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A SYSTEMATIC TECHNO – ECONOMIC - ENVIRONMENTAL ASSESSMENT PROCEDURE FOR INSTALLING A RESIDENTIAL GROUND SOURCE HEAT PUMP (GSHP) SYSTEM FOR HEATING AND COOLING PURPOSES

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Abstract: This paper presents a systematic procedure for a thorough techno-economic-environmental investigation of an open or closed Ground Source Heat Pump (GSHP) system, which is to be used for residential heating and cooling purposes. The aim of this work is to outline in a clear manner the necessary steps of the procedure that must be followed in order to verify the technical feasibility, economic viability, and environmental friendliness of the GSHP system before its actual installation and exploitation is undertaken. After the presentation of the systematic procedure, an application to a real open loop GSHP system is thoroughly examined and its relevant technical, economic and environmental evaluation is conducted. Finally, the examined GSHP system is operationally compared to two equivalent conventional heating/cooling systems (where in the first case an oil burner is used for heating and in the second case a gas burner is used for the same purpose, while both use electric air-condition units for cooling purposes).

Keywords: Ground source heat pump (GSHP), geothermal energy, open & closed loop GSHP system, technical feasibility, economic liability, environmentally friendly

1 INTRODUCTION

The ground source heat pump (GSHP) systems make use of geothermal energy, which is the heat energy stored in the earth's crust at depths up to 150 m and with associated underground temperature up to 20^{o}C, which is almost maintained throughout the year. This form of stored renewable energy is supplied constantly from two sources: a) the flow of heat from the earth's interior (50 - 100 mW / m · s), and b) the absorption of solar radiation from the earth's surface (approximately 50% of the total quantity that reaches the earth) [1-6]. It is remarked that the GSHP systems use a small amount of electricity for supplying the Geothermal Heat Pump (GHP), which is the main part of the total GSHP system. Therefore, for the operation of the GSHP system there is a small contribution to atmospheric pollution, which is related to the CO_2, released by the electrical power plants producing the respective needed electricity. In any case, the high performance of a GSHP system is not totally free from environmental impacts. In fact, the type of fuel that the power plants use determines the release of high quantities of CO_2, and it plays an important role in the environmental impact of the GSHP system. The real benefits of the GSHP system are more distinct and clear when it falls in the category of renewable systems (i.e. when it displays a Coefficient Of Performance (COP) value higher than 3.0) [7]. Therefore, a well selected and designed GSHP system can be used to assist in the reduction of environmental pollution and in this way affects positively the greenhouse effect, which lately is a world serious issue, coupled with partial savings in primary fuels. This is the reason why for instance the latest European Union's recommendations favor the exploitation of such technologies, which in Greece is specified by the national law [8]. Finally, it must be pointed out, with emphasis that before one undertakes any Renewable Energy Application (RES), including the geothermal one, must with priority deal with the relevant application of the rational use and savings of energy.

Finally, the relevant literature shows that in the past several studies [9-25] have been conducted dealing with the investigation of GSHP systems, which have demonstrated that such systems are really promising for heating/cooling of residential applications.

2 CONFIGURATION OF OPEN AND CLOSED LOOP GSHP SYSTEMS

In general, there are two types of GSHP systems: a) the open loop GSHP one, and b) the closed loop GSHP one. The open loop GSHP systems are used only when there is plenty of relatively warm underground water, while the closed loop GSHP systems are used when there is no underground available water. In Sections 2.1 and 2.2, the detailed configuration of these two systems is presented, respectively.

2.1 THE OPEN LOOP GSHP SYSTEM

The open loop GSHP systems are those that exploit for heating/cooling purposes the existing underground relatively warm water. A basic condition for the proper operation of these systems is the existence of rich and steady aquifer.

A typical schematic of an open loop GSHP system is shown in Fig. 1 [26]. The actual system consists of three main subsystems: a) the ground heat source system, b) the heat pump (HP) circuit, and c) the fan coil or the underfloor heating/cooling circuit [13]. The ground heat source system consists of a water supply well with a submerged electrically driven pump and a reinjection well into which the water is directed after being circulated through the geothermal HP. The GSHP system consists mainly of the HP which is an essential part of the total system. Finally, the fan coil or the underfloor heating/cooling circuit is very important since it transfers the heat or cooling content of the system to the desired building.

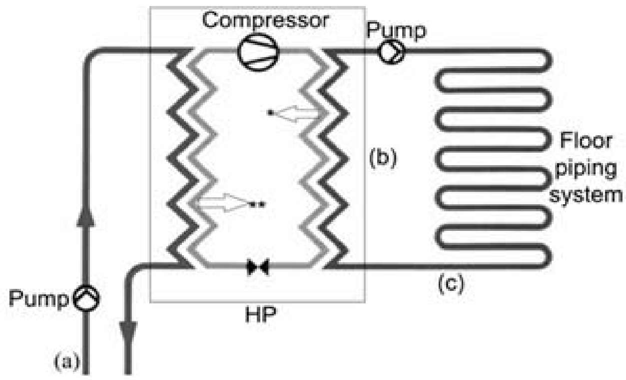

Figure 1: Simplified operational diagram of an open loop GSHP system
(where: * = evaporator, and ** = condenser)

2.2 THE CLOSED LOOP GSHP SYSTEM

The closed loop GSHP systems are those which use the temperature of the geological formations. The closed loop geothermal systems are installed in areas where underground water is absent or the cost of aquifer exploitation is quite high.

A typical schematic of a closed loop GSHP system is shown in Fig. 2 [26]. The actual system consists of three subsystems [27] that are similar to the associated ones of the open loop GSHP system. The only different part of the closed loop GSHP system is the ground heat source system, which is a closed pipe circuit grid consisting of a horizontal ground collector or a vertical loop. The vertical ground collector is preferable when there is no sufficient free ground area to install a horizontal collector. The heat transfer medium, i.e. brine (water with anti-freeze), is circulated through the collector or loop and the HP with a brine electrically driven pump.

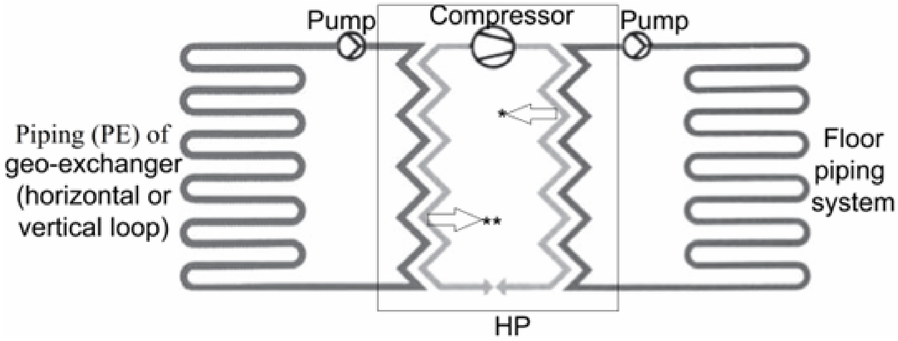

Figure 2: Simplified operational diagram of a closed loop GSHP system (where: * = evaporator, and ** = condenser)

2.3 THE GHP

In general, the heat pump (HP) is a device that has the ability to transfer heat from a low temperature medium to another medium with a higher temperature [28]. The main components of a GHP are: 1) the condenser, 2) the expansion valve, 3) the evaporator, and 4) the compressor. In most cases, the GHP is designed to reverse cooling and heating operation, allowing the use of the same device for both cooling and heating mode operation. A simplified operational diagram of a GHP is shown in Fig. 3. The proper operation of a GHP, for the case of heating mode operation, is expressed by the Coefficient Of Performance (COP), which is given by:

$$COP = \text{Desired thermal output/Required electrical input} = Q_{th} / W_{net} \qquad (1)$$

In the GHPs the COP usually ranges between 1.5 and 6, which practically means that the higher its value the more economic becomes the operation of the GHP. A satisfactory COP value of a GHP is at least 3.0. A lower COP value makes the GSHP system uneconomical for its operation, which means that in this case the geothermal energy is not practically considered a renewable source of energy [7]. Finally, in the case of the cooling mode of operation of the GHP the Energy Efficiency Ratio (EER) is used instead, where:

$$EER = \text{Desired cooling load/Required electrical input} = Q_c / W_{net} \qquad (2)$$

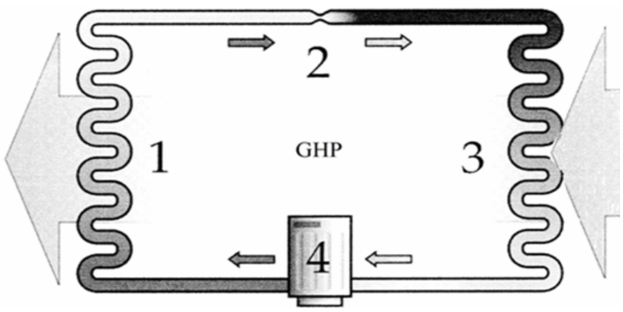

Figure 3: Simplified operational diagram of a GHP, where: (1) condenser, (2) expansion valve, (3) evaporator, and (4) compressor

3 SYSTEMATIC PROCEDURE FOR THE DETERMINATION OF OPEN AND CLOSED LOOP GSHP SYSTEMS

The main steps required to determine an open and closed loop GSHP system are the following [29-30]:

a) Determination of the thermal and cooling load requirements of the building obtained from the relevant insulation study [31-32].
b) If the GSHP system is an open loop circuit one, it is necessary to: analyze the quality of the underground water, measure its temperature, and calculate the required rate and depth of the pumping system. It is also important to calculate the exact position of the water supply and reinjection wells. The adequacy of the volume and temperature of subsurface water for operational reliability purposes should be tested for three days by continuous pumping. The subsoil water temperature should not fall below 8^{o}C to avoid any evaporator damage. To avoid erosion damages, the conductivity of the water should not exceed 450 mSiemens / cm. Attention should also be paid to the water quality since it may change as function of time (e.g. due to local use of fertilizers). The injection water well should be placed at least 10 to 15 m away from the production/supply well in the downstream direction of flow of underground water. The required pumping rate is given by:

$$m_w = P_K * 3600/c * \Delta t \quad (kg/h) \tag{3}$$

where:

P_K = cooling capacity = capacity of capturing heat from the ground (kW_{th}),
c = thermal capacity of water = 4.2 kJ/kg*K, and
Δt = temperature difference between the supply well water and the injection well water (e.g. 4K).

If the GSHP system is a closed loop circuit one, it is necessary to calculate the heat capacity of the soil and to select the appropriate horizontal or vertical geo-exchanger, which consists of a set of water polyethylene (PE) pipes. In the case of a horizontal geo-exchanger it is important to calculate the required by geo-exchanger ground surface using Table I [26]. On the other hand, if a vertical geo-exchanger is to be used, then one must calculate the position and depth of drilling in which the vertical PE pipes of the geo-exchanger will be installed. A usual depth for Greece in which the vertical PE pipes are installed is 100 m.

Table I: Heat capturing capacity of horizontal geo-exchanger of a closed loop GSHP system

Ground conditions	Specific heat capturing capacity (W/m^2)	Capturing area (m^2/kW_{th})	Capturing area (m^2/kW_{th})	Capturing area (m^2/kW_{th})
		at COP = 3	at COP = 3.5	at COP = 4
Dry, loose soil	10	66	71	75
Damp, packed soil	20 – 30	22 – 33	24 – 36	25 - 38
Saturated Sand/Gravel	40	17	18	19

Table II: Heat capturing capacity of vertical geo-exchanger of a closed loop GSHP system

Ground conditions	Specific heat capturing capacity (W/m)	Loop length (m/kW_{th}) at COP = 3	Loop length (m/kW_{th}) at COP = 3.5	Loop length (m/kW_{th}) at COP = 4
Dry, sediment	30	22	24	25
Shale, Slate	55	12	12	14
Solid stone with high thermal conductivity	80	8	9	9.5
Underground with high groundwater flow	100	6.5	7	7.5

Table II [26] may be used to determine the appropriate installation depth of the vertical PE pipes. The mathematical relationship used to calculate the nominal thermal capacity of the geo-exchanger is:

$$\text{Thermal capacity of geo-exchanger} = \text{Required heating capacity} - \text{Consumption of electrical power by GHP} \quad (4)$$

c) In case of a closed loop GSHP system, there is the need to calculate the electrical power being consumed by the electrically driven water pump required to force the circulation of the fluid through the closed circuit that includes the GHP and consists of the water PE pipes, which are installed in the ground. The flow rate of the refrigerant flowing in the closed loop of the subsurface water pipes should be able to transfer the nominal/maximum thermal capacity required by the heat source. The desired flow rate of the refrigerant is given by:

$$m_b = P_K * 3600/c * \Delta t \quad (kg/h) \quad (5)$$

where:
P_K = cooling capacity = capturing capacity of heat from the ground (kW_{th}),
c = thermal capacity of the specific refrigerant = 3.9 kJ/kg*K, and
Δt = temperature difference (e.g. 3K).

d) Selection of appropriate size of the GHP for the purpose of meeting the nominal/maximum thermal and cooling load requirements of the application building [14]. This issue is faced by using the heating and cooling load requirements of the examined building, which are derived from the results of step (a) of this procedure. There is a variety of GHPs with fixed heating/cooling capacity available in the world market, and the selected suitable GHP one must have the proper capacity to satisfy the cooling and heating load requirements of the application building. The proper selection of the nominal/maximum capacity of the GHP is very important for the efficient operation of the complete heating/cooling system [27].
e) Selection of the proper size capacity of the protection buffer storage tank (when it applies). The buffer storage tank has the ability to maintain warm or cool water, in

required quantities, and in this way to protect the GHP by avoiding often starts and stops during its operation. It should be pointed out that frequent restarts of the GHP could limit the expected useful life of its compressor. As a practical guideline for selecting the protection buffer storage tank size, one may use the value of 17 L per kW_{th} [26].

f) Using a buffer storage tank requires the use of an additional electrically driven water pump to circulate the heating/cooling water through the heat distribution system as well as another similar pump, which feeds the storage tank with water being circulated through the GHP. The flow rate of these two water pumps should be able to transfer the nominal heat capacity of the GHP. The flow rate of water should be the same in both circulation water pumps. The calculation of this required water flow rate is given by:

$$m_H = P_n * 3600/c * \Delta t \quad (kg/h) \qquad (6)$$

where:
P_n = heating capacity (kW_{th}),
c = thermal capacity of water = 4.2 kJ/kg*K, and
Δt = temperature difference (e.g. 5K).

g) Sizing and selecting the appropriate floor PE piping or fan-coil system, which distributes or absorbs the heat necessary to heat or cool the building, respectively. This can be done by taking into account the required heating/cooling requirements of the building. This procedure is also used in common conventional heating systems which use fossil fuels (oil or gas).

The systematic procedure for the determination of open and closed loop GSHP systems, outlined above, is presented in flow-chart form in Fig. 4 and Fig. 5, respectively.

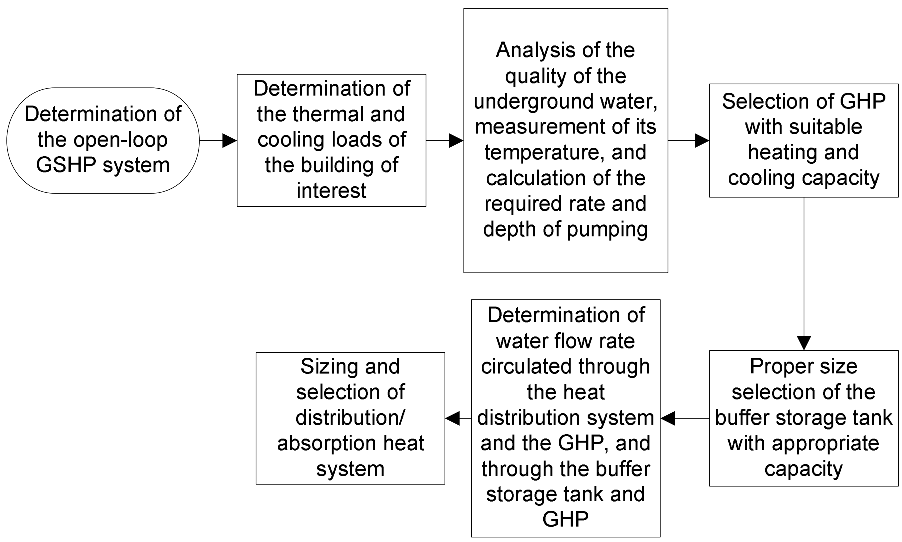

Figure 4: Simplified flow chart of the systematic procedure for the determination of an open loop GSHP system

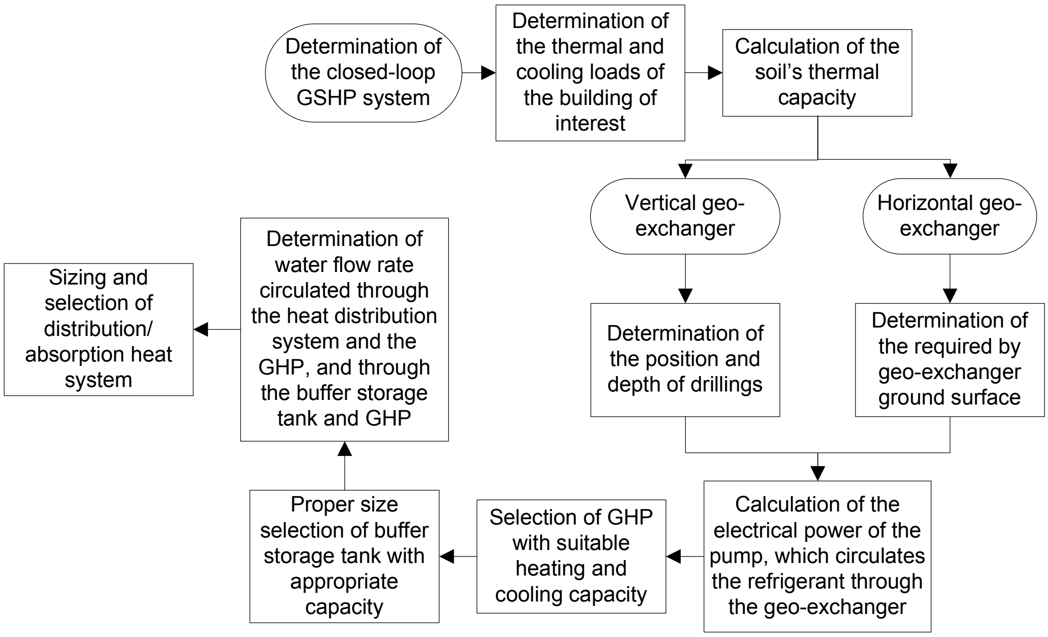

Figure 5: Simplified flow chart of the systematic procedure for the determination of a closed loop GSHP system

4 APPLICATION STUDY OF AN OPEN LOOP GSHP SYSTEM TO A TYPICAL BUILDING IN NORTHERN GREECE

An open loop GSHP system installed in a two floor house is considered for a thorough techno-economic-environmental investigation, using the presented systematic procedure. This house is located in the Central Macedonia Region of Greece (Galatades Village, near the city of Giannitsa), where plenty of underground relatively warm water is available. The first floor of the building has a surface area of 177.26 m^2 (of which 43.6 m^2 belong to non-heated area of the warehouse and the staircase), while its second floor has a surface area of 116.37 m^2 (of which 20.07 m^2 belong to non-heated area of the staircase). The calculation of the thermal and cooling load requirements of the house was based on the available relevant insulation study, which gave the following results:

Maximum thermal power Q_{th} = 19 kW, and

Maximum cooling power Q_c = 28.5 kW.

According to the geological analysis of the selected installation area, satisfactory aquifer in 3 – 4 m from the surface of the ground is expected. Also in depths of up to 80 m there is significant aquifer. In general this water is potable of good quality and, therefore, is suitable to be used by the GSHP system. In addition, two wells have been drilled. The first one is used as a warm water supply well, while the second one is used as a reinjection water well. The depth of each well is 60 m. The pumping rate of water is estimated to be 6.5m^3/h, while its temperature is estimated to be between 15 to 17^{o}C throughout the year. The temperature of the water returning to the soil is between 20 to 22^{o}C for cooling mode, and between 10 to 12^{o}C for heating mode. In addition, the water is pumped from the underground using a submersible electrically driven water pump with nominal power of 1HP (horsepower).

The next step of the procedure is to select the proper GHP unit. For this application the GHP selected to cover the thermal and cooling load requirements is the 130Z type of the Italian Company Thermocold. Some important technical characteristics of the particular GHP unit are shown in Table III.

Table III: Technical characteristics of the selected GHP unit for the open loop GSHP system

Description	Model	Maximum performance in cooling mode (kW)	Maximum performance in heating mode (kW)	Required electrical power (kW)	Electrical supply	COP
Value	130Z	30.2	36.5	6.47	400V/3ph +n/50Hz	5.7

Moreover the investigated system includes a protection buffer storage tank of 500 L capacity. The selection of this capacity is based on the size of the heating/cooling system. The selection of the distribution system is carried out in the same way followed in the conventional heating systems, which use oil or gas [31-32]. Fig. 6 and Fig. 7 show the examined heating/cooling system with the flow rate of water at various internal closed loops of the total GSHP system and the electrical consumptions for both heating and cooling modes of operation, respectively. Finally, Fig. 8 shows the detailed GSHP system configuration/representation.

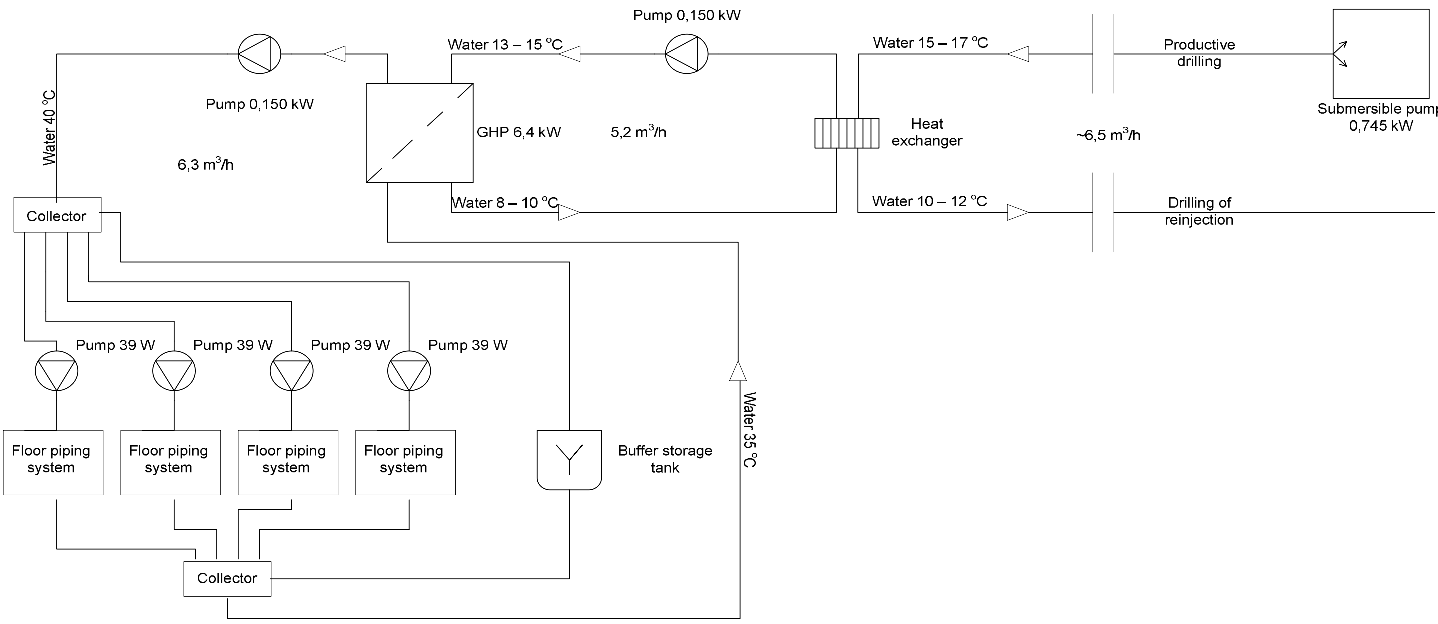

Figure 6: Simplified representation of an open loop GSHP system for heating mode operation

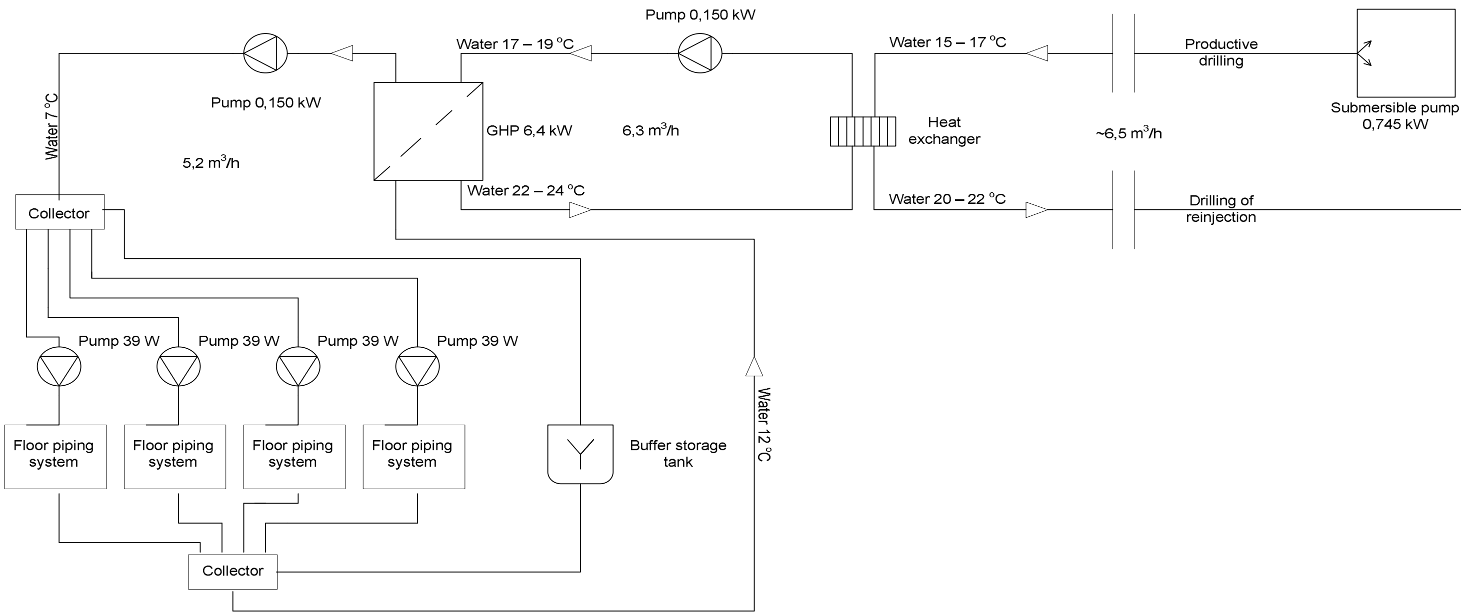

Figure 7: Simplified representation of an open loop GSHP system for cooling mode operation

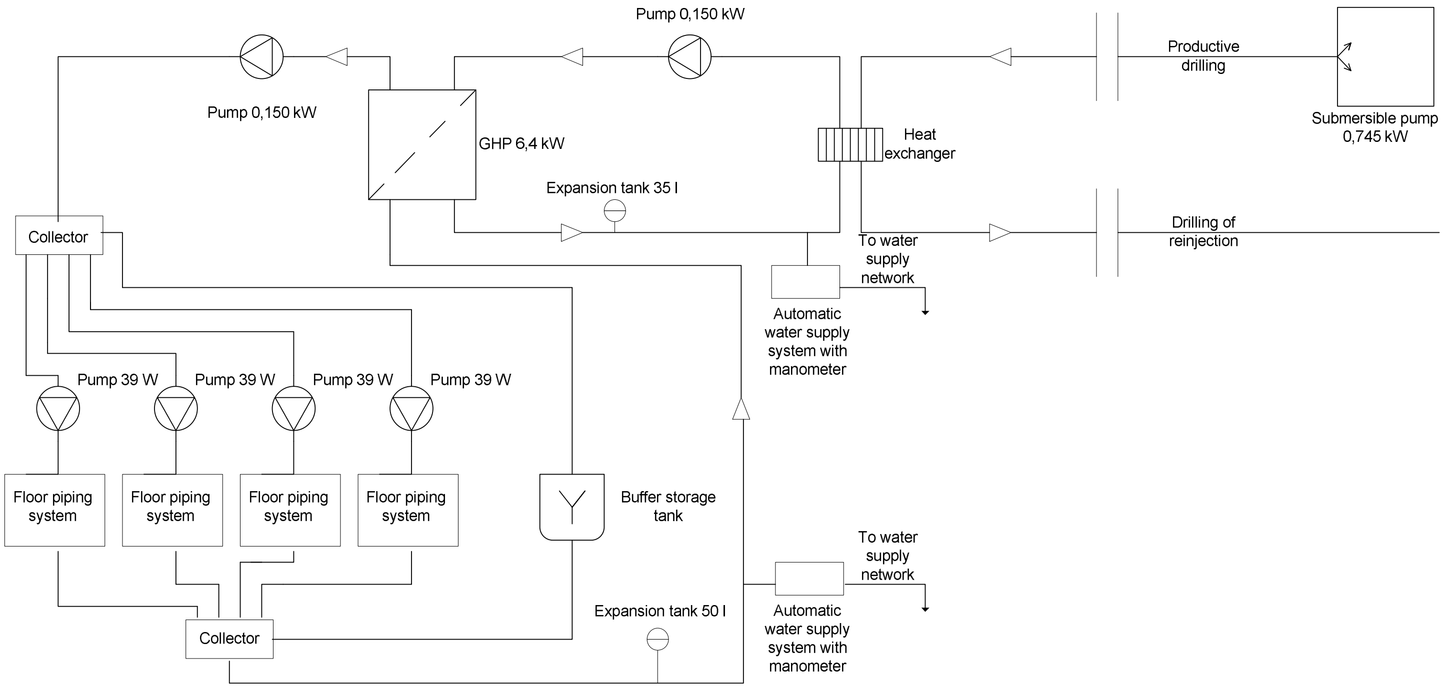

Figure 8: Simplified representation of an open loop GSHP system for heating and cooling

5 ECONOMIC AND ENVIRONMENTAL EVALUATION OF THE INVESTIGATED OPEN LOOP GSHP SYSTEM

For completeness purposes of the present investigation and in order to arrive at practical conclusions, the above open loop GSHP system is compared to an equivalent conventional heating/cooling system which uses either oil or gas burner for heating and electric air-condition units for cooling. Fig. 9 and Fig. 10 show the detailed configuration of both equivalent conventional heating systems using either oil or gas for heating purposes, respectively, while Table IV and Table V show the main technical characteristics of the selected oil and gas burner, respectively. It should be noted that in both cases each electric air-condition unit has a maximum cooling capacity of 8 kW_{th} and in order to satisfy the cooling load requirements of the building 4 such units are required. Finally, the main technical characteristics of this unit are shown in Table VI.

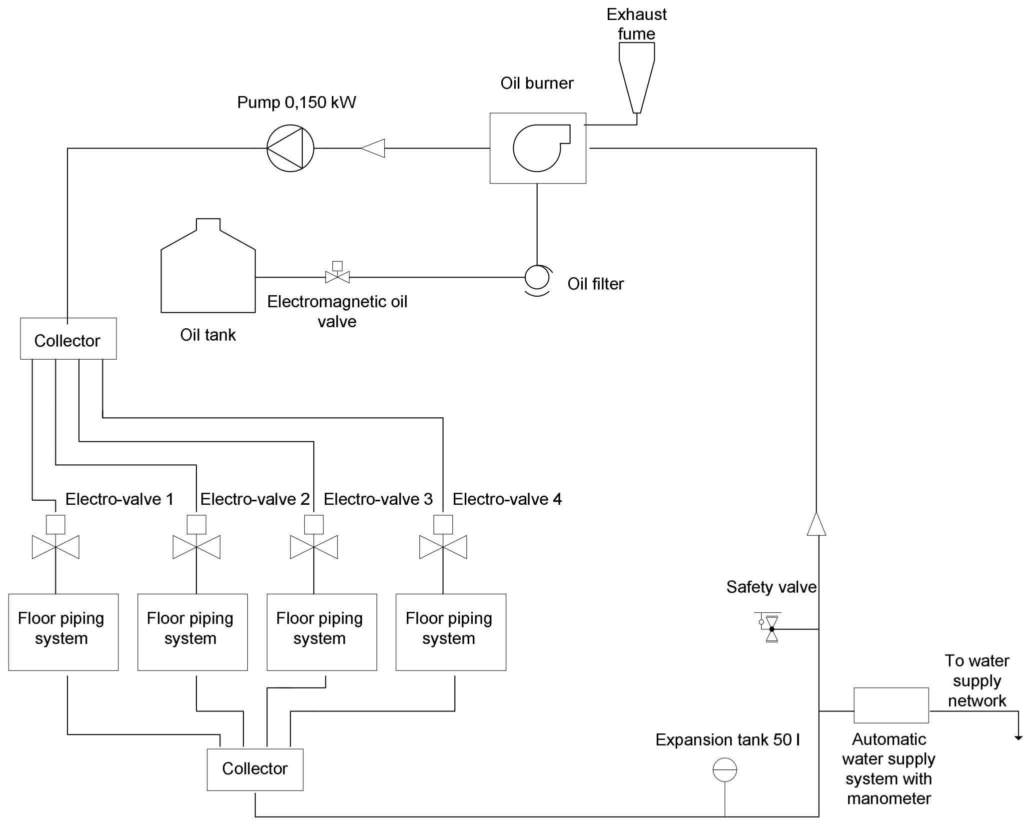

Figure 9: Simplified representation of conventional heating system using oil burner

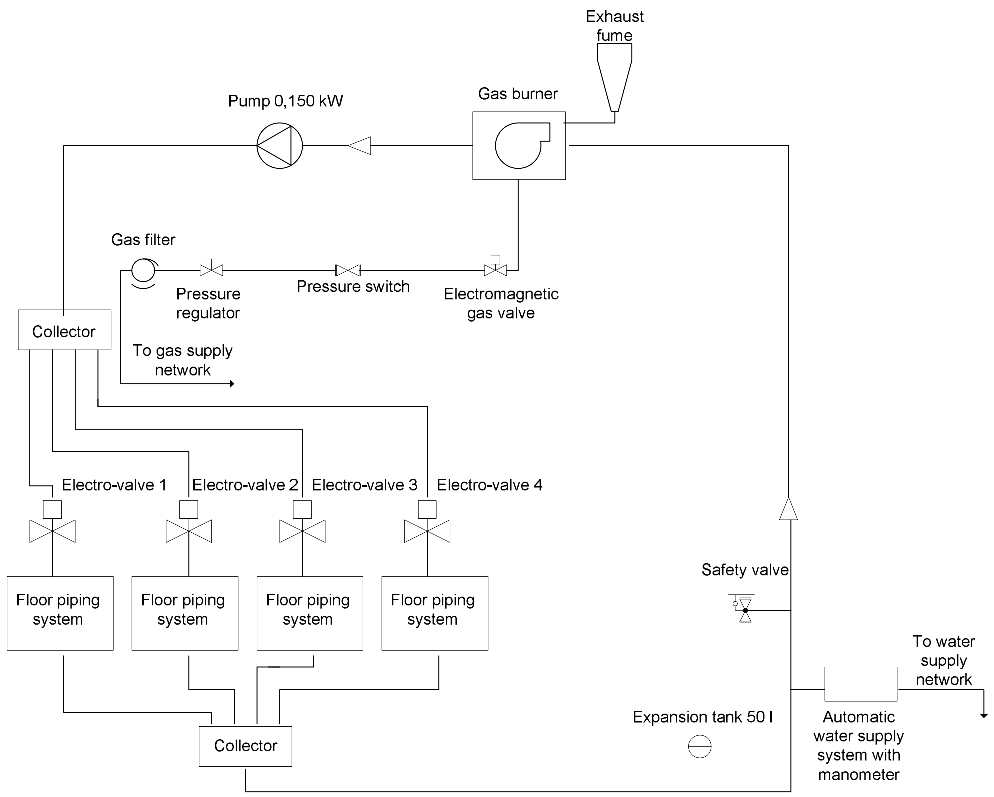

Figure 10: Simplified representation of conventional heating system using gas burner

Table IV: Technical characteristics of the selected oil burner (E01E.4L, ELCO Company of the Sweden)

Description	Model	Maximum thermal power (kW)	Nominal electrical power of motor (kW)	Electrical supply
Value	E01E.4L	23 – 40	0.09	230V/50Hz

Table V: Technical characteristics of the selected gas burner (E01E.6GTF, ELCO Company of Sweden)

Description	Model	Maximum thermal power (kW)	Nominal electrical power of motor (kW)	Electrical supply
Value	E01E.6GFT	15 – 60	0.04	230V/50Hz

Table VI: Technical characteristics of the selected air-condition units (ASYA 30LC, FUJITSU Company of Japan)

Description	Model	Maximum cooling power (kW)	Nominal electrical power (kW)	EER
Value	ASYA 30LC	8	2.66	3

5.1 DETERMINATION OF ANNUAL OPERATING COST OF THE GSHP SYSTEM

For the determination of the annual operating cost of the GSHP system it is necessary to calculate the mean value of the heating and cooling power needed to cover the heating and cooling load requirements of the application building, respectively [15, 18, 31, 32].

1. For heating mode

The available relevant heating insulation study of the considered building showed that the required maximum heating power is Q_{th} = 19 kW (for 20^{o}C desired building temperature and -7^{o}C worst environment temperature, giving a temperature difference of $\Delta T_{th} = 27^oC$).

The mean environmental temperature during winter period (November – April) according to the Greek National Meteorological Service for the area of installation is $T_m = 9^oC$ and, therefore, $\Delta T_m = 20 - 9 = 11^oC$.

Thus, the mean value of the thermal power required for heating the building the winter period is given by:

$$Q_{thm} = U * A * \Delta T_m = U * A * 11 \quad (7)$$

where:

U = heat transfer coefficient ($W/m^2 * {}^oC$),

A = heat transfer area (m^2), and

ΔT_m = temperature difference (^oC).

Similarly, the maximum thermal power required for heating the building the winter period (for worst temperature -7^{o}C) is given by:

$$Q_{th} = U * A * \Delta T_{th} = U * A * 27 =>$$

$$19 = U * A * 27 \quad (8)$$

where:

U = heat transfer coefficient (W/m^2* ^{o}C),

A = heat transfer area (m^2), and

ΔT_{th} = temperature difference (^{o}C).

From the ratio of equations (7) and (8) one obtains Q_{thm} = 7.75 kW (mean value of needed thermal power).

The application building is a village house and it is expected to be heated 30 days per month and 16 hours per day, i.e. 2880 hours for the six months winter period. The estimated energy to be consumed annually is given by:

$$E_{th} = Q_{thm} * 2880 = 22320 \text{ kWh} \quad (9)$$

The efficiency of the GSHP system for heating mode (COP) is obtained by:

$$COP = Q_{GHP} / (P_{GHP} + P_{PUMP} + P_{S\text{-}PUMP})$$

$$= 36.5 / [6.47 + (2 * 0.150 + 4 * 0.039) + 0.745] = 4.76 > \mathbf{3.0} \quad (10)$$

where:

Q_{GHP} = thermal power of the GHP (kW),

P_{GHP} = electrical power of the GHP (kW),

P_{PUMP} = electrical power of the pumps (kW),

$P_{S\text{-}PUMP}$ = electrical power of the submersible pump (kW).

Thus, the annual electrical consumption of the GHP for heating mode is given by:

$$E_{el} = E_{th} / COP = 4689.075 \text{ kWh} \quad (11)$$

The annual operating cost of the GSHP system for heating mode is computed by multiplying the annual electrical consumption E_{el} (kWh) with the proper cost of the kWh, while the maintenance cost is considered to be practically zero. Thus, by taking into account (for year 2009) the tariffs of the Greek electricity company (i.e. for 0 – 800 kWh is 0.08981 €/kWh, for 800 – 1600 kWh is 0.11443 €/kWh, for 1601 – 2000 kWh is 0.14045 €/kWh, for 2001 – 3000 kWh is 0.18790 €/kWh, and for higher than 3000 is 0.18971 €/kWh per 4 months and for 3 phase supply), the annual operating cost of the GSHP system for heating mode is calculated as:

$$K_h = 586.664 \text{ €}$$

2. For cooling mode

The available relevant cooling insulation study of the considered building showed that the required maximum cooling power is Q_c = 28.5 kW (for 24^{o}C desired building temperature and 35^{o}C worst environment temperature, giving a temperature difference of ΔT_{th} = 11^{o}C).

The mean environmental temperature during summer period (May - September) according to the Greek National Meteorological Service for the area of installation is T_m = 26^{o}C and, therefore, ΔT_m = 26 – 24 = 2^{o}C.

Thus, the mean value of the cooling power required for cooling the building the summer period is given by:

$$Q_{cm} = U * A * \Delta T_m = U * A * 2 \quad (12)$$

where:
U = heat transfer coefficient ($W/m^2 * {}^oC$),
A = heat transfer area (m^2), and
ΔT_m = temperature difference (^oC).

Similarly, the maximum cooling power required for cooling the building the summer period (for worst temperature 35^oC) is given by:

$$Q_c = U * A * \Delta T_{th} = U * A * 11 \Rightarrow$$
$$28.5 = U * A * 11 \quad (13)$$

where:
U = heat transfer coefficient ($W/m^2 * {}^oC$),
A = heat transfer area (m^2), and
ΔT_{th} = temperature difference (^oC).

From the ratio of equations (12) and (13) one obtains Q_{cm} = 5.182 kW (mean value of needed cooling power).

The application building is a village house and it is expected to be cooled 30 days per month and 16 hours per day, i.e. 2400 hours for the five months summer period. The estimated energy to be consumed annually is given by:

$$E_c = Q_{cm} * 2400 = 12436.8 \text{ kWh} \quad (14)$$

The efficiency of the GSHP system for cooling mode (EER) is obtained by:

$$EER = Q_{GHP} / (P_{GHP} + P_{PUMP} + P_{S\text{-}PUMP})$$
$$= 30.2 / (6.47 + 2 * 0.150 + 4 * 0.039 + 0.745) = 3.94 \quad (15)$$

where:
Q_{GHP} = cooling power of the GHP (kW),
P_{GHP} = electrical power of the GHP (kW),
P_{PUMP} = electrical power of the pumps (kW),
$P_{S\text{-}PUMP}$ = electrical power of the submersible pump (kW).

Thus, the annual electrical consumption of the GHP for cooling mode is given by:

$$E_{el} = E_c / EER = 3156.55 \text{ kWh} \quad (16)$$

The annual operating cost of the GSHP system for cooling mode is computed by multiplying the annual electrical consumption E_{el} (kWh) with the proper cost of the kWh, while the maintenance cost is considered to be practically zero. Thus, by taking into account the tariffs (for year 2009) of the Greek electricity company (see Section 5.1 for heating mode), the annual operating cost of the GSHP system for cooling mode is calculated as:

$$K_c = 364.73 \text{ €}$$

5.2 DETERMINATION OF ANNUAL OPERATING COST OF THE CONVENTIONAL HEATING SYSTEM WITH OIL BURNER

In Section 5.1 it was calculated that the mean value of the required annual thermal energy for the village house is E_{th} = 22320 kWh. For the computation of the relevant needed oil quantity equation (17) is used [31-32]:

$$b = E_{th} / z * n = 2482 \text{ L} \quad (17)$$

where:

n = 0.92 is the efficiency of the oil burner, and

z = 9.7744 kWh/l is the calorific value of oil.

With oil price 0.75 €/L (March 2009) the cost of the required oil for the annual heating period of the house is calculated as follows:

$$K_1 = 0.75 * b = 1861.5 \text{ €} \quad (18)$$

In addition, the cost of the needed electrical consumption of the oil burner and the pumps for the same period should be taken into account. Thus, the needed consumed electrical power is computed by:

$$E_{el} = h * (P_B + P_{PUMP}) = 691.2 \text{ kWh} \quad (19)$$

where:

h = 2880 the annual heating hours,

P_B = 0.09 kW the electrical power of the oil burner motor, and

P_{PUMP} = 0.15 kW the electrical power of the pump.

Thus, the cost of the needed electrical consumption for the annual heating period, taking into account the single phase supply cost of the kWh, is given by:

$$K_2 = E_{el} * 0.07169 = 49.55 \text{ €} \quad (20)$$

Finally, the annual operating cost should also include a representative annual maintenance cost which is taken as K_3 = 100 € [31-32].

Thus, the total annual operating and maintenance cost for heating the house is given by:

$$K_h = K_1 + K_2 + K_3 = 2011.05 \text{ €} \quad (21)$$

5.3 DETERMINATION OF ANNUAL OPERATING COST OF THE CONVENTIONAL HEATING SYSTEM WITH GAS BURNER

In Section 5.1 it was calculated that the mean value of the required annual thermal energy for the village house is E_{th} = 22320 kWh. For the computation of the relevant needed gas quantity equation (22) is used [31-32]:

$$b = E_{th} / z * n = 2148.6 \text{ m}^3 \quad (22)$$

where:

n = 0.92 is the efficiency of the gas burner, and

z = 11.2914 kWh/m^3 is the calorific value of gas.

With gas price 0.5337 €/m^3 (March 2009) the cost of the required gas for the annual heating period of the house is calculated as follows:

$$K_1 = 0.5337 * b = 1146.708 \text{ €} \quad (23)$$

In addition, the cost of the needed electrical consumption of the gas burner and the pumps for the same period should be taken into account. Thus, the needed consumed electrical power is computed by:

$$E_{el} = h * (P_B + P_{PUMP}) = 547.2 \text{ kWh} \quad (24)$$

where:

h = 2880 the annual heating hours,

P_B = 0.04 kW the electrical power of the gas burner motor, and

P_{PUMP} = 0.15 kW the electrical power of the pump.

Thus, the cost of the needed electrical consumption for the annual heating period, taking into account the single phase supply cost of the kWh is given by:

$$K_2 = E_{el} * 0.07169 = 39.23 \text{ €} \quad (25)$$

Finally, the annual operating cost should also include a representative annual maintenance cost which is taken as K_3 = 100 € [31-32].

Thus, the total annual operating and maintenance cost for heating the house is given by:

$$K_h = K_1 + K_2 + K_3 = 1286 \text{ €} \quad (26)$$

5.4 DETERMINATION OF ANNUAL OPERATING COST OF THE CONVENTIONAL COOLING SYSTEM WITH AIR-CONDITION UNITS

In Section 5.1 it was calculated that the mean value of the required annual cooling energy is E_c = 12436.8 kWh. For the computation of the relevant needed electrical consumption equation (27) is used [31-32]:

$$E_{el} = E_c / EER = 4145.6 \text{ kWh} \quad (27)$$

where:
E_c = the mean value of the required annual cooling energy (kWh), and
EER = the efficiency of the air-condition units (= 3.0).

Thus, the total electrical energy required for the operation of the air-condition units for the five months summer period (May - September) is 4145.6 kWh. By taking into account the tariffs of the Greek electrical company (see Section 5.1), the required annual cost of the electrical energy for cooling the house with air-condition units is calculated as:

$$K_1 = 540.85 \text{ €}$$

Finally, the annual operating cost for cooling the house should also include a representative annual maintenance cost which is taken as K_2 = [4 (air-condition units) x 30 € / (air-condition unit)] = 120 € [31-32].

Therefore, the total annual operating and maintenance cost for cooling the house is given by:

$$K_c = K_1 + K_2 = 660.85 \text{ €} \quad (28)$$

5.5 COMPARISON OF THE THREE CONSIDERED HEATING/COOLING SYSTEMS ON ECONOMICAL AND ENVIRONMENTAL BASIS

Finally, an economical and environmental comparison of the three considered heating/cooling systems is important for extracting practical conclusions.

Table VII shows the typical purchase and installation cost of the three considered heating/cooling systems. It is clear from Table VII that the GSHP system is the most expensive one, while the least expensive one is the conventional system, which uses oil burner for heating and electric air-condition units for cooling. Table VIII shows the required annual operating and maintenance cost of each examined heating/cooling system. It is important to note that the operating cost of the GSHP system is due to the consumption of electrical energy to meet the GHP requirements, while there is practically no maintenance cost. Moreover, in the case of the conventional system with oil burner, the operating cost is due to the consumption of oil and also due to the consumption of electrical energy, which is required by the electric air-condition units. Finally, in the case of the conventional system with gas burner the only difference by comparison to the other conventional one is the use of gas instead of oil. Table VIII shows in addition the annual operation money savings achieved using the GSHP system, because of its lower operating cost as compared to the associated one of both conventional heating/cooling systems.

Table VII: Purchase and installation cost of the three examined heating/cooling systems

Type of heating/cooling system	Open loop GSHP system	System that uses oil burner for heating and air-condition units for cooling	System that uses gas burner for heating and air-condition units for cooling
Typical purchase and installation cost (€)	18640	11301	11766

Table VIII: Annual operating and maintenance cost of the three examined heating/cooling systems

Annual operating cost of the open loop GSHP (€).	951.394
Annual operating and maintenance costs of the conventional system that uses oil burner for heating and electric air-condition units for cooling (€).	2671.9
Annual operating and maintenance costs of the conventional system that uses gas burner for heating and electric air-condition units for cooling (€).	1946.85
Annual savings of the open loop GSHP system by comparison to the conventional heating/cooling system that uses oil (€).	1720.506 (64.39%)
Annual savings of the open loop GSHP system by comparison to the conventional heating/cooling system that uses gas (€).	995.456 (51.13%)

Table IX shows the number of years needed for the additional cost required for the purchase and installation of the open loop GSHP system to be paid back (payback period). This additional cost is the difference between the initial purchase and installation cost of the open loop GSHP system (which is the highest) and the associated one of each of the two conventional heating/cooling systems. The payback period is due to the fuel savings which results in the case of using the open loop GSHP system. The actual payback period, in years, maybe computed as follows:

$$\text{Payback period} = (K_1 - K_2) / (M_1 - M_2) \qquad (29)$$

where:

K_1 = the initial purchase and installation cost of the open loop GSHP system,

K_2 = the initial purchase and installation cost of each of the two equivalent conventional system that uses oil or gas for heating and electric air-condition units for cooling, respectively,

M_1 = the annual operating and maintenance cost of each of the two equivalent conventional system that uses oil or gas for heating and electric air-condition units for cooling, respectively, and

M_2 = the annual operating cost of the open loop GSHP system.

The environmental benefits resulting from the operation of the examined actual open loop GSHP system (being in the category of renewable source of energy) when compared to the relevant operation of the two conventional heating/cooling systems are really significant. The open loop GSHP system does not use fossil fuels (oil or gas) which are burned in the conventional systems releasing CO_2, etc. to the environment. This is very important since the emitted CO_2 contributes to the air pollution and it, also, causes harm to the environment leading to global warming, etc. Table X shows the CO_2 emissions from burning 1 liter of oil and 1 m^3 of gas for heating purposes, and also the amount of CO_2 released in the atmosphere by the power plants of the Greek public power corporation (PPC) for the production of 1 kWh using oil, gas, lignite or a mixture of them. Finally, Table XI shows, for annual and for lifetime operation, the CO_2

emissions of each of the three examined heating/cooling systems. A practical conclusion drawn from Table XI is that the open loop GSHP system has the least CO_2 emissions to the atmosphere, while by comparison the conventional heating/cooling system which burns oil has the highest emissions. Based on the above it is clear that the wider spreading and exploitation worldwide of the GSHP systems becomes almost mandatory.

Table IX: Payback period of the extra cost for purchase and installation of the open loop GSHP system by comparison to the associated ones of the two conventional heating/cooling systems

Payback period of the difference of the initial cost of purchase and installation of the open loop GSHP system by comparison to the associated one of the conventional system which uses oil burner for heating and electric air-condition units for cooling (years).	4.26
Payback period of the difference of the initial cost of purchase and installation of the open loop GSHP system by comparison to the associated one of the conventional system which uses gas burner for heating and electric air-condition units for cooling (years).	6.9

Table X: CO_2 emissions from burning oil or gas for heating purposes, and for producing 1 kWh from the power plants of the PPC of Greece

a) CO_2 from burning oil and gas for heating purposes:	
-CO_2 released to the atmosphere from burning 1 l of oil.	3 kg
-CO_2 released to the atmosphere from burning 1 m^3 of gas.	1.96 kg
b) CO_2 released to the atmosphere for producing 1 kWh from the power plants of the PPC of Greece:	
-using oil	0.7599 kg
-using gas	0.5317 kg
-using lignite	1.0140 kg
-using a mixture of the above	0.82 kg

Table XI: Annual and lifetime emissions of CO_2 to the atmosphere from the operation of the three examined heating/cooling systems

Type of system	**Annually (kg/year)**	**For lifetime operation (kg/30 years)**
a) CO_2 emitted to the atmosphere from the operation of the open loop GSHP system when the electrical power comes from:		
-oil	5961.89	178856.7
-gas	4171.52	125145.6
-lignite	7955.46	238663.8
-a mixture of the above	6433.41	193002.3
b) CO_2 emitted to the atmosphere from the operation of the conventional system which uses oil burner for heating and electric air-condition units for cooling.	11412.17	342365.1
c) CO_2 emitted to the atmosphere from the operation of the conventional system which uses gas burner for heating and electric air-condition units for cooling.	8059.35	241780.5

6 CONCLUSIONS

Some main/practical conclusions of this work are:

- Before the actual design of an open or closed loop GSHP system a suitable techno-economic-environmental assessment is required for evaluating its technical feasibility, economic attractiveness and also its benefits to the environment.
- The actual design of the open or closed loop GSHP system must properly address the selection of its size capacity (so that it satisfies the thermal and cooling requirements of the building under extensive winter and summer weather conditions, respectively) and the appropriate protection buffer storage tank (to avoid often start-stop cycles of operation).
- The initial cost (purchase and installation) of the actual open loop GSHP system by comparison is higher than the associated one of the equivalent conventional system (with oil or gas burner for heating and electric air-condition units for cooling), whereas its annual operating cost is smaller than that of the conventional one(s).
- The difference in purchase and installation cost between the actual open loop GSHP system and the two equivalent conventional ones (using oil or gas) leads to a payback period of 4.22 years and 6.9 years, respectively.
- The environmental benefits of the actual open loop GSHP system, by comparison to the two equivalent conventional ones, are superior (i.e. for annual operation it emits less CO_2 to the atmosphere than each of the equivalent conventional one, while the most annual CO_2 is emitted to the air by the conventional one which uses oil). It is acknowledged that the most environmental benefits result from the annual operation of a well selected and designed open loop GSHP system, when this falls in the category of a renewable source of energy (which is secured when its COP value is greater than 3.0).

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REFERENCES

[1] Fytikas M., Andritsos N.: Geothermy. Thessaloniki, Greece: Tziola, 2004 (in Greek).

[2] Karidakis G. I.: Geothermal energy. Athens, Greece: Athlotypo, 2005 (in Greek).

[3] Christopher H., Armstead H.: Geothermal energy. London, UK: E. & F.N. SPON LTD, 1978.

[4] Goguel J.: Geothermics. USA: McGraw – Hill Inc., 1976.

[5] Pitts D., Sissom L.: Heat Transfer. Thessaloniki, Greece: Tziola, 2004 (in Greek).

[6] Dickson M., Fanelli M.: What is geothermal energy? Pisa, Italy: Istituto di Geoscienze e Georisorse, 2004.

[7] National Ministerial Decision No.:Δ9Β,Δ/Φ166/οικ 13068/ΓΔΦΠ2488/24-6-2009: Permissions for installations of energy systems for heating/cooling of self use spaces by exploiting the thermal energy of geological formations and warm water (surface and underground), which are not characterized as being of high geothermal potential (in Greek).

[8] National law 3614/3-12-2007: Management, control and application of developmental intervation for the scheduled period 2007-2013 (in Greek).

[9] Esen H., Inalli M., Esen M.: Numerical and experimental analysis of a horizontal ground-coupled heat pump system. Build Environ 2007; 42: 1126-34.

[10] Blumsack S., Brownson J., Witmer L.: Efficiency, economic and environmental assessment of ground-source heat pumps in central Pennsylvania, Proceedings of 42nd Hawaii International Conference on System Sciences, Big Island, HI, January 5-8, 2009, p. 1-7.

[11] Yari M., Javani N.: Performance assessment of a horizontal-coil geothermal heat pump. Int J Energy RES 2007; 31:288-99.

[12] Ozgener O., Hepbasli A.: Modeling and performance evaluation of ground source (geothermal) heat pump systems. Energy Build 2007; 39:66-75.

[13] Yuehong B., Xinhong W., Yun L., Hua Z., Lingen C.: Comprehensive exergy analysis of a ground-source heat pump system for both building heating and cooling modes. Applied Energy 86 (2009) 2560-2565.

[14] Weibo Y., Mingheng S., Guangyuan L., Zhenqian C.: A two-region simulation model of vertical U-tube ground heat exchanger and its experimental verification. Applied Energy 86 (2009) 2005-2012.

[15] Esen H., Inalli M., Esen M.: Technoeconomic appraisal of a ground source heat pump system for a heating season in Eastern Turkey. Energy Conversion & Management 2006; 47: 1281-97.

[16] Al-Sarkhi A., Abu-Nada E., Nijmeh S., Akash B.: Performance evaluation of standing column well for potentional application of ground source heat pump in Jordan. Energy Conversion & Management 2008; 49: 863-72.

[17] Sayyaadi H., Hadaddi Amlashi E., Amidpour M.: Multi-objective optimization of a vertical ground source heat pump using evolutionary algorithm. Energy Conversion & Management 2009; 50: 2035-46.

[18] Esen H., Inalli M., Esen M.: A techno-economic comparison of ground-coupled and air-coupled heat pump system for space cooling. Building and Environment 2007; 42: 1955-65.

[19] Pulat E., Coskun S., Unlu K., Yamankaradeniz N.: Experimental study of horizontal ground source heat pump performance for mild climate in Turkey. Energy 2009; 34: 1284-95.

[20] Doherty P., Al-Huthaili S., Riffat S., Abodahab N.: Ground source heat pump-description and preliminary results of the Eco House system. Applied Thermal Engineering 2004; 24: 2627-41.

[21] Mustafa Omer A.: Ground-source heat pumps systems and applications. Renewable and Sustainable Energy Reviews 2008; 12: 344-71.

[22] Benli H., Durmus A.: Evaluation of ground-source heat pump combined latent heat storage system performance in greenhouse heating. Energy and Buildings 2009; 41: 220-28.

[23] Tarnawski V., Leong W., Momose T., Hamada Y.: Analysis of ground source heat pumps with horizontal ground heat exchangers for northern Japan. Renewable Energy 2009; 34: 127-134.

[24] Michopoulos A., Bozis D., Kikidis P., Papakostas K., Kyriakis N.: Three-years operation experience of a ground source heat pump system in Northern Greece. Energy and Buildings 2007; 39: 328-34.

[25] Esen H., Inalli M., Esen M., Pihtili K.: Energy and exergy analysis of a ground-coupled heat pump system with two horizontal ground heat exchangers. Bulding and Environment 2007; 42: 3606-15.

[26] Ochsner K.: Geothermal heat pumps: A guide to planning & installing. London, UK: Earthscan 2007.

[27] Anonymous: Domestic ground source heat pumps: Design and installation of closed loop systems - A guide for specifiers, their advisors and potential users. UK: Energy saving trust, 2007.

[28] Lord N. W., Ouellette R. P., Cheremisinoff P. N.: Electrotechnology, Volume 4, Heat pump technology. Michigan: Ann Arbor Science Publishers Inc, 1980.

[29] Kavanaugh S., Rafferty K.: Ground source heat pumps: Design of geothermal systems for commercial and institutional buildings. USA: Ashrae, 1997.

[30] McCrea A.: Renewable energy – A user's guide. Wiltshire, UK: The Crowood Press, 2008.

[31] Sellountos B.H.: Heating – Cooling. Volume A. Athens, Greece: Selka – 4M, 2002 (in Greek).

[32] Sellountos B.H.: Heating – Cooling. Volume B. Athens, Greece: Selka – 4M, 2002 (in Greek).