www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

ARCHIVES OF ENVIRONMENTAL PROTECTION

vol. 40 no. 3 pp. 137 - 151 2014

DE GRUYTER

PL ISSN 2083-4772
DOI: 10.2478/aep-2014-0033

APPLICATION OF A HYBRID UF-RO PROCESS TO GEOTHERMAL WATER DESALINATION. CONCENTRATE DISPOSAL AND COST ANALYSIS

BARBARA TOMASZEWSKA[1]*, LESZEK PAJĄK[2], MICHAŁ BODZEK[3,4]

[1]Mineral and Energy Economy Research Institute of the Polish Academy of Sciences,
Wybickiego 7, 31-261 Kraków, Poland
tel.: +48 12 632 3300 ex. 131, fax: +48 12 632 6717
e-mail: b.tomaszewska@meeri.pl
[2]Mineral and Energy Economy Research Institute of the Polish Academy of Sciences,
Wybickiego 7, 31-261 Kraków, Poland
tel.:+48 12 632 3300 ex. 131, fax: +48 12 632 6717
e-mail: pajak@meeri.pl
[3]Silesian University of Technology, Institute of Water and Wastewater Engineering,
Konarskiego 18, 44-100 Gliwice, Poland
e-mail: michal.bodzek@polsl.pl
[4]Institute of Environmental Engineering of the Polish Academy of Sciences,
M. Skłodowskiej-Curie 34, 41-819 Zabrze, Poland
*Corresponding author's email: b.tomaszewska@meeri.pl

Keywords: Desalination, geothermal water, reverse osmosis, costs analysis, concentrate disposal.

Abstract: Membrane-based water desalination processes and hybrid technologies are often considered as a technologically and economically viable alternative for desalination of geothermal waters. This has been confirmed by the results of pilot studies concerning the UF-RO desalination of geothermal waters extracted from various geological structures in Poland. The assessment of the feasibility of implementing the water desalination process analysed on an industrial scale is largely dependent on the method and possibility of disposing or utilising the concentrate. The analyses conducted in this respect have demonstrated that it is possible to use the solution obtained as a balneological product owing to its elevated metasilicic acid, fluorides and iodides ions content. Due to environmental considerations, injecting the concentrate back into the formation is the preferable solution. The energy efficiency and economic analysis conducted demonstrated that the cost effectiveness of implementing the UF-RO process in a geothermal system on an industrial scale largely depends on the factors related to its operation, including without limitation the amount of geothermal water extracted, water salinity, the absorption parameters of the wells used to inject water back into the formation, the scale of problems related to the disposal of cooled water, local demand for drinking and household water, etc. The decrease in the pressure required to inject water into the formation as well as the reduction in the stream of the water injected are among the key cost-effectiveness factors. Ensuring favourable desalinated water sale terms (price/quantity) is also a very important consideration owing to the electrical power required to conduct the UF-RO process.

INTRODUCTION

Protection of the environment is one of our most important obligations. All types of energy production have some impact on the environment, but the degree or extent of this impact depends on the technology used. Both of the main geothermal applications – power generation and direct use – can have an effect on the environment [1, 12–13,16–17]. The key considerations here are the salinity and toxic ingredient content of the water used and, as a consequence, the manner of its disposal. These need to be identified, quantified and, if necessary, eliminated or abated, at the very least in order to comply with environmental regulations [16].

Geothermal water is either extracted using submersible pumps or flows by itself when the deposits are under artesian pressure. Extraction is carried out using [3, 22, 23]:

- a closed system of production and injection wells: cooled geothermal water is injected back into the reservoir through the well after partial heat recovery in heat exchangers or heat pumps,
- an open system of production wells: after partial heat recovery cooled water is mainly transferred to a surface reservoir,
- a mixing system: one part of cooled geothermal water is injected back into the reservoir and a second part is transferred to a surface reservoir.

An open drain system operation (without injecting cooled water into the formation) significantly improved the economic performance of the enterprise [23]. However, the water discharged into surface waters or used for other purposes must meet certain requirements set forth in legal regulations [3, 7–10, 27–29]. Even where its salinity is low, this water may exhibit elevated contents of undesirable elements such as boron, arsenic and fluorine, which significantly restricts the possibility of discharging it into surface waters. For this reason the desalination of geothermal waters is being considered in many parts of the world, in arid areas, mainly for irrigation purposes, to reduce the negative impacts of saline geothermal waters discharged to water bodies and surrounding agricultural areas and also as a possible solution leading to the decentralisation of the drinking water supply [5–6, 18]. Research aimed at assessing the feasibility of using treated geothermal water for drinking purposes has also been undertaken in Poland. Waters from three different geothermal areas were tested, i.e. the Podhale basin (GT-1), Polish Lowlands (GT-2) and Western Carpathian Mountains (GT-3), using an integrated process combining ultrafiltration and reverse osmosis with low-pressure BWRO membranes.

The research shows [19] that two independent stages of reverse osmosis (RO-1 and RO-2) connected in series together with pH adjustment, may be required where high boron content is present in the water [19, 21, 23]. During pilot tests, despite of the low pressure applied in the reverse osmosis process (1.1 MPa) a high-quality/potable water was obtained with geothermal waters containing up to 7 g/L of TDS (GT-1 and GT-2) [19–21]. However, the industrial use of water desalination processes in geothermal systems will be primarily dependent on concentrate disposal possibilities and the economic aspects [24–25].

Concentrate is generated as a by-product of the separation of the minerals from the source water used for desalination [2, 26]. The characteristics of the waste stream depend on the quality of the feed water, the quality of the produced water (depend of recovery varies level), the pre-treatment method (added chemicals) and cleaning procedures used [2, 14, 19, 26]. The concentrate TDS (or ion concentrations) can be calculated [19] in terms of the feed and permeate TDS and the fractional plant recovery (Y):

$$TDS_{concentrate} = TDS_{feed}\left(\frac{1}{1-Y}\right) - \frac{Y \cdot TDS_{permeate}}{100(1-Y)} \tag{1}$$

$$\text{where,}\quad Y = \frac{Permeate\ flow\ rate}{Feed\ flow\ rate}$$

It is also important that in industrial reverse osmosis facilities various chemicals are widely used, such as [2]: chemicals (for cleaning membranes), biocides, antiscalants, acids and bases used to adjust feed water pH. Currently, the use of environmentally friendly substances is promoted; these are easily biodegradable in the natural environment. The examples are [2] polymeric additives based on maleic anhydride that have lower eutrophication potential. It is important to note that acids and scale inhibitors added to the desalination plant source water are rejected by the reverse osmosis membranes in the concentrate and also have an impact on its overall mineral content and quality.

In sea water desalination, the concentrate is usually discharged back into the sea. More difficulty should be expected when such systems are operated inland. The concentration of minerals and contaminants in brines or concentrate is usually approximately double that in feed water or higher [2, 14, 26]. Therefore the manner in which the concentrate is disposed of will largely determine the cost of desalinating water in an inland setting. Where the reverse osmosis process is applied to the desalination of geothermal water, economic analysis should also include the operating costs of the geothermal system in place. Therefore the cost effectiveness of implementing geothermal water desalination processes will additionally depend on the possibility of utilising (selling) treated water, the level of expenditure that can be avoided by not injecting the water back into the formation (also including the expenses related to drilling the appropriate number of absorption wells and the cost of the energy used by high-pressure pumps that inject the water into the formation) or the environmental costs resulting from the discharge of cooled water (wastewater) into surface waters.

This paper presents an economic analysis of the implementation of the UF-RO process analysed in two geothermal systems operated in Poland: GT-1 and GT-2. The results of pilot studies served as the basis for the assessment of the feasibility of implementing the solution analysed on a larger scale.

MATERIALS AND METHODS

Testing equipment and water desalination procedure

Detailed testing equipment and desalination procedure were presented in our previous work [19–21]. The pilot system was fitted with typical industrial plant components and included (Fig. 1):

- a water pre-treatment facility: mechanical filter, iron removal stage and ultrafiltration module (UFC M5, X-Flow) – for removal of colloids and microorganisms;
- a two-stage reverse osmosis setup (equipped with spiral wound DOW FILMTEC BW30HR–440i reverse osmosis membranes) with HCl dosing before first stage

(the feed water before RO-1 was pH ca. 5±0.4) and with NaOH dosing before stage two (pH of the feed water before RO-2 was corrected to about 10±0.5);
- final treatment to achieve drinking water parameters (mineralisation, disinfection).

A double hybrid setup was selected that combined ultrafiltration and two independent stages of RO (RO-1 and RO-2) connected in series. The selection of a two-pass RO process was necessary because of the boron content in the water samples analysed. It was essential to bring the boron content down to drinking water standard in the final permeate water. A high boron concentration is also a common feature of geothermal water sources in Poland, particularly when the TDS is greater than 1 g/L [21].

The pilot desalination tests of water from the GT-1 and GT-2 wells was performed on a semi-production scale (respectively ca. 1.0 m^3/h of desalinated water production from the GT-1 well and 0.5 m^3/h from the GT-2). The process was carried out using module RO-1 and RO-2 at the feed water recovery level of 75% and a feed water temperature of 30°C.

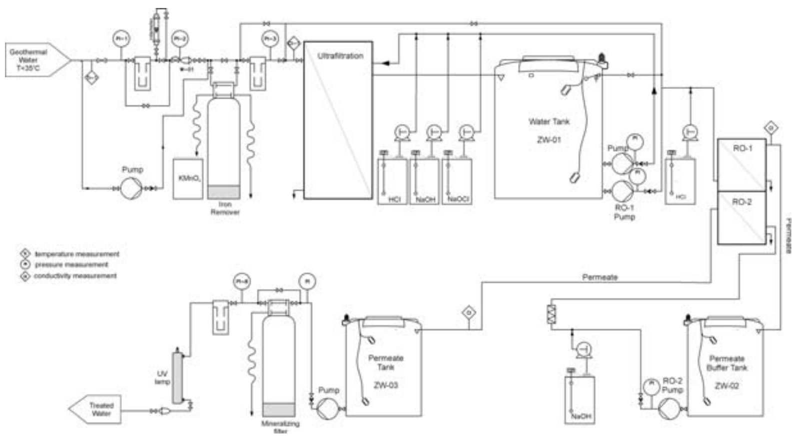

Fig. 1. Process diagram of the geothermal water desalination facility (after [19])

Geothermal waters and concentrate quality

During desalination procedure, the quality of feed water and the concentrate was assessed using a measurement of its unstable physical parameters – temperature, electrolytic conductivity of water and alkalinity – immediately after sampling the solution from the installation using the electrometric method. Inorganic components were measured at an accredited laboratory (PCA-AB 1050 and PCA-AB 176) using the inductively coupled plasma mass spectroscopy method (ICP-MS) and, for the fluoride concentration, the spectrophotometric method (Cary UV-vis). Chloride ion concentration and alkalinity were determined by titration following accredited testing procedures.

Energy and economic assumptions

In calculations concerning the energy and economic effects related to the implementation of the proposed system, the following factors were accounted for:

- the impact of the reduction in the stream of water injected back into the formation on the pressure and power of pumps,

- the impact of the concentrate stream included in the water injected into the formation,
- capital costs (depreciation),
- electricity consumption in the UF-RO facility,
- costs of chemicals (HCl and NaOH),
- revenue from the sale of drinking water, assuming that the water would be sold at a price similar to that of water obtained from sources that do not require high performance treatment methods (EUR 0.48/m^3),
- UF-RO facility operation, repair and maintenance costs.

In the economic analysis related to the implementation of the UF-RO process, it was assumed that 30% of the total extracted geothermal water stream would be desalinated, i.e. 120 m^3/h for water for the GT-1 intake and 21 m^3/h for the GT-2 one. The process analysed is presented in the diagram in Fig. 2.

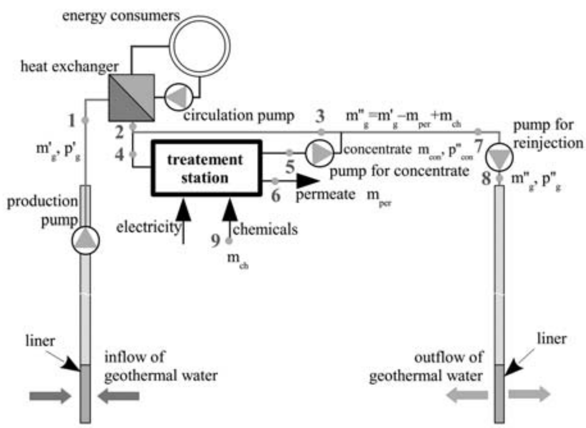

Fig. 2. Geothermal doublet with a cooled geothermal water desalination facility – diagram (The variant assuming the partial desalination of the stream of extracted geothermal water)

RESULTS AND DISCUSSION

Concentrate characterisation and quality

The comparison of physical properties and chemical composition of the "raw" waters tested and concentrate obtained are presented in Table 1. The total dissolved solids (TDS) of "raw" water ranged from 2.5 to 6.5 g/L and they had high concentrations of boron (2.53–8.98 mg/L), iron (1.93–3.89 mg/L), arsenic (0.009–0.03 mg/L), fluoride (0.696–2.60 mg/L), strontium and silica.

The total dissolved solids (TDS) of the concentrate after desalination of the water from the GT-1 well was 8.7 g/L (after both RO stages). In the solution high concentrations of silicates and microelements, such as: strontium (18.64 mg/L), boron (22.86 mg/L), arsenic (0.0165 mg/L), fluoride (5.92 mg/L) were found. A high concentration of microelements was also found in the retentate after desalination of the second geothermal water (GT-2), respectively: strontium (12.50 mg/L), boron (13.85 mg/L), arsenic (0.07 mg/L), fluoride (0.06 mg/L). The TDS of the final concentrate was 17.5 g/L.

Table 1. Physical properties and chemical composition of the “raw” thermal water and concentrate after geothermal water desalination

Parameter	GT-1		GT-2	
	raw water	concentrate	raw water	concentrate
TDS, mg/L	2561.8	8785.1	6556.0	17506.0
Total hardness, mg $CaCO_3$/L	645.4	2115	474.2	996.4
Carbonate hardness, mg $CaCO_3$/L	213.9	237.8	184.1	153
Conductivity, mS/cm	3.550	11.369	10.960	35.3
SiO_2, mg/L	42.73	202.32	35.78	81.56
Na, mg/L	466.8	1794	2297	5724
K, mg/L	45.2	145.13	27.2	60.85
Li, mg/L	0,868	3.53	0,333	0.688
Be, mg/L	<0.005	<0.005	<0.005	<0.005
Ca, mg/L	196,0	645.1	146.8	313.66
Mg, mg/L	42.7	122.83	26.2	51.98
Ba, mg/L	0,125	0.189	0,18	0.385
Sr, mg/L	6.0	18.64	5.5	12.502
Fe, mg/L	3.890	28.73	1.93	0.381
Mn, mg/L	0,12	0.434	0,181	0.169
Ag, mg/L	<0.01	<0.01	<0.01	<0.01
Zn, mg/L	0,066	0.068	<0.01	<0.01
Cu, mg/L	0,017	0.019	0,002	0.056
Ni, mg/L	0,039	0.079	<0,005	0.006
Co, mg/L	0,002	0.0014	<0.0005	<0.0005
Pb, mg/L	<0,0005	0.0011	<0,0005	<0.0005
Cd, mg/L	<0.0005	<0.0005	<0.0005	<0.0005
Se, mg/L	0.03	0.02	<0.01	0.043
Sb, mg/L	<0.001	0.001	<0.001	<0.001
Al, mg/L	<0.001	<0.010	<0.001	0.018
Cr, mg/L	0.055	0.081	0.044	0.437
As, mg/L	0.03	0.0165	0.009	0.070
Tl, mg/L	<0.0005	<0.0005	<0.0005	0.0005
W, mg/L	<0.01	<0.01	<0.01	<0.01
Cl, mg/L	636.0	2433.4	3574.0	9334
F, mg/L	2.60	5.92	0.696	0.06
SO_4, mg/L	938.2	2818.72	193.7	316.2
I, mg/L	0.73	2.47	0.5	1.4
B, mg/L	8.98	22.86	2.53	13.85

Disposing concentrate as a balneological solution

During pilot studies related to the desalination of thermal water from the GT-1 intake, the Hydrex antiscalant (an inhibitor based upon a blend of phosphonates) was used in the first month. During the next seven months, water was dosed with hydrochloric acid only in order to reduce its pH before the RO-1 stage; before the RO-2 stage, only sodium hydroxide was added to improve the retention of boron ions. No biocides were used. The desalination process proceeded in a stable manner [19–20]. The desalination of water from the GT-2 intake was conducted in the same fashion. To enable the utilisation of the concentrate following the RO process, it is advisable to limit the amount of chemicals used.

The result of our research showed that concentrate may be widely used, including as an alternative balneological product. The range of services on offer at spas that use thermal water may be extended, e.g. by using the concentrate in graduation towers, or differentiating water salinity in individual pools by mixing it with low mineral content water. The main factor conditioning the manner of its utilisation will be the chemical composition of the solution, which is strictly determined by the chemical composition of desalinated water. The microelements present in thermal water such as arsenic, barium, boron, heavy metals, etc. may restrict the possibilities in some cases. The highest admissible concentrations of compounds that are undesirable in excessive amounts or toxic in accordance with national criteria for the evaluation of therapeutic properties of waters (used, *inter alia*, in balneological facilities) are presented in Table 2 (based on [15]).

Table 2. The highest admissible concentrations of compounds that are undesirable in excessive amounts or toxic in accordance with national criteria for the evaluation of therapeutic properties of waters (based on [22])

Parameter	The highest admissible concentrations		
	Drinking cure	Inhalation	Bathing
Antymony, mg/L	0.01	0.01	-
Nitrates (III), mg/L	0.02	0.02	0.2
Nitrates (V), mg/L	10.0	10.0	20.0
Arsenic (III+V), mg/L	0.05	0.1	-
Barium, mg/L	1.0	10.0	-
Boron, mg/L	5.0	30.0	-
Cyanides, mg/L	0.01	0.01	0.01
Chrome (Total), mg/L	0.01	0.01	-
Aluminum, mg/L	0.1	0.1	-
Cadmium, mg/L	0.003	0.003	-
Nickel, mg/L	0.03	0.03	-
Lead, mg/L	0.01	0.01	-
Mercury, mg/L	0.001	0.001	-
Phenols, mg/L	0.002	0.002	0.002
Surfactants (anionic)	-	-	-
Pesticides	-	-	-
PAHs, ng/L	100	100	100
Benzo (a) pirene, ng/L	10	10	10

Analysis results of the retentate (Table 1) obtained as a result of the desalination of water from the GT-1 and GT-2 wells meet the required parameters for water used externally. The content of dissolved substances in the concentrated solution obtained as a result of desalinating water from the wells covered by the study significantly exceeds the concentrations found in "raw" thermal water (Table 1). The TDS of the concentrate obtained as a result of desalinating the water from the GT-1 intake exhibits a mineral content of 8.78 g/L, with an elevated concentration of specific substances that determine the therapeutic/balneological properties of water: metasilicic acid (262.99 mg/L), fluoride ions (25.92 mg/L) and iodide ions (2.47 mg/L). As a result of the solution having been concentrated, the boron ion content of water increased to 22.86 mg/L. Concentration limits of chromium (0.081 mg/L while the admissible limit is 0.01 mg/L) and nickel (0.079 mg/L while the admissible limit is 0.03 mg/L) were only exceeded for water used for drinking therapy and inhalations, while boron ion content (22.86 mg/L while the admissible limit is 5.0 mg/L) was exceeded for drinking therapies exceeding 1 month. Taking the parameters listed in Table 2 into account, no substances were found that would prevent the use of the concentrate in water used externally, e.g. in pools.

The TDS of the concentrate obtained as a result of desalinating the water from the GT-2 well exhibits a mineral content of 17.506 g/L, with an elevated concentration of metasilicic acid (106.03 mg/L), and boron content of ca. 13.8 mg/L. In this case also, no substances were found that would prevent the utilisation of the concentrate for external use. In comparison to requirements for water used for drinking therapy and inhalation, arsenic (0.07 mg while the admissible limit is 0.05 mg/L), chromium (0.437 mg/L while the admissible limit is 0.01 mg/L) and boron (13.81 mg/L while the admissible limit is 5.0 mg/L) levels were exceeded.

It should be emphasised that owing to its temperature (ca. 30°C), the concentrate can still be used as thermal water.

Disposing of concentrate by injecting it back into the formation

The injection of concentrate into deep geological structures together with a stream of cooled geothermal water is the safest option for the environment. The chemical composition of the liquid injected is of key importance for the success of the formation of injection process and therefore for the proper operation of the entire geothermal facility. During water-rock reaction, the composition of the solution obtained by mixing the concentrate with natural formation water may result in the precipitation of certain mineral phases, which may lead to the clogging of the absorption well and deterioration in the performance of the process of injecting water into the formation. Therefore the concentrate stream that can be mixed with geothermal water must be determined. The use of available geochemical modelling software makes it possible to forecast such processes and draw up plans for proper water management.

Economic analysis related to the implementation of a desalinating system for part of the geothermal water stream used must account for local hydrogeothermal and environmental conditions so that the process does not generate additional cost.

In accordance with the process presented in Fig. 2, the operation of the system analysed in this paper is characterised by points (1,2,3...9), to which the operating parameters defined by the following elements have been assigned: V_s – the volumetric flow rate of the solution [m^3/s], p – pressure [Pa], t – temperature [°C], TDS – total dissolved solids [kg/m³], S – salinity (the percentage of substances dissolved in the solution by mass) [%], ρ – solution density [kg/m³].

Mass flows at individual points can be described by the following set of equations:

$$\begin{cases} m_s(2) = m_s(1) \\ {}^*m_s(3) = f\left(m_s(2), TDS(2)\right) \\ {}^*m_s(4) = f\left(m_s(2), TDS(2)\right) \\ {}^*m_s(6) = f\left(m_s(2), TDS(2)\right) \\ m_s(5) = m_s(4) - m_s(6) + m_s(9) \\ m_s(7) = m_s(3) + m_s(5) \\ m_s(8) = m_s(7) \end{cases} \tag{2}$$

* the initial value assigned on the basis of experimental data,
where: $m_s(n)$ – mass flow at the n^{th} point of the system [kg/s] (according to the diagram in Fig. 2), f(x, y) – is the functional relationship of the variables x, y.

On the basis of water salinity, temperature and pressure, volumetric flow rates at individual points were determined:

$$V_s(n) = \frac{m_s(n)}{\rho(n)} \tag{3}$$

It was assumed that solution density depends primarily on water salinity S, pressure and temperature.

It was assumed that the pump injecting the concentrate into the geothermal water stream (Fig. 2) has a power rating resulting from the need to overcome flow resistance between points 5 and 7 (Fig. 3). This power rating is described by the following equation:

$$P_{conc} = \frac{V_s(5)\left[p(7) - p(5)\right]}{\eta} \tag{4}$$

where:
η – pump efficiency (a value of 0.8 was assumed).

As a result, the pressure of geothermal water after the concentrate has been added (point 7 in Fig. 2) is equal to pressure at point 3. The temperature of the solutions mixed was determined on the assumption that the sum total of the dissolved solids does not result in a change of the specific heat of water. From the physical point of view, this assumption is incorrect since the specific heat of water with elevated salinity levels is lower than that of water with low salinity levels. Nevertheless, taking into account the low salinity of the geothermal water analysed (GT-1: ca. 2.5 mg/L, GT-2: ca. 7 mg/L), the error resulting from the assumption adopted is negligible. Ultimately, the temperature of the mix of geothermal water and concentrate is described by the following equation:

$$t(7) = \frac{m_s(3)\ t(3) + m_s(5)\ t(5)}{m_s(3) + m_s(5)} \tag{5}$$

Aqueous solution salinity (S) was determined in accordance with the following equation:

$$S(7) = \frac{S(3)\ m_s(3) + S(5)\ m_s(5)}{m_s(3) + m_s(5)} \tag{6}$$

The investment expenditure related to the purchase of the UF-RO facility (INV_{wt}) was estimated in an indicative manner, taking into account the amount spent on the pilot geothermal water desalination facility. An amount of EUR 14,300/($m^3_{raw\ water}$/h) was assumed. The requirement for pumping power for the UF-RO system is a function of the stream of treated water, its mineralisation, and permeate and concentrate recovery ratios. For the GT-1 system, the power requirement was 1 kW/($m^3_{raw\ water}$/h), and for GT-2 it was 1.25 kW/($m^3_{raw\ water}$/h).

Economic assumptions were as follows:

- electricity purchase cost – EUR 0.117/kWh (PLN 0.49/kWh) (net)
- revenue from the sale of drinking water – EUR 0.476/m^3 (PLN 2/m^3) (net)
- chemical purchase costs: 35% HCl – EUR 390/m^3, 98% NaOH (solid) – EUR 0.78/kg.

It was assumed that the UF-RO facility operates at rated power for 300 days each year.

The total costs for the system presented in Fig. 2 (net C_t) are described by the following equation:

$$C_t = C_{el} + C_{ch} + C_{mrs} + D_{ft} - R_{tw} \tag{7}$$

where:

C_{el} – the cost of purchase of electricity for injecting the water used into the formation, the operation of the UF-RO system and the operation of the pump injecting the concentrate into the geothermal water pipeline
C_{ch} – chemical purchase costs
C_{mrs} – operating and maintenance costs of the UF-RO system (2% of total investments per year)
R_{tw} – revenue from drinking water sales
D_{ft} – fixed asset depreciation (investment expenditure spread evenly over 15 years).

Simple payback time (SPBT) for the investment expenditure related to the UF-RO facility was determined according to the following equation:

$$SPBT = \frac{INV_{wt}}{(C_o - C_t) - D_{ft}} \tag{8}$$

where: C_o – current cost of injecting thermal water into the formation without the desalination process (only taking the cost of energy carriers purchased into account).

Economic analysis results for the two cases examined (GT-1 and GT-2 intakes) are shown in Table 3.

Table 3. Main technical and economic parameters for the GT-1 and GT-2 systems examined
Modelling results based on indicative operating data obtained from existing geothermal systems (GT-1 and GT-2) and pilot UF-RO water desalination studies (based on [24])

Geothermal water parameters at the wellhead	GT-1	GT-2
Yield [m^3/h]	400	70
Temperature [°C]	70	69
Pressure [MPa]	2.4	0.6
TDS [g/L]	2.6	7
S [% by mass]	0.26	0.7
pH	7.5	7.5
Water parameters in the UF-RO facility		
Stream of raw water – subject to desalination [m^3/h]	120	21
Permeate yield [m^3/h]	58	10.8
Permeate pH (following pH adjustment – end product)	7	7
Concentrate yield [m^3/h]	58	10.8
Concentrate pH	10	10
Pressure of water injected into the water bearing layer		
In the reference variant* [MPa]	4.4	1.0
After mixing geothermal water with the concentrate [MPa]	3.7	0.84
Energy consumption		
Electricity consumption in the reference variant* [MWh/year]	2096	87
Total electricity consumption for the UF-RO process and for injecting geothermal water mixed with the concentrate into the formation [MWh/year]	2043	243
Consumption of chemicals		
HCl (35% aqueous solution) [kg/year]	445	78
NaOH (98% solid) [kg/year]	1298	227
Net costs		
Electricity in the reference variant* [EUR thousand/year]	252	10
Total electricity for injecting geothermal water mixed with the concentrate into the formation [EUR thousand/year]	139	6

Energy for the UF-RO process [EUR thousand/year]	104	23
Purchase of chemicals (HCl and NaOH) [EUR thousand/year]	2.3	0.4
Treatment facility operation, repair and maintenance [EUR thousand/year]	34	6
Depreciation charges for the UF-RO facility (depreciation over 15 years) [EUR thousand/year]	114	20
Net revenue from water sales [EUR thousand/year]	158	28
Total net operating cost for the UF-RO process and for injecting geothermal water mixed with the concentrate into the formation, taking revenue from sales of drinking water into account [EUR thousand/year]	235	27
Total net operating cost for injecting geothermal water into the formation in the reference variant* (include electricity consumption only) [EUR thousand/year]	252	10
Simple payback time for the investment expenditure for treatment facility [years]	13	-
Unit indicators		
Energy consumption of the UF-RO process per unit of treated water produced [kWh/m^3]	2.0	2.6
Investment expenditure per unit of treated water produced [EUR/m^3]	0.27	0.27
Electricity purchase cost of the UF-RO process per unit of treated water produced [EUR/m^3]	0.25	0.39
UF-RO facility operation, repair and maintenance costs per unit of treated water produced [EUR/m^3]	0.08	0.08
Total cost of the UF-RO process per unit of water subject to desalination [EUR/m^3]	0.6	0.66

A favourable economic effect was obtained for the GT-1 system. The assumption is that a 120 m^3/h stream of water is desalinated at a permeate recovery rate of 50%. Simple payback time for the forecast investment expenditure is 14 years in this case. An important factor affecting the energy efficiency and economic performance here is the decrease in the pressure at which water is injected into the formation by 0.7 MPa, which reduces the power required by 24 kW. This decreases annual electricity consumption by 172.8 MWh/year (EUR 20,200/year). The advantageous effect of the reduction in pumping power does not fully balance the power requirements of the UF-RO facility, but increased electricity consumption may be offset by revenue from the sale of treated drinking or household water.

A less favourable energy and economic effect was obtained for the GT-2 system (Table 3). In calculations, a reduction in the stream injected to the formation by 21 m^3/h and the injection of cooled water into the formation at the rate of 49 m^3/h was assumed. In practice, the disposal of cooled geothermal water is more complex in this case. As a consequence of technical problems, related *inter alia* to corrosion, two absorption wells were put out of operation and the geothermal water used is discharged into surface waters, generating additional environmental costs. Therefore the geothermal water desalination facility is an interesting alternative for utilising thermal water compared to the cost of reconstruction of two absorption wells or the cost of drilling a new well. At Polish market rates, the cost of drilling an absorption well to the depth of ca. 2,000 m b.g.l. would be around EUR 3 million. Summing up, drilling another well would involve an expenditure around ten times higher than that required for the desalination facility in the variant planned for the GT-2 system.

CONCLUSIONS

Membrane-based water desalination processes and hybrid technologies that combine membrane processes are widely used to produce drinking water in many regions of the world. They are also considered as a technologically and economically viable alternative for desalination of the geothermal waters. From the economic point of view it is important to perform the membrane processes efficiently and at reasonably low costs.

Pilot studies concerning the desalination of geothermal water extracted from various geological structures in Poland have demonstrated that using a relatively low range of transmembrane pressures (ca. 1.1 MPa) in the reverse osmosis process it is possible to produce high-quality permeate that meets the requirements applicable to drinking water [19–21]. The assessment of the feasibility of implementing the UF-RO system analysed on an industrial scale is largely dependent on the manner and possibility of disposing of, or using, the concentrate. The potential balneological use of the concentrate is strictly determined by its physicochemical properties. In the opinion of the authors, the best solution from the environmental point of view is injecting the concentrate into the formation using the existing absorption well system. The chemical composition of the liquid injected is of key importance for the performance of this success and therefore for the proper operation of the entire geothermal facility. Therefore, a concentrate stream that will not clog the absorption well has to be determined using geochemical modelling methods. Design of deep well disposal systems is generally dictated by site selection and consideration of geologic and hydrologic factors, as demonstrated, *inter alia,* by the energy efficiency and economic analysis conducted for the GT-1 and GT-2 geothermal systems.

The main factor that determines implementation is cost. The calculations conducted in this paper justify the claim that no universal statements can be made concerning the cost effectiveness of implementing the process for producing drinking water from thermal water. It should be emphasised that the implementation of a specific geothermal water desalination system is largely dependent on the factors related to geothermal system operation: the amount of geothermal water extracted, water salinity, the absorption parameters of the wells used to inject water back into the formation, the scale of problems related to the disposal of cooled water, local demand for drinking and household water, etc. These aspects should be examined comprehensively, taking local hydrological and environmental considerations into account. The decrease in the pressure required to inject water into the formation as well as the reduction in the stream of the water injected are among the key cost-effectiveness factors. Ensuring favourable desalinated water sale terms (price/quantity) is also a very important consideration owing to the electrical power required to conduct the UF-RO process.

Recent technological progress has reduced water desalination costs by driving down equipment prices, reducing energy consumption and facilitating access to knowhow related to water treatment.

Renewable energy and desalination are two different technologies that can be combined in various fashions. The desalination process may be assisted by energy generated on site from renewable sources. Depending on local hydrogeothermal conditions, this energy may be generated in various forms as heat, electricity or mechanical energy.

ACKNOWLEDGEMENTS

This work was financed by the Polish Ministry of Science and Higher Education, grant No. N R09 0003 04, during the period 2008-2012.

REFERENCES

[1] Barbacki, A. (2010). Geological and technical aspects of geothermal energy utilization in South-East Poland, *Environment Protection Engineering*, 36, 1, 25–34.

[2] Bodzek, M. & Konieczny, K. (2011). Membrane techniques in the removal of inorganic anionic micropollutants from water environment – state of the art, *Archives of Environmental Protection*, 37, 2, 15–29.

[3] Dulewski, J. & Tomaszewska, B. (2012). Kompleksowe wykorzystanie i zagospodarowanie ochłodzonych wód termalnych na tle uwarunkowań prawnych. *Miesięcznik Wyższego Urzędu Górniczego*, 4, 10–16.

[4] Gallup, D.L. (2007). Treatment of geothermal waters for production of industrial, agricultural or drinking water, *Geothermics*, 36, 473–483.

[5] Kabay, N., Yilmaz, I., Yamac, S., Samatya, S., Yuksel, M., Yuksel, U., Arda, M., Saglam, M., Iwanaga, T. & Hirowatari, K. (2004). Removal and recovery of boron from geothermal wastewater by selective ion exchange resins – I. Laboratory tests, *Reactive and Functional Polymers,* 60, 163–170.

[6] Kabay, N., Yilmaz, I., Yamac, S., Yuksel, M., Yuksel, U., Yildirim, N., Aydogdu, O., Iwanaga, T. & Hirowatari, K. (2004). Removal and recovery of boron from geothermal wastewater by selective ion-exchange resins – II. Field tests, *Desalination,* 167, 427–438.

[7] Kania, J., Rozanski, K., Witczak, S. & Zuber, A. (2006). On conceptual and numerical modeling of flow and transport in groundwater with the aid of tracers: a case study. In: Soil and Water Pollution Monitoring, Protection and Remediation. Proceedings of the NATO Advanced Research Workshop on Viable Methods of Soil and Water Pollution Monitoring, Protection and Remediation, Krakow. *NATO Science Series: IV: Earth and Environmental Sciences*, 69, 199–208.

[8] Kania, J., Haładus, A. & Witczak S. (2006). On Modelling of Ground and Surface Water Interactions. In: Baba A., Howard K.W.F., Gunduz O. (Eds.) Groundwater and Ecosystems. Proceedings of the NATO Advanced Research Workshop on Groundwater and Ecosystems, Canakkale, Turkey, *NATO Science Series: IV. Earth and Environmental Sciences*, 70, 183–194.

[9] Kania, J., Witczak, S. & Różański, K. (2011). Classification of Groundwater Quality Based on Variability of Hydrogeochemical Environment. In: Baba A., Tayfur G., Gunduz O., Howard K.W.F., Friedel M.J., Chambel A. (Eds.). Climate Change and its Effects on Water Resources, *NATO Science for Peace and Security Series C: Environmental Security*, 3, 247–257.

[10] Kmiecik, E., Zdechlik, R. & Drzymała, M. (2013). Ocena stanu chemicznego wód podziemnych w zlewni Sękówki, *Biuletyn Państwowego Instytutu Geologicznego*, 456, 1, 287–291.

[11] Öner, Ş.G., Kabay, N., Güler, E., Kitiş, M. & Yüksel M. (2011). A comparative study for the removal of boron and silica from geothermal water by cross-flow flat sheet reverse osmosis method, *Desalination*, 283, 10–15.

[12] Pająk, L. & Bujakowski, W. (2013). Energia geotermalna w systemach binarnych, *Przegląd Geologiczny*, 61, 11/2, 696–702.

[13] Pająk, L. & Barbacki, A. (2013). Ocena możliwości akumulacji ciepła w rozległych systemach przesyłowych współpracujących z hybrydowymi źródłami wykorzystującymi zasoby energii odnawialnej, *Ciepłownictwo Ogrzewnictwo Wentylacja*, 7, 44, 267–273.

[14] Péréz-González, A., Urtiaga, A.M., Ibánez, R. & Ortiz, I. (2012). State of the art and review on the treatment technologies of water reverse osmosis concentrates, *Water Research,* 46, 267–283.

[15] Rozporządzenie Ministra Zdrowia z dnia z dnia 13 kwietnia 2006 r. w sprawie zakresu badań niezbędnych do ustalenia właściwości leczniczych naturalnych surowców leczniczych i właściwości leczniczych

klimatu, kryteriów ich oceny oraz wzoru świadectwa potwierdzającego te właściwości (Dz. U z 2006 r. Nr 80 poz. 565).

[16] Rybach, L.(2003). Geothermal energy: sustainability and the environment, *Geothermics,* 32, 463–470.

[17] Sowiżdżał, A., Papiernik, B., Machowski, G. & Hajto, M. (2013). Characterization of petrophysical parameters of the Lower Triassic deposits in a prospective location for Enhanced Geothermal System (central Poland), *Geological Quarterly*, 57, 4, 729–744, DOI: http://dx.doi.org/10.7306/gq.1121

[18] Şimşek, Ş., Yıldırım, N. & Gülgör, A. (2005). Developmental and environmental effects of the Kızıldere geothermal power project, Turkey, *Geothermics* 34, 239–256.

[19] Tomaszewska, B. & Bodzek, M. (2013). Desalination of geothermal waters using a hybrid UF-RO process. Part I: Boron. removal in pilot-scale tests, *Desalination,* 319, 99–106.

[20] Tomaszewska B. & Bodzek, M. (2013). Desalination of geothermal waters using a hybrid UF-RO process. Part II: Membrane scaling after pilot-scale tests, *Desalination,* 319, 107–114.

[21] Tomaszewska B. & Bodzek, M. (2013). The removal of radionuclides during desalination of geothermal waters using BWRO system, *Desalination*, 309, 284–290.

[22] Tomaszewska, B. & Pająk, L. (2012). Dynamics of clogging processes in injection wells used to pump highly mineralized thermal walters into the sandstone structures lying under the Polish Lowlands, *Archives Of Environmental Protection,* 38, 3, 105–117.

[23] Tomaszewska, B. (2011). The use of ultrafiltration and reverse osmosis in the desalination of low mineralized geothermal waters, *Archives Of Environmental Protection*, 37, 3, 63–77.

[24] Tomaszewsk, B. & Pajak, L. (2012). Geothermal water resources management – economic aspects of their treatment, *Gospodarka Surowcami Mineralnymi-Mineral Resources Management*, 28, 4, 59–70.

[25] Tomaszewska, B. & Pajak, L. (2013). Cooled and desalinated thermal water utilization in the podhale heating system, *Gospodarka Surowcami Mineralnymi-Mineral Resources Management*, 29, 1, 127–139.

[26] Voutchkov, N. (2011). Overview of seawater concentrate disposal alternatives, *Desalination*, 273, 205–219.

[27] Wiatkowski, M. (2010). Impact of the Small Water Reservoir Psurów on the Quality and Flows of the Prosna River, *Archives of Environmental Protection*, 36, 3, 84–96.

[28] Witczak, S., Szklarczyk, T., Kmiecik, E., Szczepańska, J., Zuber, A., Różański, K. & Duliński, M. (2007). Hydrodynamic modelling, environmental tracers and hydrochemistry of a confined sandy aquifer (Kędzierzyn-Głubczyce Subtrough, SW Poland), *Geological Quarterly,* 51, 1, 1–16.

[29] Zdechlik, R., Drzymała, M. & Wątor, K. (2013). Praktyczne aspekty opróbowania wód w systemie monitoringu wód podziemnych, *Biuletyn Państwowego Instytutu Geologicznego,* 456, 2, 659–663.

WYKORZYSTANIE HYBRYDOWEGO PROCESU UF-RO W ODSALANIU WÓD GEOTERMALNYCH. UTYLIZACJA KONCENTRATU I ANALIZA KOSZTÓW

Odsalanie wody z wykorzystaniem procesów membranowych oraz technologii hybrydowych rozważane jest jako technologiczna i ekonomiczna alternatywa dla klasycznych metod utylizacji wykorzystanych wód geotermalnych. Taką możliwość potwierdziły przeprowadzone badania pilotowe odsalania w systemie UF-RO wód geotermalnych eksploatowanych w obrębie różnych struktur geologicznych Polski. Ocena możliwości wdrożenia tych rozwiązań na skalę przemysłową, w dużej mierze zależy od kierunków i możliwości utylizacji/zagospodarowania koncentratu. Przeprowadzone analizy w tym zakresie wykazały możliwość wykorzystania uzyskanego roztworu jako produktu o cechach balneologicznych, z uwagi na podwyższoną zawartość: kwasu metakrzemowego oraz jonów fluorkowych i jodkowych. Biorąc pod uwagę jednak względy środowiskowe, alternatywnym rozwiązaniem może być wtłaczanie koncentratu do górotworu. Przeprowadzona analiza energetyczna i ekonomiczna wykazała, iż opłacalność wdrożenia na skalę przemysłową procesu UF-RO w systemie geotermalnym w dużej mierze zależy od czynników związanych z jego pracą, a w szczególności: wielkości wydobycia wód geotermalnych, zasolenia wód, parametrów chłonnych otworów przeznaczonych do wtłaczania wód do górotworu, skali problemów związanych z utylizacją schłodzonych wód, lokalnego zapotrzebowania na wody pitne i gospodarcze i in. Kluczowa dla opłacalności tego procesu jest między innymi redukcja wymaganego ciśnienia przy wtłaczaniu wód do górotworu i redukcja wielkości strumienia zatłaczanych wód. Bardzo ważnym elementem jest również zapewnienie odpowiednich warunków zbytu odsolonych wód (cena/ilość) celem pokrycia zapotrzebowania na energię elektryczną wykorzystaną w procesie UF-RO.