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Multi-criteria optimization for a residential horizontal ground heat exchanger

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Abstract. Ground source heat pumps (GSHP) are the most efficient heat pump systems currently in use for residential sector today. Although these systems outperform all other heat pump systems when considering the energy source, the installation costs represent an ongoing issue. For the market to increase in this area, multi-criteria optimization for the ground heat exchanger (GHE) is the main research topic today. The main objective of this study is to search ways to optimize the horizontal ground heat exchanger focusing on two distinct viewpoints: physical and energetic optimization. To achieve this goal, the entropy generation number and the coefficient of performance based on several configuration are studied. Using the Pareto optimal set obtained from two objectives provides useful information about the design optimization. In comparison with traditional single objective optimization, multi-criteria optimization avoids cost increase when regarding only the performance or performance decrease when regarding only the cost. The results indicate that the use of a cheaper heat source such as solar panels to mitigate the energy needed for peak loads during the heating and cooling systems can reduce the horizontal ground heat exchanger size and therefore the installation cost. A hybrid solar assisted ground source heat pump system, using more than one renewable energy source, shows a much higher flexibility for residential purposes than a heat pump system that uses only one renewable energy source.

1. Introduction

Energy demand continues to increase as the population grows, with an undesirable effect on the Earth's climate. Around 81% of the electrical energy generated on Earth is obtained from fossil fuels [1]. Renewable energy sources are commonly used today, especially from sources that store energy more efficient [2]. The focus today is on researching efficient ways for reducing the greenhouse gas emissions, such as in [3, 4], by developing more energy efficient systems.

Ground-coupled heat pumps are considered efficient systems that use geothermal energy [5]. Their usage has increased especially in the residential and commercial building sectors [6]. Recently several optimization researches have been performed for horizontal geothermal heat exchangers [7], which focused on the optimization using a single criterion. Single criteria optimization usually results in favorizing a parameter in the detriment of another. The purpose of this study is a multi-criteria optimization for HGHEs.

2. Materials and procedures

To solve these problems for heat pump systems, a multicriteria optimization is required. Establishing the parameters that have the most impact on the performances of the HGHE is required. Thus, three types of parameters were considered: physical, operational, and energetic. Limit intervals were set for this to narrow the results as can be seen in table 1.

Table 1. Parameters considered for multi-criteria optimization.

Type	Parameter	Limit
Physical	HGHE Surface	20÷100 [m^2]
	Pipe depth	-1 ÷ -3 [m]
	Pipe step	0.3 ÷ 1 [m]
	Pipe length	50 ÷ 200 [m]
	Pipe diameter	0.02 ÷ 0.032 [m]
	Soil thermal conductivity	0.5 ÷ 2.5 [W/mK]
Operational	Fluid flow	0,1 ÷ 1 [kg/s]
	Soil temperature with depth	-10 ÷ 30 [°C]
	Exterior temperature	-30 ÷ 30 [°C]
	Fluid temperature	-5 ÷ 40 [°C]
Energetic	Thermal energy extracted/supplied/restored	variable [kWh]

Optimization problems that consider multiple criteria simultaneously provide reliable results. However, not even this optimization strategy can offer the best optimization solution, because some criteria usually cannot be compared. Vilfredo Pareto's research [8] shows us that it is impossible to optimize all parameters simultaneously, because the improvement of one parameter will lead to the worsening of another.

By using several optimization criteria, a set of solutions is searched, that provides a reasonable compromise for several parameters, including the best solution of each parameter. The solutions can be found on the curve called the Pareto Front, among which the best solution resides. To obtain reliable results, in this study two criteria were used. Firstly, the Entropy Generation Number criteria (EGN) that determines the entropy of the system. Secondly, the Coefficient of Performance (COP) was used as a criterion to consider as many parameters as possible.

3. Entropy generation number criteria

Geothermal heat exchangers use the earth soil as a source of renewable energy. Thermodynamic irreversibility is an important criterion when regarding the overall operation of the heat pump system. Entropy, as the unit that measures the thermodynamic irreversibility, can provide a useful view on how the heat pump system impacts the earth.

Assuming this, the calculation of the entropy according to the average temperature of the fluid inside it and the cost of electrical energy in operation offers a perspective on the energy optimization that can be achieved. This optimization criteria is characterized by the function with the same name and is calculated with the formula:

$$\mathrm{N_s} = \frac{\mathrm{S_{gen}} \times \mathrm{T_{f,a}}}{\mathrm{Q}} \tag{1}$$

In which, S_{gen} represents the generated entropy, $T_{f,a}$ represents the average fluid temperature and Q represents the energy provided by the HGHE. The average temperature of the thermal fluid is directly influenced by the soil temperature, which is approximately equal to the outlet temperature. To increase this temperature external energy must be used. The cost for the electricity needed to increase the fluid temperature based on the monthly cost in Romania was calculated using the formula:

$$\mathrm{W_e} = \mathrm{Q_c} \times \mathrm{w_1} \times \mathrm{n_h} \tag{2}$$

In which, W represents the electricity cost, w_1 the cost for 1 kWh of electricity, Q_c represents the heat flux needed to increase the fluid temperature and n_h represents the average monthly operating hours. In figure 1, the results of all EGN solutions are illustrated based on inlet fluid temperature, average fluid temperature and electrical energy cost.

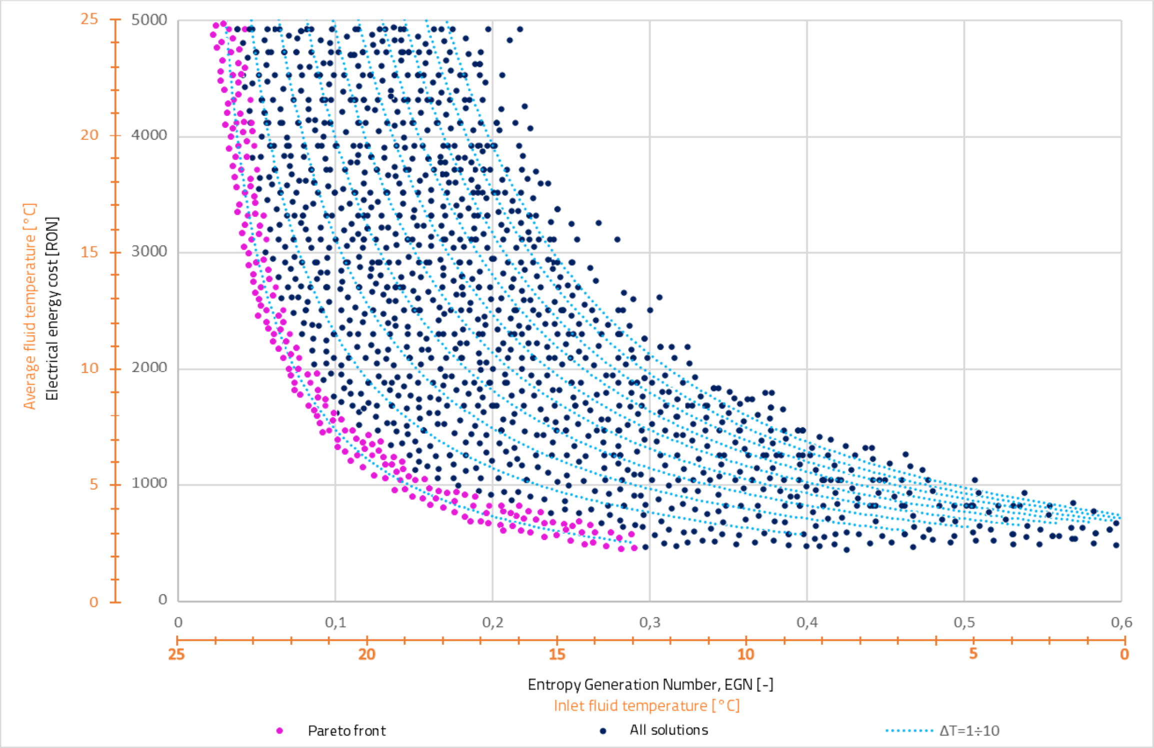

Figure 1. Solutions for the Entropy Generation Number for HGHE.

To highlight only the Pareto front optimum solutions, the rest of the solutions were eliminated as can be seen in figure 2. The optimum desired point is the closest one to 0.

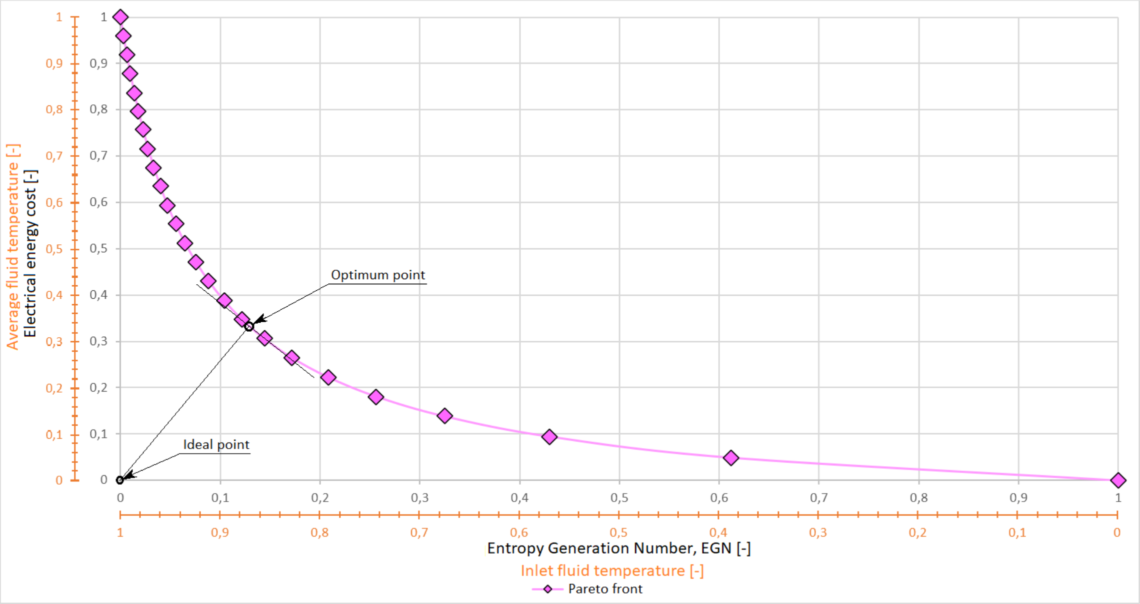

Figure 2. Pareto front of the Entropy Generation Number for HGHE.

4. Coefficient of performance criteria

In use, heat pump systems provide thermal energy at the expense of electrical energy. The ratio between the supplied energy and the energy that is used is called the coefficient of performance. For heat pump systems the COP represents an indicator of its overall performance, meaning that when the ratio has a higher value the system is more efficient and when the ratio has a lower value it is less efficient.

With the COP as a base point, this criteria purpose is to compare the thermal performances generated by a large set of HGHE configurations, for which the COP will be established based on the thermal output of the ground heat exchanger. Afterwards, the installation cost for all these configurations was established, based on average excavation prices, pipe prices and workmanship prices that are common today in Romania.

In order to establish the COP of the large set of configurations the GLHEPro Software was used to simulate the thermal performances of all configurations. After analyzing all the important parameters shown in Table 1, the configuration number was reduced based on common HGHE configurations. This led to configurations for three different diameters at pipe steps between 30cm and 100cm and HGHE surfaces between 20m^2 and 100m^2. The burial depth of the pipes was also considered at first, between 1 and 3m. The results were very similar and so this parameter was considered neglectable.

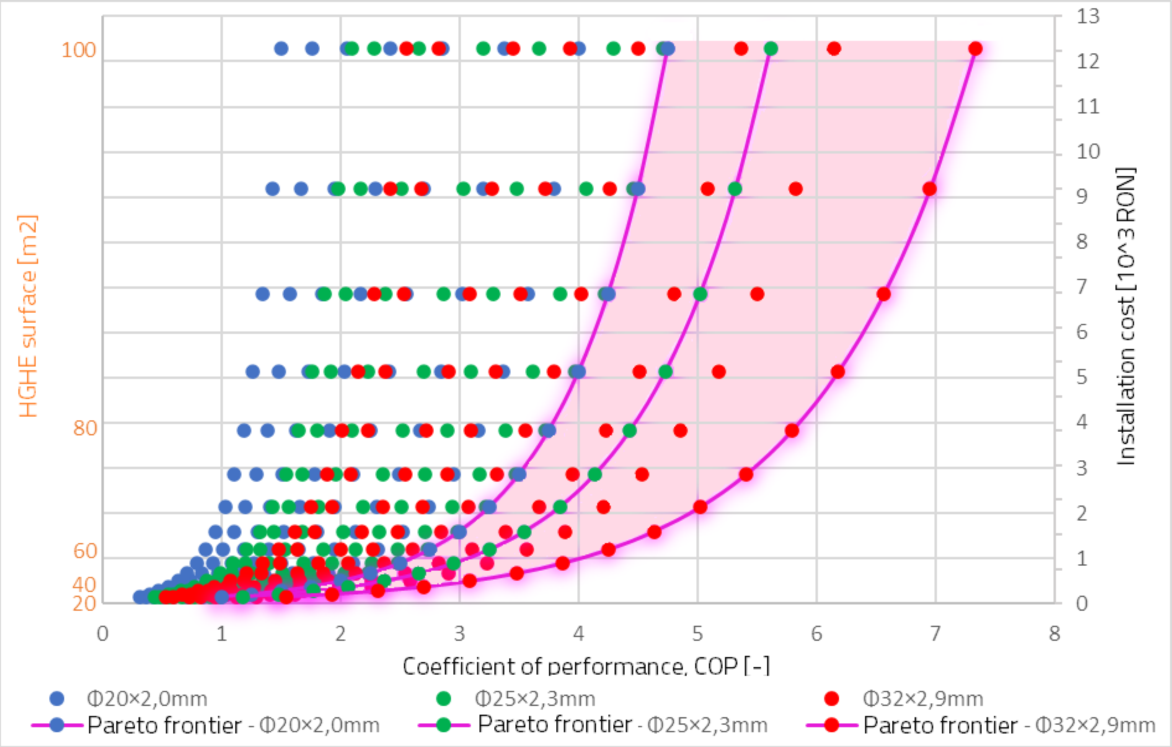

Figure 3. Pareto fronts of the Coefficient of Performance criteria for HGHE with 3 pipe sizes.

In figure 3 all the results simulated and calculated are presented. As this figure shows, the higher the HGHE surface and pipe step the better the COP is, but the installation cost increases. With all the results available and represented in a chart, the Pareto frontier was chosen and corresponds as the highlighted area between results for the 20 mm and 32 mm pipes for the pipe step of 30 cm. It is clear that in order to achieve better COP a higher surface is needed.

In figure 4 the solution outside the Pareto frontier were eliminated. Because all three different pipe diameters offered good results, it was decided that three Pareto frontiers will be represented, one for each diameter. Even if their results are close, the difference is high enough such as pipe diameter must be taken into consideration when designing the HGHE.

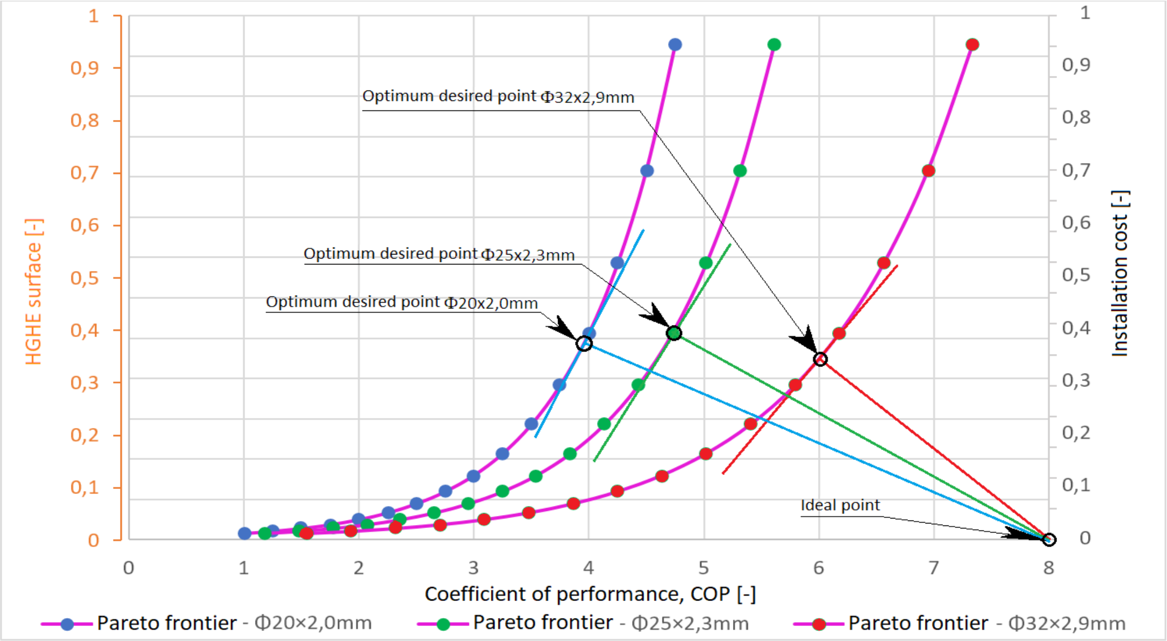

Figure 4. Pareto fronts of the Coefficient of Performance criteria for HGHE with 3 pipe sizes.

5. Discussion

After both criteria were calculated the decision-making process was made. The main topics considered were the reducing of the total entropy, increasing the heat pump performance and reducing the overall installation and exploitation costs. When accounting for all of those, it is difficult to find the optimum desired point and difficult to comprehend how the parameters can be optimized when they affect each other. In figure 5 all Pareto frontiers were overlayed according to the HGHE thermal output and both criteria costs. The optimum EGN point corresponds for a HGHE with a thermal output of approximate 700 W while the optimum COP points correspond to approximate 1900 W, 2400 W, and 3000 W respectively.

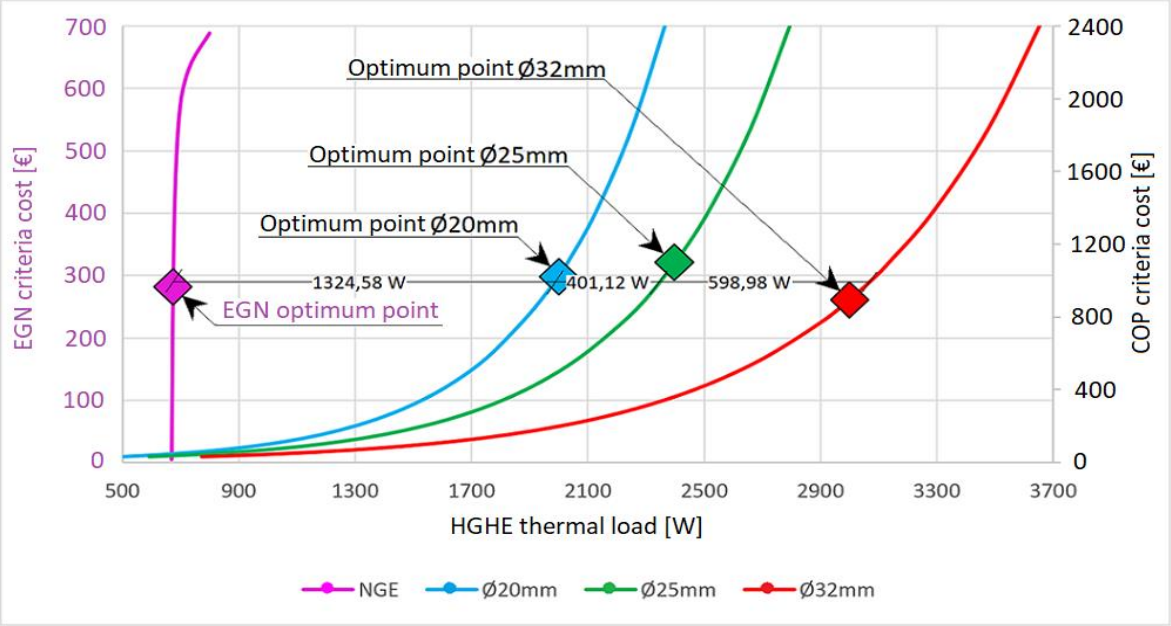

Figure 5. Optimal points from the EGN and COP criteria.

The first criteria, EGN, provides excellent results for reducing thermal irreversibility and maintaining thermal equilibrium in the HGHE but it does not consider the whole system and the thermal loads variation during the year. This means that in order to reduce the total entropy of the system, the HGHE configuration must be as small as possible, but this impacts the thermal output and reduces the heat pump system COP.

The second criteria, COP, provides very good results for choosing the optimal physical configuration, but does not consider both the thermal irreversibility and available HGHE install space. This means that in order for the heat pump system to use less electrical energy, which also translates to less amount of greenhouse gas emissions, the entropy must be neglected.

Therefore, analyzing the results from the two criteria used, the optimal points of the physical configuration of the heat exchanger can be achieved, while maintaining the optimal entropy generation only by providing external energy. This can be achieved by combining the geothermal energy source with another energy source such as solar energy or taking into consideration residual thermal energy from building basements or foundations.

6. Conclusions

Analyzing the results obtained with the two optimization criteria, it was observed that the optimal points, although they are the best solutions, have several disadvantages. The lack of space is one of the biggest disadvantages for physical parameters. Also, limiting the thermal load of the system in terms of thermal irreversibility is a disadvantage, especially when the install space is sparce. The pipe diameter and the pipe step have an important impact, representing the largest share of the thermal load of the HGHE, followed by the material-based parameters. It was also found that the installment depth is not an important parameter, the difference in thermal load of HGHE being insignificant. This aspect being due to the large temperature variation at the soil surface, up to a depth of 7-10 m. The main conclusion of the study is that to optimize the thermal performances of HGHEs, external energy is needed to be supplied to the system from auxiliary sources. The impact of an auxiliary source consists in providing help during peak loads and maintaining thermal equilibrium inside the HGHE.

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