Development of a standardized method for determining the free-cooling performance of ground-source heat pumps

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Abstract

Ground-source heat pumps (GSHPs) offer a unique opportunity for energy-efficient cooling through free-cooling—an operating mode where the system delivers cooling using only circulating pumps, without activating the compressor. This significantly reduces energy consumption compared to conventional active cooling systems such as chillers and air conditioners. The relatively constant ground temperature throughout the year enables boreholes, originally intended for space heating, to serve as a free cold source during the summer season.
Despite its high efficiency, free-cooling remains underutilized and insufficiently studied, with no established methodology, until recently for predicting its performance prior to system installation. To address this gap, this paper presents a standardized method for estimating the free-cooling capacity of GSHP systems based solely on their heating performance.
Through extensive simulations, the study demonstrates strong correlations between the space heating capacity of a GSHP, its geographical location in Europe and its free-cooling potential. The proposed method yields two key correlations. The first one enables estimation of free-cooling capacity for each of the three European reference climates defined in Ecodesign Regulation EU 811/2013 and for two types of emitters. The second one allows calculation of the Energy Efficiency Ratio (EER) for free-cooling mode, again specific to climate zone. This method provides a practical and scalable way to evaluate the cooling potential and efficiency of GSHPs early in the design process, promoting wider adoption of this ultra-low-energy cooling technique. It offers manufacturers, designers, and policymakers a valuable tool for advancing decarbonized, energy-efficient cooling solutions across Europe.

Keywords: heat pump, free-cooling, energy efficiency ;geocooling

1. Introduction

In the EU COMMISSION DELEGATED REGULATION (EU) 2022/759 free cooling “means a cooling system using a natural cold source to extract heat from the space or process to be cooled via fluid(s) transportation with pump(s) and/or fan(s) and which does not require the use of a cooling generator ». Unlike active cooling, free cooling systems do not require any energy to run a generator but only to operate the means to circulate the cooling media from the cooling emitters to the cold source. Therefore, free cooling can be a really efficient way of cooling buildings.

Ground source heat pumps (GSHPs) use the ground as an energy source. They can be connected to boreholes or to horizontal collectors usually buried between 0.8 and 2 meters depth from the surface. Water or brine is circulated in the boreholes or horizontal collectors where it exchanges heat with the bedrock. The water or brine temperature is then leveraged in the heat pump at a suitable temperature for space or domestic water heating. GSHPs are among the most efficient heating systems as shown in a report from a vast monitoring campaign done by ADEME in France where the averaged annual performance of GSHPs reaches 4.3 in comparison to air to water that reaches 2.9 [1]. This study confirms results obtained by Fraunhofer ISE that monitored over several campaigns from 2005 to 2024 more than 177 heat pumps, both GSHPs and air to water heat pumps [2], [3], [4], [5] and [6].

At 10 m below ground, the temperature is very stable throughout the year and roughly equal to the average annual air temperature at the surface. In temperate or cold climate zones, this temperature is far below the air temperature during the summer season and therefore low enough for providing cooling. GSHPs connected to boreholes can take advantage of the bedrock constituting a cold source and provide free-cooling during the summer season. The building is cooled by circulating the water or brine between the boreholes and the cooling emitters, as shown in Fig 1.

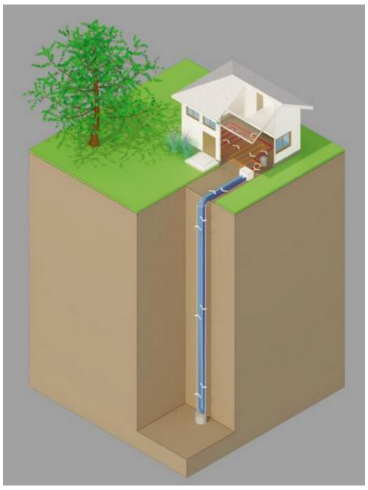


Figure 1. GSHP installation with boreholes (source : BRGM: Plateforme Géothermie : optimiser les performances énergétiques et environnementales des échangeurs géothermiques)

Although free-cooling using the bedrock as cold source is recognized as being a very efficient cooling mean with energy efficiency ratio (EER, ratio of cooling energy provided and electric consumption needed to provide this energy) reaching 45 as shown in the EU project Ground-med [7] and in other reports published by the Swiss Federal office of Energy [8, 9], free-cooling capacity is largely untapped in Europe.

One of the identified reasons for this general overlook of free-cooling from GSHPs is the lack of information about the free-cooling performance in particular the cooling capacity that the system can provide. Until 2024, there was no methodology available to evaluate the free-cooling performance of a GSHP installation before all the technical details of the installation were known: depth of boreholes, nature of the bedrock, characteristics of the building etc. Therefore, the free-cooling capacity was not an argument to choose a GSHP against other type of heat pump, typically an air-to-water heat pump, for which the cooling capacity and related EER are documented.

To remedy this situation, a consortium was formed to perform a study aiming at defining a standardized method for determining the free-cooling performance of GSHPs which is solely based on the heating performance of the GSHP. The consortium is made of ADEME (Agence de l'environnement et de la maîtrise de l'énergie), Mines Paris, Electricité de France (EDF), BRGM (Bureau de recherches géologiques et minières) and the Swedish heat pumps manufacturer NIBE. The project started in February 2024 and ended in December 2024. A report is publicly available on ADEME website [10].

The study focuses on GSHPs installations for residential applications where the GSHPs are designed primarily to provide space heating. The results cover all residential applications, and single-family homes. In order for the study to also cover the multifamily homes, it would be needed to study the impact boreholes interaction in the boreholes field.

2. Methodology

Unlike active cooling, it is not possible to evaluate by means of a test the free-cooling capacity and energy that a GSHP associated with boreholes can provide throughout the cooling season. Indeed, these performances are not related to the compressor performance but solely dependent on the brine or water temperature returning from the borehole to the GSHP. In turn, this temperature depends not only on the location but also on the energy that will be used over the cooling season. Indeed, depending on the cooling demand of the building, the temperature of the bedrock might increase alongside the cooling season, and the cooling capacity might decrease.

Unlike space heating, the space cooling demand is not easy to evaluate as it cannot be directly correlated with the outdoor temperature as it is the case for space heating demand. Indeed, the indoor temperature in a building is highly influenced by solar radiation on windows and roof and internal gains that increase the cooling needs even when outdoor temperature is not higher than 27°C.

Because of the two above mentioned reasons, simulation seems to be the most appropriate means for the evaluation of the free-cooling potential of a GSHP installation primarily designed for space heating demand.

Within the simulation, the maximum heating capacity required by the building is evaluated. From this maximum heating capacity, an appropriate GSHP is selected and the borehole depth is calculated. The simulation is done over 12 months on an hourly basis. At each step, the indoor temperature in the building, inlet and outlet temperatures on the emission and borehole sides are calculated. From these temperatures, it is possible to determine the heating and free-cooling capacities delivered to the building.

The building is simulated with EnergyPlus V8.6, a worldwide reference software for building energy simulation, which includes the building's envelope characteristics, internal loads, schedules, occupancy patterns, and weather conditions. Since the modeling of HVAC systems is a challenge with EnergyPlus, Modelica has been selected to model the heating system including the GSHP system, boreholes, emitters and control strategies. The coupling between the two tools is achieved by Spawn of EnergyPlus, a co-simulation engine [11]. The HVAC models are selected from the Buildings Library [12] as presented in Table 1.

Table 1. Parameters used for the simulation for each of the three climates

HVAC components	Selected Models	Main parameters
Double-U geothermal Borehole	*Borefields. TwoUTube*	Borehole diameter = 160 mm Borehole thermal resistance = 0.06 m.K/W
Heat pump model	*Carnot_TCon*	COP (0°C/35°C) = 4.8
Heat Exchanger	*Plate HeatExchanger Effectiveness NTU*	*Efficiency=0.9*
Underfloor	*Single CircuitSlab*	

The following variable parameters are applied to the building and emitters:

- Location: the three climates defined by Energy Labelling Regulation 811/2013 are considered, i.e. warmer, average and colder climates corresponding respectively to the cities of Athens, Strasbourg and Helsinki
- The type of emitter: underfloor heating/cooling and radiators for heating coupled with fan coil units dedicated to cooling avoiding condensation constraints and sized for cooling.

The temperature set points in the building are taken to be equal to 19°C during heating season and not more than 27°C during the cooling season (cooling starts only when indoor temperature exceeds 27°C). The choice of 27°C comes from the standard NF EN14511 and corresponds to the indoor temperature at which air conditioners are tested. Using the same indoor temperature allows to compare both cooling capacity and EER between active cooling provided by air conditioners and chillers and free-cooling.

For each of the combinations of the parameters above described, dynamic simulations are carried out over a full year, from 1st of October until 30th of September, to determine the air temperature in the building and the temperature of the heat transfer fluid coming from the boreholes throughout the year. The thermal discomfort is quantified via discomfort degree hours (DDH in °C.hour). The latter are calculated by summing the temperature exceedances above the threshold (27 °C) for each hour.

Other parameters such as the building's insulation and the production of domestic hot water were studied to evaluate their influence on free-cooling capacity. All the results can be found in the ADEME report [10]; however, they are not described in this paper.

3. Model description

The climate data that are considered correspond to the average temperature from 2000 until 2016 according to meteonorm 8 [13] for the cities of Athens, Strasbourg and Helsinki. The living scenario is the one described in the French building code RT2012.

The building is a single-family house, one storey, 100m² built 50 years ago. The underfloor heating system is sized according to the French standard DTU 65.14. The building insulation is defined according to the French building code RT 1974. The needed space heating capacity is calculated according to the standard NF EN 12831. The GSHP is connected to a borehole sized to cover for the space heating needs. The depth of the borehole is crucial for the simulation as the incoming brine temperature to the GSHP depends on this depth. Therefore, seven standards for sizing boreholes have been compared (methods from AFPAC and ASHRAE, NF X 10-970, MIS 3005, VDI 4640, SIA 384/6 and Cartodim). Among them, NF X10-970 that has been retained as it was the closest to the average depth calculated with the seven considered standards [10].
Table 2 described the GSHP characteristics for each of the three climates:

Table 2. Parameters used for the simulation for each of the three climates

Parameters (units)	Colder climate	Average climate	Warmer climate
City	Helsinki	Strasbourg	Athens
Initial ground temperature (°C)	6.0	11.3	18.5
Heat pump heating capacity (kW)	8	5	2.5
Needed cooling capacity (kW)	1.8	3.6	5.2
Borehole depth (m)	181	104	42

The heat transfer media circulating in the borehole is brine. The GSHP installation is described in Fig 2:

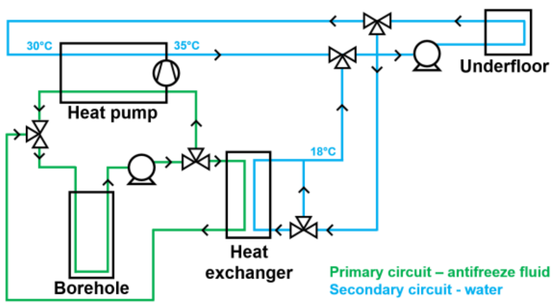


Figure 2. Schematic of the GSHP installation when connected to underfloor heating/cooling emission system

During summer time, the brine bypasses the GSHP and passes through a heat exchanger where the heat is transferred from water circulating in the underfloor cooling system or the fan coil units to the brine. In the case of underfloor cooling, the water temperature cannot go below 18°C to avoid condensation, whereas in fan coil units, the water temperature can go down to 7°C.

4. Results

4.1. Discomfort

The comfort is quantified using the discomfort degree hours (DDH). Fig 3 shows the DDH reached in the three climates with and without free-cooling:

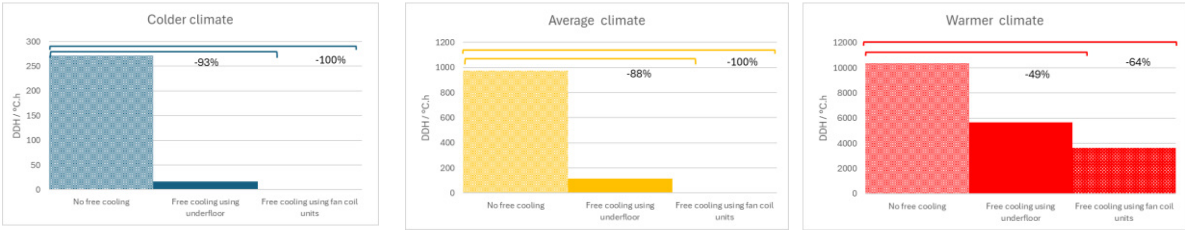


Figure 3. Number of discomfort degree hours

One can observe that in colder and average climates, free-cooling, even when provided via underfloor, designed for space heating, reduces by respectively 93% and 88% the discomfort degree hours. When using cooling emitters sized for cooling, fan coil units in the study, the free-cooling capacity and energy is enough to maintain the indoor temperature below 27°C during the entire cooling season.

In warmer climate conditions, free-cooling can reduce by up to 64% the discomfort hours but the discomfort hours are still high. The insufficient performance can be explained by the fact that GSHP are sized on heating requirements which are, in Athens, much lower than the cooling requirements and the fact that the initial ground temperature is higher than in other climate zones (Table 1). Even though active cooling would be needed to reach full comfort, active cooling will be switched on much later in the cooling season with free-cooling. Therefore, the overall energy demand for cooling over the summer season will be reduced thanks to free-cooling.

4.2. Brine temperatures

The average temperature across the entire borehole surface is calculated throughout the year and the results are shown for each of the three climates on Fig 4.

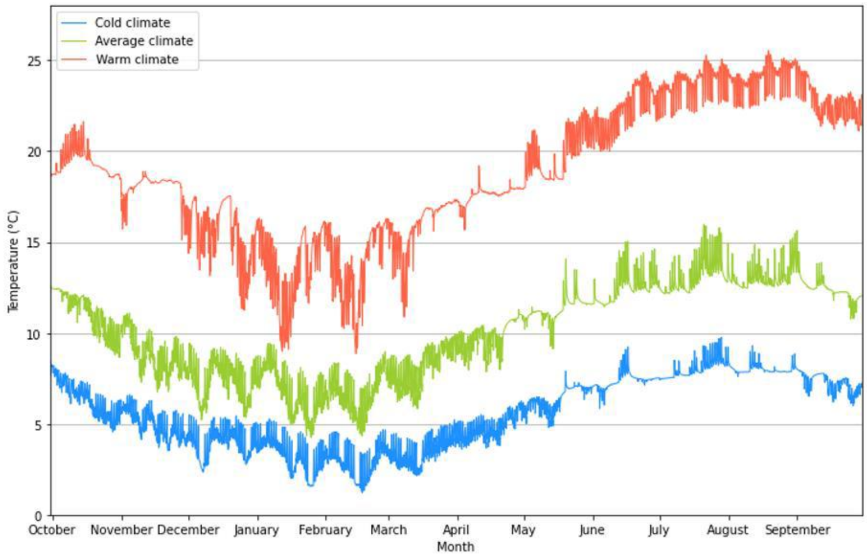


Figure 4. Borehole's surface temperature

One can observe that for average and colder climates, the borehole surface temperature always remains below 13°C, at least 14°C below 27°C. This means that the brine temperature returning from the borehole to the GSHP is always low enough to be used to provide free-cooling. In addition, the brine temperatures reached at the end of September are not higher than these of the previous 1st of October, meaning that the heat reinjected into the ground is not significant, under the considered climate conditions, compared to the natural regeneration.

Under warmer climate, the borehole surface temperature reaches 20°C already in May. This high temperature is partly explained by the fact that even during the heating season, the borehole temperature is kept at a fairly high level, around 13°C. At the end of September, the brine temperature overtakes the level of the previous October, meaning that over the years, the free-cooling capacity will decrease. In the case of warmer climate, the sizing of the borehole should be made according to the highest requirements between cooling and heating.

4.3. Cooling capacity and EER

The simulations allowed to determine the free-cooling capacity that is provided to the building. For the calculation, it is assumed that the cooling function is activated throughout the entire summer season to maintain the indoor temperature below 27°C. The underfloor system is dimensioned for space heating while the fan coils are sized for cooling.

Table 3 shows the the maximum cooling demand of the building in colder and average climates, as well as the available free-cooling capacities.

Table 3. Maximum cooling demand and available free-cooling capacity

	Colder climate	Average climate	Warmer climate
Maximum cooling demand; W	1800	3600	5200
Free-cooling capacity with underfloor; W	1840	1670	500
Free-cooling capacity with fan coils; W	8510	5050	500

The simulations show that, under colder and average climates and with the assumptions made on the building, borehole, system, scenario etc, provided the emitters are sized to meet the cooling demand, the free-cooling capacity is enough to cover for the need all over the cooling season. In the case of colder climate, the free-cooling capacity is the same level as the maximum cooling demand, even with underfloor emitters. In average climate, even if the free cooling capacity with underfloor is lower than the maximum cooling demand, the free-cooling can cover most of the cooling demand since the DDH are low (Fig.3). In addition, for colder and average climates, the simulation shows that the heat rejection during the cooling period does not change the undisturbed temperature, therefore the free-cooling capacity would not decrease over the years.

The seasonal energy efficiency ratios (SEERs) that are obtained are shown in Table 4. These SEERs do not encompass the electrical consumption of fan coils and circulating pump on the emitters' side.

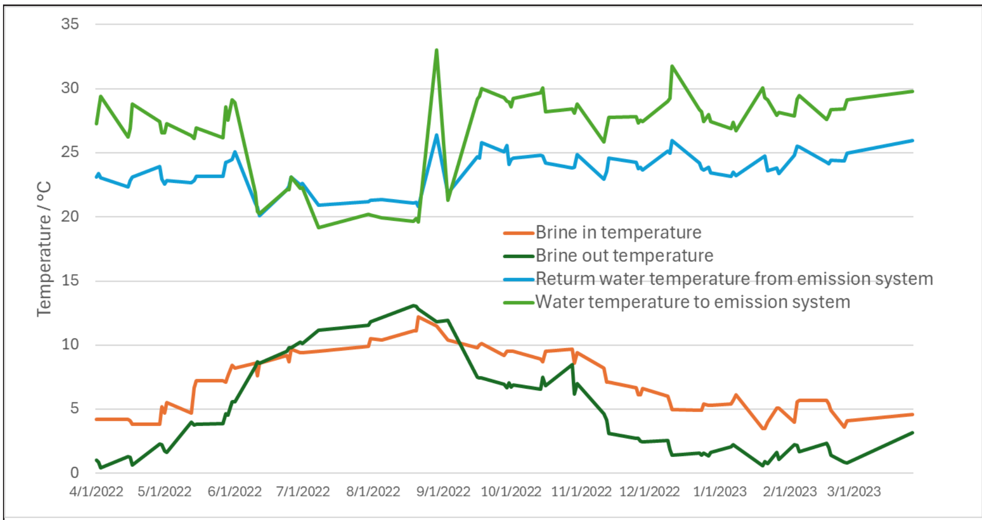
Table 4. Seasonal energy efficiency ratio (SEER)

	Colder climate	Average climate	Warmer climate
SEER	31	42	27

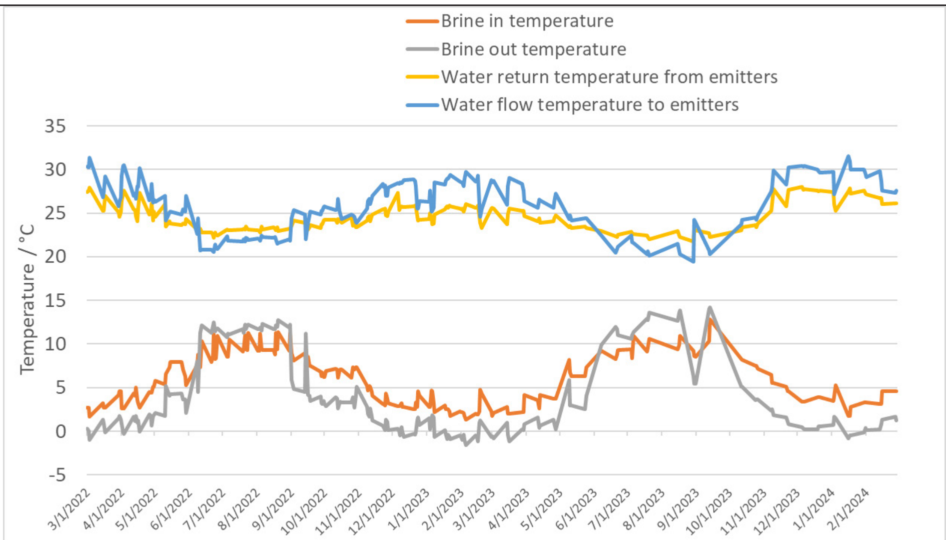
These SEERs are obtained while considering the cooling needs of the building and not the maximum cooling capacity that can be provided by the GSHP system. This SEERs are much higher than the ones of air conditioners or chillers that can hardly be higher than 6.

5. Field data on free cooling through GSHP

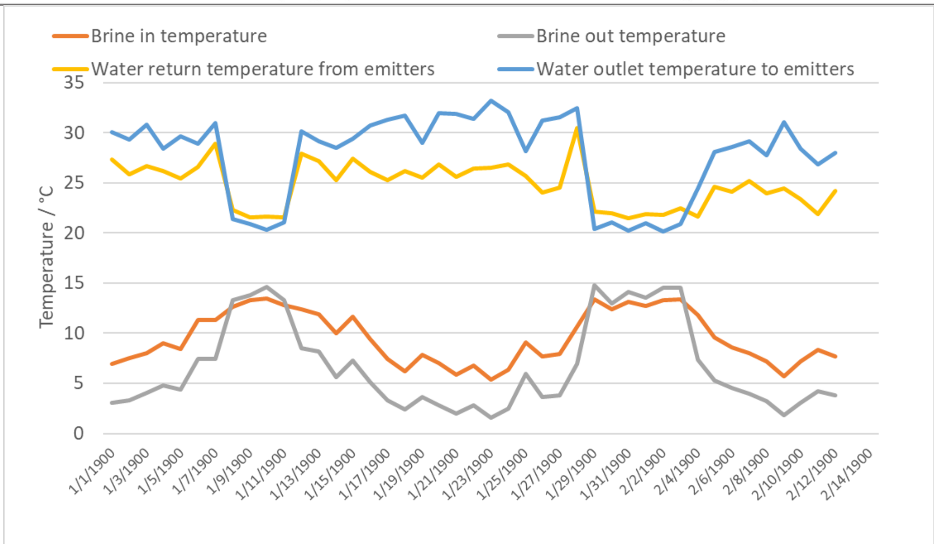
Data were collected from installed GSHPs in order to establish a preliminary comparison between the results of the study and what is happening on the field. The data are provided by NIBE and come from GSHPs installed in private homes before 2020. These GSHPs are monitored continuously. One or two years of data recording for the borehole inlet/outlet temperatures and emitter inlet/outlet temperatures are shown in the graphs below. Three cases, all located in average climate, are shown on Fig 5.



Case 1: location: Hagau, Germany Year 2022-2023



Case 2: location: Eidendorf, Austria Years 2022-2024



Case 3: Location: Heeswijk-Dinther, Holland Years 2022-2024

Figure 5. Field data

During the heating season, the inlet brine temperature to the GSHPs is higher than the outlet brine temperature whereas it is the opposite during the cooling season. One can see on the above graphs that the incoming brine temperatures from the boreholes never exceed 13°C as shown in the simulations for the average climate. No direct comparison with simulations can be made, as data on the buildings is not available, but these tests corroborate the potential of free-cooling.

6. Correlation for free-cooling and EER

In this study, the free cooling capacity of the heat pump is defined as the maximum cooling power achieved when the ground reaches its highest temperature during the simulation. This provides a conservative estimate of the system's ability to deliver free-cooling.

An extensive parametric analysis was conducted, showing that the cooling capacity is only weakly influenced by ground thermal conductivity and the GSHPs' COP. However, a significant difference was observed between the fan coil unit and the underfloor heating system. In addition, the cooling capacity also depends on the climate.

From these observations, the simulations allowed to establish a correlation between the heating capacity of the GSHPs and the free-cooling capacity. Indeed, assuming that the GSHP is correctly sized to meet the heat demand of the building, and that the borehole is correctly sized in accordance with the GSHP heating capacity, the simulations showed that the free-cooling capacity solely depends on the location and on the type of emitters.

The correlation between the space heating capacity and the free-cooling capacity is established in Eq. (1):

$$P_{FC} = \gamma P_{rated} \tag{1}$$

Where
P_{FC} is the free-cooling capacity, in W
γ is the correlation coefficient
P_{rated} is the heating capacity under average climate declared according to EU regulation 813/2013, in W

The coefficients γ depend on the climate and emitters' temperature and can be found in Table 5.

Table 5. γ coefficient for each of the three climates

Emitters	Colder climate	Average climate	Warmer cliamte
Underfloor	0.22	0.33	0.2
Fan coil	1.00	1.00	0.2

The EER is established while considering the consumption of the circulation pump needed to circulate the water from the borehole to the GSHP using Eq. (2). This consumption depends on the depth of the borehole and therefore on the nature of the bedrock.

$$EER = \frac{P_{FC}}{P_{elec}} \tag{2}$$

Where
P_{elec} is the electrical consumption of the circulating pump, in W calculated according to Eq. (3)

$$P_{elec} = 0.26\frac{P_{rated} - {P_{rated}}/{COP_d(T_{design})}}{\lambda} + 20.6 \tag{3}$$

Where
$COP_{d\ (Tdesign)}$ is the coefficient of performance (COP) under condition E according to EN14825
λ : borehole's sizing coefficient, in W/m, , determined according to the NF X10-970 standard.

In order to estimate EER, it is possible to use λ default values shown in Table 6.

Table 6. λ default values

	Colder climate	Average climate	Warmer climate
λ (W/m)	35	38	47.5

These default values are indicative and λ value corresponding to the bedrock where the GSHP is installed may be considered.

7. Conclusion

The study showed that there is a correlation between the heating capacity of a GSHP and the free-cooling capacity that the system GSHP and boreholes can provide. In particular, the study highlighted that:

- Assuming that the boreholes are well designed in relation with the GSHP capacity, the free-cooling capacity does not depend on the bedrock but only on the location, GSHP heating capacity and the type of cooling emitters. The coefficient of performance of the GSHP has neglectable influence on the free-cooling capacity,
- The EER depends on the borehole depth and therefore depends on the bedrock; clay, granite…. The better the conductivity of the bedrock the better the EER.

The study demonstrated that the free-cooling capacity is important and may contribute significantly to cover for the cooling needs of residential buildings located in colder and average climates. In order to compensate for the simplified assumptions made to perform the simulations, the correlation is established while considering the maximum cooling capacity reached at the end of the cooling season.

The SEER achieved with free-cooling in average climate is around 40, whereas the best air conditioners have a SEER of 6. Thus, the use of free-cooling reduces electricity consumption for cooling residential premises by more than six.

For warmer climate, the free-cooling capacity is limited because of the cooling needs which are higher than these of the other climates and borehole temperature which exceeds 20°C during the cooling season. In warmer climate, although the heating capacity required by a building could be similar to that of buildings located in other climates, the heating energy needed during the heating season is much lower. Therefore, other borehole's sizing rules should be used. It might be preferable to size the borehole according to cooling need instead of the heating need. Optimization of the boreholes' depth in warmer climate would be a very interesting topic to study as free-cooling in warm countries could dramatically decrease the energy consumption for cooling and reduce the heat island effect created by outdoor units of air conditioners, in particular in cities.

A parametric study aiming at evaluating the impact of the insulation of the house, and therefore the annual heating and cooling loads on the free-cooling capacity was performed as well as the influence of the production of domestic hot water. The results of the parametric study are available on the report publicly available on ADEME website [10].

As of today, there was no possibility to evaluate the free-cooling performance of GSHPs, therefore there was no common rules to declare free-cooling capacity. This study provides a useful tool to remedy the situation. Indeed, the correlation that is established allows to evaluate the free-cooling potential and EER. Providing information about the free-cooling performance is essential to help end-users in their choice of heating and cooling appliances. Thanks to this information, end-users would be given the opportunity to compare heat pumps using active cooling with GSHP providing free-cooling and would get to know the benefit they could get from investing in a GSHP.

Ecodesign and Energy labelling regulation in the European Union aim at promoting the best performing products, for the sake of promoting energy efficient cooling systems, it would be of a major importance that free-cooling is considered in those legislation.

Acknowledgement

This study was co-financed by ADEME and NIBE, it was supported by EDF R&D and BRGM, which provided their expertise and gave access to essential resources and documentation.

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