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Simulation of the thermal performance of a Solar Assisted Ground Source Heat Pump system in climatic conditions of Algeria

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Abstract
In order to provide a reliable energy supply, hybrid systems that employ several energy sources in buildings have attracted more attention in recent years. This requires improving the performance of these hybrid systems. This work presents a simulation study of the solar-assisted ground source heat pump system carried out by the TRNSYS software. The underground loop heat exchanger's length was designed using ground loop design software (GLD). The energy consumption and the annual mean coefficient performance (COPs) of the systems analyzed, as well as temperatures of the building and the domestic hot water during one year of operation were obtained and compared. The analysis of dynamic results has shown that a hybrid system with a heat storage tank was able to supply 76% renewable energy. Furthermore, total uptake of electricity decreases by 15.43% compared to the GSHP autonomous system. Moreover, a technoeconomic study was performed to compare the suggested optimal system with the conventional ones, where a payback period of around 7.3 years was achieved.

Keywords
Space heating; dynamic simulation; solar collector; TRNSYS; ground source heat pump

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1. Introduction

To mitigate global warming, alternatives to fossil fuels must be developed and carbon emissions must be reduced. Currently, the use of renewable energy has become a fundamental choice in order to minimize energy demand and CO2 emissions. Therefore, Algeria was one of the first developing countries to submit its Intended Nationally Determined Contribution (INDC), pledging to reduce carbon emissions by at least 7% by 2030 (Bouznit et al, 2018). Hence, Algeria has presented a strategy to increase the percentage of power generation using renewable energy to 30% to 40% by 2030, which is expected to expand the supply of renewable energy (Algerian Ministry of Energy and Mines, 2015; Ali-Toudert et al., 2017; Hamiche et al., 2015). However, in the field of energy use in rural houses in developing countries like Algeria, we mainly use gas or petroleum products such as firewood and straw, which present disadvantages such as poor thermal conditions and low calorific value, for example. On the other hand, devices using these fuels have low energy efficiency, which also generates significant atmospheric pollution.

In this challenging energy context, a hybrid system consisting of solar collectors and ground source heat pumps (SAGSHP) is known as a wonderful type of renewable energy system, that has been widely utilized for providing the required heating and cooling loads of buildings and domestic hot water (DHW). Several research reports are available in open literature. An overview of the development of GSHP technology, concentrated on GSHP systems and their applications, is presented in (Nouri et al., 2019b; Ozgener and Hepbasli, 2007; Sarbu and Sebarchievici, 2014). Boukli Hacene et al., (2019) investigated the viability of installing GSHP systems for bioclimatic house heating in Tlemcen, Algeria. It was shown that the only sustainable way to be competitive with natural gas is by combining solar collectors and the GSHP. Previous research, such as (Kjellssonet et al ., 2010; Xi et al., 2011), studied a hybrid system of GSHP and solar collectors over a 20-year period using experiments and long-term simulations with various control strategies. They found that it was a good option for space heating and DHW.

Bakirci et al ., (2011) investigated experimentally the performance of the SAGSHP. The experimental results indicated that the heat pump COP and all systems' COPs values ranged from 3.0 to 3.4 and 2.7 to 3.0, respectively. (Reda et al ., 2015) evaluated the energy performance of a SAGSHP system using TRNSYS software at different Italian sites. They showed that solar energy storage in the ground saves energy consumption in sunnier cities. In another research, different configurations of the SAGSHP system, including direct and indirect expansion modes (DX, IDX), were tested to meet the different energy needs for a 100 m2 room in Iran (Nouri et al.,2019a). The simulation was carried out using TRNSYS software with 9 m2 of evacuated tube solar collectors and three boreholes. The results showed that the IDX-SAGSHP mode is the optimal design with a weak energy consumption value and a global COP of 3.96. On the other hand, (Busato et al., 2015) presented a study carried out on the basis of a heating system based on multi-source heat pumps. Diverse schemes were evaluated to determine the better choice for investing in additional sources compared to main power consumption. Adopting a multi-source farmwork shows that it is the most energy efficient option selection for systems based on the absorption and the compression heat pump.

As mentioned above, numerous solar-assisted GSHP systems have been suggested for various appliances. Our GSHP standalone, located in Batna City in the northeast of Algeria, is well elaborated, modeled, and simulated for space and DHW heating. Furthermore, three different SAGSHP system combinations are separately simulated to determine the most effective one.

2. Potentialities

The geothermal gradient map is an important device to help assess the effective value of geothermal energy (Benzaama et al ., 2018). as illustrated in Figure 1. It is possible to identify three regions of strong geothermal gradient in the northeast and northwest, with geothermal gradient values that can reach up to 4 °C / 100 m and 6 °C / 100 m, respectively.

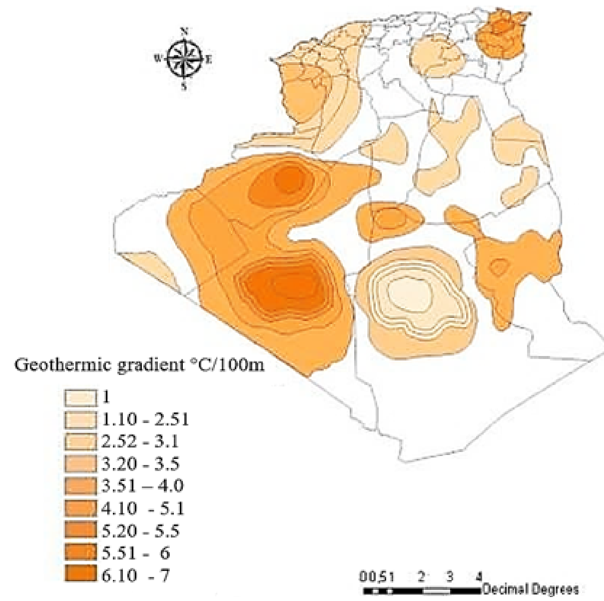

Figure 1. Geothermal gradient map in Algeria.

Due to its geographical location, Algeria has one of the world's highest rates of solar energy reserves. as shown in Figure 2, Summers are hot, dry, and mostly clear, while winters are very cold and partly cloudy, and it is dry year-round. Ambient temperatures vary between -4.21°C and 29°C in winter and between 8.20°C and 43°C in summer. The coldest month is January. The solar energy incident on the horizontal plane is presented in Figure 3. It is low in winter, rarely exceeding 3600 kj/h.m2, and peaks at 4068 kj/h.m2 in summer.

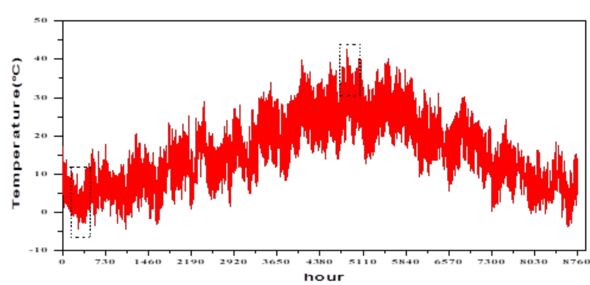

Figure 2. The ambient temperature of Batna.

A house with an area of 100 m2 and five different thermal zones provides space for a family of 4 to 6 members. It was designed to obtain the annual heating demand and peak at an indoor set temperature of 19°C. Figure 4 illustrates that the heating demand is 5759 kWh, and its peak is 4.88 kW.

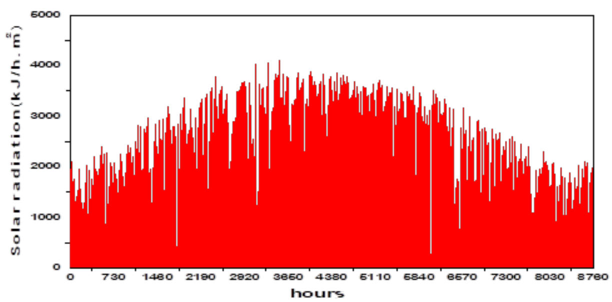

Figure 3. Total incident radiation at the Batna site.

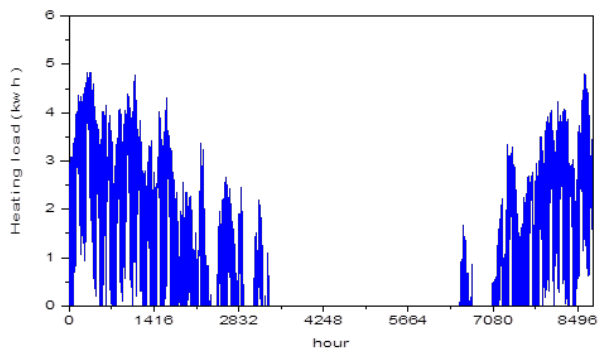

Figure 4. Hourly heating loads of the proposed building.

3. Mathematical models of the system

To simulate and model the systems studied, we used the TRNSYS software. The TRNSYS dynamic simulation software (TRNSYS16,2006) is a suitable and scalable software simulation environment for the transient simulation of energy systems .This software includes a library of interconnected model components called "TYPE." We develop a typical TRNSYS simulation project by selecting the system components and connecting their inputs and outputs. The mathematical models that are included in this paper are the types that were implanted in the TRNSYS library. The components used in the simulation are listed in Table 1, and the main parameters and inputs used are presented in Table 2.

Table 1. Parameters employed for system simulation

Parameter	TRNSYS type
Weather data	Type 109-TMY2
Water to Water Heat Pump	Type 668
Flat solar collector	Type 1b
Pumps	Type 3b, Type 656
Storage tank	Type 4a
Ground Heat Exchanger	Type 557a
Tee-Piece	Type 11h
Diverting Valve	Type 647
Ground Temperature	Type 501
Quantity Integrator	Type 24
Multi-zone building model	Type 56b
Printer	Type 25c
Online Plotter	Type 65c
Three-stage room thermostat	Type 8
Controller	Type 2b
Equations	-

Table 2. Main system input parameters used for simulation

Parameter depiction	Value
solar collector	
Type	Flat plate collectors
Total collectors' area	$6.6m^2$
Optical efficiency a0	0.807
Loss coefficient a1	$3.766W/(m^2K)$
Loss coefficient a2	$0.0059W/(m^2K^2)$
Collector inclination	36° is the latitude of the city of Batna
Water to Water Heat Pump/668 heating power:	7.7 kW in heating mode for an inlet temperature to the condenser of 35 °C and an inlet temperature to the evaporator of 0 °C
Storage tank	
Tank volume	$0.5m^3$
Fluid specific heat	4.19 kj/kg.k
Tank loss coefficient	$0.833(W/m^2.k)$
Ground heat exchanger	
Borehole depth	50 m
Number of boreholes	2
Pipe thermal conductivity is	0.45 w/m.k
Volume	$1054.34m^3$

3.1 Solar collectors

The mathematical model used for flat plate solar collectors (FPCs) efficiency ŋ, is obtained from the Hottel–Whillier–Bliss equation (Duffie and Beckman, 1980). A general equation is determined as follows:

$$\eta = \frac{Q_u}{AI_T} = \frac{m^{\cdot} cp_f\,(T_{out} - T_{in})}{AI_T} \tag{1}$$

$$= F_R.(\tau\alpha) - F_R U_L \frac{(T_{out}-T_{in})}{I_T}$$

Where Q_u is the useful energy gain, A is the collector area and I_T is the global radiation incident on the solar collector. U_L is the overall thermal loss coefficient of the collector. Since the heat loss coefficient U_L is not actually constant, so a better expression is obtained by taking into account a linear dependency:

$$\eta = F_R.(\tau\alpha) - F_R.U_L \frac{(T_{out} - T_{in})}{I_T} \tag{2}$$

$$-F_R.U_{L/T} \frac{(T_{out}-T_{in})^2}{I_T}$$

Where $U_{L/T}$ is the thermal loss coefficient dependency on temperature. The thermal efficiency is defined by three parameters: α_0, α_1 and α_2 as:

$$\eta = \alpha_0 - \alpha_1 \frac{\Delta T}{I_T} - \alpha_2 \frac{\Delta T^2}{I_T} \tag{3}$$

These parameters are available for collectors tested according to the maker. The FPCs are modeled by the “type b1” model from the TRNSYS standard library. The fraction of solar energy is expressed by:

$$f_{re} = \left[\frac{1 - P_{el-hp} + P_{pump)/year}}{(E_d + DHW)/year}\right] \tag{4}$$

Where f_{re} is the renewable energy fraction, P_{el} is the electrical power consumed by heat pump, Pump is the pumping electricity consumption per year. Ed is the energy demand for space heating and DHW per year.

3.2 Ground heat exchanger

Two ways have been implemented to assess the required borehole length (L) as GLD (GLD ,2018). ASHRAE method.

The ASHRAE equation to calculate the length of BHE can be expressed as follows:

$$L = \frac{q_h R_b + q_y R_y + q_m R_m + q_h R_h}{(T_g + T_p) - \frac{T_{in,ground} + T_{out,ground}}{2}} \tag{5}$$

Where, q_h is the peak hourly ground load, q_{mis} the highest monthly ground load, and q_y is the yearly average ground load, and the variables R_y, R_m , and R_h represent effective ground thermal resistances for 5 years, 1 month, and 6 hours thermal pulses, R_b is the effective borehole thermal resistance while, T_p is the long-term ground temperature penalty, T_g the undisturbed ground temperature and $\frac{T_{in,ground}+T_{out,ground}}{2}$ the average fluid temperature in boreholes. In heating mode, the ground loads are obtained by relation:

$$q_{g,l} = q_{b,l}.(1 - \frac{1}{COP}) \tag{6}$$

$q\_(g,l)$ and $q\_(b,l)$ are the ground and the building load respectively. The geothermal exchanger is modeled using a model from the TRNSYS library, noted by "type 557".

The GLD software is an analysis program tool that was used in this study to evaluate the length of the GHX. The length obtained from this is 100 m. Figure 5 shows the evolution of the average temperature of the water entering the GSHP unit over 20 years.

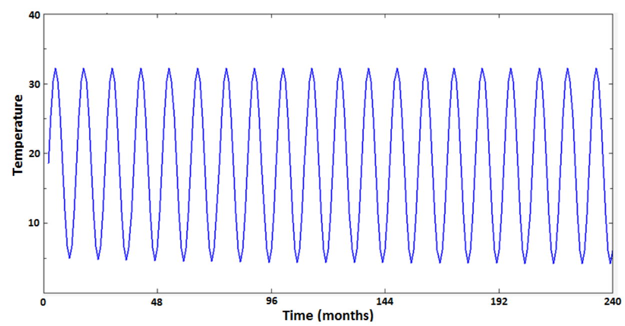

Figure 5. Average water temperature recorded in the GSHP unit by GLD for 20 years.

It’s important to know the geology and hydrogeology of the subterranean. Batna’s sol is composed, in varying amounts, of argil, slime, grit, and gravel (Bendib et al., 2017) The thermic and geological features of the soil can be summarized as follows:

Thermal conductivity $\lambda = 1.5 w/m.k$

Specific heat $Cp = 1340 j/kg.k$

Thermal diffusivity $\alpha = 6.219 * 10^-7 m^2/s$

Figure 6 indicates the underground temperature for the given climate at various depths beyond a year. We can show that the temperature signal of the soil decreases as the depth increases.

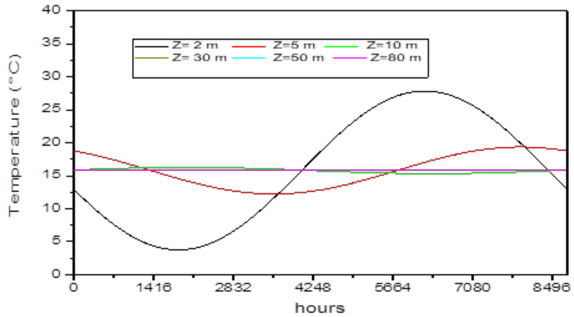

Figure 6. Soil temperature evolution vs depth (m) in Batna.

3.3 Water-to-water heat pump

The "type 668" is a simplified water–to–water heat pump model, based on user-supplied data files containing catalog data for providing capacity and power draw of the heat pump as functions of entering load and source temperatures. The COP and output conditions of the heat pump are calculated by the following equations:

$$COP = \frac{Q_{heating}}{P_{hp}} \tag{7}$$

$$Q_{absorbed} = Q_{heating} - P_{hp} \tag{8}$$

$$T_{load,out} = T_{load,in} - \frac{Q_{heating}}{m_{load}^{\cdot} Cp_{load}} \tag{9}$$

$$T_{source,out} = T_{source,in} - \frac{Q_{absorbed}}{m_{source}^{\cdot} Cp_{source}} \tag{10}$$

Here, COP indicates the coefficient of performance of the heat pump. T, Q, and m represent the temperature, heat, and flow rates. The indices accompanying these parameters refer to the sides of the different elements of the unit.

3.4 Building modelling

TRNSYS software integrates a module for thermal calculation in the modeling of the thermal computation of the different-zone of the house. The module (Type 56) reads external files containing the building description generated by running the preprocessor program TRNBuild coupled with TRNSYS. This building model can furnish an assessment of the space-heating charge to determine the suitable size and to evaluate the functionality of hybrid and GSHP systems within particular climate conditions. To measure the heating charge demand of this house, the internal gains due to people, lighting, and appliances and the external charges have been considered. The case study is a typical single-family house with 100 m2 and a height of 3 m. It is assumed to be located in Batna city. The thermo-physical properties of the building construction materials used in the modeling were determined according to the local regulations (DTR C3.2, Fascicule 1, 2004; DTR C3.4, Fascicule 2, 2004) are listed in Table 3.

Table 3. Properties of building components

Building component	Structure Component	δ[m]	λ [W/m. K]	ρ [kg/ m3]	U [W/m2K]
Floor	1 ceramic product (tiles and slab)	0.02	1.0	1900	1.06
	2 cement mortar	0.02	1.4	2200	
	3 polyurethane	0.05	0.038	27	
	4 reinforced concrete	0.10	1.75	2350	
	5 hard stones	0.16	2.4	2400	
Exterior wall	1 cement mortar	0.02	1.4	2200	0.44
	2 hollow brick	0.1	0.48	900	
	3 polystyrene foam	0.05	0.031	40	
	4 hollow brick	0.1	0.48	900	
	5 plasters	0.02	0.35	850	
Roof	1 cement mortar	0.02	1.4	2200	0.608
	2 Polyurethane full	0.16	0.23	830	
	3 plasters	0.02	0.35	850	
Window	Double glazing				2.95

4. Description of the System Configuration and Operation Strategy

4.1 System 1

The return case is the autonomous GSHP system wanting solar collector integration, composed of three important elements:

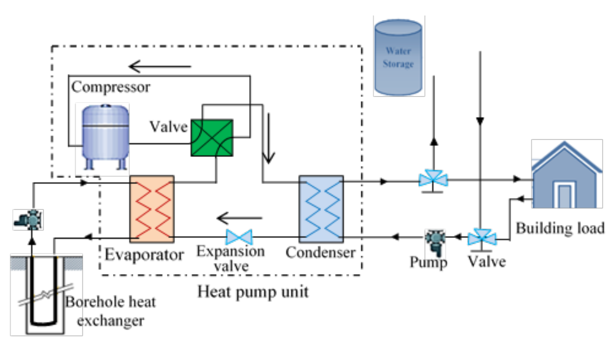

Figure 7. Schematic representation of system 1.

heat pump, vertical borehole heat exchanger (BHE), and distribution system. In heating mode, fluid circulates through an underground loop to collect low-quality ground heat and transfer it to the facility's evaporator system. The compressor increases the temperature and pressure of the refrigerant. The high-temperature heat is then transmitted to the heat transfer fluid and sent to the building via the diffusion system. Thus, the GSHP system provides all the thermal needs necessary for the building and domestic hot water. Figure 7 shows a schematic representation of this system.

4.2 System 2

This is recognized as a parallel construct and is defined in the same way as system 1, with the integration of the solar collector's part.

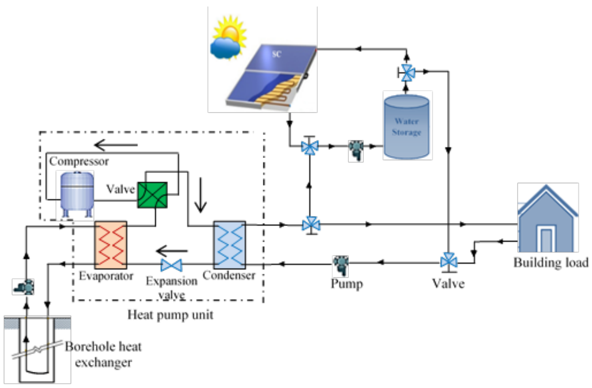

Figure 8. Schematic representation of system 2.

In this device, the useful power delivered by the solar captor is used to heat DHW. When solar energy is absent or unable to heat the DHW, which causes drops below the desired temperature. To address this issue, we use the heat pump to cover the space heating by using it as ancillary heating for the DHW. A schematic of this setting is presented in Figure 8.

4.3 System 3

The main heat source in this system is the heat pump. the highest heat source is chosen from ground heat and stored solar heat.

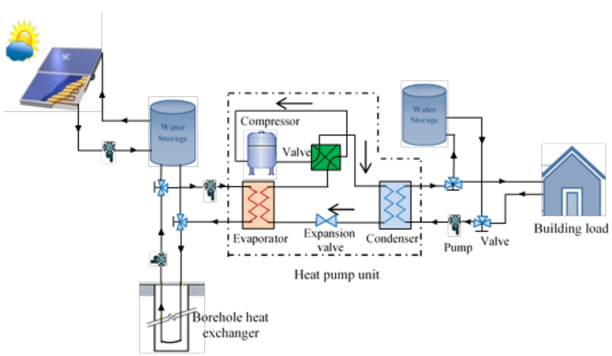

Figure 9. Schematic representation of system 3.

Once the collector outlet temperature is equal to or above 16 °C, collection starts and the process continues to transfer energy to the storage tank. When the tank outlet temperature is lower than that of the geothermal heat source, the pump uses BHE. Figure 9 shows the diagram of this adjustment, and Figure. 10 describes the system control strategy.

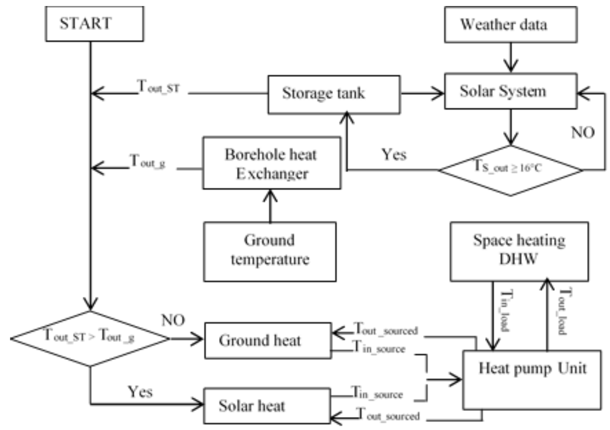

Figure 10. Schematic representation of control strategy of system 3.

4.4 System 4

System 4, which is known as a serial concept, is linked to the low-temperature side of a heat pump to increase the temperature of the entering flow to the heat pump. This is achieved by adding solar heat to the fluid leaving the borehole heat exchanger, thus increasing the efficiency of the geothermal heat pump. Figure 11 shows the diagram of this system.

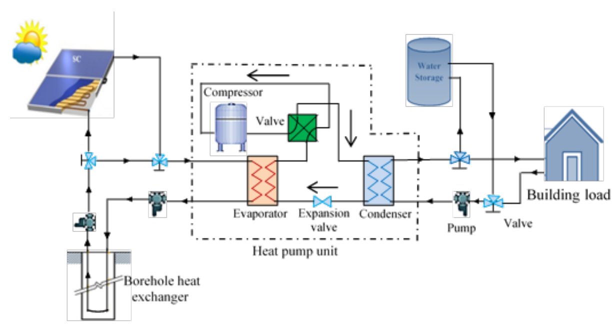

Figure 11. Schematic representation of system 4.

5. Simulation results and discussion

The findings obtained for all of the systems simulated an indoor temperature fluctuating between (19.8 °C to 25 °C) during the winter, which properly satisfies the space heating demand with a minimum room temperature of up to 19 °C. since the graph of house temperature for systems is quite close in shapes with a 0.195% difference between them. In Figure 10 we presented the temperature distribution of the house for a stand-alone GSHP (system

1) during a year of simulation. As shown in Figure. 12, the house temperature rises above 25 °C during the summer. The reason is that cooling was not done in this study.

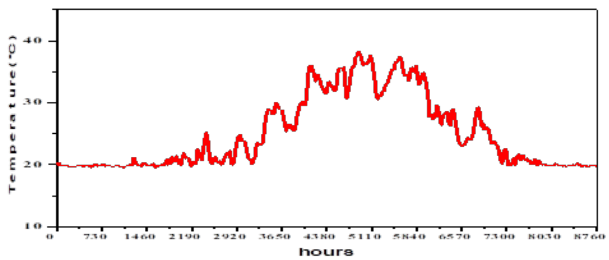

Figure 12. House temperature-system 1.

The DHW temperature during a year of simulation is presented in Figure.13. It is clear that in all cases, the water temperature is extremely beneficial in the summer. During winter, there are weak temperatures in the DHW reservoir assigned to System 1, where the GSHP simultaneously has to heat the building and the tank. In system 2, the hot water temperature is always at the desired level. However, because of the intermittent and unforeseeable nature of solar radiation, there is some fluctuation compared to other systems. For system 3, the values of the desired temperatures remain within the required range, even in the worst conditions. In this system, energy is generated quite regularly due to the use of a stable heat source and the minimum inlet source temperature to the heat pump is kept above 0 °C (see Figure 14). This means that the heat pump can work in the best conditions. In system 4, preheating the temperature inlet to the evaporator with the solar collector increases the temperature slightly, but it does not stop the tank temperature from falling anywhere under 40 °C.

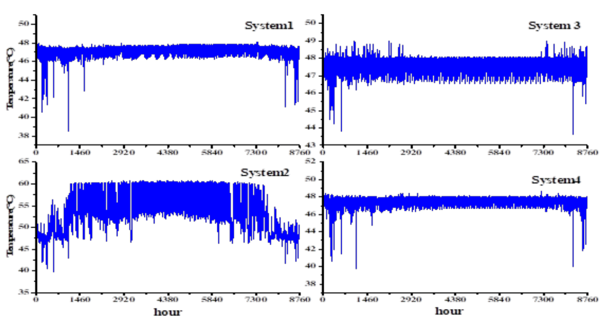

Figure 13. Average temperature of the DHW tank.

Figure. 15 shows the average annual coefficient performance of the system (COP s). Systems 3 and 4 give the best COPs value, whereas System 3 has the best performance with average annual COPs of 3.84. This can be explained by the heat pump system, which uses not only efficiently stored solar heat equal to or above 16 °C but also a relatively higher ground temperature For system 4,

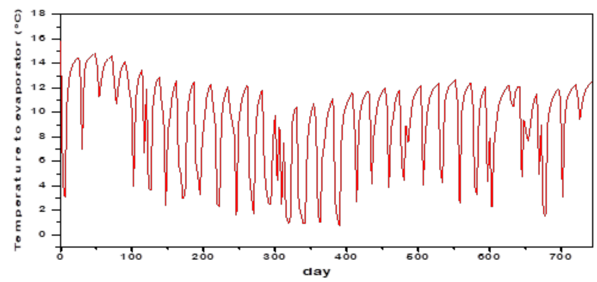

Figure 14. Temperature to evaporator of heat pump system 3.

preheating the source water temperature by adding solar heat to the borehole heat exchanger fluid improves the COPs. In the first system, the GSHP operates during the summer with higher ground temperatures near the BHE, generating some high COPs records that increase the annual COPs average value for the year. Unlike System 2, the solar heat is used for the DHW preparation. Therefore, the GSHP is almost always off during the summer and operates only in winter with a high heat extraction rate, which decreases the ground temperature and, thus, decreases COP records.

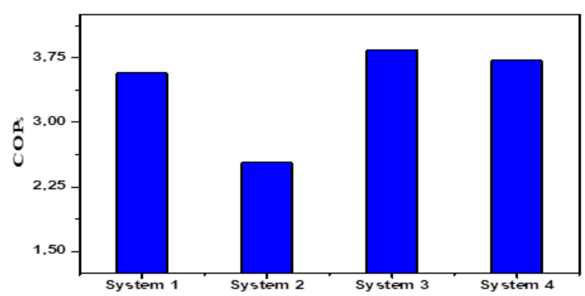

Figure 15. COPs of system simulated

The COP is defined as the ratio between the thermal power supplied by the heat pump and the electrical consumption of its compressor. Figure. 16 shows that System 3 provides the best operating conditions for the heat pump as well as the highest COP compared to the other systems.

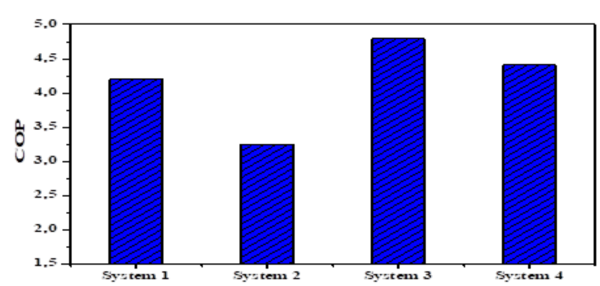

Figure 16. COP of heat pump for System simulated

The total power consumption of all systems during a year of operation is illustrated in Figure. 17. System 3 has the lowest energy consumption. This was produced by a lower heat pump energy charge because the source temperature is stable in this system, and since it uses low energy from the collectors even during low sunshine hours stored in the storage tank. In system 2, the most energy-intensive unit is the heat pump, which is turned off during the summer. For this reason, while this combination has a lower average global COP, thus, power dissipation is lower than in other cases. It is clearly evident that these combinations have lower energy consumption than stand-alone systems. Figure. 18 shows the monthly electricity savings in System 3 compared to System 1 without solar heat. Although the energy consumption of circulating pumps is added, this has an effect on the total energy consumed, especially in a small-scale heating system. The energy consumption of System 3 decreases by 15.43% compared to a GSHP standalone system per year.

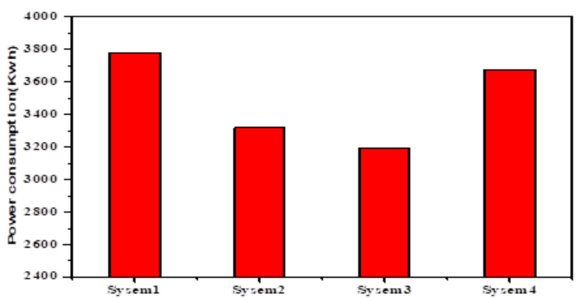

Figure 17. Comparison between power consumption of system simulated

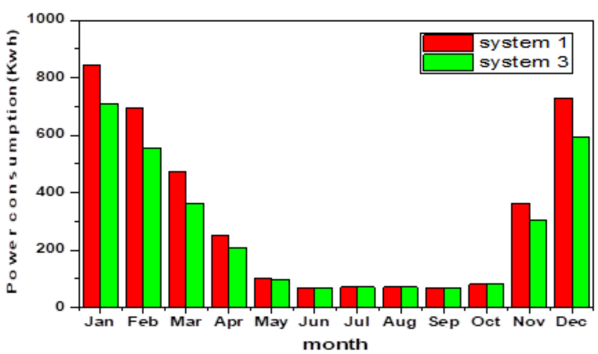

Figure 18. Monthly power consumption

We compared the space heating results with the experimental results of (Ozyurt and Ekinci, 2011) and this shows the remarkable validity of this model. Figure 19 shows the evolution of experimental and numerical simulation efficiency coefficients for System 1. The results obtained were compared with those of similar literature for heating water and space on an annual basis. The comparison is summarized in Table 4. For the comparison with the annual data of (Kjellsson et al.,2010), Our

Table 4. Comparison of results with related literature

study	This study (system 3)	Kjellsson (system 2)
Average soil temperature [° C]	15.8	7
Depth of GHE [m]	100	120
Building type[m2]	100	120
Heat pump nominal heating capacity [kW]	7.7	7
Energy consumption [kWh]	∼3195	∼8000
Solar collector area [m2]	6.6	10
Mean COP	3.84	3.50

COPs (3.84) was greater than the COPs (3.50) of the compared system. This effect can be attributed to the fact that the evaporator temperature is high enough, which reduces the temperature gap between the evaporator and condenser. The energy consumption of this study was significantly lower than the Kjellsson simulation (System 2, using all solar energy to recharge the borehole), which can be explained by deeper boreholes > 100 m. There is no advantage to charging the borehole when the depth is sufficient for the natural recharge. Furthermore, the demand for electricity for circulating pumps is increasing due to their increased running time. However, the previous comparison needs to be assessed qualitatively because certain operating conditions were different, though similar to those of other studies.

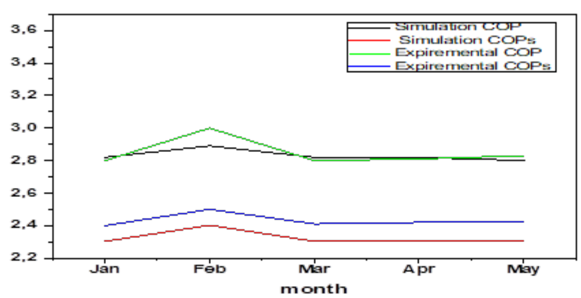

Figure 19. Experimental vs numerical of performance coefficient of heat pump (COP) and overall system (COPs) of system 1

We conducted an economic analysis of the Air Heat Pump System (ASHPS), Natural Gas Space Heating System (NGSH), GSHP and SAGHP to determine the viable choice between these systems. Initial costs are the sum of the costs of the GSHP system, including installation of the ground loop, heat pump, piping, pump and control systems. BHE's installation cost is the largest contributor to GSHP's cost premium (30% of total cost.) They include labor and materials for drilling, grout, horizontal trench and head pipes. For each system, the initial and operating costs were determined by the market and electricity prices of the Algerian company. In this study, the cost of BHE is assumed to be $29/m. As shown in Figure 20, device prices (SAGSHP and GHSP) were significantly

Table 5. Economic comparison among different systems

system	Total Costs ($)	Energy consumption (KWh)	CO2 emissions (kg)
NGSH	1737	11273	6177.6
ASHP	5868.62	4820.1	2400.9
GSHP	11239	3567.4	1776.5
SAGSHP	12285.2	2902.8	1445.61

higher compared to the other two installations. This is principally due to the investment costs of the heat pump with a ground connection. In contrast, we compare carbon dioxide (CO2) emissions for heating systems. Giving us the importance of CO2 emissions through its impact on climate change as greenhouse gases. Table 5 shows the total costs, energy consumption and CO2 emissions from the use of heating systems. It is clear that the SAGSHP offers the greatest emission reductions compared to the other three systems in terms of low energy consumption, making it one of the most environmentally beneficial applications.

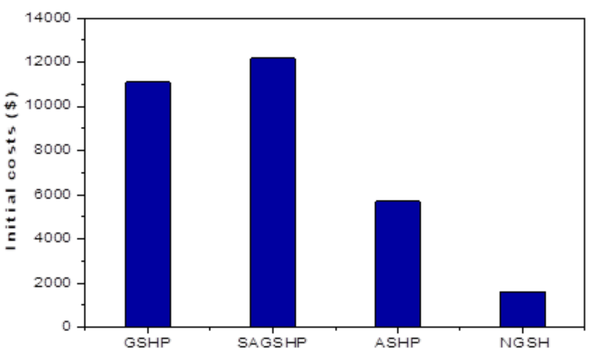

Figure 20. Initial cost presentation of the different systems

As a major system, the typical lifespan of an ASHP was estimated to be 10 to 12 years. However, GSHP does not exhibit the corrosion problems typically seen with ASHP. In fact, the installation group is situated inside, the loop pipes are entombed, and thus the installation is not exposed to the ambient air. Thus, GSHPs are generally protected from ambient air. Thus, GSHPs generally have a longer lifespan (20 years and more), or double the lifespan of an ASHP. Additionally, the solar system is changed every 20 years. To evaluate the investment feasibility of a new system, we calculate the simple payback period as follows (Biglarian et al., 2019):

$$\sum_{i=0}^{PBP} [C_i^e - C_i^a] \tag{11}$$

C0 is the initial cost, and Ci , i > 0 is the annual exploitation cost, and the superscript letters e and a denote the currently existing and alternative systems.

Table 6. payback period of the systems

system	SAGSHP vs GSHP	SAGSHP vs ASHP	GSHP vs ASHP
PBP (year)	7.3	11	11.1

6. Conclusion

A number of schemes of a SAGSHP to meet the energy needs, climatic conditions of the city of Batna, of a building with low energy consumption were examined in this work. The site was selected for the purpose of providing access to renewable energies. The essential results are summarized as follows:

- A combined system is more efficient than an autonomous system. The cooperation effect is obviously visible in the case of System 3, which has a storage tank with the highest annual average COPs value of 3.84 and the lowest energy consumption with a 15.43
- The obtained results showed that SAGSHP systems can provide a good solution for heating and domestic hot water with good performance compared to GSHP systems, which could not provide heat supply for domestic hot water and space heating on some days in winter

The prospects of this investigation are large and touchy, especially the optimization design methods considering the device capacities and investment costs.

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