The paper was published in the Proceedings of the 8th International Symposium on Deformation Characteristics of Geomaterials (IS-PORTO 2023) and was edited by António Viana da Fonseca and Cristiana Ferreira. The symposium was held from the 3rd to the 6th of September 2023 in Porto, Portugal.

Proceedings of the 8th International Symposium on
DEFORMATION CHARACTERISTICS OF GEOMATERIALS
Porto, 3rd - 6th September 2023

Assessing the potential of using geothermal energy in buildings: parametric analysis

Batool Ajeeb[1#], *António Figueiredo*[2], Kamar Aljundi[3], Ana Vieira[3], Claudino Cardoso[2] and Raoof Gholami[4]

[1]*University of Aveiro. Civil Engineering Department*
[2]*RISCO-Research Centre for Risks and Sustainability in Construction, Civil Engineering Department, University of Aveiro*
[3] *Geotechnics Department, LNEC – National Laboratory of Civil Engineering*
[4] *Department of Energy Resources, University of Stavanger, Norway*
[#]*Batool Ajeeb: ajeebbatool@ua.pt*

ABSTRACT

For the development of more energy-efficient buildings, pursuing comprehensive sustainable solutions can help decrease greenhouse gas emissions, and using natural resources sustainably and at low cost are challenging objectives for the achievement of the United Nations (UN) sustainable development goals. In this context, the main objective of this research is the evaluation of the energy-efficiency improvement of shallow geothermal systems, based on one case study building located at Aveiro University. The present research undertakes the improvement of several parameters with influence on the shallow geothermal systems efficiency, using as a demonstrator a university building in Aveiro University, the CCCI department building. The performed work was developed in three phases: (i) the acquisition of vertical temperature profiles in 15 exploration boreholes, (ii) the simulation of the buildings' energy needs using EnergyPlus® software, and (iii) the evaluation of the energy demand of the geothermal system using HYGCHP® software. A sensitivity analysis was carried out with HYGCHP® by changing several parameters (average ground temperature, soil thermal conductivity, pipe radius, and total installation length) to assess the reduction potential of the annual energy consumption. Combining different parameters in the design phase allows a considerable reduction in the annual energy consumption. Two parameters are highlighted with a higher influence: the soil thermal conductivity and the average soil temperature (measured in the boreholes). A synthesis of the simulations carried out will lead to concrete recommendations and guidelines for future planning actions regarding geothermal systems installation to ensure sustainable use conditions, comfort, and health in the campus environment.

Keywords: Geothermal energy; HYGCHP software; Sustainable buildings; Parametric analysis.

1. Introduction

Heating and cooling systems in buildings consume more than 30 % of the of the total energy use in building sector (Ürge-Vorsatz et al. 2015) also driven by the demographic growth of the world population in the last decades. Additionally, the well-being requirements of the developed countries is increasing, which in turn leads to growth in energy consumption. Making matters worse, countries with a high level of economic growth, such as China and India, have a crucial impact on energy consumption related to the use of heating and cooling systems (World Bank 2015). Consequently, the electricity network loads are estimated to triple by 2050. On the other hand, 80 % of the energy produced in 2050 will be obtained from renewable sources such as solar, wind, hydropower and geothermal (Yang et al. 2016). Also, it is expected that 2090 is going to be the first year with 100 % renewable energy (DNV 2018). Therefore, it is of vital importance to reduce the percentage of buildings that use high levels of cooling and heating from non-renewable sources and develop new technologies able to fulfil with thermal comfort of indoor spaces with lower energy costs (Niza et al. 2022).

Regarding the energy use context of Portugal, renewable energy was the source of 25.7% of total energy consumption in 2013 (Silva 2022). In 2014, 27 % of Portugal's energy loads were supplied by renewable sources. In 2016, 28 % of final energy consumption in Portugal came from renewable sources which shows an increase of around 1 % per year (Silva 2022). Aligned with the European objectives, Portugal aims to be climate neutral by 2050 and to cover 80 % of its power consumption using renewable energy sources by 2030 (IEA 2019). Portugal is committed to close all of the country's coal-producing facilities by 2030, making it almost completely reliant on renewable energy in the incoming years (Gonçalves et al. 2022).

Currently, different types of renewable energy are used in Portugal such as wind, tides, biomass, hydro and solar, while geothermal energy is still not well exploited. On other hand, geothermal energy is considered one of the most promising energy source regarding their availability in comparison with other renewable sources.

Shallow Geothermal Energy systems (SGEs) depend on the nearly constant temperature of the superficial ground layers. SGEs are usually constituted of heat pump units, which connect the primary with the secondary circuits of the system (e.g. Bouheret and Bernier 2018). The primary circuit exchanges energy with the ground, while the secondary circuit exchanges energy with the conditioned space (e.g. building).

The motivation of this research work is to improve the knowledge on the global efficiency of geothermal installations (as renewable energy systems) promoting their use in buildings for cover heating and cooling needs towards climate neutrality. It is mandatory to improve the energy performance of buildings eliminating the use of fossil fuels for energy purposes such as heating, cooling and others. It is common knowledge that CO_2 emissions have been increasing every year as a result of the energy consumption generated by fossil fuels with emphasis on the buildings sector. Therefore, the use of renewable sources of energy, such as geothermal, are considered among the best strategies to achieve sustainability in the buildings sector with evident benefits to reduce energy consumption as well as the related CO_2 emissions (Roka et al. 2023).

2. Methodology

The present work is divided into four main topics organised with the following structure:

- Whole building dynamic simulation: EnergyPlus® software was used to estimate the energy needs for heating and cooling demand;
- Underground temperatures data collection: a total of 15 boreholes were instrumented with vertical profiles of temperature sensors;
- Geothermal system simulation: using real data from the monitoring as well as, the energy needs estimated using the whole building dynamic simulation;
- Different scenarios analysis: this step was divided into two sub-tasks (1 – simulation changing individual parameters; 2 – parametric analysis combining different parameters).

The geothermal systems simulations were conducted by the software HyGCHP® (Hybrid Ground-Coupled Heat Pump). This software is available in open-source and was developed by the Energy Center of Wisconsin with the assistance of the University of Wisconsin Solar Energy Laboratory in 2011. The main inputs for HyGCHP® are: building information (details about the building's size, layout, and occupancy), geothermal parameters (information about the site's geology, soil properties, and available land area for ground loop installation) and heat pump system specification. The principal outputs are: the heating and cooling performance, the ground loop performance and information on the efficiency of heat exchange. The Ground Heat Exchanger only (GHX-only), a specific calculation model of this software, was adopted for the case under study in this paper. The used methodology is schematically depicted in Fig. 1.

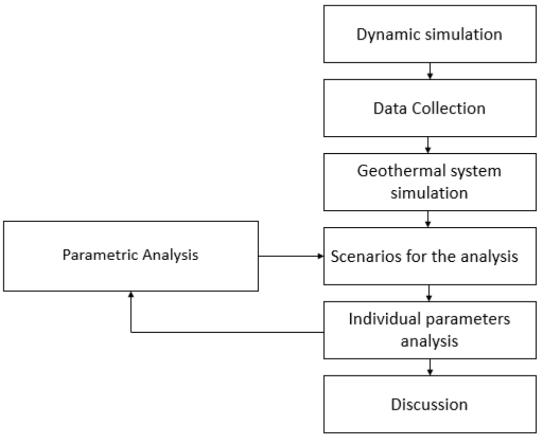


Figure 1. Schema of the used methodology.

3. Case study: identification

Currently, the University of Aveiro has five buildings equipped with shallow geothermal systems. One of those buildings is the CCCI ("Complexo das Ciências de Comunicação e Imagem", in Portuguese) building, in which a full monitoring system has been installed to collect data regarding the temperature in depth in several boreholes (Fig. 2).

Figure 2. CCCI building (20mx80m floor area) location at the University of Aveiro campus.

3.1. Location

The building under study (CCCI) which is shown in Fig. 3, is located on the campus of the University of Aveiro at about 10 km away from the Atlantic coast in the centre-north of Portugal's mainland. The location of Aveiro city in the Portugal map is shown in Fig. 4.

Figure 3. The building under study: south and west façade views.

Figure 4. Aveiro city location.

Regarding geology, the building CCCI is located in a flat morphology of the Aveiro estuary between 10 $^{-1}$1 m depth. The geological surface could be characterized by the occurrence of cretaceous materials, with deposits of old beaches and fluvial terraces. The performance of the building's piles and boreholes depends on the characteristics of the soils, thus a physical characterization was performed during the construction period. The results reveal that there is a layer of claystone until 90 m of depth. Also, it was revealed that there is a layer of clayed sand between the 90 m and 132 m depth). The level of water was found at 2.0 m depth. The information regarding soil properties could be detailed consulted in (Néri 2016).

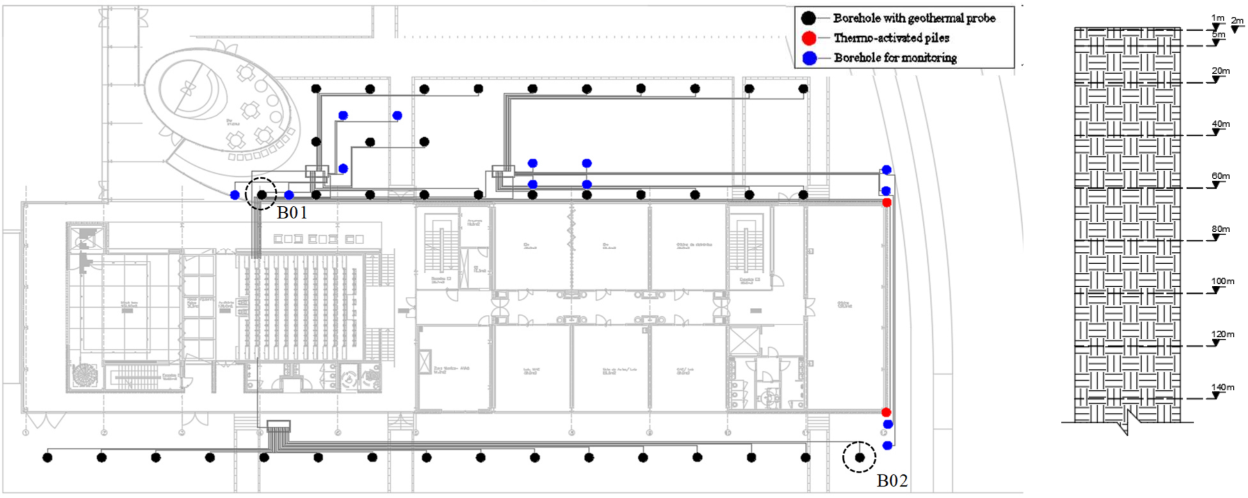
The climate is characterized by a warm-summer Mediterranean climate, some respective data are depicted in Table 1. The average annual temperature is 15.3 °C and the daily ranges can be up to 15 °C (Table 1).

Table 1. Current Aveiro climate data.

	Winter	**Summer**
Climate zone	i2	v2
Heating degree days on the base of 18°C	1337	…
Season length (month)	6.3	4
Average temperature	9.5° C	20.6°C

3.2. Building characteristics

The gross area of the building is 5490 m^2 which is divided into 4 levels (1 underground partial level, a ground floor, and 2 elevated floors). The geothermal system with GSHP is applied to the building for the heating and cooling demands (Fig.5). The coefficient of performance (COP) of the heat pump is 4.5. This system comprises 53 boreholes (each borehole has 150 mm diameter and 130 m depth) and also 2 foundation piles, that include heat exchange pipes (ground heat exchangers) usually known as ''thermoactive pile foundations'' or ''energy piles''. The piles have 600 mm diameter and 10 m depth.



(a) (b)

Figure 5. Monitoring plan: (a) boreholes plan distribution; (b) schematic view of a cross section.

3.3. Constructive solutions: thermal characterization

The main properties of the building envelope, have the following characteristics:

- Slabs are composed of a massive structure of concrete, with a grid of pipes, constituting a thermally activated structure. These slabs are suitable for the heat and cooling exchange process;

- External walls are composed of a double brick wall with an air gap partially filled with thermal insulation;
- Translucid envelop, is composed of windows with high efficiency and low thermal conductivity.

The main properties of the building constructive solutions are presented in Table 2 (Figueiredo et al. 2019).

Table 2. The main properties for the envelope solutions.

Constructive element	Insulation thickness (mm)	U value (W/m^2 °C)
GF slab*	-	0.40
Flat roof	40	0.78
External walls	60	0.38
Windows and doors	-	1.70

*GF – Ground floor

Despite reasonable envelope thermal characteristics, the objective of this work is to assess the potential of using geothermal energy to make buildings more energy efficient.

4. Results and discussion

This section is organized by presenting the following sequence of activities:

a) Parameters: list and range definition of the different parameters under study, to evaluate the improvements of energy efficiency considering the influence of single parameters change;
b) Building loads estimation: Energy Plus software was used to estimate the building loads for heating and cooling;
c) Reference building results: characterization of the overall system consumption considering the values of the original parameters, used in the real building construction and installed system;
d) Improved performance of the building: due to characterizing each parameter individually;
e) Improved performance of the building: combining different parameters through the development of a parametric combination.

4.1. Parameters

A parametric analysis was performed considering new suggested values of the parameters of the GHE, mainly for the borehole radius, ground temperature, drilling depth, U-tube size, grout thermal conductivity, ground thermal conductivity, ground thermal diffusivity, bore spacing, and the header depth. Those new suggested values are different from the original ones that have been used for the original simulations, corresponding to the original parameters used in the real building. It was expected that by changing some of those parameters, the total energy efficiency of the GHE system might be enhanced.

Table 3. The reference and the parametric values applied in the system.

Parameter	Reference values (a)	Parametric values (b,c,d)
Ground temperature	16 (°C)	15; 17;18 (°C)
Borehole Radius	0.075 (m)	0.100; 0.125; 0.150 (m)
Drilling depth	130 (m)	200; 300; 350 (m)
U-Tube size	25 (mm)	20; 32; 63 (mm)
Grout thermal conductivity	0.741 (W/m·K)	1.55; 1.05; 2.42 (W/m·K)
Ground thermal conductivity	2.401 (W/m·K)	3.2; 1.65; 0.8 (W/m·K)
Ground thermal diffusivity	0.090 (m^2/day)	0.043; 0.10; 0.12 (m^2/day)

4.2. Building loads

The heating and cooling loads applied to the system were calculated using a building model that is decoupled from the details of the heating and cooling equipment. This corresponds to operating the equipment using energy rate control and implies that the equipment is adequately sized to meet the peak load experienced by the building. This approach is necessary to allow the optimization routine to design the heating/cooling system. The obtained file from the Energyplus software for the building loads (in this case study) includes data for 8760 hours (hourly time step) that make up the year. The data includes values at each hour for the total cooling load required by the building; the total heating load required by the building; the average ambient temperature; and the average wet bulb temperature. These data are saved and well analysed as presented in Fig.6.

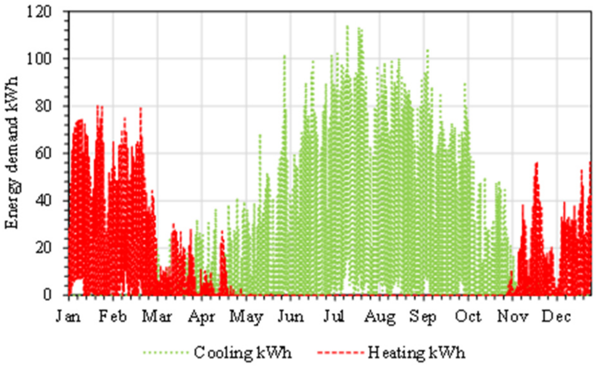


Figure 6. The data obtained for the building loads from EnergyPlus software.

4.3. Results for the reference building

After being properly set all the previous parameters according to the real installation, the simulation using HYGCHP software was performed. The yearly amount of total energy consumption for heating and cooling was estimated as 119972 KWh to supply thermal comfort to the building occupants (considered between 20-25ºC). The energy needs for heating and cooling and the average annual temperature are shown in Fig. 7. The results showed that the system is not significantly affected by falling temperatures, requiring only a small amount of energy to warm the building in the winter season. The maximum peak of heating consumption takes place in January with temperatures lower than 10 °C and the value of the energy consumption is found to be equal to 193.74 kWh. Regarding cooling, the peak energy takes place in August with a value of 7841.27 kWh and with outdoor air temperature higher than 31°C.

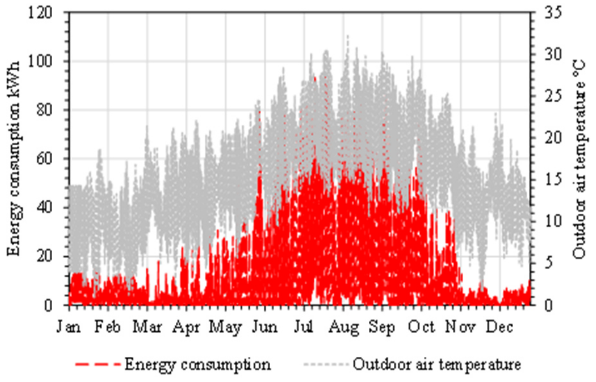


Figure 7. Energy needs (kWh) and average annual temperature.

4.4. Results considering the new parameters ranges

A new simulation was run for each new value of the parameters. The obtained results for each case are compared to the results of the reference building. In other words, the objective of this process is to evaluate the effect of each parameter on energy consumption to choose the best parameter value to get the minimum energy consumption. The results in terms of energy, for the investigated range of values for each parameter is presented in Fig. 8.

Different new values of the parameters were used for the simulations by HYGCHP software, representing different scenarios to improve the performance of the system. Then, the results obtained were verified regarding the total energy consumption of the system, in comparison with the use of the original values. The results of the simulations showed that energy consumption decreases when:

- The borehole radius decreases;
- The ground temperature decreases;
- The ground thermal diffusivity decreases;
- The depth of the drilling increases;
- U-Tube size increases;
- The grout thermal conductivity decreases;
- The ground thermal conductivity decreases.

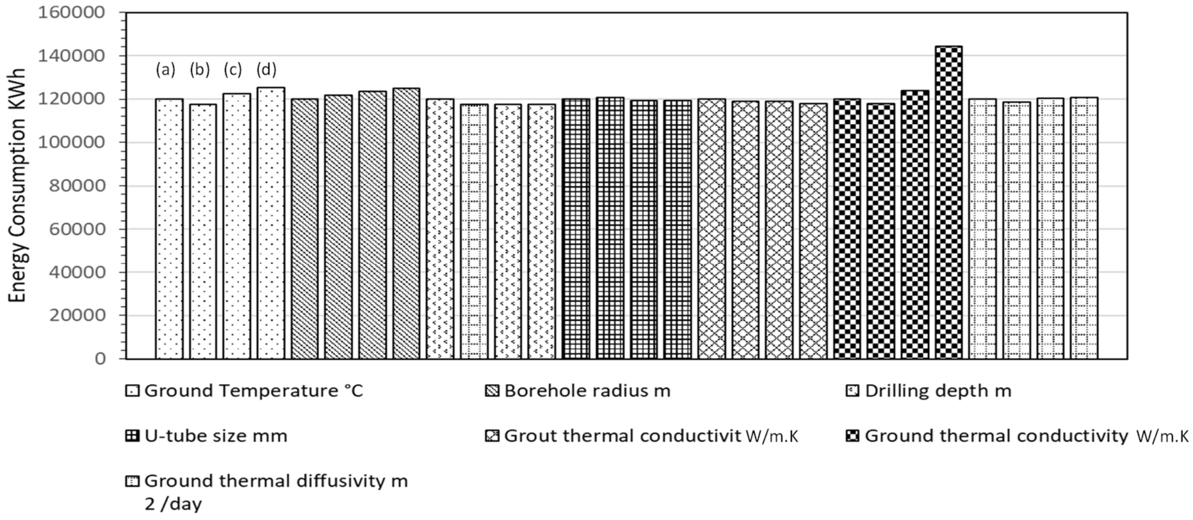


Figure 8. Energy consumption evaluation after changing the ground temperature.

4.5. Parametric analysis

After analysing the individual results, a parametric analysis was performed changing the parameters with a higher influence on the system performance. The summary of the results in terms of annual energy consumption is shown in the Fig. 9. Three main parameters were chosen as they were found to have a big influence on the system performance for different values. The parameters are the ground temperature, the U-Tube size, and the ground thermal conductivity. Then those parameters were applied as shown in the hierarchy below. After conducting the simulations for all the values (keeping the other parameters the same in the original one), the results were obtained and showed the minimum energy consumption is 112975.5 KWh which is inferior to the original one (119972 KWh) resulting in 5.9 % of reduction. Depending on the results, the best values of the considered parameters (the chosen ones) for the building under this study are:

- The ground temperature is 14 °C;
- U-Tube size is 32 mm;
- The ground thermal conductivity is 3.2 (W/m.K).

Choosing the best scenario to get the minimum energy consumption to acclimate the building required trying more different values and more different scenarios. The results of the conducted simulations showed that the minimum energy consumption (equal to 112975.5 KWh) is obtained when the ground temperature was chosen as

14°C, U-Tube size was chosen as 32 mm, and the ground thermal conductivity was chosen as 3.2 W/m.K.

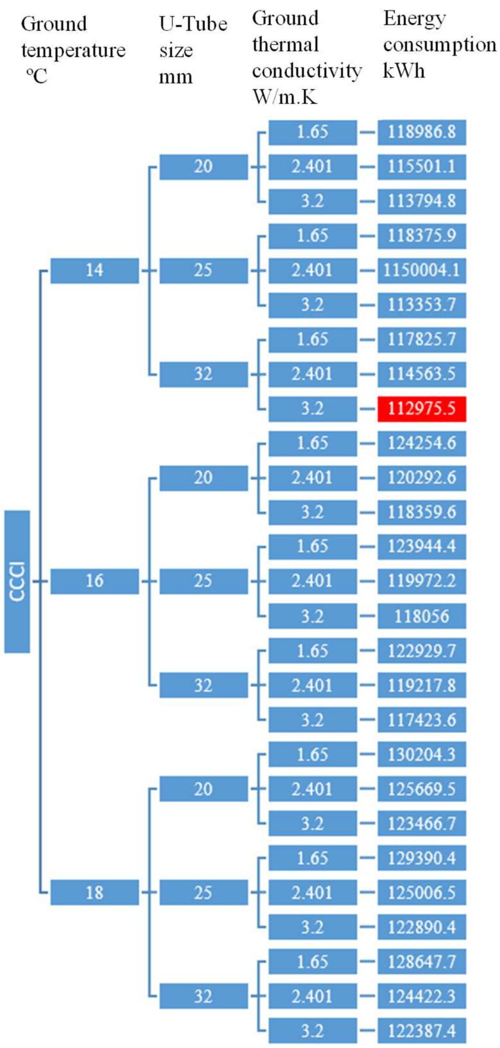


Figure 9. Energy consumption of the parametric analysis

5. Conclusions

This work intended to analyze the improvement of the performance of geothermal systems towards a climate neutrality by using these systems to reduce the heating and cooling needs in the buildings sector. The results showed that the total energy consumption needed in this building is equal to 119972 kWh for an annual operating cycle. From the results of the simulation, it was defined that the peak power for both heating and cooling in one year (for heating mode it was in January - 193.74 kWh, and for cooling mode was in August - 7041.27 kWh). Also, it was concluded that the cooling demand and peak load for the acclimatization of the building were higher in the cooling mode of the system. The geothermal system parameters were optimized and simulated by HYGCHP software and evaluated using different scenarios. Then, the results obtained from each scenario were analyzed including the total energy consumption in comparison with the original scenario. Regarding the results, it was concluded that the energy consumption decreases with lower values of some parameters (the borehole radius, the ground temperature, and the ground thermal diffusivity) and increasing the other ones (the depth of the drilling, the U-Tube size, the grout thermal conductivity, and the ground thermal conductivity). Finally, the best scenario was defined as the one that achieves the minimum energy consumption to acclimate the building under the study. Therefore, the minimum energy consumption (equal to 112975.5 kWh) was achieved when the ground temperature was chosen as 14°C, the U-Tube size 32 mm, and the ground thermal conductivity as 3.2 W/m.K, presenting the best scenario for saving energy in the building. The conducted work in this research is an important step toward the use of the geothermal system as a renewable and sustainable energy technology (for acclimatization purposes in buildings) to make buildings more energy efficient and environmentally friendly.

Acknowledgments

The authors acknowledge the financial support provided by the FCT (Portuguese Foundation for Science and Technology) under Project GeoSustained (PTDC/ECI-CON/1866/2021); and to EEA Grants Portugal & Norway Partnerships for Innovation Project Store2Sustain - FBR_OC2_31 (Shallow geothermal system integration with underground thermal energy storage for a sustainable heating and cooling); and Aveiro Research Centre for Risks and Sustainability in Construction (RISCO), Universidade de Aveiro, Portugal [FCT/UIDB/ECI/04450/2020].

References

Bouheret, S., Bernier, M. 2018. “Modelling of a water-to-air variable capacity ground-source heat pump” Journal of Building Performance Simulation 11 no, 283-293, https://doi.org/10.1080/19401493.2017.1332686

DNV GL Annual Report 2018. Retrieved September 06, 2022, from https://www.dnv.com/publications/dnv-gl-annual-report-2018-145535

Figueiredo, A., J. Lapa, C. Cardoso, J. Macedo, F. Rodrigues, A. Vieira, A. Pinto, and J. R. Maranha 2019. "Shallow geothermal systems for Aveiro University departments: a survey through the energy efficiency and thermal comfort", Proceedings of the XVII ECSMGE-2019, https://doi.org/10.32075/17ECSMGE-2019-0583

Goncalves, S. Khalip, A. and Kerry F. 2023. “Portugal to speed up switch to renewable power in wake of Ukraine War”, 2022. Reuters. Retrieved March 13, , from https://www.reuters.com/business/sustainable-business/portugal-speed-up-switch-renewable-power-wake-ukraine-war-2022-04-01/

IEA. 2019 “Roadmap for carbon neutrality 2050 (RNC2050) – policies”. IEA. Retrieved on March 13, 2023, from https://www.iea.org/policies/12026-roadmap-for-carbon-neutrality-2050-rnc2050

Niza, I. L., Luz, I. M. da, Bueno, A. M., and Broday, E. E. 2022. “Thermal Comfort and Energy Efficiency: Challenges, Barriers, and Step towards Sustainability”. Smart Cities, 5, no. 4, 1721–1741. https://doi.org/10.3390/smartcities5040086

Néri, C. 2016. “Study of Mechanical Behaviour of soils under the influence of Geothermal Systems”. Master degree thesis, Aveiro University, Aveiro, Portugal, (*in Portuguese*).

Roka, R.; Figueiredo, A., Vieira, A., Cardoso, C., 2023. A systematic review on shallow geothermal energy system: a light into six major barriers. Soils and Rocks 46, no1, 1, https://doi.org/:10.28927/SR.2023.007622

Silva, L. 2022. “Energy in Portugal: Where does Portugal get its energy from?”,. Retrieved March 13, 2023, from https://www.portugal.com/science/energy-in-portugal-where-does-portugal-get-its-energy-from/?cn-reloaded=1

Ürge-Vorsatz, D., Cabeza, L. F., Serrano, S., Barreneche, C. 2015. “Heating and cooling energy trends and drivers in buildings”. Renewable and Sustainable Energy Reviews 41, 85–98, https://doi.org/10.1016/j.rser.2014.08.039

World Bank Blogs. 2015. “The future of the world's population in 4 charts”. Retrieved September 06, 2022, from https://blogs.worldbank.org/opendata/future-world-s-population-4-charts

Yang, X. J., Hu, H., Tan, T., and Li, J. 2016. China's renewable energy goals by 2050. Environmental Development, 20, 83–90. https://doi.org/10.1016/j.envdev.2016.10.001