 [1]. That corresponds to the 12-16% of national consumption in the considered period and the total nominal capacity of a nuclear reactors at the level of 3,200-4,800 MW (Fig. 1., see Appendices). The application of both pressurised-water (AP-1000, EPR-1650) and boiling-water (ESBWR, ABWR) reactors should be considered in the tendering process. Three main sites for a first Polish nuclear power plant were investigated at the location studies: Żarnowiec (the Krokowa Municipality), Lubiatowo-Kopalino (the Choczewo Municipality) and Gąski (the Mielno Municipality). All of them have a strong technical background due to the proximity of the Baltic Sea. Furthermore, Żarnowiec, thanks to the 716 MW Pumped Storage Power Station located nearby, may appear to have the largest potential for electricity generation and trading. Moreover, an especially interesting utilization of the nuclear energy, linked to the presence of a large number of energy users in close proximity to the NPP, may be district heat as well.

In order to comply with the European environmental policies, Polish government developed several guidelines and assessments concerning the structure of national energy sector and the national emissions of major pollutants in the perspective of next 30-50 years (Fig.1.). Studies show that, among others through the implementation of new renewable energy sources and nuclear power technologies, the releases of greenhouse gasses, sulphur dioxide, nitrogen oxides and dusts, should be significantly reduced in comparison to the present situation (Tab. 1., see Appendices) – despite the natural growth in the consumption of electricity (by 35% in comparison with 2013) and heat. It can safely be ascertained that the sustainable development, regarding the power sector, in Poland in the middle of the 21st century should be introduced mainly by the construction of 2-6 nuclear power units (first in Poland) with the total capacity of 5-6 GW_{el} [2].

While the combined heat and power generation may be implemented in a nuclear power plant, the assessment of a local heat consumers is necessary in order to optimise the economic background of the enterprise. The same requirements must be investigated in the case of a first Polish NPP. Importantly, NCHP (nuclear combined heat and power) would be a favourable element in a future transformations of national heating sector. In 2014, commercial Polish heating units transferred to the final recipient 279 PJ of heat. The household and welfare sector consumed then 59% (165 PJ supply about 50% of Polish people – one of the highest share in a EU) of it, while the industry only 28% [6-7]. Furthermore, the 15% increase of district heat demand in domestic activities is expected here by 2030. While between 2001 and 2010 the heat consumption was decreased (by 18% - mainly due to the thermo-modernisation of buildings), the household emissions reducing programmes involved the progressive growth of commercial heat capacities after 2010 [6].

In 2014, the highest share (75.1%) in a fuel structure of Polish heating sector fell on the coals (bituminous, lignite) (Fig. 2., see Appendices). The substantial use of fossil fuels in a conventional water-steam boilers results in the emissions of various pollutants [3, 8]. Facing the challenges of new environmental protection policy, they are going to be reduced in closest future, therefore environmentally friendly, economically justified power technologies – amongst others nuclear combined heat and power units – are strongly favourable in a Polish energy sector. Furthermore, while the adverse consequences of a domestic individual heating units were identified and pointed in a national assessments of a emissions of different air pollutants [3], the increase of a district heating systems should be noticed in a future, supporting the NCHP economical background as well.

To sum up, sustainable development in Poland will be enhanced by the future changes within the national energy sector, strongly connected to the electricity and heat generation sources in professional power plants and national fuel structure. However, in order to improve the conversion rate of fuels (that leads to higher sustainability as well), the implementation of polygeneration technologies is vital. While the coal-, oil- and gas-fires cogeneration units are relatively common in Polish cities, there is a lot of technical possibilities to introduce it in future nuclear units.

1.2. Nuclear CHP

According to [8, 10-13] the extraction of heat from nuclear power plants is possible and economically justified - both heat-only stations and cogeneration units might be technically optimised and introduced in order to supply heat for district and industrial heating applications. From a technical point of view, the heat extraction at a temperature of 135-160°C, that is a common value in heat distribution networks, from all types of reactors is possible. Moreover, for example, the secondary loop operation in a PWR or WWER technologies, substantially similar to the steam-water circuits in a conventional power plants fired by the fossil fuels, seems to be more favourable than BWR mostly due to low level of radiation, operation properties and overall safety culture. This fact is reflected in historical applications of cogeneration in a commercial nuclear sector. Heat extraction from nuclear power plants for the purpose of external heating networks were previously conducted i.e. in Kozloduy (Bulgaria, 9 MW of heating peak capacity), Dukovany (The Czech Republic, 680 MW), Cernavodă (Romania, 520 MW), Leningrad (former USSR, 110 MW), Bohunice (Slovakia, 147 MW), Beznau (Switzerland, 100 MW) or Paks (Hungary, 148 MW) [13]. Several nuclear (WWER, CANDU, RBMK, PWR) reactor were adopted in order to supply district heating systems.

In last years, many NCHP projects and studies have been conducted. Both Polish [10] and foreign researchers highlighted the evaluations of several a cogeneration in a NPP or calculated the possibilities of a district heating networks. In 2008-2009 Fortum carried out the studies concerning the possibilities of the implementation of district heating unit in the case of Helsinki region [12], where annual heat consumption reaches 11-12 TWh. On this basis, the heat capacity up to 1,000 MW from the future NCHP Unit 3 at Loviisa NPP (80 km from the capitol of Finland) were assumed and indicated as technically possible. 5 possible reactors were taken under the considerations: ABWR-1600, VVER-1200, EPR-1650, ESBWR-1650 and APR-1450. Proposed pipeline technology concerns the pre-insulated pipelines installed in a underground tunnel (double pipeline with a dimension of 1,200 mm each under the maximum pressure of 25 bar) [14]. The calculated reduction of Finish CO_2 emission after the NCHP implementation was assumed as a 4 million tonnes. Furthermore, the significant heat releases from Loviisa NPP to the Gulf of Finland would be decreased as well [13]. In turn, in 2012 the NCHP unit in French Nogent-sur-Seine NPP (located 110 km from Paris) were analysed. The covered heat demand of 3000 MW were proposed. By the limiting of the condensation temperature to 120°C (condensation pressure to 2 bar) and the modification of a low pressure turbine, the heat extraction at the district heating system temperature might be then technically obtained. Two options of heat transport were investigated: in underground channel and open trench buried in the ground. In both cases a proper thermal insulation of a pipeline was applied. The distance of a main pipeline was assumed to 150 km [11].

Former Polish nuclear project assumed implementation of total 900 MW of heat extraction (50% of peak demand in the local area) as well. Four WWER-440/213 nuclear units should have cooperated with coal-fired heating units in Gdańsk and Gdynia. 2 pipelines with a dimension of 1000 mm and range of 85 km were proposed. The usage of extraction-condensing steam turbines were investigated – the maximum electric power decrease of 123 MW was expected during the highest heat demand. In addition, in the cases of other Polish nuclear projects (Warta NPP in Klempicz, in the proximity of Poznań, and 2 NPP, situated in the basin of the River Wisła, 20-30 km from Warsaw), the completion of a cogeneration was included as well. When the heat in a quantity of 1000 MW from single steam turbine was extracted, the electricity generation in power turbine would have decreased from 1000 MW to 850 MW [13]. Moreover, thanks to the remarkable reduction of an energy intensity within the heat consumers in the last few decades in Poland (last Polish nuclear program was suspended 1990s), the quantity of a heat extracted and transferred related to the assessments in the 1980s and 1990s might be significantly limited [6].

2. Simplified feasibility study

Calculations of the Ministry of Economy of the Republic of Poland indicates the expected growth of a prices of electricity and heat over 400 zł'07/MWh (200% of a value in 2006 for industry consumers; for individual customer – 600 zł'07/MWh, 78% growth) and 40 zł'07/GJ (172%; 177% and 52,1 zł'07/GJ), respectively, in 2030 [1]. It can be explained by the final implementation of a CO_2 emission charges from industry in EU after 2020 [6]. The significant emission cuts of SO_x, NO_y, dusts, heavy metals are expected as well. Moreover, mainly due to the existence of first Polish nuclear power plants, the mentioned increase might be limited. This fact was specified in the Polish national assessment [15], where the nuclear energy was advised as the cheapest among other major power technologies. Furthermore, the implementation of cogeneration units was proposed in that case as well.

In order to prevent mentioned aspects in a future energy sector, the NCHP in a first Polish NPP is suggested. The implementation of a Żarnowiec or Lubiatowo-Kopalino NPP would be a source of district heating system in a Tricity (Gdańsk-Gdynia-Sopot) area. When licensed for operation (in 2020-2030), the NCHP should replace or assist the existing coal-fired units in Gdańsk and Gdynia (Tab. 2., see Appendices) and cover up to 4,65 TWh (16,73 PJ) of annual heat consumption. In comparison to the demand assessed in the Loviisa 3 CHP project it is 2.5 times less value, however, it is believed that the district heating network would be still cost-effectively justified. In addition, the evaluated technical factors (distance) and solutions may be easily converted to adopt first Polish NPP standards (i.e. PN25 bar).

During the author's research activities, the investigations of a different heat extraction from secondary loop in a PWR unit were conducted. Four technical concepts of NCHP were evaluated: from regenerating heat exchangers, bleeding from the steam turbine (after high pressure stages – with and without the further expansion) and by-passing the steam after the Moisture Separator Reheater. Studies have so far indicated that for all mentioned solutions the stable operation of a NPP can be obtained and optimised in order to supply district heating network. However, to obtain the most favourable economic, operational and technical indices of NCHP enterprise, some basic rules of heat network should be introduces [17]:

- the pipelines' route should be as short as possible,
- the area covered by the pipelines' heat capacity should be populated by as many residents as possible,
- the favourable both technical and economic solutions should be introduced (i.e. self-compensation of the pipelines, no interference in the city infrastructure, possibility of inspections and renovations) - routed overhead (overground) or underground (in a tunnel or buried, both as shallowly as conceivable),
- good engineering practices ought to be obey (i.e. minimum gradient of 3‰).

The distance from both Żarnowiec and Lubiatowo-Kopalino to Gdańsk – the largest city in the Pomerania region and 6th most populated in Poland - is approximately 60-70 km (Fig. 3., see Appendices), hence the implementation of heat network between NPP and Tricity is technically justified.

Both mentioned locations are suitable for the implementation of NCHP unit that can cover heat demand in the area o Gdańsk-Gdynia-Sopot agglomeration and neighbouring towns and villages. In 2010, the district heating network in Gdańsk supplied about 8,000 TJ (2.22 TWh) of heat in the average heat price of 26 PLN per GJ (Wybrzeże CHP plant) [6]. Taking into account the 15 % rise in the estimated district heat consumption, the heat demand at the NPP launch in 2030 should be 9,200 PJ (2,56 TWh).

Tab. 3. The assessment of the heat demand coverage and nominal capacity days depending on the nominal heat power (own elaboration)

nominal heat power	heat demand covered*	annual heat extraction	days with a nominal capacity of the network
MW	*%*	*PJ*	-
1200	96,2	16,7	4
1000	95,2	16,5	17
800	92,6	16,1	39
600	84,2	14,6	148
400	64,4	11,2	262
250	41,5	7,2	344

* in calculations, annual NPP down time of 31 days was included

That results in an annual heat generation of 5.53 MWh per capita. In further assessments, the implementation of the district heating system only for Tricity (Gdańsk-Sopot-Gdynia; calculated total number of residents – 748,000), Wejherowo (76,000), Rumia and Reda (47,500) regions will be investigated, therefore the total number of customers should exceed 850,000. The assessment of an annual cumulative heat distribution in Tricity region was presented in Tab. 3., while the evaluated pipeline route was submitted in a Tab. 4. and Fig. 4. The mass flow per 1 MW of a heat capacity in a pipeline was designated and equals 3.634 kg/MJ.

Tab. 4. The main pipeline segments in the case of Żarnowiec NPP (own elaboration)

segment of a network	distance	heat extraction
	km	*%*
NPP → Wejherowo	19.2	8.7
Wejherowo → Rumia	11.2	53.0
Rumia → Gdynia	11.1	4.4
Gdynia → Sopot	9.2	5.5
Sopot → Gdańsk	11.2	28.5

Fig. 4. The main pipeline segments in the case of Żarnowiec NPP (own elaboration; map: © OpenStreetMap contributors, CC-BY-SA 2.0 licence on www.openstreetmap.org/copyright)

The suitable heat distribution in a heating network correlates with the energy efficiency of a whole system. Lower energy factors are particularly noticeable in a summer. When the main structure of a network meets the requirements of an increased heat demand periods, the value of heat losses in hottest months is above 20-30% [18]. Furthermore, the appropriate insulation should be introduce to increase the thermal resistance of a pipeline system. Therefore, in order to maximise the annual heat efficiency of a proposed NCHP enterprise, the nominal thermal capacity of 250-270 MW should be introduced and 41.5% of annual heat consumption will be satisfied. Moreover, in order to increase the rate of heat demand coverage, the maximum heat capacity of the pipeline should be increased (Tab. 3.). For example, when the peak capacity of 800 MW is introduce, almost 93% of annual demand will be supplied from the NCHP, but only for 39 days in a year the operation parameters meet the nominal values, therefore, potentially, the average efficiency of a heat transfer will be lower. In order to determine the best technical and economical solution of a heat network, both the cooperation with a sources of peak power and proper regulation (quantitative and qualitative) are strongly advisable.

Depending on the final thermal and flow conditions in a pipelines, the heat and pressure losses are likely to differ. When optimal heat capacity is determined, the pressure drop and total energy graphs along the entire lengths of the pipelines may be identified. Example solutions can be found in [11-12, 19]. It is crucial to reduce the pressure losses in order to limit the electricity consumption by the circulations pumps. However, according to the prevailing technical standards, the necessary limitations must be satisfied i.e. the maximum average velocity of a water could not exceed 3 m/s. In Poland for example, PN-EN 253+A2:2015-12, PN-EN 448:2015-12, PN-EN 488:2015-12 and PN-EN 489:2009 standards should be taken into account at the time of design. The high-quality durable components and materials (pipes, insulation, valves and other apparatus) ought to be applied as well to meet operational period for at least 50-60 years.

Underground heat pipelines are especially preferred when the existing infrastructure (buildings, roads, railroads) is well developed. Moreover, its implication to reduce the heat losses correlated with the weather conditions (forced convection, ambient temperature). In recent times, the technology of channel-free, pre-insulated heating lines can be easily implemented, and, therefore, appears to be suitable for the district heating systems combined with NPP as well. In further calculations, the channalless pipe laying technology was analysed and three main equations were introduced:

$$\Delta p = L\,\lambda\,\frac{\rho}{2}\,\frac{w^2}{d_{\mathrm{pi}}},\ \mathrm{Pa} \quad (1)$$

$$\lambda = 0.0032 + \frac{0.221}{\mathrm{Re}^{0.237}},\ - \quad (2)$$

$$q = 2\left(\frac{1}{R_{\mathrm{s}} + R_{\mathrm{i}} + R_{\mathrm{h}}}\right)\left(\frac{t_{\mathrm{av}}}{2} - t_{\mathrm{s}}\right),\ \frac{\mathrm{W}}{\mathrm{m}} \quad (3)$$

where: L – length of a pipeline in metres, ρ – the density of water in kg·m^{-3}, w – average flow velocity of a water in a flow cross-section in m·s^{-1}, d_{pi} – inner diameter of a pipe in metres, R_{s} - heat resistance of a soil, R_{i} - heat resistance of insulation in m·K·W^{-1}, R_{h} - heat resistance between supply and return lines m·K·W^{-1}, t_{av} – average temperature of water in supply and return line in $^{\mathrm{o}}$C, t_{s} – temperature of soil (8$^{\mathrm{o}}$C was adopted), Re – Reynolds number of a flowing water (dimensionless).

To evaluate the basic parameters of a heating network (geometry, heat losses, pumping power), the simplified engineering calculations were performed. The Darcy-Weisbach formula (1) was used in order to calculate the pressure drop (Δp) in a single pipeline. For the assessment of a Darcy friction factors (λ), equation (2) was included. Finally, the equivalent hydraulic resistance of a series-parallel system was used introduced. In order to determine the heat dissipation (q) from symmetric system (both feeding and return pipeline), the formula (3) proposed in a PN-EN 13941+A1:2010: *Design and installation of pre-insulated bonded pipe systems for district heating* standard was taken into account.

The calculation model of a analysed pipeline system is presented in Fig. 5. (see Appendices).

For the case of 250 MW nominal heat capacity of the pipeline, the calculated total pumping power – to compensate the pressure drops – equals 11.77 MW, while the heat losses – 21 MW (maximum value of R_s was 0.212 m·K·W^{-1}, R_i – 3.01 m·K·W^{-1} and R_h – 0.81 m·K·W^{-1}; therefore. The total heat dissipation factor was 60-92 W·m^{-1} (higher values of q were observed for larger pipeline diameters with value of R_i below 2 m·K·W^{-1} – DN700 and DN500). Summing up, the heat extraction from the NPP should be round 270 MW at the temperature of 135°C - the stream of hot water in a network between NPP an Wejherowo need to be close to 1 m^3·s^{-1} (DN700 pipeline).

3. Water issues

Sustainable energy means the energy that is fully affordable, clean, generated without the emissions of hazardous substances into the environment as a whole (not only single geospheres). Protection of the atmosphere (i.e. through the construction of nuclear power plants in replacement for units fed by fossil fuels – to keep the new carbon change policy) must be performed while preserving the hydrosphere. To protect our planet in an integrated way and promote the sustainable development, water savings and improved water management must be conducted in power technologies and energy sector as well as in agriculture, manufacturing, household activities or transport. The relationship between the water used for electricity and heat generation and the consumed energy is presented by the concept of water-energy nexus and strongly suggest the need for integrating energy and water systems. Hybrid Sankey diagram [20] concerning interconnected water and energy flows shows that cooling technologies in thermoelectric power stations, accompanying electricity generation (39·10^{15} Btu per year), extract and utilize 196 billion gallons of water per day, constituting the largest water consumer. Most of this stream, after the production process, is discharged into surface water-bodies (137 billion of gallons per day) and oceans (55 billion of gallons per day). Therefore, to save water reservoirs and to implement the sustainable development, beyond the improvements in an total energy efficiency of power technologies, limiting of water consumption in NCHP are crucial. All these saving can be made by:

- improving of cooling conditions of condenser, turbine set (oil, hydrogen), electric motors, bearings,
- reducing all leakages of water in both steam cycle and district heating network (glands, valves, operation of control instruments and automation apparatuses), efficient water use in social and servicing activities,
- implementation of waste heat power technologies,
- increasing the efficiency of operation in water treatment stations (water circulation in power plants and heating systems need to be demineralised or even accurately deionised – to guarantee long life of boilers, pipes, turbines).

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All mentioned techniques are vital and justified in terms of both economy and hydrosphere protection in NCHP project. Furthermore, new, highly efficient (in terms of both heat and water) pipelines and control devices seem to be necessary for district heating systems against the idea of sustainable development combined with water-energy nexus.

As was already pointed out, access to cooling water sources is a crucial aspect in designing process of every new power station. Cooling of condensers and generators, in order to achieve the most cost-effective solution, should be based on an open system – without the cooling tower, with the heat discharge to a river, lake, sea or ocean. However, from an environmental point of view, that technologies seem to be dangerous due to permanent heating of local waters, that may have adverse environmental impact. According to its own estimates, while cooling of six 360 MW of electricity each coal-fired power units requires about 86 m^3 of fresh water (at ambient temperature) per second, four 1000 MW each nuclear units consume more than 200 m^3 of water per second. Understandably, national authorities imposes several limitations (i.e. maximum water intake in relation to the design flow or temperature of water introduced to the environment) in the case of a use of surface water, but, in order to execute the development of modern societies in the most sustainable way, interferences by the industry in the hydrosphere should be limited or even abandoned – as often as possible. The use of cooling tower significantly reduces the water intakes from rivers and seas, however, during its operation about 1.5-2% of water pumped in a cooling system is carried in a form of drops by the flowing air (in a chimney draught zone) and must be supplemented continuously from the water treatment units. The feasibility studies of a nuclear unit with PWR technology and electrical capacity of 1000 MW [21] showed, that to meet cooling demands of condenser, 1,994.5 MW of heat need to be removed continuously to the environment (in a water, heated from the temperature 20 degrees Celsius to 30 degrees Celsius). Moreover, 47.8 m^3 of water per second have to circulate in a closed-loop system with cooling tower (882 kg/s of water is, in adopted parameters of ambient air, removed by flowing air, however it can be significantly limited by the installation of demisters). Finally, when justified, there is a possibility to introduce the combination of two systems (both opened-loop and closed one). That solution was introduced in Ascó Nuclear Power Station (Spain).

The dissipation of energy and discharges of water may be significantly limited among others by the implementation of polygeneration techniques within the power sector, including nuclear units. That concept becomes more essential in the light of progressing global challenges – climate changes, population growth, improving of living standards and, what is most important, increase of local and global energy demand. All mentioned transformations must include the minimum impact on water supplies and, again, can be promoted by NCHP. Low temperatures of water-steam mixture after the turbine zone can be compensated by the limitation of expansion rates or implementation of low rank heat utilization technologies – heat pumps, organic Rankine cycles [22], direct heating systems – additional heating sources (in combination with heat streams from NPP) or steam extractions from the stream cycle.

4. Other advantages of NCHP in Poland

A number anticipated benefits, other than the stable, cheap source of heat, are recognised in a field of environmental protection and fossil fuels savings.

In 2014, 2853,8 PJ of primary energy were acquired in Poland. Hard coal was its main source of first mentioned (61,0%; brown coal – 18,2%, RES – 13,8%, natural gas – 5,5%, crude oil – 14%). At least 50% of Polish bituminous coal (37 billion tonnes) was utilized in commercial power engineering sector. Furthermore, almost 100% of lignite from Polish mines (63,9 billion tonnes) was utilized in a power plants and heating units as well. When introduced, NCHP can save a significant quantities of coal that would normally be utilized in both electricity and district heat generation.

Moreover, the shift towards a low-coal consumption power sector would significantly decrease the annual releases of various pollutants from power plants, CHP units and only-heat stations. Furthermore, the household emissions could be reduced as well. In general, the environmental benefits of the implementation of NCHP (in replacement for coal-fired heating units, both commercial and domestic ones) are:

- notable reduction of the emissions of various pollutants, i.e. CO_2, NO_x, SO_2, CO, TOC, particulates (including PM_{10}, $PM_{2.5}$ and soot), PCB, HCB, PAH (including benzo(α)pyrene), PCDD/Fs, heavy metals (Hg, Cd, Pb, As, Cu, Ni) etc.,
- higher NPP efficiency and reduction of the heat loads introducing to the Baltic Sea.

To sum up, the implementation of analysed cogeneration technology within gradually growing nuclear sector seems to be favourable in terms of environmental protection and, when reasonably implemented, power generation economy as well [23].

5. Conclusions

As revealed in this paper, the NCHP enterprise in first Polish nuclear power plant located in the proximity of Tricity area may be considered as technically justified. When the heat extraction (at the temperature of minimum 130-150^{o}C) from PWR or BWR technology is stable throughout the year, the energy efficiency of the nuclear cogeneration should be the highest. Since the Polish heating sector currently bases on the combustion of fossil fuels (mainly coal), the implementation of NCHP should reveal many environmental and economic advantages, especially in view of the expected tightening of EU environmental policy. The new emission standards (i.e. Industrial Emission Directive - 2010/75/EU) will determine the increase the costs of heat generation in coal-fired plants. Furthermore, the charges for emission of CO_2 is expected in third decade of the XXI century.

There are, however, many significant technical challenges of a NCHP in a PWR and BWR technologies. Key aspects of the mentioned implementation are:

- the possible steady heat demand – both high efficiency of heat transfer and stable operational NPP parameters are required for the positive cost-effectiveness factors – including future heat consumption growth,
- highly efficient, resilient heat network should be designed (long-time operation),
- the most favourable heat extraction should be recognized and introduced (from the various steam bleeders within the turbine, internal regeneration heat exchangers), affecting the construction of steam turbine and thermal-flow conditions with minimum disruption; an expected relation between the additional heat capacity from NCHP and the reduction of electricity generation is 6:1 - for every 6 MW of heat gained from the extracted steam 1 MW of generated power is decreased.

Nuclear power stations cooperate with uranium mining industry - both of this sectors are strongly connected to water consumption. Depending on the technologies, efficiencies and operation culture in a field of power generation from nuclear fission, the quantity and quality of water, used and finally released to the environment, may vary significantly. To introduce the sustainable development, understandably, some action aimed at water protection are necessary and crucial. In the case of nuclear power plant, one of the most important stream of water covers cooling processes (condenser). However, the use of water can be significantly reduced - by using waste heat (at low exergy level) in additional power technologies, for example in cogeneration, that seems to be one of the most interesting ways to protect hydrosphere – including future nuclear industry and power stations. When identified and optimised, the idea of the combination of nuclear reactors and district heating networks should be considered as a significant in terms of the sustainable development policy.

While the implementation of a CHP within the existing NPP requires undertaking notable technical and organizational actions, the completion of a heat extraction from secondary loop in a new PWR projects is justified and should be introduced in the most densely populated areas. When the covered heat demand is relatively stable and the quantity of surrounding heat users substantial, the NCHP technologies may be an environmental friendly, cheap solution of the municipal heat source. When constructed and commissioned, the NCHP should replace the coal-fired units located in a Tricity region. The idea of a heat extraction from a NPP ought to be included in a plans of a future district heating system transformations.

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References

[1] Ministry of Economy of the Republic of Poland. Forecast need of fuel and energy by 2030. *Appendix 2*. (in Polish) 2009.

[2] Ministry of Economy of the Republic of Poland. *Conclusions from prognostic analyzes for the needs of Poland's Energy Policy until 2050. Appendix 2. to the Energy Policy of Poland until 2050,* Warsaw, June2015.

[3] KOBiZE. *National assessment of SO_2, NO_x, CO, NH_4, NMVOC, dust, heavy metals and POPs emissions in a SNAP and NFR systems of classification. The basic report*. Warsaw. 2016.

[4] KOBiZE. *Inventory of greenhouse gases for the years 1988-2014. Synthetic report for the United Nations Framework Convention on Climate Change and the Kyoto Protocol.(in Polish),* Warsaw. 2016.

[5] Energy Market Agency S.A. Polish Power Industry Statistics, yearbook ARE, Warsaw. 2014.

[6] PWC. *Heating market in Poland*. http://www.pwc.pl/pl/publikacje/2012/rynek-ciepla-w-polsce-2012.html. 2012 (date of download: 22.06.2016)

[7] GUS (Central Statistical Office). *Energy statistics in 2013 and 2014*. Statistical Information and Elaborations. 2015. http://stat.gov.pl/obszary-tematyczne/srodowisko-energia/ (the date of download: 22.06.2016).

[8] Celiński Z., Strupczewski A.. *The basis of nuclear power engineering* (in Polish). 1984. Wydawnictwo Naukowo-Techniczne, Warsaw.

[9] Energy regulatory office. Thermal power sector in numbers – 2014. 2015. Warsaw.

[10] Minkiewicz T., Reński A. *The Possibility to use a Nuclear Power Plant as a Source of Electrical Energy and Heat*. Acta Energetica, 2014, Vol. 3/20, p. 114-118.

[11] Safa H.. *Heat recovery from nuclear power plants*. Electrical Power and Energy Systems, 2012, Vol. 42, p. 553–559.

[12] Tuomisto H.. *Safety Aspects Related to Deploying Nuclear Cogeneration for District Heating: Case Helsinki*. 7. International School on Nuclear Power, Warsaw, 4th-7th November 2014.

[13] Kuźniarski Ł., Ferdyn B.. The nuclear cogeneration plants (in Polish). 2013. http://atom.edu.pl/index.php/technologia/nie-tylko-prad/cieplownictwo.html (the date of download: 22.06.2016).

[14] Bergroth N.. *Large-scale combined heat and power (CHP) generation at Loviisa nuclear power plant unit 3*. Proceedings of the 8th international conference on nuclear option in countries with small and medium electricity grids, Dubrovnik, Croatia, 16–20 May 2010.

[15] McKinsey&Company. *Assessment of Greenhouse Gas Emissions Abatement Potential in Poland by 2030. Summary of findings.* 2009. http://www.mckinsey.com/ (date of download: 22.06.2016).

[16] EDF Poland S.A., Branch of the Coast in Gdansk. *The environmental statement 2014* (in Polish). 2015. Available on the EDF Poland official website (https://edf.pl/).

[17] Krygier K.. *Heating networks. Auxiliary materials for exercises* (in Polish). Warsaw University of Technology publishing house, Warsaw 2006.

[18] Jachura A., Sekret M.. *Urban energy efficiency heating system* (in Polish). Ciepłownictwo, Instal 7-8/2013, p. 7-12.

[19] Babiarz B., Zięba B.. *Heat losses in the preinsulated district heating systems* (in Polish). 2012. Zeszyty Naukowe Politechniki Rzeszowskiej 283, z. 59 (4/12), p. 5-19.

[20] Bauer D., Philbrick M., And Vallario B.. *The Water-Energy Nexus: Challenges and*

Opportunities. 2014. U.S. Department of Energy, Water-Energy Technology Team, http://www.energy.gov/sites/prod/files/2014/06/f16/Water%20Energy%20Nexus%20Report%20June%202014.pdf (date of download: 03.11.2016).

[21] Cholewiński M., Pospolita W., Kamiński M.. *Concept design of a cooling tower for a nuclear unit with an electric power of* (in Polish). Proceedings of Puzzel 2016: V Wrocław Students Conference of Technical Science, Wroclaw, pp. 364-371.

[22] Kubski P., Lewandowski W.M., Ryms M.. *Increasing the efficiency of technological processes through the use of ORC and trigeneration systems.* NAFTA-GAZ, October 2010, Year LXVI, pp. 886-891.

[23] World Nuclear Association. *World Nuclear Performance Report 2016*. Report No. 2016/001. June 2016. http://world-nuclear.org/getmedia/b9d08b97-53f9-4450-92ff-945ced6d5471/world-nuclear-performance-report-2016.pdf.aspx (date of download: 29.03.2017)

Appendices

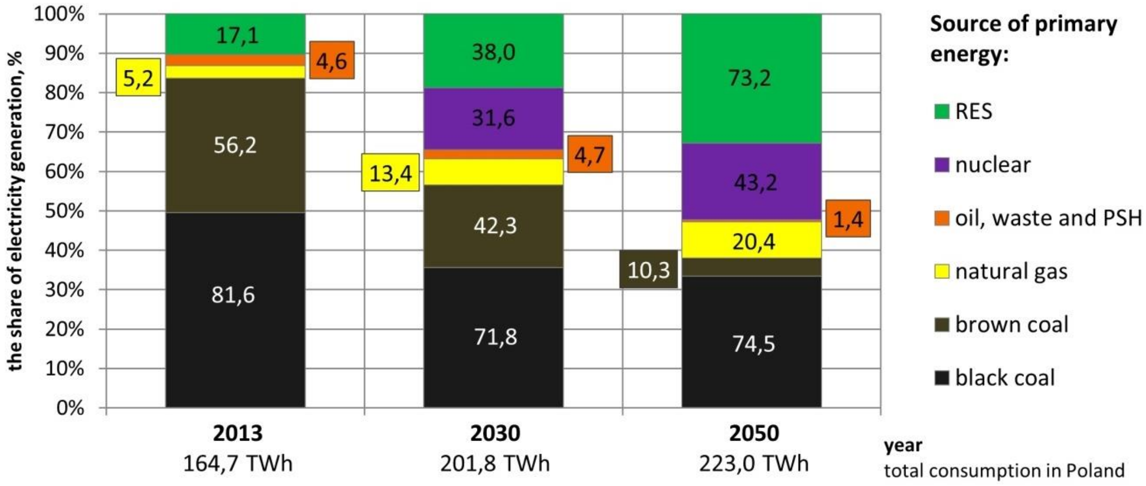

Fig. 1. Electricity generation from various fuels in Poland in the future - own elaboration on the basis of [1-5]

Tab. 1. National emissions of GHG (greenhouse gasses, in CO_2 equivalent), SO_2, NO_x and TSP (total suspended particles) and electricity generation (E_{tot}) in Poland - in 2013 (assessed), 2030 and 2050 (both predicted); the percentages represent the shares with respect to the base year 2013 - own elaboration on the basis of [1-3]

year		2013		2030		2050	
E_{tot}	TWh	164,7	100%	201,8	123%	223	135%
GHG	mill. tons of CO_{2e}	397,0		350,0	88%	239,0	60%
	tons per MWh	2,41		1,73	72%	1,07	44%
SO_2	thous. tons	853,4		447,5	52%	410,0	48%
	kg per MWh	5,18		2,22	43%	1,84	35%
NO_x	thous. tons	774,1		628,6	81%	315,0	41%
	kg per MWh	4,70		3,11	66%	1,41	30%
TSP	thous. tons	402,5		298,0	74%	198,0	49%
	kg per MWh	2,44		1,48	60%	0,89	36%

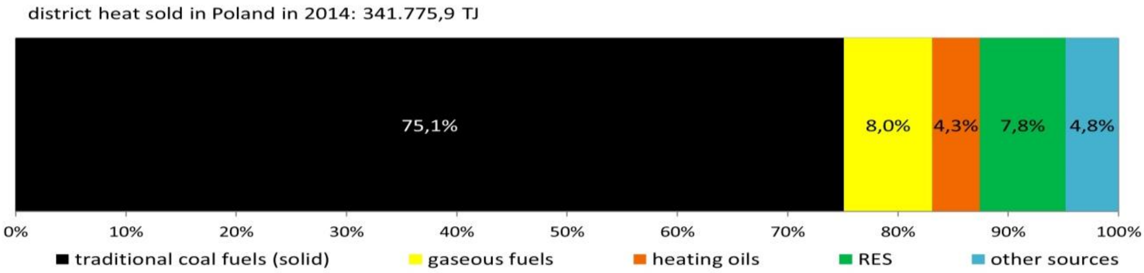

Fig. 2. Fuel structure of heat demand coverage from commercial sources in Poland in 2014 – own elaboration on the basis of [9]

Tab. 2. The impact of Tricity main district CHP units on the environment in 2014 [16]

CHP station	**nominal capacity** electric / thermal	**production (gross)**		**emissions**			**waste generation (all types)**
		heat	**electricity**	**dust**	**SO_2**	**NO_x**	
	MW	*TJ*	*GWh*	*tones*			*tones*
Gdansk	217.3 / 736.2	6,952	796	110	3,356	2,033	1,059.1
Gdynia	105.2 / 470.3	3,755	498	116	1,740	971	511.4

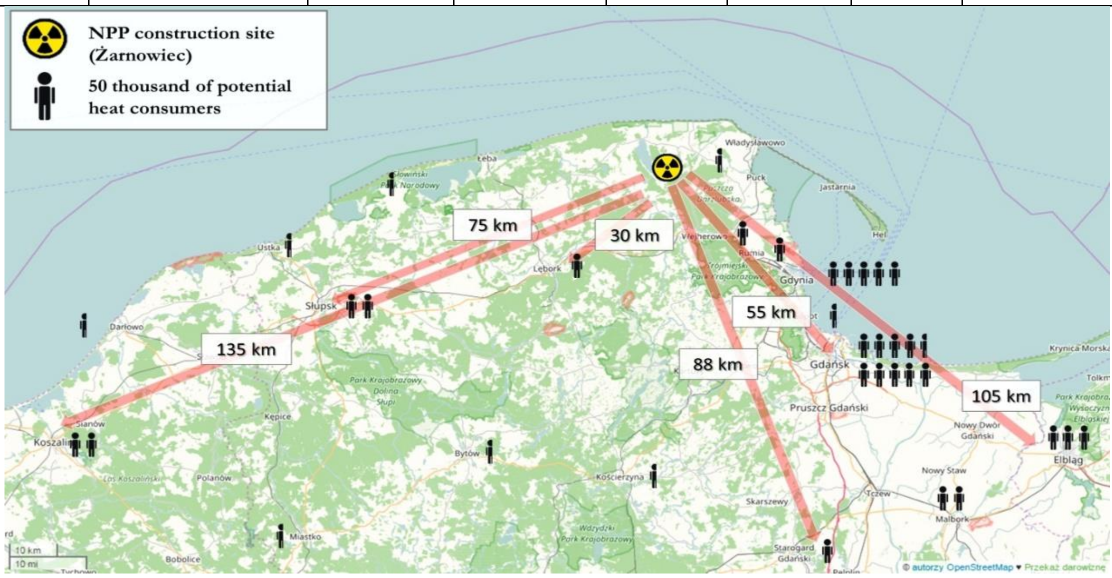

Fig. 3. The assessment of a heat recipients and the distance of NCHP in the case of Żarnowiec NPP (own elaboration; map: © OpenStreetMap contributors, CC-BY-SA 2.0 licence on www.openstreetmap.org/copyright)

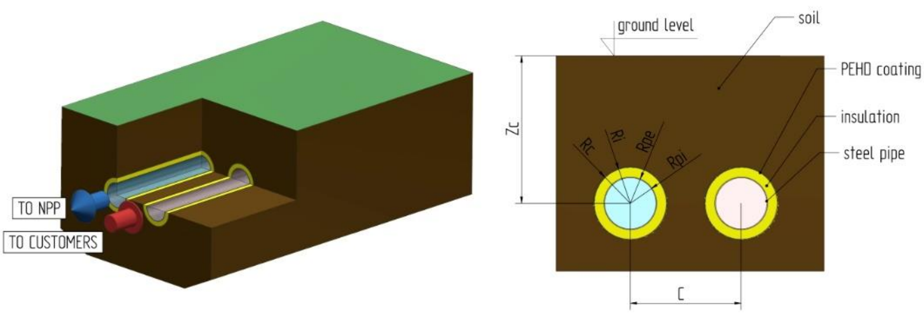

Fig. 5. Simplified model of a pipeline (own elaboration)