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# Achieving sustainable work of the heat pump with the support of an underground water tank and solar collectors

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ABSTRACT

This paper deals with the methodology of sizing a sustainable heating–cooling system, which consists of a heat pump, thermo-solar collectors and underground water tank, as a seasonal thermal energy storage. The methodology is based on successive and coupled energy balancing of all system elements for time intervals of 1 h, during one representative calendar year. The starting assumption for the calculation contains the size of the underground storage tank, its burial depth, the size of building that is heated or cooled, and the temperature of air in the building. To make the calculation, it is necessary to know the so-called dynamic boundary conditions during a calendar year, comprising the following: hourly outdoor air temperature, hourly insolation (received solar radiation energy) and hourly temperature of the ground surface. The calculation result is the size of the thermal–solar collectors surface, which will ensure the sustainability of the system, i.e. it will ensure that after one year of operation this system is restored to the original conditions, without disturbing natural environment in which it is used.

For the purpose of presenting the methodology and checking the influence of individual parameters of the system's operation, a numerical simulation was performed and required surfaces of thermo-solar collectors were determined for one of the system models. Analyses of the influence of the underground tank burial depth, tank size and the initial water temperature in the tank on the required size of thermal–solar collectors were also performed.



## 1. Introduction

Today, due to the growing environmental threats, the use of renewable energy sources has become increasingly important. Besides their basic characteristic – renewability, economic reasons may often have a decisive influence on their implementation. In other words, it is frequently the case that the use of renewable energy sources, in addition to reducing the harmful impact on the environment, substantially reduces the operating costs of particular systems. Also, it frequently happens that the over-exploitation of these resources disrupts the natural mechanisms through which these sources are recovered and returned to their original state, undermining their characteristic renewability.

Generally speaking, it can be said that the technological development of civilization came to the end of an era when fossil fuels, conventional or non-renewable sources of energy, cannot be considered as the basis for planning future development and that we are living in times when energy technologies are rapidly changing. More and more, consumers and companies are turning to the usage of renewable energy sources and technologies that provide their use. Besides the basic property of these sources – the property of renewability it is of great importance that they also fulfil an other important condition during their use – the condition of sustainability. Namely, it often happens that the use of energy resources declared as renewable (biomass, hydropower, geothermal energy), their unplanned or excessive exploitation, distorts their surroundings and disrupt natural mechanisms that allow these sources to recover and return to their original state. In that way, the utilization of these resources is jeopardized and, in some cases, their renewability is permanently violated.

Geothermal energy is a renewable energy source, which has always attracted an increased interest, especially when it appears in the forms of hot water and steam. Examples of its use go back to the very beginning of civilization. However, in the case of thermal energy of dry ground layers, regardless of their theoretically unlimited heat capacity, their utilization was not possible until recently because of their low temperature. Only in recent decades, with the development and mass production of heat pumps, this renewable energy source has been experiencing its full affirmation.

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But, the new problem related to the sustainability of these sources – the so-called issue of thermal exhaustion of the ground – has emerged with the first year of their use. To some extent, the problem has been overcome by the use of these systems for cooling buildings in the summer, when the heat energy collected from the conditioned space has been accumulated in the ground. However, it turned out that this thermal energy is not sufficient to keep the system fully sustainable. It just delayed the problem of soil thermal exhaustion for some time. In order to overcome this problem, the idea of inclusion of an the additional sub-system in the heat pump system arose – the idea of a thermal energy storage – underground tank with water, and solar collectors – that will supply this thermal tank with additional thermal energy [1–4].

Until now, mathematical modelling of such systems [1–7] referred only to obtaining mathematical relations for determination of the temperature field in the soil around the tank under steady state heat load. Considering that the sustainability of the system still has the key position for its operation, this paper presents a methodology for determining the necessary size of thermo-solar collectors, which will ensure the sustainable work of the cooling–heating heat pump system with an underground thermal energy storage water tank. In other words, this means that in case of solar collectors' sizing in accordance with the methodology presented in this paper, it would ensure that after one year of operation, this system would be restored to its original condition, without disturbing natural environment in which it is used.

For the purpose of presenting the methodology and checking the influence of individual parameters of the system's operation, a numerical simulation was performed and required surfaces of thermo-solar collectors were determined for one of the system models. In particular, analyses of the influence of underground tank burial depth, as well as the tank size and the initial water temperature in the tank on the required size of thermal–solar collectors were also performed.

## 2. Physical model

Water–water heat pump system was chosen as the model space heating–cooling system. This system uses a spherical tank having the volume of 200 $m^3$, completely buried in the ground and filled with water, as a heat source in winter time, and a heat sink in summer time. It was assumed that the heating–cooling system should provide air temperature of 20 °C in the model houses – "C" energy classes (annual energy consumption for space heating per $m^2$ is 74 kW/$m^2$ a), having 170 $m^2$ heating area, located in Belgrade – throughout the calendar year.

Because of the climate conditions in this region, and greater annual needs for thermal than for cooling energy, it was predicted that the lacking heat energy in a tank should be compensated with solar energy collected with thermal–solar collectors directly linked to the buried tank (Fig. 1). The thermal storage is not active during the transitional periods between heating and cooling seasons and during these periods there is no heat transfer between solar panels and underground thermal energy storage. Solar energy is collected throughout the year except in the period from 16th April to 8th May, because it would only reduce the cooling capacity of the underground tank. During the whole year, the corresponding heat transfer between the tank (water) and the soil is achieved, depending on the current temperature of water in the reservoir and the temperature of the soil (Fig. 2).

As already mentioned, the basis of the methodology for dimensioning the sustainable heating–cooling system is the coupled energy balance for three sub-systems: heating demands for model building, energy balance of underground tank and energy balance of solar collectors. Due to the lack of exact solutions of differential equations which describe the transient temperature field around the sphere with variable heat transfer buried in a semi-infinite medium, this non-stationary problem has been solved numerically by successive calculations for time intervals of 1 h. The time interval of 1 h was chosen because, for this time interval, changes of water temperature and temperature of the ground surface are sufficiently small that the process could be treated as quasi-stationary.

At the same time, non-stationary feature of the calculation is provided by taking into account the dynamic boundary conditions, so-called hourly value of all influential external parameters:

- hourly temperature of the outside air,
- hourly temperature of the earth's surface and
- hourly insolation – solar radiation energy

In other words, this transient heat problem was solved by $3 \times 8760$ calculations for quasi-stationary conditions of the three subsystems, whose effect is mutually coupled to the energy balance of the underground storage tank.

According to experimental investigation [8–11] and manufacturers' data [12,13], it was assumed for the purposes of this calculation that the coefficient of performance of heat pumps for heating $COP_H$ and coefficient of performance for cooling $COP_C$ can be expressed as a linear function of difference between water temperature in the tank $\theta_w$ and ambient air temperature (designed temperature of the air inside the building) $\theta_i$. Since the coefficient of performance of heat pumps for heating is expressed as:

$COP_H = 3.5 - 0.125 \cdot (\theta_i - \theta_w)$ for $4\,°C < \theta_w < 25.6\,°C$, and for $\theta_w \geq 25.6\,°C$, is $(COP_H)_{max} = 4.2$, and the coefficient of performance for cooling is expressed as:
$COP_C = 3.4 - 0.04 \cdot (\theta_w - \theta_i)$ for $T_w > 20\,°C$ and $(COP_C)_{max} = 3.4$ for $8\,°C < \theta_w \leq 20\,°C$.

## 3. Energy balances for heat storage

The crucial and definitely the most sensitive part of the methodology is not only the definition, but also the way of calculating the individual members of the energy balance for the underground thermal energy storage.

The energy balance for the underground thermal energy storage – hot water tank – for a period of 1 h can be expressed as follows (Fig. 2):

$$Q_{(+hp),1\,h} + Q_{+\lambda,1\,h} + Q_{sol,1\,h} = \Delta U + Q_{-\lambda,1\,h} + Q_{(-hp),1\,h} \quad (1)$$

where $Q_{(+hp),1\,h}$ is amount of heat received by the water in the tank from the heat pump for 1 h (cooling mode); $Q_{+\lambda,1\,h}$ is amount of heat received by the water in the tank by conduction from the surrounding ground; $Q_{sol,1\,h}$ is amount of heat received by the water in the tank from solar collectors and which originates from solar energy; $Q_{(-hp),1\,h}$ is amount of heat delivered by the water in the tank to the heat pump for 1 h (heating mode); $Q_{-\lambda,1\,h}$ is amount of heat delivered by the water in the tank by conduction to the surrounding ground; $\Delta U$ is the change of internal energy of the water in the tank, which is defined as:

$$\Delta U = \rho_w \cdot V_w \cdot c_{pw} \cdot \Delta\theta_w \quad (2)$$

where $\rho_w$ is the density of water (for the calculation, the value of water density for the assumed range of operating temperatures $\rho_w = 998.2$ kg/$m^3$), $V_w$ is the tank volume, $c_{pw}$ is the specific water heat capacity at constant pressure (for the calculation, $c_{pw} = 4186$ kJ/(kg K)), and $\Delta\theta_w$ is changes of water temperature in the tank.

Somewhat simpler Eq. (1) can be written as:

$$Q_{in,1\,h} = \Delta U + Q_{out,1\,h} \quad (3)$$