

Heat transport processes operated by geothermal energy at gas pressure reduction stations

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ABSTRACT

Pressure reduction is necessary between high-pressure natural gas transporting pipelines and low pressure distributing networks. Pressure reduction requires pre-heating the gas to compensate for the Joule-Thomson effect. Gas fired boilers will be replaced by geothermal heat pumps at more than 400 Hungarian gas pressure reduction stations (GPRS). The necessary thermal power and the temperatures required of the system still have to be determined.

Natural conditions for geothermal production are rather good in Hungary. Both the geothermal gradient and the terrestrial heat flow are significantly larger than the continental average. In any area of the country, one could reduce system costs by applying one of the various geothermal-energy production technologies to preheat gas at gas-pressure reduction stations (GPRS).

1. INTRODUCTION

The Hungarian hydrocarbon industry is dated back to 1937, when the crude oil and natural gas field at Budafapuszta was discovered. The first gas pipeline in Hungary was constructed in 1938, and it connected drilling sites with various operating facilities. The first international gas transmission pipeline was commissioned between Romania and Hungary in 1958. The Hungarian transmission system was connected to the Soviet natural gas network in 1975. The gas transmission pipeline between the Austria and Hungary was commissioned in 1996, thus Hungary connected to the European network, opening the way for trading gas with the EU member countries. The length of the existing transmission system is 5784 km long, of which the length of the transit transmission direction is 370 km. The gas transmission system has nearly 400 gas transfer stations and 6 compressor stations. Their typical diameter is between 100-1400 mm with a pressure of 40-75 bar. This high pressure increases the pipeline's delivery capacity, but consumers of natural gas need to have it at a lower pressure. Natural gas distributing networks therefore operate at a lower pressure.

The sole purpose of gas pressure-reduction stations is to provide and maintain a suitable chosen downstream pressure. These stations' most important components are: the pressure regulating valve, the pressure gauges, the in-line filter or strainer, gas odorant unit and the heating unit.

The pressure-regulating valve is a self-regulating unit. As gas flows through an adjustable opening, its pressure drops substantially. At the same time the valve temperature also decreases. If the downstream gas temperature is to remain above the hydrate zone and dew point, the gas must be pre-heated before it enters the pressure-reducing valve.

The inflowing high-pressure natural gas is pre-heated by gas-fired boilers as it flows across a water-gas heat exchanger. Replacing the boilers with geothermal heating can eliminate these boilers' gas consumption and their carbon-dioxide emissions. The geothermal energy is extracted by means of a closed-loop system, the so-called borehole heat exchanger (BHE). Generally, the warmed-up water is not warm enough to pre-heat the gas directly, so a heat pump is used to boost the BHE's contribution to the higher temperature required of the pre-heater.

2. TEMPERATURE DROP OF THE REDUCED-PRESSURE GAS

As the pressure of the natural gas is reduced, it expands. If the expansion is isentropic the expanding gas does positive work during the expansion and its temperature decreases substantially. If the gas does no work, there is no change in the enthalpy. The temperature of an expanding ideal gas would remain constant, but the temperature of a real gas may either increase or decrease depending on the initial temperature and pressure. This temperature change is called the Joule-Thomson effect. For most gases at atmospheric pressure the isenthalpic expansion causes a temperature decrease.

The rate of change of temperature with respect to pressure in a Joule-Thomson process is the Joule-Thomson coefficient:

$$\mu = \left(\frac{\partial T}{\partial p} \right)_H \quad (1)$$

The value of μ has a dimension of °C/bar or K/Pa and depends on the type of gas and the initial pressure and temperature before expansion. In the familiar range of pressures and temperatures obtained in a pressure reduction station, a linearized expression can be accepted:

Toth

$$\mu = \frac{T_1 - T_2}{p_1 - p_2} \quad (2)$$

Temperatures and pressures were measured in front of the regulation valve (T_1, p_1) and also downstream (T_2, p_2). This value of μ can be used between two arbitrary points in a similar pressure/temperature range.

3. THERMAL POWER NECESSARY FOR PRE-HEATING

Upstream pressure p_1 and downstream pressure p_2 , together with downstream temperature T_2 , depend on available technology. Thus the necessary upstream temperature can be determined as

$$T_1 = T_2 + \mu(p_1 - p_2) \quad (3)$$

The gas must be pre-heated at least to this temperature. Thermal power need for the pre-heating is

$$\dot{Q}_G = \dot{m}_G c_p (T_1 - T_0) \quad (4)$$

where \dot{m}_G is the mass flow rate of the gas, c_p is its specific heat at constant pressure, and T_0 is the gas temperature before heating. Figure 1.

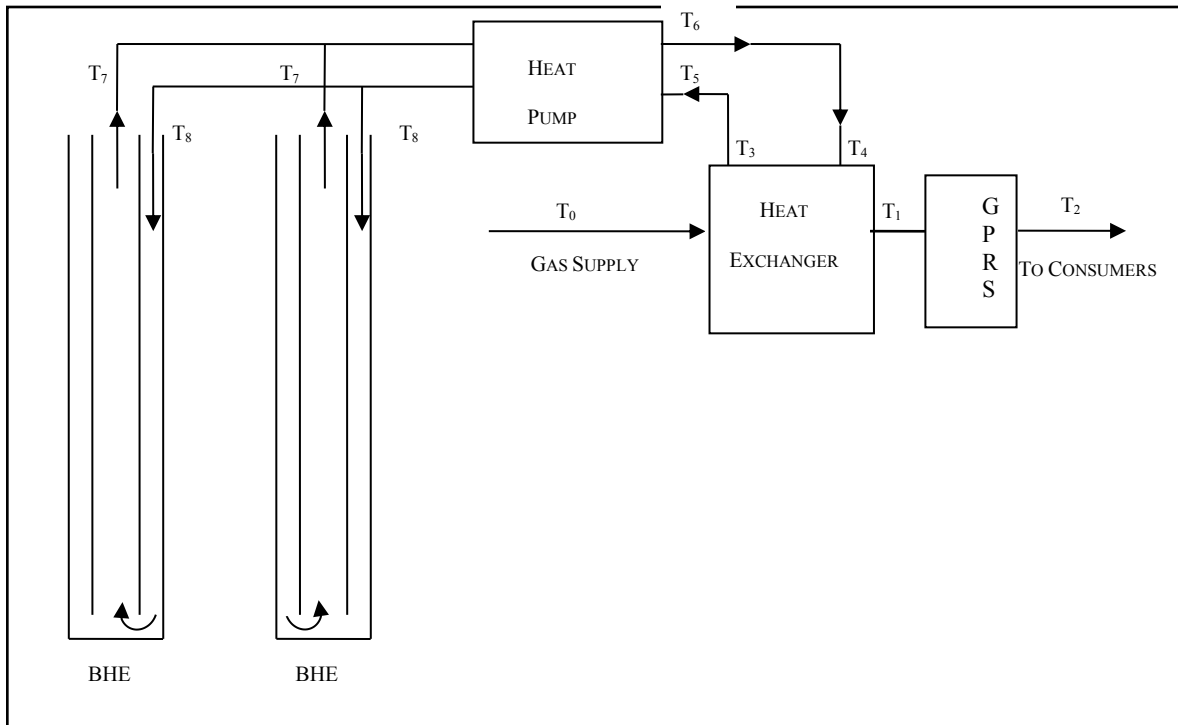


Figure 1: The recommended system

The heat transferred by the circulating water is

$$\dot{Q}_w = \dot{m}_w \cdot c_w (T_3 - T_4) \quad (5)$$

where T_3 and T_4 are the water temperatures at the inlet and outlet cross-section of the heat exchangers. The heat balance of the pre-heater is

$$\dot{Q}_w = \dot{Q}_G + \dot{Q}_{loss} \quad (6)$$

where \dot{Q}_{loss} is the heat which escaped across the shell of the heat exchanger. If its heat insulation is efficient, the heat loss can be neglected

$$\dot{Q}_G = \dot{Q}_w \quad (7)$$

The thermal power of a countercurrent shell and tube heat exchanger is

$$\dot{Q} = U \cdot A \cdot \Delta T_{\ln} \quad (8)$$

where U is the overall heat transfer coefficient, A is the heat transfer area, and ΔT_{\ln} is the so-called mean temperature-difference logarithmic

$$\Delta T_{\ln} = \frac{(T_3 - T_2) - (T_4 - T_0)}{\ln \frac{T_3 - T_2}{T_4 - T_0}} \quad (9)$$

Thus the relation of $T_4 > T_0$: if the $T_4 - T_0$ temperature difference is small, the logarithmic mean difference is also small. That would mean that the necessary heat transfer area is too great and the size of the exchanger is too large.

In cases where the heat exchanger would otherwise be too long, it is convenient to employ multipass units: several units in series or other configurations. In a multipass heat exchanger the flow is both concurrent and countercurrent, hence the effective mean temperature difference lies between the values of the arithmetic and logarithmic means:

$$\Delta T_{\text{eff}} = F \cdot \Delta T_{\ln} \quad (10)$$

The correction factor F is plotted as a function of the heat capacity ratio

$$R = \frac{T_3 - T_4}{T_2 - T_0} \quad (11)$$

and thermal effectiveness

$$P = \frac{T_2 - T_0}{T_3 - T_0} \quad (12)$$

The value of F also depends on the configuration of the exchanger and the number of transfer units. Finally, the suitable chosen value of T_4 determines T_3 .

4. THE HEAT PUMP

Neglecting the temperature drop between the heat exchanger and the heat pump $T_3 = T_5$ and $T_4 = T_6$

The performance characteristics of a heat pump are shown in Figure 2. The thermal power of heating and the electric power consumption of the compressor are plotted in Figure 2., depending on the temperature of the heated water T_4 . The parameter of the different curves is the temperatures of the water as it enters and as it exits on the heat source side (T_7, T_8).

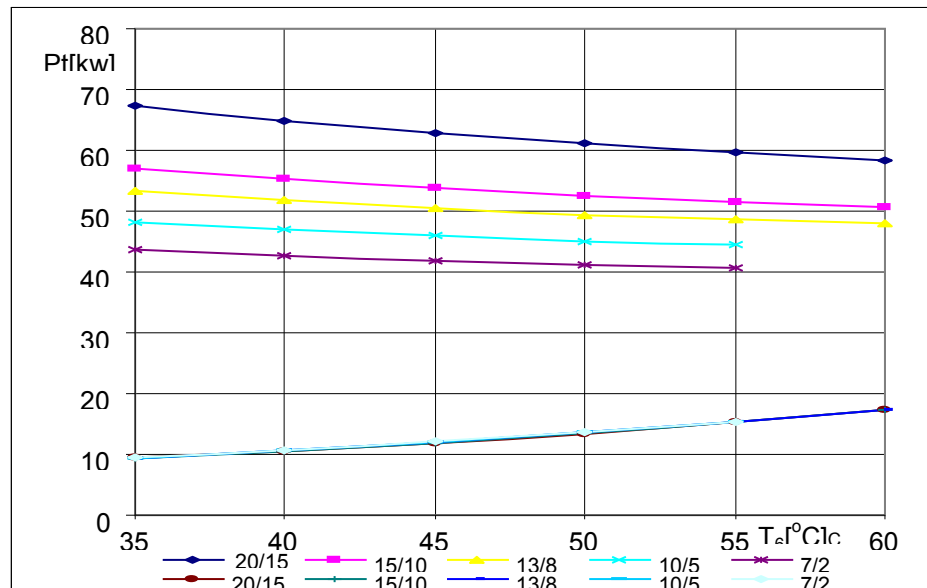


Figure 2: Heat Pump Performance Curves

The coefficient of performance (COP) is the ratio of the heating's thermal power and the compressor's electric power:

$$COP = \frac{\dot{Q}_w}{P_c} \quad (13)$$

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COP is plotted in Figure 3 depending on T_4 , while source-side temperatures are the parameters on the different curves.

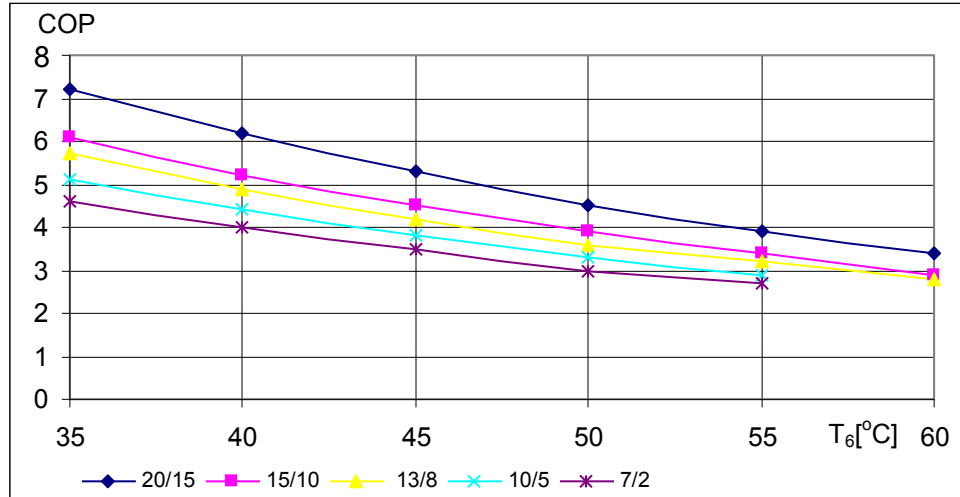


Figure 3: Heat Pump COP curves

5. OPERATION OF THE BOREHOLE HEAT EXCHANGER

Obviously, higher COP are more economical, and source-side temperatures T_7 and T_8 depend on the BHE's performance. A shallow BHE can only produce a low outflowing-water temperature, for a moderate COP.

The necessary ground-source thermal power is determined by the heat pump's heating power and COP:

$$\dot{Q} = \dot{Q}_{HP} \left(1 - \frac{1}{COP} \right) \quad (14)$$

This thermal power requires a number of BHE units. The performance of an individual BHE unit can be determined by considering the following variables:

- BHE geometry, i.e., production through a hairpin form or some other configuration
- Depth of the borehole
- Diameters of casing and tubing, or of the U-tube
- Materials: heat conductivities of pipe materials, cement sheet or grout, and insulation
- Thermal parameters of the area surrounding the BHE, i.e., the area's geothermal gradient and heat conductivity
- Mass flow rate of the circulated water
- Temperature of the injected water
- Duration of the operation

Many of these variables are given, while others can be chosen. The outflowing water temperature and the extractable thermal power can be calculated by known methods Horne (1980), Rybach (1999),

If one knows how much thermal power a single BHE provides, one can calculate how many BHEs are needed for any given operation.

6. POSSIBLE HEAT PUMP SOLUTIONS

If the hydrogeological conditions are favorable, a ground water heat pump can be used. This would incur extremely low investment and operating costs. Given the depth of the upper Pannonian sandstone reservoirs, thermal water can safely meet the heating requirement of even the largest gas-pressure reduction stations.

The closed-loop heat exchangers, or Borehole Heat Exchangers (BHE), do not require water production and can therefore function regardless of the hydrogeological conditions. The deeper BHEs could be adapted for use in abandoned hydrocarbon wells. Any arbitrary

number (even hundreds) of less deeply placed BHEs could also meet geothermal heat demand. Although horizontal ground loops are the most common and cost-effective system, the gas-pressure reduction stations usually don't have enough land to use this configuration.

The following review of various Hungarian gas-pressure reduction stations shows us where different kinds of geothermal applications are most appropriate and why.

6.1 Shallow bore-hole heat exchanger at Kőröshegy

The capacity of Kőröshegy GPRS is 1500 m³/h (Fig. 4). A BONGIOANNI EURO GX-4NI furnace heats the gas. The furnace provides 23.6 KW of power, with an outflow gas pressure of 10 bar and an outflow temperature of 10° C. The inflow parameters are 40 bar of gas pressure and a gas temperature of 10° C. The Kőröshegy GPRS is situated in a built-up area on a relatively small plot of land, making a horizontal loop system unfeasible.



Figure 4: The Kőröshegy gas-pressure reduction station

The required temperature in front of the pressure relief valve is:

$$T_1 = T_2 + \mu(p_1 - p_2) = 10 + 0.553 \cdot (40 - 10) = 26.9 \text{ } ^\circ\text{C} \quad (15)$$

The performance requirements are:

$$P_G = m \cdot c_p \cdot (T_1 - T_0) = 0.283 \cdot 2.156 \cdot 16.59 = 10.12 \text{ KW} \quad (16)$$

Assuming a DIMPLEX SI 11ME-type heat pump with 12.1 KW of power and an outgoing temperature of 35° C, the COP is 4.4.

The required BHE power is

$$P_{BHE} = P \left(1 - \frac{1}{COP} \right) = 12.1 \left(1 - \frac{1}{4.4} \right) = 9.35 \text{ KW} \quad (17)$$

Based on a conservative estimate, we can assume a 45 W/m specific heat capacity for a BHE that is 207.8m long. Installing two 100m-deep BHEs, placed 8m apart, can satisfy heating needs.

Toth

6.2 Using a Deep Bore-Hole heat Exchanger in an abandoned hydrocarbon well in Nagylengyel

The Nagylengyel GPRS has a capacity of 20,000 m³/h (Fig. 5). The natural gas is heated by a BONGAS furnace, which provides 106.2 KW of power. The outflowing gas pressure is 8 bar, at an outflow temperature of 10° C. The inflow parameters are 36 bar of gas pressure and a gas temperature of 10° C.



Figure 5: The Nagylengyel gas pressure reduction station

Next to the Nagylengyel GPRS there is a 2070m-deep abandoned hydrocarbon. At a depth of 1960 m, the rock's measured temperature was 105°C. The geothermal gradient is 0.0485°C/m. The casing diameter of the well is $6\frac{5}{8}$ ". The well is currently used for CO₂ production. The required temperature in front of the pressure relief valve is:

$$T_1 = T_2 + \mu(p_1 - p_2) = 10 + 0.553(36 - 8) = 25.48 \text{ } ^\circ\text{C} \quad (18)$$

The performance needs:

$$P_G = mc_p(T_1 - T_0) = 3.77 \cdot 2.156 \cdot 15.48 = 126.08 \text{ KW} \quad (19)$$

We can assume a HIDROS WDH 070-type heat pump with 45°C outgoing temperature, 107.5 KW of power and a COP of 5.2. The BHE power requirement is:

$$P_{BHE} = P \left(1 - \frac{1}{COP}\right) = 107.5 \left(1 - \frac{1}{5.2}\right) = 86.42 \text{ KW} \quad (20)$$

The temperature distribution through the annulus and the tubing is determined, based on the heat balance equation of the DBHE-flow. The difference between the outflowing (T_{out}) and inflowing (T_{in}) temperatures at the surface determines the thermal power of the DBHE: $P_{Th} = mc_p(T_{out} - T_{in})$. The outflowing water temperature depending on the performance time and the mass flow rate is shown in Fig. 6. The thermal power of an 1800m depth DBHE is shown in Fig. 7. A characteristic feature of the power curves belonging to different mass flow rates is the convergence after a few hundred hours of operation.

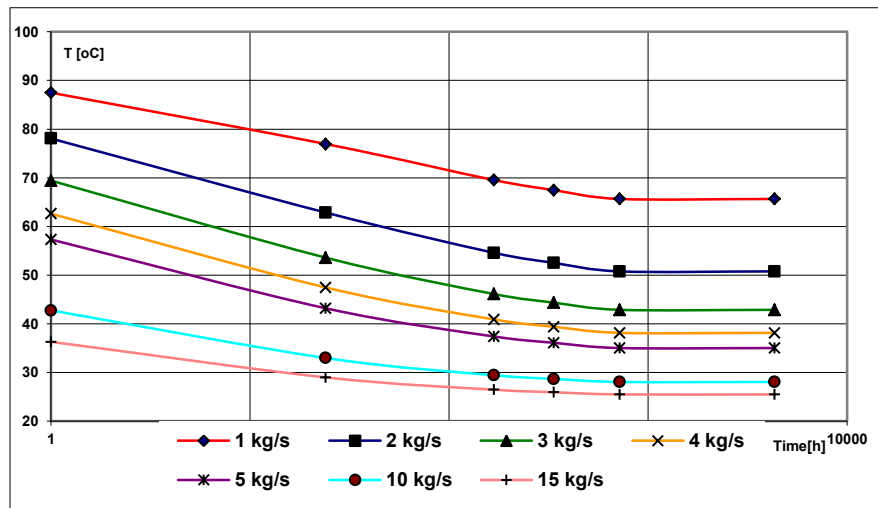


Figure 6: Outflowing water temperature decrease vs. time

The influence on the temperature and thermal power of operation can be seen in Figures 4. and 5. Toth and Bobok (2008).

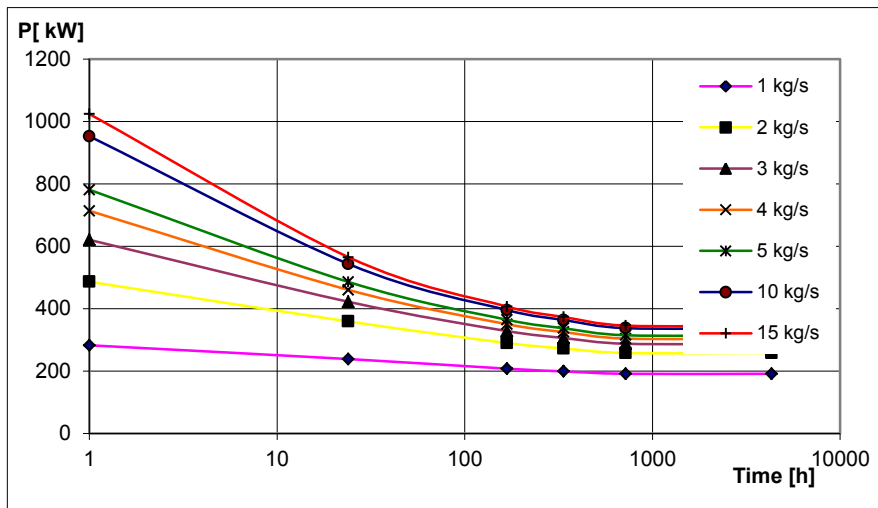


Figure 7: Thermal power decrease vs. time

6.3 Heating by thermal water at Szeged

The capacity of the Szeged GPRS is 30,000 m³/h (Fig. 8). The natural gas is heated by a BKG 20,000 gas furnace, which has a performance of 326 KW. The outflow gas pressure is 6 bar, and the outflow temperature is 10° C. The inflow natural gas pressure is 40 bar, at 10° C.

The required temperature in front of the pressure relief valve:

$$T_1 = T_2 + \mu(p_1 - p_2) = 10 + 0.553(40 - 6) = 28.8 \text{ } ^\circ\text{C} \quad (21)$$

This performance requires that:

$$P_G = mc_p(T_1 - T_2) = 5.66 \cdot 2.156 \cdot 18.8 = 229.68 \text{ KW} \quad (22)$$



Figure 8: Szeged gas pressure reduction station

The heat source can be the A-338 thermal well, which has a flow rate of 10 kg/s assuming a $\Delta T=15^\circ\text{C}$ we can get:

$$P_k = mc_v(T_7 - T_8) = 10 \cdot 4.187 \cdot 15 = 628 \text{ KW} \quad (23)$$

About 300-500 m from the Szeged GPRS there are several thermal wells. For geothermal-energy purposes, the two closest wells were investigated: Algyő-2 and Szeged-1. The temperature of the Algyő-2 well is 98°C and the Szeged-1 well temperature is 96°C . In this area the geothermal gradient is 0.0444°C/m . The average rock thermal conductivity around the wells is $2.1 \text{ W/m}^\circ\text{C}$. The transient thermal conductivity value is $f(t) = 2.48$.

Producing by means of a 7" diameter casing tube, the outflowing water temperature can be obtained Toth, (2005) by Eq. 24.

$$T_{out} = T_o + \gamma A - \gamma A e^{-\frac{h}{a}} = 10 + 0.044 \cdot 9725 - 0.044 \cdot 9725 \cdot e^{-\frac{1982}{9725}} = 89.61^\circ\text{C} \quad (24)$$

Since the thermal wells are about 400 m from the GPRS, the water cool as it is transported. Assuming a winter temperature of $T_L = -5^\circ\text{C}$ the arriving water temperature (Toth and Bobok, 2008) at the GPRS is:

$$T_{arr} = T_L + (T_{out} - T_L) \cdot e^{-\frac{D\pi LU}{mc}} = -5 + (89.6 + 5) \cdot e^{-\frac{0.013 \cdot 14 \cdot 356 \cdot 110}{10 \cdot 4187}} = 86.86^\circ\text{C} \quad (25)$$

It can be seen, that the arriving thermal water has enough enthalpy to heat the gas.

7. FUTURE PROSPECTS

Hungary has more than 400 gas pressure reduction stations, whose capacities cover a wide range. Gas pre-heating in these stations requires 20 kW to 1 MW of thermal power. Recently a new project began, the goal of which was to replace gas-fired boilers with geothermal heat pumps. Because of the stations' different capacities and the locally varying geothermal conditions, each station's geothermal upgrade requires a customized approach.

The total built-in boiler capacity of all the pressure-reduction stations is 76.45 MW. The effective thermal power is less, of course, because of seasonally fluctuating heating requirements. Thus the fluctuation in the amount of power the stations require for their own operation. Their average yearly heating requirement is only 49.6 MW. Assuming an average heat-pump COP of 4.5, an average station's electric power consumption is 11.02 MW.

8. SUMMARY

All of Hungary is well-suited for using geothermal heat sources to heat the country's many gas-pressure reduction stations. In different places, different solutions are required. After looking at every Hungarian GPRS, three specific sites were chosen in Kőröshegy, Nagylengyel and Szeged. Each site represents a different but suitable method for using geothermal heat sources to reduce natural gas or other fossil fuel consumption. Regardless of locally variable hydrogeological conditions, these BHE systems can be applied almost everywhere. Because of Hungary's favorable geological background, fairly high geothermal gradient and many abandoned hydrocarbon wells, thermal wells represent a great opportunity for the country to develop a clean, renewable and independently-owned source of energy.

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