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ENHANCING THE EFFECTIVENESS OF THERMAL WATER CONSUMPTION VIA HEAT PUMPING

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Abstract: *Renewable technologies and the extension of their scope of usage basically has to face the general obstacles like any other novelties newly introduced to the market. In the case of environmentally friendly and clean technologies we must consider another critical aspect: the knowledge and the trust of the potential future users. To influence these people first we must extend their knowledge regarding renewable energies so they will be able to change their own approach about them. Usually the most crucial factor is the economic efficiency which determines the attitude of the majority of the users. Even the ones whose decision making process is highly based on the environmental patterns. In the case of any technology, the economic aspect is significantly influenced by its operational effectiveness. So this analysis – besides the direct economic matters – aims to examine how the performance of thermal water heating in greenhouses can be improved by using heat pumping.*

Keywords: *renewable energy, thermal water heating, energy efficiency, heat pumping, cost-effectiveness*
(JEL classification: Q42)

Introduction

According to geothermic assets and potentials Hungary is considered as one of the best countries in Europe. It is originated from the fact that the average crust of the earth has around 22-28 km of thickness at the Great Plain and it does not go above 30 km at the rest of the plain territories within the country (Nagygál, 2005). Therefore the geothermic gradient (thermal gradient) is also favourable which means a 5 °C/100 m value while the European average is 3 °C/100 m. The same advantage is valid in the case of the heat flux data which is also higher in Hungary (90-100 mW/m^2) than in Europe (62 mW/m^2 in average) (Nagygál, 2014).

The point of the geothermal energy utilization is to use the inner energy content of the water from the hot rocks below the ground. There are two ways for the water to reach the surface: its own elastic expansion and the excess pressure of the steam. During the extraction the layer pressure of the storage starts to lessen which is followed by the decrease of the yield and the temperature of the well. To maintain the layer energy of the storages and avoid the environmental pollution, it is inevitable to reinject the thermal water into the ground. In case of the older wells the fluid is only accessible with artificial methods. It means that the certain thermal water systems can be distributed into closed or open systems based on their structure (Csikai, Nagygál, 2007). Whenever we utilize thermal water from closed systems it releases heat on the surface under excess pressure then it returns to its original layer by reinjection. While the cold water flows from the injection well to the production well, the direction of the thermal conductivity goes the opposite (Tóth et.al. 2012, Fogarassy et al., 2009).

Considering the uneven usage of the thermal water, it is better to keep them in large storage tanks from where it could be pumped into the heat exchanger devices (Fogarassy et al., 2011b).

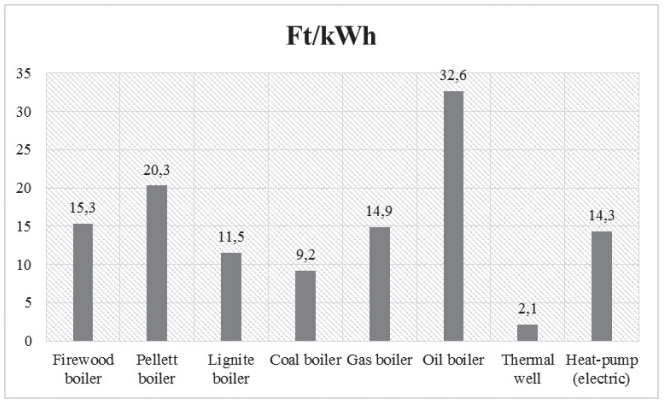
After the heat exchanger the water with a decreased enthalpy flows through the reinjection pumps to the reinjection well (Ádám, Tóth, 2011; Holm et al., 2010). According to the new Hungarian regulations from 2018 wells can only be drilled for heat production if the conducting company makes sure of the reinjection procedure as well.

Today the 30-35% of the thermal water usage serves communal activities while the same amount is used for greenhouse heating (Figure 1).

Figure 1: Greenhouse structure with three several heating purposes (air, ground and plant row side)

Heating greenhouses is being considered as a business activity so there is a competition in the market of energy resources. During our previous research, we analysed these resources and heating technology variants applicable to winter heating greenhouses by their respective pros and cons, and took a look at their investment and maintenance costs as well. We also evaluated the specific energy yield costs of the systems (Figure 2).

Figure 2: The price of 1,0kWh heat energy in case of the system's 15 year return



Source: Self-made after own calculations, 2015

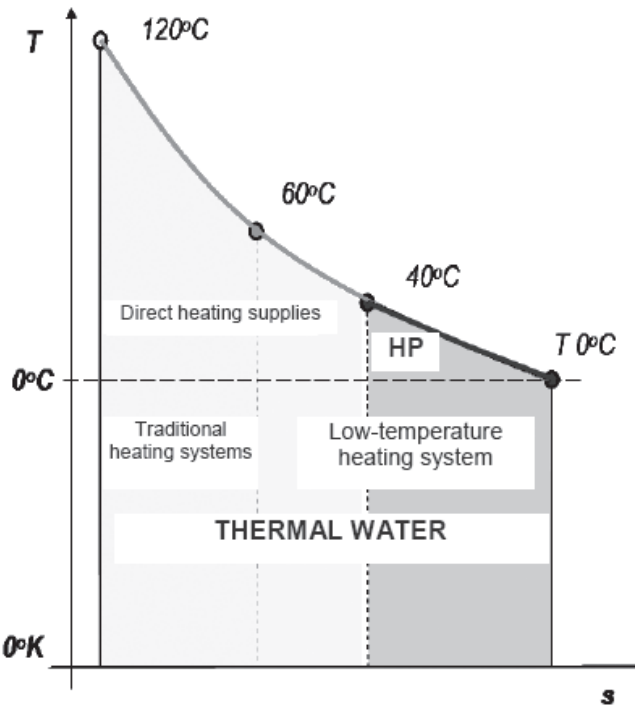
We successfully determined that using geothermic heat energy gained from thermal water would be the most economically sound decision (2,1 HUF / kWh). We also analysed the specs of heat pumping already consumed heating water, its opportunities, pros, and cons.

Literature review

Introducing the technological system

Figure 3 shows a T-s diagram which illustrates the temperature ranges of the certain thermal heating forms. So the entropy content and the temperature altogether determines the applicable heating mode and the necessary technological equipment (Büki, 2010a).

Figure 3: The utilization of thermal water on the T-s diagram

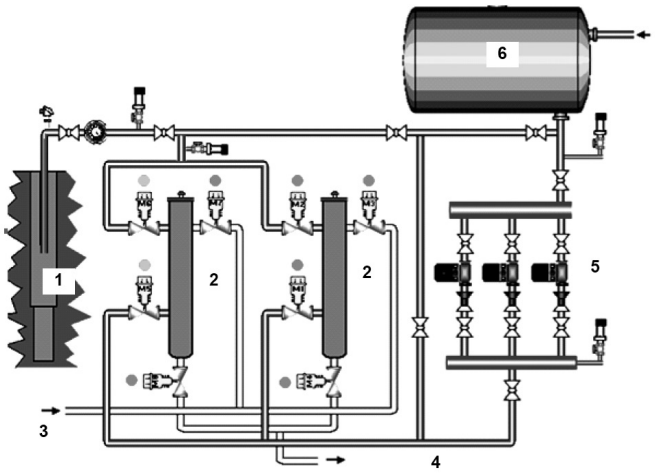


Today's thermo-conventional systems siphon the heat energy from wells through heat exchangers - almost exclusively (Figure 4), and transport it to the consuming side.

Figure 4: Sheet-metal heat exchanger used at the first heating cycle

For the protection of the thermal water assets we must only reinject the completely pure fluid into the origin layers. (Ádám, Tóth, 2010; Holm et al., 2010). This can only be conducted with the appropriate storage and filtering system (Figure 5).

Figure 5: The treatment of the thermal water before the reinjection

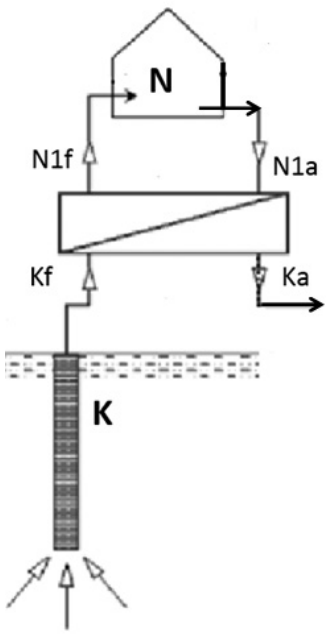


Explanation: 1- reinjection well, 2- filters, 3- rinse the filters with clean water, 4- settling the filtered minerals and the other pollutants, 5- pumps, 6- storage tanks (Tóth et al., 2012)

Letting thermal water from wells off on the surface (Figure 6) and relocating it (into lakes and rivers) poses environmental protection risks due to its high salt content (this is why an environmental load fee exists). Sequestration into thermal wells - the aquiclude - in case of more shallow bands - also becomes a problematic factor due to water purity protection. Contrary to this, these have to be utilised due to sustainability reasons.

Siphoning heat energy via heat pumping from the high-enthalpy fluid before sequestration, or subterranean placement is a definite option (Büki, 2010a; Nagygál, 2007)

Figure 6: Heating greenhouse with fluid let off (N-greenhouse)



Abbreviations on the illustration are as follows (Láng, 1999):

- Temperature of the well fluid – **Kf** (60-80°C)
- Temperature of fluid leaving - let off - from the heat exchanger – **Ka** (25-32°C)
- Temperature of heating water entering the greenhouse – N1f
- Temperature of heating water returning from the greenhouse – N1a

Due to the theorem of energy conservation, we can define that the heat absorbed by the medium being heated equals the heat expended by the medium losing heat (Beke, 2000), which is as follows:

$$Q_K = \dot{m}_1 c(T_{Kf} - T_{Ka}) = \dot{m}_2 c(T_{Nf1} - T_{N1a}) = Q_N$$

Meaning the heat successfully produced from the well is dependent on the difference in inbound and outbound temperatures, and the mass flow volume of the fluid from the well. When deciding the performance of the heat exchanger, the defining factor is obviously the supported maximum mass flow rate.

Heat supplied to the greenhouse is as follows:

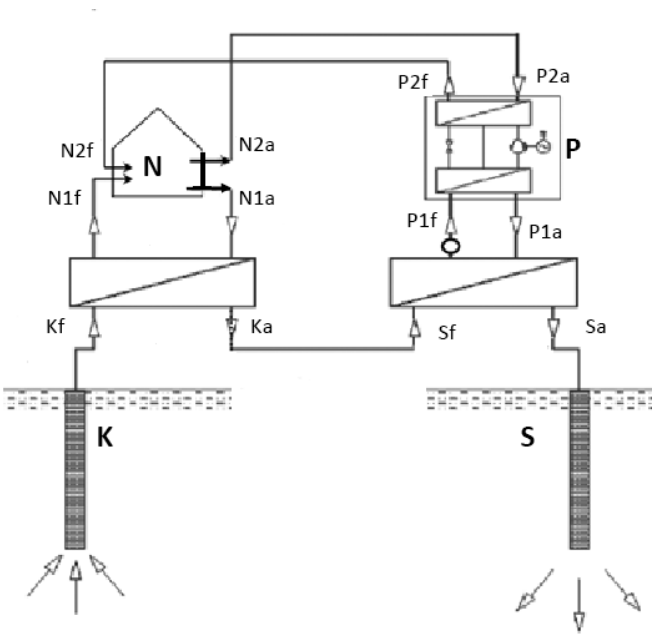
$$Q_N = \dot{m}_2 c(T_{Nf1} - T_{N1a})$$

Even in case of soil cooling, the temperature of water let off in case of greenhouses is between 25-32 ^{0}C (ANSI/ ASEA, 2003).

For such a medium temperature, heat pumps can be operated with a high COP value (COP=4-5). This is why heat pumping water before letting it off into open water, or sequestrating it may be productive.

In this case, the heat exchanger on the heat pump's vaporizer side can be linked directly to the fluid to be sequestrated, but in case of a higher concentration of minerals, operating it from an inserted heat exchanger which also allows for mass flow rate control might be more preferable (Figure 7).

Figure 7: Installing the heat pump



Abbreviations:

- Sf (=Ka) – temperature of the fluid arriving in the inserted heat exchanger,
- Sa - temperature of the fluid leaving the inserted heat exchanger - via letting off, or sequestration.
- The respective values of P1f and P1a are dependent on the DT value possible to realise on the heat exchanger, but even more dependent on the mass flow rate set in this support circulation.
- The respective values of P2f and P2a are the temperatures of heating water leaving, and returning to the heat pump's capacitor. Their ranges are defined by the attributes of the heat pumps, and the heat extraction of the greenhouse.

The heat extracted, and the temperature of the fluid before sequestration may be changed by the mass flow volume induced by the circulating pump inserted between the heat exchanger, and the other heat exchanger on the heat pump's vaporizer side (Ghosal et al., 2003). With a higher mass flow rate, temperature can be lowered, if the vaporizer of the heat pump can absorb heat.

Therefore, heat gained via the heat pump is as follows:

$$Q_s = \dot{m}_1 c(T_{Sf} - T_{Sa})$$

And the total heat extracted from the fluid is as follows:

$$Q_{\ddot{O}} = Q_N + Q_S$$

The amount of heat energy diverted from the heat pump to the greenhouse (taken from the capacitor) is higher, via the coefficient of performance (COP) of the heat pump (see Illustration 3).

$$Q_{N2} = \dot{m}_3 c(T_{N2f} - T_{N2a})$$

Where: m_3 is the mass flow rate of this cycle.
When heat pumping, COP is fundamentally influenced by the average difference in temperature (DT) between the capacitor and the vaporizer (Frank, David, 1990).

Therefore, our theoretical heating coefficient is as follows:

$$\varepsilon_f = \frac{\overline{T}_K}{\overline{T}_K - \overline{T}_{Ep}}$$

- The average outbound temperature of the capacitor:

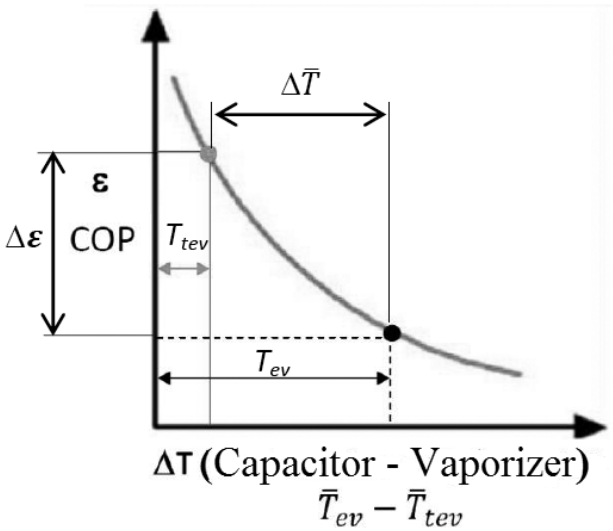
$$\overline{T_K} = \frac{\overline{T}_{P2f} - \overline{T}_{P2a}}{\ln \frac{\overline{T}_{P2f}}{\overline{T}_{P2a}}}$$

- The average temperature of the heat-absorbing side (vaporizer):

$$\overline{T_{EP}} = \frac{\overline{T}_{P1f} - \overline{T}_{P1a}}{\ln \frac{\overline{T}_{P1f}}{\overline{T}_{P1a}}}$$

According to what was written until now, if we chose a vaporisation temperature too low, thereby lowering the sequestration temperature, but disregard to do the same with the capacitor's temperature, the value of the COP will be worse. The similar can be said about the capacitor side, if we want to raise the heating temperature (Figure 8) (Ghosal et al., 2003).

Figure 8: Changes in COP due to temperatures of the capacitor and the vaporizer



Using an example close to real values, we calculated the COP for a system (Rennie, Raghavan, 2015):

Example:

a. The fluid's inbound temperature is 30°C, and outbound temperature is 13°C at the vaporizer side, while the respective temperatures are 50°C outbound and 38°C returning respectively.
   This results in a theoretical 13,78 COP value, which in practice[1] (including various losses) is reduced to a 5,5-6,0 value, which can be said to be economically positive.
b. If the fluid's inbound temperature is 25°C, and outbound temperature is 8°C at the vaporizer side, while the respective temperatures are 55°C outbound and 40°C returning respectively, theoretical COP value is only ~7,0, which in practice (including various losses) becomes a 2,8-3,0 value. This can't be said to be economically positive anymore.

For the economic evaluation, let's take a look at an example really close to actual facts (Thulukannam, 2013):

- The well's mass flow rate is 100m³/h.
- The extracted heat energy at the first heat exchanger at DT = 30°C (68-38) value is 3540kW.
- The second heat exchanger's DT = 17°C (30-13), while the heat energy value is 2006kW. This heat exchanger's cold side is linked to the vaporiser of the heat pump.

– This heat energy has a ~5.0 COP value, which means the operating energy is around 400kW.

If we take 8000 hours of annual operation time for the system, the annual electricity costs for 18-25 HUF / kWh adds up to about 60-80 million HUF annually.

The energy gain at the heat pump re-calculated for the case of using gas heating results in a 90% furnace efficiency, which would cost about 160 million HUF annually, at an average gas energy price of 2,8 HUF / MJ.

This way, the system results in a cost reduction of about 80 million HUF (about 50%) annually for a COP value of 5 (which is completely possible).

If we take a look at the costs of gas heating on Illustration 1, which is at a 14,9 HUF / kWh on average, half of which is 7,45 HUF / kWh, we can see that this kind of heat pumping is the cheapest compared to other variants.

Which means it's implementation is an economically sound decision!

The costs of the heat pump, the heat exchanger, and the various accessories (including installing fees) is about 60 million HUF. Figure 9 shows an example for a regular heat pump system.

Figure 9: AERMEK twin-capacitor heat pump

Using this for estimations, and a 5-year life cycle (we won't expand on amortisation and continual costs), it wins even against the cheapest coal heating. If we calculate as a further variation for this efficiency (even if digging a new, average H=1400-1600m well), we still get a positive result.

Methodology

General energetic evaluation

The question of how effectively heat pumping uses the renewable energy (in our case, post-heating of geothermal heat) pops up concerning our introduced heat pumping method. We arrive at the most critical answer if we compare the heat pumping method to more traditional heat extraction methods (f.e. natural gas-based) (Büki, 2010b).

In case of producing Q amount of heat with heat pumping, the consumed electric energy's

$$P = \frac{Q}{\varepsilon_f},$$

Primary energy complement, f.e. when using the aforementioned natural gas is as follows:

$$G_{fg} = \frac{P}{\eta_E} = \frac{Q}{\varepsilon_f \eta_E}$$

Where $e_f = Q/P$ is the heat factor of the electric heat pump, and $h_E = P/Q_{fg}$ (45%) is the production efficiency of consumed electric energy.

We disregard volume losses of heat pumping.

Heat produced by the pumping method - for identical Q heat requirement - turns out to be better, compared to natural gas heating, if $G_{fg} < G_K$, meaning:

$$\bar{\varepsilon}_f > \frac{\eta_K}{\eta_E}$$

Heat extracted via heat pumping can be considered renewable energy[1] if the following holds true for the heat pump's heating factor:

$$\bar{\varepsilon}_f > \frac{1{,}15}{\eta_E} \text{ (condenser furnace)}; \quad \bar{\varepsilon}_f > \frac{0{,}95}{\eta_E} \text{ (traditional furnace)};$$

This condition means that the COP value of heat pumping had to be above 0,38.

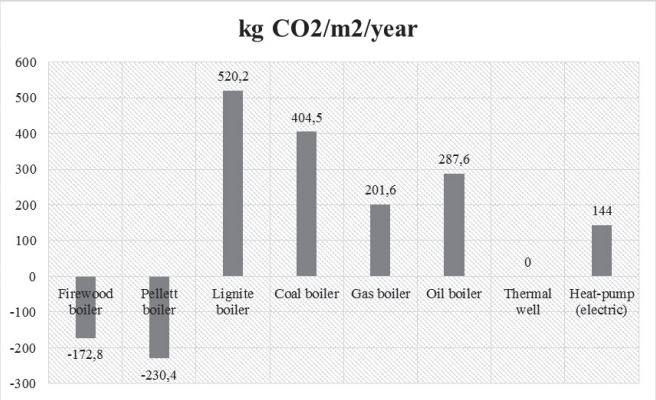
This condition, as we saw before, will hold true for heat pumping geothermic fluid, if size adjustments are correct. When improving the heating factor and the efficiency of electric energy production, the condition is even easier to satisfy. When thermal water is further cooled at an average heating factor of = 4-5, a consumption efficiency of 50-80% can be realised (Büki, 2010b).

This concludes that heat energy extractable via heat pumping before sequestrating, or letting off thermal water may be up to 50-70% of the energy extractable at the original consumption. If correct calculations are prepared, this energy, and the respective costs of the heat pump's initial investment and operation all have to be compared to heat production using natural gas furnaces, or the costs of digging a new well. In places where sequestrating thermal water can be done without any problems, this solution is more than adequate as an alternative to other energy resources. However, using electric energy from renewable sources, heat pumping serves the goals of sustainability best.

Regarding the environmental aspect we also examined the CO_2 emissions of the certain heating methods. Even though the firewood and the pellet boilers look the most efficient forms, previously they proved to be the most expensive ones

too. So it can be concluded that the utilization of geothermal energy is the best way for greenhouse heating in the case of the economic and the environmental aspects as well.

Figure 10: The CO_2 emissions of the certain fuels in a calendar year



Source: Self-made after own calculation, 2015

The chart does not include the follow-up pumping method. It is obvious that the operation of the heat-pump is going to generate CO_2 emissions which can be calculated with the energy mix of the used electricity (Fogarassy et al., 2011a).

The current value of this data in Hungary is 0,35 kg CO_2/kWh. In case COP is equal with the value of 5, it means that the utilized energy will be 20% of the all CO_2 emissions from the energy mix (Büki, 2010b).

Therefore: 0,37 x 0,2 = 0,074 kg CO_2/kWh. If the heat energy from the heat-pump system reaches 40% of all the utilized energy, then the previous data will be modified to (0,074/1,4) = 0,052 CO_2/kWh.

The required 3100 MWh/year energy for a 1ha sized greenhouse generates (3100 x 0,4=) 1240 tons of CO_2/year emission level even with the most efficient gas burning system. In the case of the geothermal heating system and its reinjection the emission level is only (3100 x 0,052=) 161,2 tons of CO_2/year which is only 30% of the gas boiler system emissions.

Conclusions

In this article, we analysed the respective costs of energy resources usable for the winter heating of greenhouses. We also examined the accessible energy resources in Hungary and their yearly costs for a 1 ha sized greenhouse. One of the main outcomes of the research was that geothermal heating proved to be the cheapest and the most environmentally friendly method. It can be concluded that if the COP value of the heat pumping system is higher than 3,8, then it will be cost-effective in any cases and it will operate on a low CO_2 emission level (only 30% of the emissions of the gas boiler). Furthermore, it is an efficient way for energy utilization to use the thermal water of the greenhouses before the reinjection. However in the case of greenhouse heating this method turned out to be the most cost-effective among all of the energy resources.

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