Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1024934

57 (2016) 5317–5324
March

Taylor & Francis
Taylor & Francis Group

Optimization of integrated building solutions: efficiency of a heating and cooling ground source heat pump

M.A. Boukli Hacene[a,b,*], N.E. Chabane Sari[a], A. Benzair[b], A. Iznassni[c]

[a] *Materials and Renewable Energy Research Unit (U.R.M.E.R), University of Tlemcen, Tlemcen, Algeria, Tel./Fax: +213 4321589089; emails: aamineboukli@yahoo.fr (M.A. Boukli Hacene), nchabanesari@ymail.fr (N.E. Chabane Sari)*
[b] *Physics Department, University of Sidi Bel Abbes, Tlemcen, Algeria, Tel. +213 0770481587; email: abenzair@yahoo.fr (A. Benzair)*
[c] *EPSES CSG, Tlemcen, Algeria, Tel. +213 0555767476; email: aiznasniali@hotmail.fr*

Received 7 January 2014; Accepted 20 February 2015

ABSTRACT

In order to deal effectively with energy supplies and climate change, it is imperative to move towards more sustainable solutions. For the housing sector which represents 45% of a country's overall energy expenditure and one quarter of carbon dioxide production, it is essential that a building is no longer a mere consumer of energy, but it should become an energy producer. There is a need to optimize integrated solutions to the building envelope. With soil as the sole source for deriving heat, the efficiency of a heating and cooling pump was assessed. The research also focused on analysis of socioeconomic aspects, related to the integration of renewable energy in the habitat, that included action on the issue of technology transfer from laboratories to industry and secondly, the extent of the social acceptability of these new forms of energy and direction, by the adoption of appropriate economic policy measures. The feasibility study in this work showed that heating and cooling through a system of ground source heat pumps (GSHPs) is possible based on economics and optimizing energy efficiency used in the town of Tlemcen in Algeria as a case study. The optimal depth to place a heat pump for air conditioning and heating was similar, so that the same depth could be considered for both applications. Note that this is the first study of GSHP in Algeria.

Keywords: Energy; Thermal; Heat; Economic

---

1. Introduction

Ground temperature constitutes essential input data for various construction projects such as the design of airport runways and roads, determining the depth at which drains can be installed in buildings without the risk of freezing, the excavation of building foundations, and the design and construction of basements [1]. As the conservation and storage of energy becomes increasingly necessary, the ground temperature is an important aspect in calculation and evaluation of energy needs when determining heat loss in basements and examining the possibility of using ground heat as a source for heat pumps. It is therefore incumbent on engineers and architects to understand

---

*Corresponding author.

Presented at the International Conference on Water and Energy (ICW'13) Chlef University, Algeria, 16–17 December 2013

the factors that determine soil temperatures and how they vary with season and depth. Soil temperature varies throughout the year and is constant at some depths regardless of ground type [1].

The aim of the current study was to assess the efficiency of a heating and cooling of a ground-source heat pump (GSHP), with the sole source of heat derived from the soil. An economic analysis was also performed.

2. Principles, technology, and economics of a GSHP system

A GSHP draws heat from the soil via sensors that are buried in pipes. A typical heat pump requires only 100–200 kWh electricity to transform environmental heat, and provides 300 kWh of freely available useful heat. In all cases, the useful heat generated will be greater than the primary energy used to operate the pump itself. Heat pumps also have a relatively low level of CO_2 emissions [2]. The three important elements of a GSHP include: the ground loop, a heat pump, and a system for heat distribution. The sensors (of the GSHP System) can be installed horizontally or vertically. In the latter case, they are also known as geometric probes.

Horizontal sensors (usually polythene) are buried horizontally at shallow depth (0.6–1.2 m) in which circulates a coolant. The sensors are installed on the land adjacent to the building (Fig. 1). With vertical sensors, a vertical probe draws energy from the basement of the ground (Fig. 2). A sensor is placed inside a hole in the pump tube (U-tube, double U, or polyethylene) containing a heat transfer fluid bearing. The hole is then sealed with cement and bentonite. The depth of drilling is up to 200 m. At 10 m depth, soil temperature is effectively constant throughout the year and is close to 13˚C. The temperature rises from 2 to 3˚C per 100 m of increasing depth.

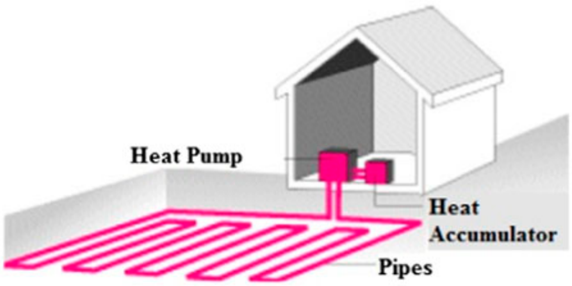

Fig. 1. Representation of horizontal sensors [1].

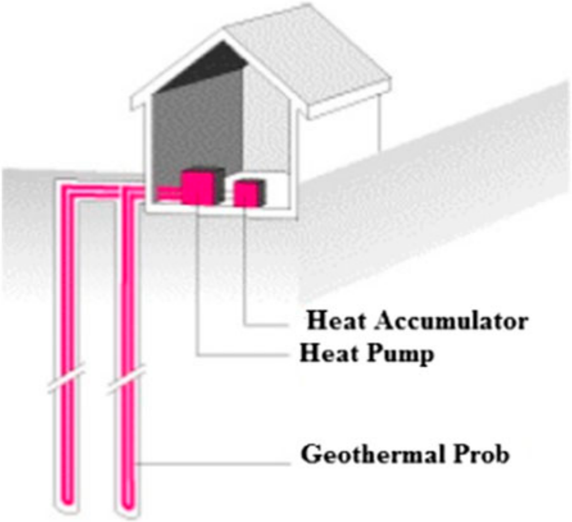

Fig. 2. Vertical sensors representation [1].

The running costs depend on a number of factors which include the size of the hot/cold water loads and the size of the home [3]. Using average system efficiencies from a GSHP field trial, when replacing conventional existing heating system in a three bed semi-detached home, it was shown that the cost of a GSHP system varies from €10,000 to €18,000.

The investment required to integrate the GSHP system in a building can be recovered within a few years by compensation investment through energy savings from reduced energy consumption. Nevertheless, the paramount benefit lies in the exploitation of renewable energies, respect for the environment, and following the example of other traditional energy systems.

3. Using the GSHP system for energy needs in a house

A house is said to be ecologically sound when two criteria are met. First, there must be at least an 80% reduction in energy consumption compared to a classical house. Second, the use of ecologically acceptable and durable materials must be employed [4]. The principal requirements of an ecological dwelling are orientation and understanding of how to make use of the sun, the assessment carbon: to track the hidden emissions, thermal isolation, walls made of healthy and natural materials, ventilation that uses new air in sufficient quantity, windows to banish simple glazing, and making use of renewable energies for heating and cooling [1].

The theoretical operation of GSHP system in a house located at Tlemcen, in a district called “Birouana” was

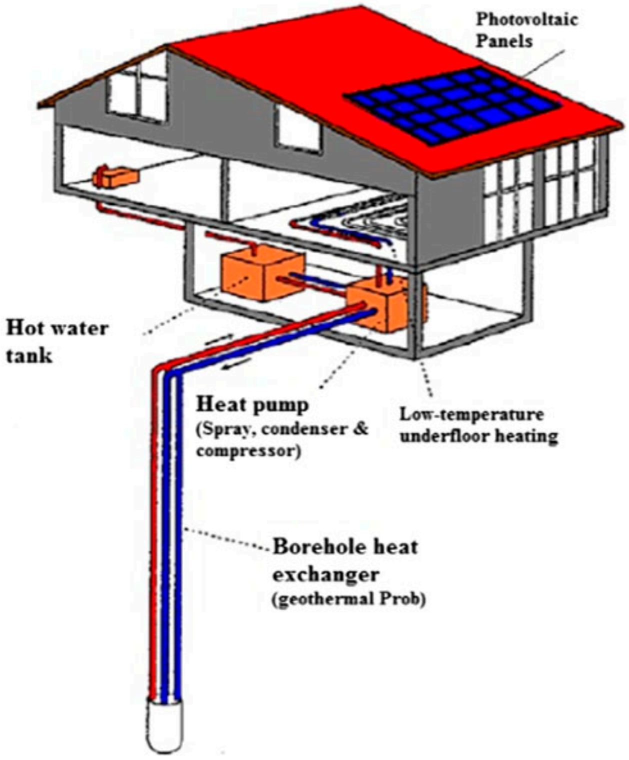

Fig. 3. Heating by GSHP system [5].

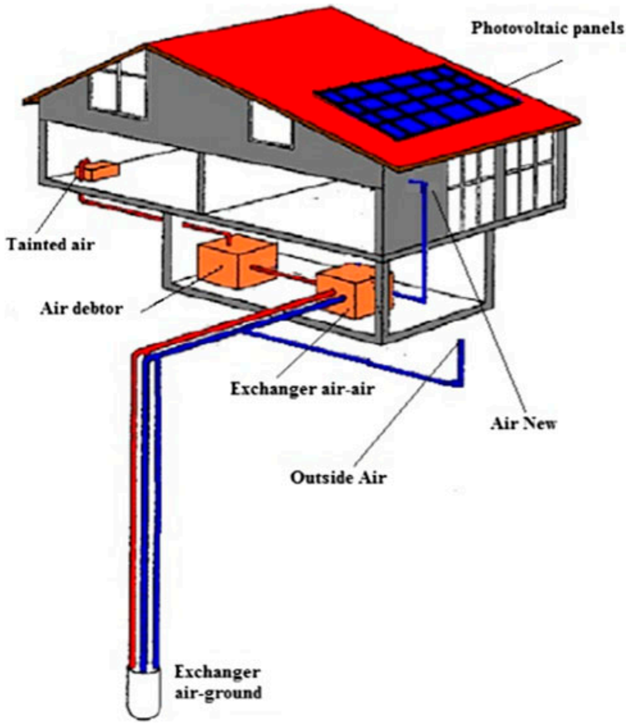

Fig. 4. Cooling by GSHP system [5].

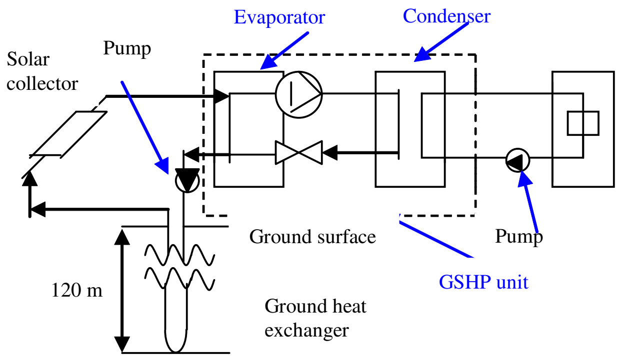

Fig. 5. Schematic of GSHP system coupled with solar collectors (winter cycle) [1].

assessed. This requires an understanding of the compatibility of the installation as well as the variation in ground temperature. Figs. 3 and 4 show the integration of a GSHP system in an ecological house. Figs. 5–7 show a schematic of the GSHP coupled with the solar panels, for winter and summer cycles.

4. The ground temperature

The ambient air temperature fluctuation around average T_a, daily or annually, could be considered as a sinusoidal function with an angular frequency ω during the period t_0. Mathematically, this fluctuation is described by:

$$T(t) = T_a + A_a \cdot \cos\left(2\pi \cdot \frac{t}{t_0}\right) \tag{1}$$

The ground temperature at depth z (m), with thermal conductivity λ (W/m, K), and volumetric heat capacity

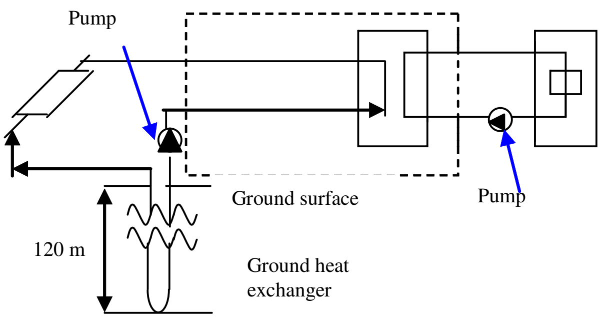

Fig. 6. Schematic of GSHP system coupled with solar collectors (summer cycle) [1].

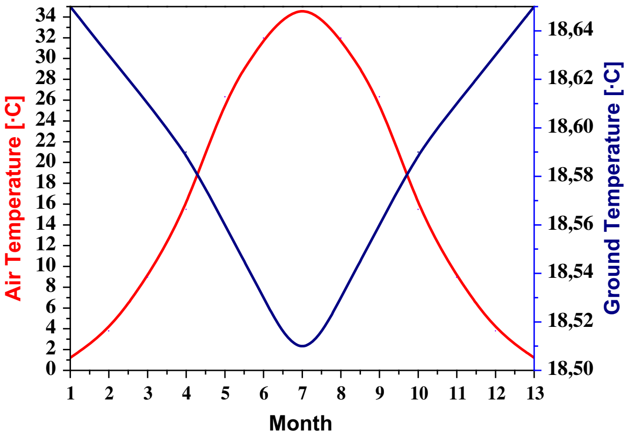

Fig. 7. Temperature fluctuations in air and ground, for $D_f = 0.6939.10^{-6}$ m/s, entire year $Z_{op} = 7.305$ m [1].

C (J/m^3, K), also oscillates in a sinusoidal pattern according to Eq. (2) [6–8]:

$$T(t,z) = T_a + A_a \cdot e^{-\frac{z}{d_0}} \cdot \cos\left(2\pi \cdot \frac{t}{t_0} - \frac{z}{d_0}\right) \tag{2}$$

The amplitude of temperature change at the ground surface generally corresponds to that of air. Eq. (2) indicates that the amplitude decreases exponentially with distance from the surface at a rate prescribed by the time required to complete a cycle. Soil temperatures are generally constant over the year for depths greater than 5–6 m. The mean annual ground temperature is almost constant with depth, but it increases by about 1˚C/50 m due to geothermal heat from the center of the earth [6].

An inspection of the expression of soil temperature (Eq. 2), reveals two effects of depth on ground temperature: a damping of the amplitude of variation and a phase shift of the peak temperatures. For example, the amplitude is damped to a tenth of its value to a depth equal to 2.3 times that of penetration, d, and the heat wave in the ground. This leads to a constant temperature (i.e. a variation of less than 0.1˚C throughout the year) for depths greater than 4.6 d. The phase shift is beneficial because it increases the temperature difference between ambient air and soil. The maximum phase shift, that is to say a phase shift equal to half of the year, occurs at a depth of 3.14 d. However, at this depth the amplitude of the temperature variation is damped to 4% of its value at the surface. This means that we cannot fully benefit from an energy standpoint.

Depth of penetration of the heat wave in the ground is represented as d_0. It is given by:

$$d_0 = \sqrt{\frac{\lambda \cdot t_0}{C \cdot \pi}}$$

or

$$d_0 = \sqrt{\frac{D_f \cdot t_0}{\pi}} \tag{3}$$

Knowing the thermal diffusivity of the soil, D_f, is sufficient to assess soil temperature as a function of time and depth. Thermal diffusivity, D_f, depends on the nature of the soil. Different compositions of the outer layer of the basement of Maghreb have been examined [5,9] (Table 1).

Generally, the magnitude of the soil temperature A_g decreases with depth:

$$A_g = A_a \cdot e^{-\frac{z}{d_0}} \tag{4}$$

The amplitude of the air temperature (A_a) relative to the soil temperature is half of the difference between the daytime maximum value and the night time minimum value.

The shifting time φ between outside temperature and soil temperature at depth z is given by:

$$\varphi = t_2 - t_1 = \frac{z}{2} \cdot \sqrt{\frac{C \cdot t_0}{\lambda \cdot \pi}} \tag{5}$$

The depth z_{op} can be determined from the thermal properties of soil. The optimal depth z_{op} is the depth at which the temporal shift is equal to $t_0/2$, i.e. where the maximum outside temperature is associated with the minimum temperature at z_{op}, we deduce from Eq. (5) that

Table 1
The different layers of ground Maghreb [9]

Composition	D_f (m/s)
Lime stone	0.6939×10^{-6}
Dry gravel	0.2666×10^{-6}
Saturated gravel	0.75×10^{-6}
Dry sand	0.2758×10^{-6}
Saturated sand	0.9230×10^{-6}
Dry clay/silt	0.3226×10^{-6}
Saturated clay silt	0.7083×10^{-6}

$$\varphi = \frac{t_0}{2} = \frac{z_{\mathrm{op}}}{2} \cdot \sqrt{\frac{C \cdot t_0}{\lambda \cdot \pi}} \Rightarrow z_{\mathrm{op}} = \pi \cdot \sqrt{\frac{\lambda \cdot t_0}{C \cdot \pi}} = \pi \cdot d_0 \qquad (6)$$

The amplitude of ground temperature, at depth z_{op} is shown in Fig. 7.

$$A_{\mathrm{g}} = A_{\mathrm{a}} \cdot e^{-\pi} \Rightarrow \frac{A_{\mathrm{g}}}{A_{\mathrm{a}}} = 4.321 \qquad (7)$$

It follows from Eq. (7) that the temperature amplitude at optimal depth z_{op} is not a function of ground's thermal properties, but depends on the temperature amplitude at ground surface. Fig. 7 shows the difference between air temperature (i.e. ground surface temperature) and ground temperature at optimal depth for annual cyclic change of ambient air temperature.

All soils do not have the same thermal conductivity. For example, a clay soil does not conduct heat the same way as bedrock. An experiment by Stambouli-Meziane [7] showed that rocky soils have greater thermal efficiency. Soil thermal diffusivity in the case study area (i.e. Tlemcen) was 0.6939×10^{-6} m/s (Fig. 7), because the land was rich in limestone lithothamniées fossil shells of coquina type of post-Miocene aquifers. These are based on calcareous clays interbedded sandstone of Tortonian age [7]. Fig. 8 shows the subterranean temperature, which is a function of depth at different times of the year. The ground composition of this site is shown in Fig. 9.

Below a critical depth, which is a function of thermal properties of the earth, seasonal temperature changes at the soil surface become equivalent to the temperature of the air. At this critical depth, the soil temperature is warmer than the air temperature during the winter and cooler than the air temperature during the summer. The heat absorbed by the earth in summer is stored in the soil and then available for use in winter [8]. The extracted thermal energy is a renewable resource due to seasonal variation in temperature. The effect of global warming on soil temperature was neglected in the current analysis.

5. Limitations of GSHP

The disadvantages in general are that the first cost can be significantly higher than conventional systems; not all system types are feasible in all locations, and there is a limited pool of qualified designers and installers in many locations; In addition, there is a lack of awareness and a lack of uniform standards; thus design and installation accreditation has yet to receive nationally standardized accreditation.

An overview of some of the disadvantages of the various systems are provided here:

The disadvantages of the *horizontal ground-coupled heat pump system* are:

(1) Requires more space; horizontal systems generally require 1,500–3,000 ft^2 of land area per ton of heating or cooling.

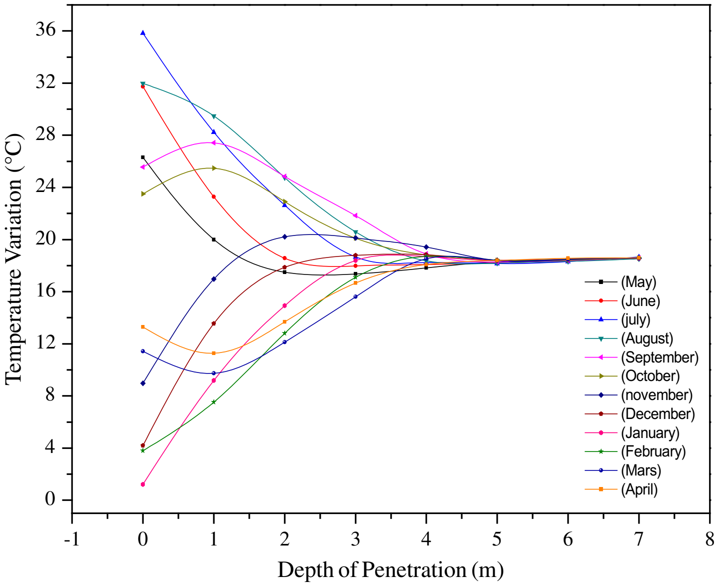

Fig. 8. Temperature profile through the ground in Tlemcen (limestone ground) [10].

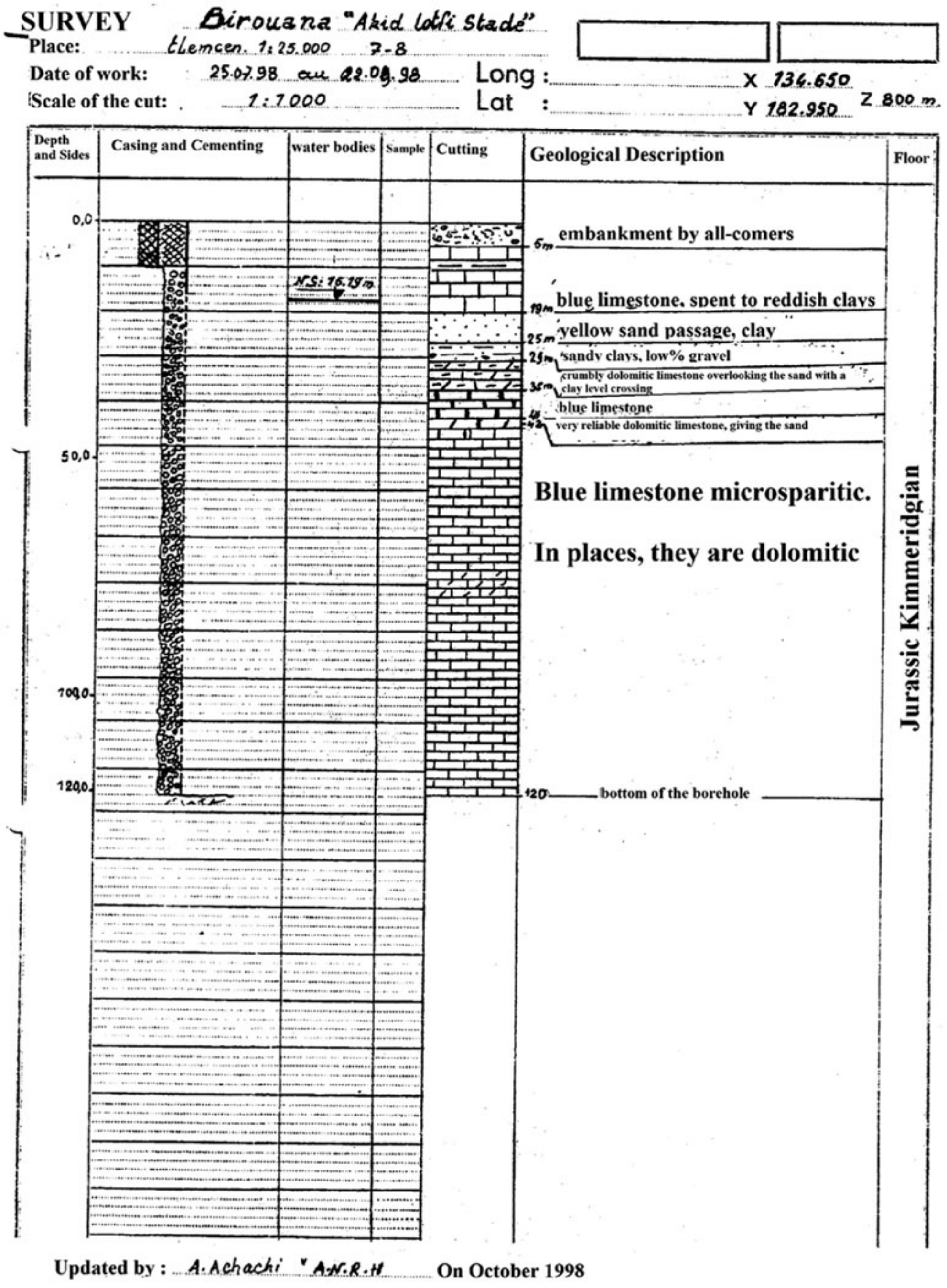

Fig. 9. Ground composition at Birouana (Tlemcen) [11].

(2) Requires more piping hence use of the "slinky" formation typical slinky configurations require 150 ft of three-foot-wide area per ton. A slinky configuration can require one acre per 90 tons of peak block load, and the entire area must be excavated or filled to a depth of 6–8 ft.
(3) Ground temperature and thermal properties fluctuate with season, rainfall, and burial depth.
(4) Lower efficiency than vertical GSHP.
(5) Problems in some geological formations.

The disadvantages of the *vertical ground-coupled heat pump system* are:

(1) Higher initial cost due to the drilling of boreholes.
(2) Problems in some geological formations.
(3) Limited availability of experienced drillers and installers [12].

5.1. Economic aspects of the GSHP

GSHPs are characterized by high capital costs and low operational costs compared to other heating, ventilation and air-conditioning systems. Their overall economic benefit depends primarily on the relative costs of electricity and fuels, which are highly variable over time and across the world. Based on recent prices, GSHPs currently have lower operational costs than any other conventional heating source almost everywhere in the world. Natural gas is the only fuel with competitive operational costs, and only in a handful of countries where it is exceptionally cheap, or where electricity is exceptionally expensive [13]. In general, a homeowner may save anywhere from 20 to 60% annually on utilities by switching from an ordinary system to a ground source system [14,15].

Capital costs and system lifespan have received much less study until recently, and the return on investment is highly variable. The most recent data from an analysis of 2011–2012 incentive payments in the state of Maryland showed an average cost of residential systems of $1.90/W, or about $26,700 for a typical (4 ton) home system [16]. An older study found the total installed cost for a system with 10 kW (3 ton) thermal capacity for a detached rural residence in the US averaged $8,000–$9,000 in 1995 US dollars [17]. More recent studies found an average cost of $14,000 in 2008 US dollars for the same size system.

6. Future trends questions and perspectives

The European experience with GSHP systems so far is excellent. It is expected that the market will further expand, in the leading countries like Sweden and Switzerland as well as in other countries to follow. The growth can be exponential as the Swiss example.

An important factor, related to the further development of electric heat pump systems in general and the GSHPs in particular, is the current process of deregulation in Europe. The energy sector, especially the electric utility companies, is currently under deregulation and privatization [18].

This affects not only the producers but also the customers. The deregulation process may affect the heat pump market in two ways: (1) heat pump economy might be influenced by changes in the energy price structure, and (2) the heat pump market might be stimulated or hindered, depending on changing utility market strategies [19].

There is a growing interest for underground thermal energy storage systems with GSHP for energy efficient heating and cooling of buildings, and these applications will be important in reaching their national energy targets. Norwegian heat pumps have at present a total annual heat supply of about 7 TWh/a. The estimated heat pump potential by 2020 is 10–14 TWh [20].

The GSHP could be used in new systems, not only for the development of eco-house, but also GSHP could be used to improve the energy rating of buildings, and could be taken into account in developing new systems as SEDICAE. The perspectives are to use and develop the SEDICAE project, which applies a new methodology based on a tabu search and a simplified method to calculate the demand. A tabu search is a good method to avoid local minima and to permit an evaluation of different solutions. The methodology is designed to estimate the annual energy demand, life cycle cost, the energy rating, and the time requirements in building design [21].

7. Concluding remarks

The feasibility study in this work showed that heating and cooling through a system of GSHPs is possible based on economics and optimizing energy efficiency using the town of Tlemcen in Algeria as a case study. The optimal depth to place a heat pump for air conditioning and heating is similar, so that the same depth could be considered for both applications. There is a depth that maximizes the number of days during which a large thermal potential is available. However, the technical and economic optimization of the depth can be done only after choosing the type of technology and site location, because the depth of the plant influences the cost in two ways. First, the cost of opening a well increases with depth. But at the same time, the thermal potential increases, which reduces the size and cost of the system. The number of days that potential heat is maintained profitably also dictates the viability of the system. A techno-economic study of the optimal pump depth, comprising various case studies, could form an extension of this work.

List of symbols

A_a — air temperature amplitude (℃)
A_g — ground temperature amplitude (℃)
C — volumetric heat capacity (J/m^3 K)

d_0 — penetration depth (m)
T — time over a year (s)
T_a — average ambient air temperature (°C)
t_0 — temperature variation period (s), in this case to = 24 × 3,600 s for daily variation, or to = 8,760 × 24 for annual variation
$T(t,z)$ — ground temperature at depth h m below ground surface (°C)
z — depth (m)
z_{op} — optimal depth (m)
λ — thermal conductivity (W/m K)
φ — shifting time (s)

References

[1] M.A. Boukli Hacene, N.E. Chabane Sari, Using an ecological system for heating and cooling an ecological house, Int. J. Ambient Energy (2013), doi: 10.1080/01430750.2013.845601.

[2] M.L. Allan, A.J. Philippacopoulos, Ground water protection issues with geothermal heat pumps, Geotherm. Resour. Coun. Trans. 23 (1999) 101–105.

[3] X. Liu, Installing a ground source heat pumps, Solar Today 25 (2011) 14–28.

[4] C. Chitour, Dures verites sur l'avenir energetique de l'Algerie (Hard Truths to Energy Future of Algeria), Liberty J. (Daily Algerian J.), Tuesday 16 February 2010.

[5] B. Nordell, M. Soderlund, Solar Energy and Heat Storage, Luleå University of Technology, Lulea, 1998.

[6] M.A. Boukli Hacene, N.E. Chabane Sari, L'utilisation de la pompe à chaleur source sol (GSHP) pour le chauffage et le refroidissement d'une maison écologique (Heating & Cooling a Bioclimatic House by using GSHP's), J. Sci. Res. 1 (2010) 58–61.

[7] H. Stambouli-Meziane, La diversité floristique de la végétation psammophile de la région de Tlemcen (nord–ouest Algérie) (The diversity of the flora psammophile vegetation of the Tlemcen region (Northwest Algeria)), C. R. Biol. 332 (2009) 711–719.

[8] F. Al-Ajmi, D.L. Loveday, V.I. Hanby, The cooling potential of earth–air heat exchangers for domestic buildings in a desert climate, Build. Environ. 41(3) (2006) 235–244.

[9] M.S. Guellouz, G. Arfaoui, Potentiel de la géothermie de surface pour le chauffage et la climatisation en Tunisie (Potential of geothermal energy surface for heating and air conditioning in Tunisia), in: Revue des Energies Renouvelables CICME'08, Sousse, 2008, pp. 143–151.

[10] M.A. Boukli Hacene, S. Amara, N.E. Chabane Sari, Analysis of the first thermal response test in Algeria, J. Therm. Anal. Calorim. 107(3) (2012) 1363–1369.

[11] A. Achachi, Hydraulic Direction of the City of Tlemcen (Algeria), 1998.

[12] Technical News Bulletin, Geothermal or ground source heat pumps part iii: Advantages and disadvantages of geothermal heat pumps and lessons learned, National Institutes of Health, Issue 20, September 2013.

[13] J. Hanova, H. Dowlatabadi, Strategic GHG reduction through the use of ground source heat pump technology, Environ. Res. Lett. 2(4) (2007) 1–18, doi: 10.1088/1748-9326/2/4/044001.

[14] Geothermal Heat Pump Consortium, Inc. Retrieved October 19, 2007.

[15] P.J. Lienau, T.L. Boyd, R.L. Rogers, Ground-Source Heat Pump Case Studies and Utility Programs, Geo-Heat Center, Oregon Institute of Technology, Klamath Falls, OR, April 1995. Retrieved March 26, 2009.

[16] P. Cummings, Indiana Residential Geothermal Heat Pump Rebate, Program Review (PDF), Indiana Office of Energy and Defense Development, June 2008. Retrieved March 24, 2009.

[17] P. Hughes, Geothermal (Ground-Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers, Oak Ridge National Laboratory, 2008, doi: 10.2172/948543.

[18] L. Rybach, Ground-source heat pump systems the European experience, GHC Bulletin, 2000.

[19] G. Breembroek, The role of heat pumps in a deregulated energy market, Newsletter IEA Heat Pump Centre 16(3) (1998) 26–27.

[20] C. Grorud, I. Rasmussen, S. Strøm, Future Contribution from Heat Pumps in the Norwegian Energy System, Vista Analyse AS on behalf of The Norwegian Water Resources and Energy Directorate (NVE), 2007.

[21] P.A. Ruiz, J.G. Martín, J.M.S. Lissén, An integrated optimisation method for residential building design: A case study in Spain, Energy Build. 80 (2014) 158–168, September 2014, ISSN: 0378-7788, doi: 10.1016/j.enbuild.2014.05.020.