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Filippo Busato[1]*, Fabio Minchio[2], Francesco Castellotti[2]

The use of geothermal heat pump systems for climatisation in hot climates

L'uso di pompe di calore geotermiche per la climatizzazione nei climi caldi

[1] Università telematica Mercatorum, Roma, Italy
[2] 3F engineering Studio, Verona, Italy

*Corresponding author:
Filippo Busato
Dipartimento di Economia
Università telematica Mercatorum
Piazza Mattei 10
00186 Roma, Italy
filippo.busato@unimercatorum.it
tel +39 347 1207174

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Abstract

The design of geothermal systems for climatisation application in hot climates, heavily dominated by the cooling energy demand, poses problems in the sizing of the geothermal circuit, mainly due to the difficulties of limiting maximum temperatures of the geothermal fluid. Several solutions that integrate the geothermal borehole field with cooling towers or dry coolers with different control strategies are proposed in scientific and technical literature. This paper analyzes the state of the art of geothermal systems application in hot climates and assesses a comparison among different strategies applied to a commercial building through dynamic software simulation.

Keywords:

- Geothermal heat pumps
- Hybrid systems
- HyGSHP
- Control
- Software simulation

Sommario

La progettazione di sistemi geotermici per climi caldi, dominati dal fabbisogno di energia per la climatizzazione, pone alcuni problemi per quanto riguarda il dimensionamento dell'impianto geotermico, essenzialmente dovuti alla difficoltà di limitare le temperature massime del fluido geotermico per la compatibilità con i materiali di cui sono composte le sonde. La letteratura tecnica e scientifica propone diverse soluzioni che integrano il campo sonde con torri evaporative e dry cooler, con diverse strategie di controllo. Questo lavoro analizza lo stato dell'arte dell'applicazione di questi sistemi nei climi caldi ed effettua una comparazione tra differenti strategie di funzionamento applicate a edifici commerciali attraverso la simulazione dinamica.

Parole chiave:

- Pompe di calore geotermiche
- Sistemi ibridi
- HyGSHP
- Controllo
- Simulazione dinamica

NOMENCLATURE

T	*Temperature [°C]*	Subscripts			Greek		
ΔT	*Temperature difference [°C] or [K]*	*OW*	*Outlet Water from the borehole field*		η	*Efficiency of solar system*	
		WB	*Wet bulb*		η_0	*Zero loss solar collector efficiency*	
		1	*Set for the activation of cooling tower*		β	*Solar system tilt angle*	

Introduction

Heat pump geothermal systems are mainly spread in application where the heating demand is greater or equal to the cooling demand, generally speaking in the temperate and continental climates; much less those installation are diffuse in warmer climates, i.e. in regions with high summer temperatures and where the cooling load exceeds by far the heating load in buildings.

This is mainly due to the historical development of technology and to cultural aspects, but as well as to specific technical aspects. In the sizing of geothermal heat pump systems, the length of the borehole field is affected from the peak power exchanged with the ground, but especially from the net energy balance to/from the ground in the year round operations. The net energy balance will determine the medium to long term equilibrium in the field ground temperature that will be different from the undisturbed ground. This equilibrium temperature will be higher or lower than the undisturbed one if the heat rejected to the ground will be in a higher or smaller amount to the heat drawn from the ground. The maximum and minimum temperature of the borehole fluid entering the condenser in summer and the evaporator in winter will then vary along the years, making it necessary to size the system according to numerical simulation accounting for 20-25 years (or even more) of operations.

The climates that lead to cooling loads much higher than the heating ones, imply an energy rejection to the the ground that will accordingly be much higher than the heat drawing from the ground. Therefore main problem will be that of limiting the maximum borehole fluid temperature, considering that the undisturbed ground temperature (at 10-15 m depth) will be higher than in temperate climates.

The condenser inlet fluid temperature should be kept within the range allowed by the heat pump manufacturer, and guarantee an adequate energy efficiency performance. This will in most cases imply extensive borehole fields that will make the geothermal system not economically viable.

In order to optimise the investment and keep temperatures in an acceptable range, it is possible to design the so-called hybrid systems. A possible solution is that of coupling two different technologies, the reversible geothermal heat pump to face the base load of the building, and an air condensed reversible heat pump to cover the peak load. However the air condensed units will operate in the worst conditions (higher loads, most likely corresponding to the higher outdoor temperatures) with respect to energy efficiency, and the ground coupled units will be operating at higher load factor, then with a limited benefit in terms of borehole length reduction. A much better solution it is that of providing a hybrid system on the thermal sink side, thus having a second heat rejection system in series to the ground, like a closed/open circuit cooling tower or a dry cooler. This solution belongs to the category named Hybrid Ground Source Heat Pump Systems (HyGSHP) [1][2][3].

HyGSHP have been widely studied theoretically and monitored in working applications mainly in USA [4][5], and are well known in the ASHRAE community, with special regard to the control strategy in order to reach the optimum from the technical-economic point of view.

This paper aims at a critical analysis of the possible application of these systems for building located in hot climates, starting from the design guidelines and then evaluating energetic performances and technical limits of the different solutions.

Configuration of HyGSHP for hot climates

Technical literature on hybrid ground source heat pump systems incorporate several solutions, that integrate the vertical ground heat exchangers to one or more additional heat rejection systems.

The choice of a second dissipation system is based on three main alternatives:

- Open loop cooling tower;
- Closed loop cooling tower;
- Dry cooler.

The cooling tower allows to operate at lower temperatures, being bound to the wet bulb air temperature. Usually the open loop cooling tower requires an additional heat exchanger to isolate the fluid flowing in the ground exchangers from the cooling tower fluid because:

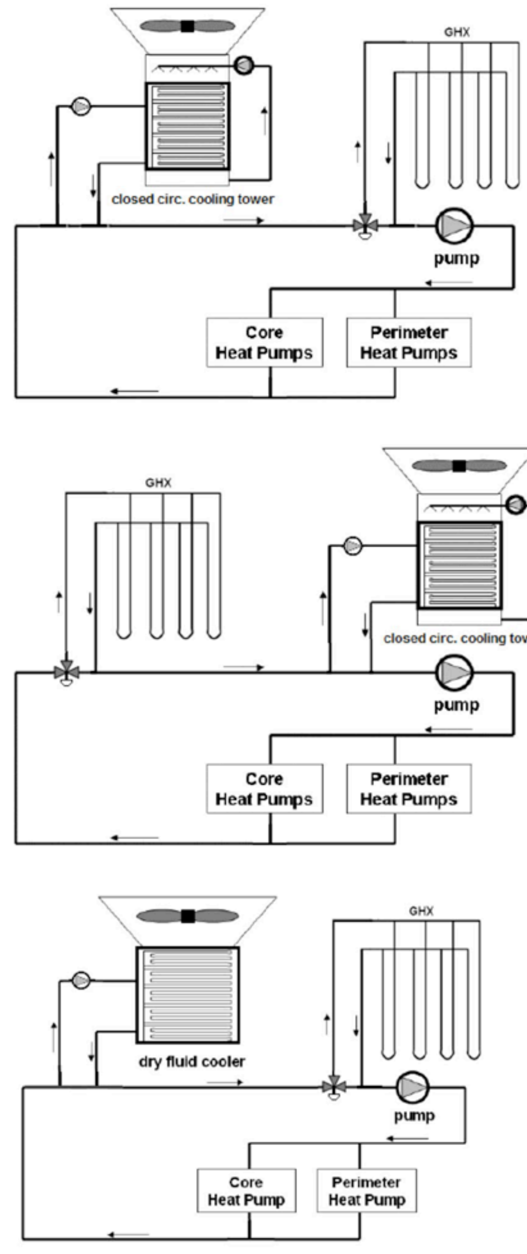

Figure 1 – Possible layout of boreholes and cooling towers

Figura 1 – Possibili disposizioni del campo geotermico e delle torri evarporative

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- The cooling tower fluid is in direct contact with outdoor air;
- The ground fluid can be additive with antifreeze solution (glycol). However this doesn't affect systems in hot climates or where the cooling load dominates the heating.

These reasons makes it more suitable to prefer closed circuit cooling towers.

The use of closed loop cooling towers instead of dry coolers is more advantageous with higher differences between dry bulb and wet bulb temperatures, then it should fit for arid climatic conditions. The possible loop layout are depicted in Figure 1, top, middle and bottom. Figure 1 top shows the most classic configuration of the system, with the cooling tower upstream the ground circuit: this is the most expensive in terms of electric energy consumption, and it is necessary to maximize the difference between the fluid and the air wet bulb temperature.

Figure 1 middle switches the position of the cooling tower and the ground loop; this solution can be adopted in extremely hot climates where the ground temperature can reach higher values and it is necessary to have the cooling tower downstream the ground loop, according to [2][3][4].

Finally Figure 1 bottom shows dry coolers upstream the ground circuit; this solution is the less expensive in terms of cooling tower operation, since there is no need for water (which be better saved in arid climates), and can be chosen for hot climates with high value of relative humidity (e.g. tropical) thus with a small temperature difference between dry bulb and wet bulb conditions.

The Dry-coolers can be adopted for seasonal or nocturnal pre-cooling of the ground field, if cold winter or remarkable daily temperature ranges happen.

Application of HyGSHP where alternative heat sinks (e.g. lakes) are used can also be found in literature.

The optimal control strategy for HyGSHP in hot climates

Whatever solution is chosen for heat rejection (among those presented above), it is in any case a solution with non negligible electric energy consumption, due to electric equipments (fans, circuit pumps, spray water pumps), and moreover require a certain amount of water in case cooling towers are selected. Then the matter of optimisation has been deeply investigated in order to identify the correct control strategy.

The optimisation of the systems can be quite complicated since there are several boundary condition that needs to be defined. Not only it is necessary to find the correct ratio between the cooling tower size and the borehole length, but also the criteria to operate the auxiliary heat rejection system (cooling tower).

Several studies where carried out on the subject, especially in USA, where different solutions where examinated and case studies where monitored and analised.

The general methodology for the sizing has been analysed by Kavanaugh [5] and Xu [6]; an analysis of the control strategies updated with respect to the first ASHRAE Guidelines [5] and oriented to climates with dominant cooling load is well presented by Yavuzthurk and Spitler [7] and analysed in the Fort Polk case study by Thorton [8].

The most interesting document is undoubtedly that of Energy Center of Wisconsin [1], based on the works from Hackle and Pertzborn [2][4], that describe a very deep study on the optimisation of control parameters for ground hybrid systems, validated by means of three real operating case studies. The work has led to the release of a software called HYGCHP [1], developed as a TRNSYS application package, adopted to develop the present study.

Nevertheless the analysis of these systems and of the possible control strategies requires further studies also related to their application in different climates, since the results widely vary according to the variation of heating and cooling load along within the day and the year, and of dry and wet bulb temperature during the seasons.

It is broadly known that the control strategies for these systems can be ascribed essentially to the following three:

1. Control with set-point temperature: the cooling tower is activated when the borehole outlet temperature exceeds a threshold;
2. Differential control on temperature: the cooling tower is activated when the difference between borehole outlet temperature a air wet bulb exceeds a threshold;
3. Pre-cooling: the cooling tower is activated when there's no cooling demand, during the night (night pre-cooling) o in the cold season (seasonal pre-cooling), or on a hourly schedule, or as a function of outdoor climate; this strategy can be adopted in combination with strategy 1 or 2.

The studies that were previously quoted proved that in most cases, for hot climates, the optimum strategy is n.2 (differential control), since it optimises the performances of the cooling tower that is used only in the most appropriate conditions.

The pre-cooling technique aims to compensate the energy drawn and rejected to the ground, by dissipation of an amount of heat that doesn't provide any heating to the building; however the energetic and economical analysis should be investigated for each singular case and requires an accurate evaluation of the building thermal load by dynamic simulation.

The optimum control strategy can be different from each specific application, and can also be related to the economic scenarios and to the time horizon that is considered. Very attention must be paid in the evaluation of electric auxiliary and pump consumption.

Specific problems of HyGSHP in extreme hot and dry climates

The very problem in geothermal reversible heat pump installation in hot climates with cooling demand that dominates the heating load, is in the higher ground temperature than in temperate climates. HyGSHP systems are undoubtedly considered a very interesting

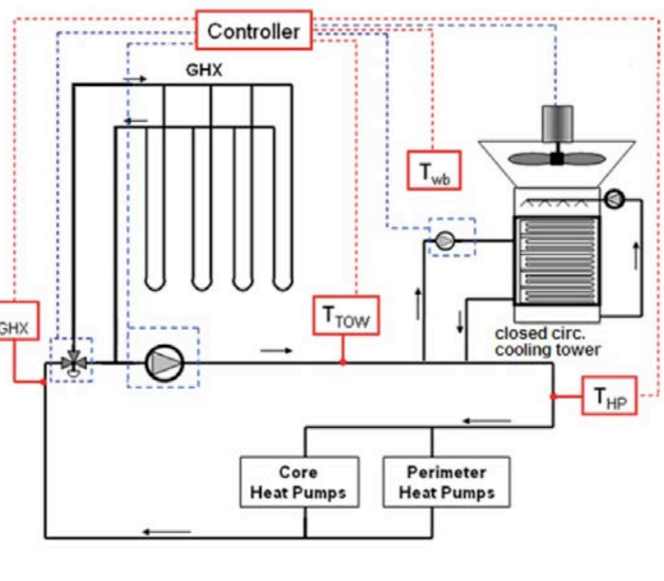

Figure 2 – Optimal control strategy solution

Figura 2 – La strategia di controllo ottimale solution. Extremely hot and dry climates suggest a solution as the one depicted in Figure 1 middle.

The optimal control strategy solution is presented in Figure 2 [2] [3]. The cooling tower is activated when the temperature difference between the ground loop outlet temperature and the wet bulb air temperature exceeds a fixed parameter ΔT_1. This logic is expressed by the following activation condition:

$T_{TOW} - T_{WB} > \Delta T_1$

The most appropriate values for ΔT_1 in a hot and dry climate is [2][3]:

- 15 °C if the monthly average wet bulb air temperature in July is lower than 21 °C;
- 13 °C if the monthly average wet bulb air temperature in July is between 21 and 24 °C.

A further control is necessary when the ground fluid outlet temperature T_{TOW} exceeds a given temperature (e.g. 35 °C), and should set the cooling tower fans (if modulating) at the highest speed.

Should colder winter than usual or high temperature range between nigh and day happen, it is possible to implement a pre-cooling control strategy that operates the circuit without cooling demand, therefore the cooling tower will pre-cool the ground.

The guidelines for technical and economical optimisation in hot climates are presented in [2][3], and are:

- the ground boreholes sizing should be performed in order to cover the heating load, if present;
- the cooling tower should be sized on the cooling load left from the ground, although if variable speed fans are adopted a larger cooling tower can be selected, up to the double size to the cooling load left from the ground;
- despite the aim of an technical and economical optimum, the perfect balance of heat extracted and rejected to the ground can hardly be reached. Therefore there is a tendency to increase the ground temperature along the years, so to reach a long-term equilibrium at a higher temperature with respect to the undisturbed ground;
- it is necessary to provide a bypass of the ground circuit, to avoid the ground loop operate in unfavourable conditions.

However the extreme hot climates are not all the same, that means that the solution must be selected according to specific climatic variables and the thermal load curve of the building. To the scope of the paper, an office building has been chosen as the case study, and was simulated in three distinct extreme hot and dry climates.

The remarkably high temperature and temperature ranges make it interest to evaluate the pre-cooling option, so even when heating loads are negligible, the pre-cooling can increase the EER of the chiller having without necessarily compromising the economic optimum with undue auxiliary consumption.

The case study

The task of studying the application of HyGSHP systems to extreme hot and dry climates has been performed through dynamic simulations of an office building located in three different cities of the same climatic zone "desertic-arid", marked BWh according to the Koppen-Geiger classification [9].

The analysis has been performed by means of dynamic simulation of the building and thermal plant systems —cooling tower, borehole exchangers— with the TRNSYS software and the HyGCHP tool, developed and released by the Energy Center of Wisconsin and the Solar Energy Laboratory SEL of University of Wisconsin [1]. The simulation was conducted in two steps: on the first step the heating and cooling loads (latent and sensible, accounting for ventilation as well) were calculated on an hourly time step; on the second step the loads were given as input to an ideally convective climatisation system fed by the thermal plant that will be explained further.

The HyGCHP tool allows to simulate different plant configurations, and to optimise from the technical economical point of view the different setup parameters and the sizing of the different main components of the system. To the extent of this study the tool has been used only for simulation purposes, thus excluding the optimisation features, since the main task is to evaluate the performances in different locations, not that of optimisation for a single application.

The building is in the shape of a parallelepiped, 76 m long (North to South oriented), 35 m large, 3 floors of 1,800 m² each, a global air conditioned volume of 20,000 m³.

The window surface is approximately 1/8 of the floor area, 225 m² per each floor, half of it facing northeast and the other facing southwest. The solar factor of the glazing assumed is 0.5 and no shading is considered.

The building behaviour was simulated considering the following set of assumptions:

- indoor temperature 26 °C in summer, 20 °C in winter, 50% Relative Humidity;
- HVAC plant scheduled on 6.00-20.00 from Monday to Friday, 6.00-14.00 on Saturday, off on Sunday.
- Thermal transmittance considered for different building elements are the following:
  - Outer walls: 0.18 W/(m² K);
  - Roof: 0.17 W/(m² K);
  - Ground floor: 0.22 W/(m² K);
  - Windows: 0.9 W/(m² K).

To the extent of the study, the building is an invariant, in order to provide a consistent base for the analysis.

The geographical locations for the simulations are Riyadh (Saudi Arabia), Abu Dhabi (United Arab Emirates) and Phoenix (Arizona, USA). As it can be seen from the data in Table 1, from Meteonorm [10], those climates present low values for wet bulb temperature with respect to dry bulb; Phoenix shows the lowest winter temperature, while in Abu Dhabi the dry bulb temperature annihilates the heating loads.

It must be reminded that, with the same highest temperatures, lower yearly average temperatures lead to lower undisturbed ground temperatures, therefore to better cooling performances for the geothermal heat pumps.

By the same rationale, higher differences between dry bulb and wet bulb temperature makes the use of cooling tower more favourable; if heating loads are absent, a water-to-water chiller coupled to the sole cooling tower could score performances that are not much different from those of a HyGSHP.

Table 1 – Average dry bulb, lowest dry bulb, highest dry bulb, average wet bulb temperatures for the considered locations

Tabella 1 – Temperatura media a bulbo secco, temperatura minima a bulbo secco temperatura massima a bulbo umido e media a bulbo umido per le località considerate

Location	Average dry bulb temperature (°C)	Lowest dry bulb temperature (°C)	Highest dry bulb temperature (°C)	Average wet bulb temperature (°C)
Riyadh	25.60	3.30	44.00	13.90
AbuDhaby	26.74	9.10	45.65	20.19
Phoenix	22.53	-2.80	46.10	12.67

Table 1 shows the outdoor air temperature values to be accounted for in the design of the systems, while Table 2 presents the yearly net heating/cooling energy demand (detailed on a monthly basis in

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Figure 5), the heating/cooling peak power determined on a hourly basis with dynamic simulation.

From the data analysis it comes out that for every location considered the cooling loads dominates by far the heating demand, with a minimum ratio of 4.8 between cooling and heating energy in Phoenix, and a nearly negligible heating load in the other two locations. Since the building is not occupied only during the day, despite the cool night temperatures, even in Riyadh, the heating loads are very small.

Table 2 – Peak heating and cooling power, net heating and cooling demand, cooling to heating energy ratio for the considered locations

Tabella 2 – Potenza di picco in riscaldamento e raffrescamento, fabbisogno netto di riscaldamento e raffrescamento, rapporto tra i fabbisogni nelle località considerate

Location	Peak heating load (kW)	Peak cooling load (kW)	Net heating demand (MWh)	Net cooling demand (MWh)	Cooling to Heating energy ratio
Riyadh	98	192	9	217	24.1
AbuDhaby	22	190	1	214	214.0
Phoenix	183	179	35	167	4.8

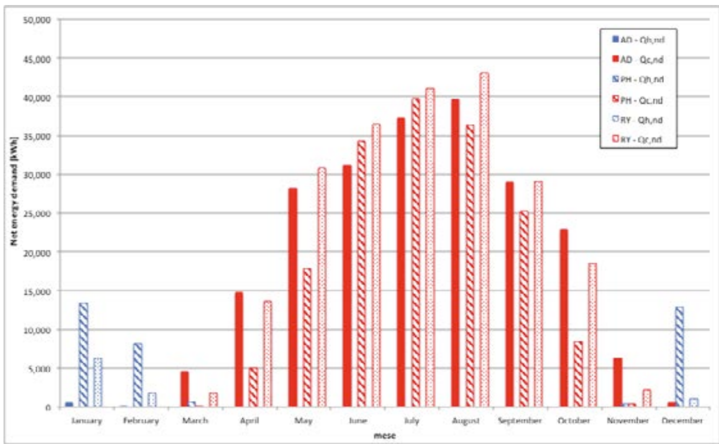

Figure 3 – Monthly net energy demand for heating and cooling (AD-Abu Dhabi, RY-Riyadh, PH-Phoenix)

Figura 3 – Fabbisogno netto di riscaldamento e raffrescamento (AD-Abu Dhabi, RY-Riyadh, PH-Phoenix)

As per the heat pumps system modelling the following assumptions are made:

- For the geothermal ground field the DST model was used [11]; U-shaped pipes with outer diameter 32 mm in HDPE (high density polyethylene), borehole diameter 152 mm and 80 m depth. The depth is more suitable than the usual 100 m, for hot climates, since it helps to limit the average ground temperature in presence of geothermal gradient, that is considered as a parameter in the DST model. The distance between boreholes is 8 m; the model considers a cylindrical geometry of the thermal field and therefore accounts for the layout influence only in terms of distance between the boreholes and thus of the cylindrical volume that participates to heat storage.
- The ground has a thermal conductivity of 2 W/(m K) (average typical value) and a diffusivity of 0.1 m²/day with a geothermal gradient of 0.03 K/m; to the extend of the study, the choice of the same conductivity helps to concentrate the analysis on the influence of the climate.
- The closed loop cooling tower model is based on the Zweifel model [12] implemented in Trnsys Type 150 and can calculate the water and electric auxiliaries consumption.
- The heat pumps is simulated according to reference performance curves as in the Hackle study [4].
- The circulation pump of the ground loop is considered as a variable speed pump.

The simulations were run on the three different climates on a 20 years horizon, for different plant layout (Tables 3, 4, 5), that are:

- Several HyGSHP solutions, indicated as *HyGSHP-x*, for each climate, that differentiate for overall borehole length, cooling capacity, and control parameters set;
- A solution with sole ground exchangers indicated as *GSHP only*;
- A "traditional" solution with boiler and chiller coupled to a cooling tower, *indicated as Cooling Tower + Boiler.*

The different plant layouts are compared with respect to:

- Maximum heat pump (or chiller, in case of the "traditional" solution) condenser inlet temperature;
- Average yearly electric energy consumed;
- Average yearly fuel energy consumed (only for the "traditional" solution).

Table 3 – Simulation output for Riyadh (CT = Cooling Tower; EWT: Entering Water Temperature to heat pump/chiller)

Tabella 3 – Risultati delle simulazioni per Riyadh (CT = Torre evaporativa; EWT: temperatura di ingresso alla pompa di calore/chiller)

Riyahd	Total borehole length (m)	Cooling capacity CT (kW)	DT activation CT (K)	Max EWT 20 years	Yearly average electricity consumption (MWh)	Yearly average fuel consumption (MWh)
HyGSHP-1	960	210	15	35.5	93	0
HyGSHP-2	2560	150	13	34.4	100	0
HyGSHP-3	2560	150	15	36.4	89	0
HyGSHP-4	4000	91	15	36	86	0
GSHP only	8000	0		39.5	94	0
Cooling Tower+Boiler	0	250		32.1	110	10

Table 3 shows the results for the town of Riyadh. It can be seen that the overall length needed to operate in GSHP mode is quite high: 8,000 m, corresponding to 30 W/m at the condenser side, the ground temperature reached is nearly 40 °C. Given the favourable wet bulb temperature, the traditional solution shows energy performances that are not much different from some of the hybrid ones; though even with only 1,000 m of boreholes it is possible to reduce the electricity consumption by 15% with respect to the traditional solution; then the fuel savings to the winter heating must be added. A significant increase in borehole overall length doesn't lead to remarkable improvements.

A further simulation was run to determine the benefit of ground cooling by means of the cooling tower alone, when the cooling load is absent and the wet bulb temperature is below 20 °C. This strategy of plant conduction exploits the daily temperature range and compensate the ground heat injection with a dissipation of the ground heat to atmosphere and vapour. The operation leads to a reduce the condenser inlet temperature of about 3 °C on average, but generates an increase in cooling tower fan and pumps consumption of 36 MWh/y, from 20 to 56; therefore the energetic return is almost null.

Table 4 reports the results for Abu Dhabi, location with climate that is much more wet than that of Riyadh but with a smaller annual temperature range. This is the case where hybrid systems are affected from the absence of winter ground heat extraction on one side, though

Table 4 – Simulation output for Abu Dhabi (CT = Cooling Tower; EWT: Entering Water Temperature to heat pump/chiller)

Tabella 4 – Risultati della simulazione per Abu Dhabi (CT = Torre evaporativa; EWT: temperatura di ingresso alla pompa di calore/chiller

Abu Dhabi	Total borehole length (m)	Cooling capacity CT (kW)	DT activation CT (K)	Max EWT 20 years	Yearly average electricity consumption (MWh)	Yearly average fuel consumption (MWh)
HyGSHP-1	2000	170	11	37.6	67	0
HyGSHP-2	4000	100	13	38.2	62	0
HyGSHP-3	4000	100	11	38.1	61	0
GSHP only	9000	0		39.5	92	0
Cooling Tower+Boiler	0	230	0	37.4	75	0

Table 5 – Simulation output for Phoenix (CT = Cooling Tower; EWT: Entering Water Temperature to heat pump/chiller)

Tabella 5 – Risultati della simulazione per Phoenix (CT = Torre evaporativa; EWT: temperatura di ingresso alla pompa di calore/chiller

Abu Dhabi	Total borehole length (m)	Cooling capacity CT (kW)	DT activation CT (K)	Max EWT 20 years	Yearly average electricity consumption (MWh)	Yearly average fuel consumption (MWh)
HyGSHP-1	3600	85	13	36.5	88	0
HyGSHP-2	3600	85	15	37.5	88	0
HyGSHP-3	5120	20	13	36	85	0
GSHP only	6400	0		35.7	79	0
Cooling Tower+Boiler	0	250		33.2	103	39

they can benefit from electricity saving up to 20% for a total borehole length of about 4,000 m. The optimal configuration from the technical and economical point of view must be verified accounting for operating cost and water consumption. The "GSHP only" solution in this climate can't be adopted, due to the operating that doesn't not include the heat extraction from the ground. If an enhancement in the efficiency of cooling tower fan was implemented, it could be possible to achieve a remarkable improvement, since the fan consumption accounts for 21% of the electric consumption but reaches 50% in the "traditional" configuration (without ground boreholes) with closed loop cooling tower, as reported in Figure 4.

Finally Table 5 shows the results for Phoenix, where the advantages of the hybrid solution are outstanding due to the higher winter energy needs. The primary energy saving (evaluated with a electric to primary conversion factor of 2.5) is of 25%. Better figures of saving can be reached for buildings with a higher weekly utilization or higher winter energy needs. It can be noted that even in this case the "GSHP only" solution, although balanced in terms of sizing, shows the better performances that are only 10% worse than a hybrid system that has only a half of the borehole length.

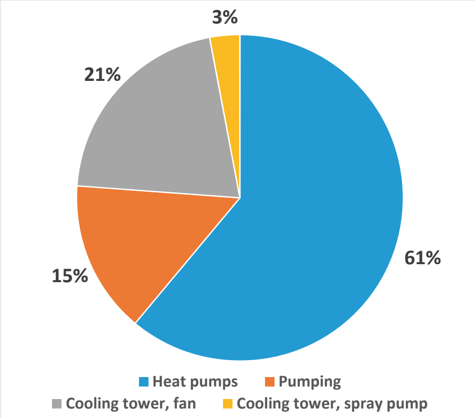

Figure 4 - Electric energy distribution on different system components (ref. Abu Dhabi).

Figura 4 – Ripartizione dell'energia elettrica sui diversi sistemi e componenti (Rif. Abu Dhabi)

Conclusions

The paper presents the energetic evaluation of the possibility for implementing geothermal hybrid systems in extremely hot and dry climates (desertic, of type BWh in the Koppen-Geiger classification). The optimal control strategy implicate the installation of the cooling tower downstream the geothermal borehole field, with the activation of the tower based on the temperature difference between the ground loop and the wet bulb temperature. The optimal value of the temperature difference depends of the average wet bulb temperature and for these climates is between 13-15 °C.

A case study has been presented, for an office building, on three locations in the desertic climate, having three different annual temperature profiles in terms of dry bulb and wet bulb. For every configurated simulation, the hybrid solution allows for remarkable electricity and primary energy savings (from 15% to 25%); the greater the winter heating demand or the lower the wet bulb temperatures, the higher is the saving. The desertic climates with high daily temperature range, or colder winter (even without heating demand), the pre-cooling strategy must be evaluated in order to reduce the ground temperature and then increasing the seasonal EER. The optimal configuration should be selected carefully, since there are many variables that affect the performances, and the dynamic simulation needs to be run in order to size the plant correctly; it will never be possible to ignore the energetic context of the country examined for the installation.

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