Modelling of Shaded and Unshaded Shallow-Ground Heat Pump System for a Residential Building Block in a Mediterranean Climate

M Bottarelli[1], **C Yousif**[2]

[1] University of Ferrara, Via Quartieri 8 – 44121 Ferrara, Italy
[2] University of Malta, Barrakki Street, Marsaxlokk, MXK 1531, Malta

Corresponding author: michele.bottarelli@unife.it

Abstract. Heat pumps may be coupled to shallow-ground geothermal fields and used for the purpose of space heating and cooling of buildings. However, quite often it is not possible to locate the geothermal field in cleared grounds, especially in cities where building density is high and land has a high premium. This leads to the possibility of burying the geothermal field under the basement of new building blocks, before construction of the building.
In the present work, the shaded-unshaded arrangement is numerically studied by coupling the software DesignBuilder-EnergyPlus to assess the building's energy requirement with the software FEFLOW to solve the heat transfer equation in porous media. Assuming a standard residential building block, the coupling between the two software is performed by assigning the thermal energy requirement for air conditioning, as calculated by EnergyPlus, to a flat-panel typology of ground heat exchanger simplified in a 2D FEFLOW's domain.
The results show that it is necessary to opt for a dual-source heat pump (air/geothermal) system to ensure that the ground is not frozen or over-heated at peak times and to improve the overall performance of the system.

1. Introduction

The dawn of the EU Energy Performance in Buildings Directive Recast 2010/31/EU has put new demands on new and renovated buildings to achieve zero net-energy buildings by 2021, while at the same time, one is witnessing greater importance being given to energy storage, which in this case is the underground thermal energy storage (UTES). For that scope, ground-coupled heat pumps (GCHPs) are commonly depicted as energy efficient systems for air conditioning [1].

But, whereas the use of GCHPs is widespread in Northern Europe, they are still quite uncommon in Southern Europe. So far, the most common system is the reversible air-source heat pump.

Solar systems can easily satisfy the heating and cooling demands of single storey building blocks, which generally have relatively low energy demand and sufficient roof space area to install solar systems to counter-balance their energy consumption and bring them to near zero-energy status. However, the situation could be completely different in urban areas, where multi-storey buildings are more common due to the high value of land and it would not be profitable for the developer to limit the number of storeys. Furthermore, the available roof space and possibly part of the façade would not be sufficient to offset the total energy demand of the building, even when it is built with the highest energy efficiency standards.

In such cases, the building's footprint could be used for shallow-ground thermal energy storage to be exploited for air conditioning of the building block [2], albeit the fact that the building's footprint does not see the sun, which may reduce the final ground energy balance. Consequently, the use of a traditional GCHP coupled to shallow-ground heat exchangers may not be suitable, whereas a dual-source heat pump (DSHP) combining the air-source with the ground-source could be a good compromise [3,4,5], because it would have the potential of minimizing the size of the ground heat exchanger and utilise the underground thermal energy storage more effectively, while preventing frosting at times of low ground thermal energy [6,7,8].

The present paper reports the numerical analysis of a so-called dual-source heat pump (DSHP) in shaded and unshaded conditions, as a first step for future studies in urban cities.

2. Methodology

In the present contribution, a numerical analysis is carried out for the behaviour of a very shallow ground heat exchanger system coupled with a so-called dual-source heat pump (DSHP), which is able to switch between air and ground heat source/sink, according to the best availability. As a consequence, a DSHP can also help to keep the size of the ground heat exchanger system smaller than that when only the ground-source is used. Here, the ground heat exchanger system was assumed to be buried only a few meters below the slab foundation of a four-storey residential building, located in an urban area and hence surrounded by other building blocks. Therefore, the DSHP has been chosen because the heating and cooling demand per square metre is quite high, as a consequence of building typology and its urban location.

The energy requirement for space heating and cooling was calculated by the software DesignBuilder (DB) coupled with the energy model EnergyPlus, for two different locations (Malta and Ferrara, Italy), which represents a Mediterranean and a continental climate, respectively. Then, the resulting thermal loads in terms of hourly time series were imposed in a 2D finite elements model implemented in FEFLOW software, to evaluate the heat transfer in the ground and to determine the temperature of the working fluid and the energy share of air and ground thermal exploitation.

2.1. DesignBuilder-EnergyPlus Model

DesignBuilder software is one of the most popular graphical interfaces to EnergyPlus software, which is one of the most known energy simulation software tools to model the energy use and thermal loads throughout the building. EnergyPlus is a combination of the best capabilities and features of the previous DOE-2 and BLAST models [9,10].

One of the interesting features of EnergyPlus is that it has taken the approach of organising software tools in modules that can easily work together or separately. Given that EnergyPlus had no visual interface up to a few years ago to allow users to draw and see the building, it was necessary to link it up with a third-party software tool, which is DesignBuilder [11]. DesignBuilder has an extensive library of building materials, which makes the input of components faster. ACAD drawings can be imported into DesignBuilder or otherwise drawings can be created directly into the software itself using 3D elements. Building blocks can also be cut, stretched and partitioned into zones [12].

The building block comprises of semi-basement garages, 3 elevated ground floor apartments, 3 first floor apartments, 3 second floor apartments and 2 top floor penthouses. The building has an average floor area of 100 m² per apartment, except for the top 2 penthouses that have around 125 m² each.

Figure 1 shows the details of the building block as follows:

1. The elevated ground floor apartments have an exposed floor to underground garages.
2. The first floor apartments are fully surrounded by buildings and only have the front, back and central walls exposed to the ambient.

3. The second floor apartments are similar to the first floor apartments but have some more exposed walls on the eastern and western parts as well as part of the ceiling of the front rooms, given that there are terraces on top of them.
4. The penthouses are practically exposed from all sides but have an insulated roof, in accordance with the minimum energy performance requirements as set in the Technical Guidance F for Minimum Energy Requirements in Maltese buildings [13].

The total ground floor area covered by the apartments amounted to 405 m² and this is the area under which the shallow-ground geothermal field is placed, as explained in Section 2.2 below. The total floor area of all the floors is 1621 m², out of which 1,188 m² is conditioned space, while the remainder is the unconditioned space in the common areas and lifts. The set point temperature for the conditioned space was 21 °C for winter and 24 °C for summer. However, the operation of the air-conditioning system was set to match the activity schedule of the occupants. This was set as 07:00-09:00 and 16:00-23:00, which would reflect the lifestyle of a typical working family.

Figure 2 shows the percentage distribution of energy consumption of the main four sectors, namely, space heating, space cooling, lighting and water heating. In this case, only natural ventilation is assumed and hence there are no mechanical fresh air systems. Also, it is assumed that the building has no renewable energy installations. It is clear now that in residential buildings, energy used for space cooling and heating is the bulk amount of energy consumed and one has to focus on reducing it.

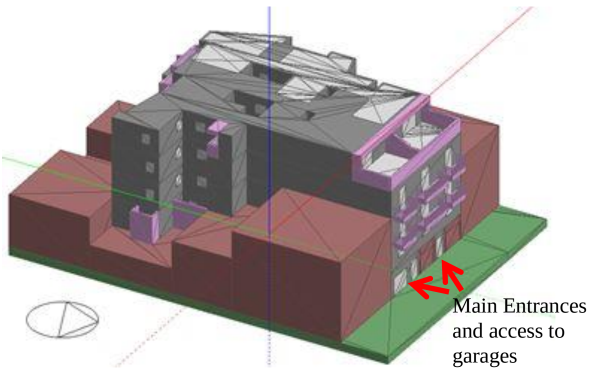

Figure 1. A pictorial demonstration of the building block, with two main entrances and the entrance to the underlying garages.

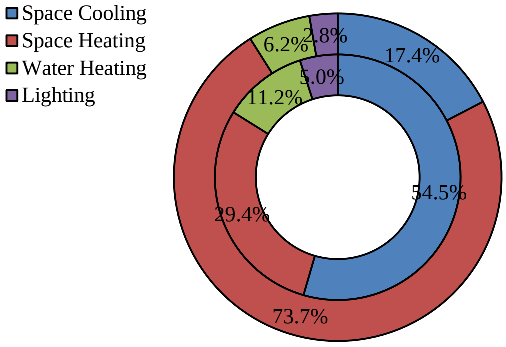

Figure 2. Percentage distribution of energy consumption for Malta (inner doughnut) and Ferrara (outer doughnut).

The building materials for this apartment block are summarized in Table 1. Following the construction of the building block in DesignBuilder, as shown in Figure 1, other input parameters were made according to the specific characteristics of the building. This included the thermal properties of all walls, floors, roofs, windows and doors, as well as all the operational schedules for occupancy and usage of different systems together with the set point temperatures for heating, cooling and water heating and finally the characteristics of all the energy services within the building. One is to note that the construction of this building block does not include any energy efficient measures and the U-values of the building envelope are high. Therefore, this study would give us an idea about the worst case scenario under such circumstances.

Figure 3 shows a comparison between the ambient temperatures in Malta and Ferrara, respectively. It is clear that although the winter temperatures in Ferrara do fall below 0°C, it never drops below 6°C in Malta. At the same time, there are several weeks when the temperatures are quite high in July and August.

A number of scenarios were run in DesignBuilder using the weather data files for Malta and Ferrara. Hourly heating and cooling demands for both models were calculated in DesignBuilder. The weather data for Malta was tailor-made because the default Malta file in DesignBuilder actually refers to Cozzo Spadaro, which is in the nearby island of Sicily. However, it was previously shown that the weather there does not represent that of Malta [14]. The results for the simulations are shown in Figure 4, which are the actual thermal energy requirements for heating and cooling the building. These results served as input values for the design of the dual-source heat pump system. It is to be expected that the heating demand for Ferrara is higher than that for Malta, given that the ambient temperature in winter is much lower there. However, it is interesting to note that the cooling load for Ferrara has reached that in Malta for a significant number of weeks, between June and August. This can be explained by the fact that Ferrara has a continental climate with extremes in weather conditions being experienced in winter and summer, while Malta has a Mediterranean climate and is surrounded by the sea, which moderates temperature swings.

Table 1. Technical description of the building's major envelope elements and materials.

	Actual U-value (W/m^2K)	**Description**	
External façade	1.513	limestone blocks	180 mm
		air cavity	30 mm
		limestone blocks	180 mm
		lightweight plaster	6 mm
Unconditioned walls and Internal walls	2.040	lightweight plaster	6 mm
		hollow concrete blocks	230 mm
		lightweight plaster	6 mm
Other external walls	2.067	lightweight plaster	6 mm
		hollow concrete blocks	230 mm
		lightweight plaster	6 mm
Floor and ceiling	2.059	lightweight plaster	6 mm
		reinforced concrete	200 mm
		screed	100 mm
		ceramic tiles on floor	12 mm
Main door	3	solid wooden door	35 mm
Windows and doors	6	Single glazing with aluminium frame (no thermal break)	
Façade door	4	Double glazing with 6mm air gap and aluminium frame (no thermal break)	

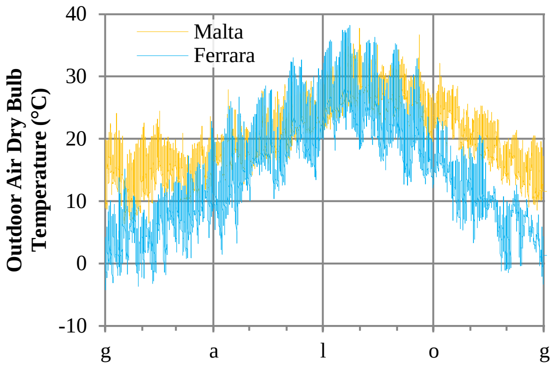

Figure 3. Distribution of external dry bulb temperature in Malta and Ferrara, Italy.

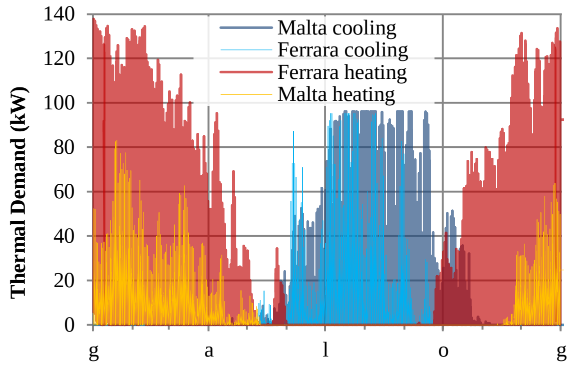

Figure 4. Hourly heating and cooling demand for the building block under the weather climate of Malta and Ferrara, Italy.

2.2. FEFLOW model

FEFLOW is an advanced commercial software that apply the finite element approach for solving flow, heat and mass transfer in porous media, variously saturated and non-homogeneous [15]. In the present study, FEFLOW is used to solve the ground heat transfer through a flat-panel system installed under the building's foundation, and as constrained by the thermal loads resulting from the DesignBuilder analysis. For simplicity, the thermal requirement is here fully applied on the geothermal system, neglecting the reduction driven by the coefficient of performance of the heat pump. As ground heat exchanger, the flat-panel (FP) is innovative and very effective, due to its large surface area that is in contact with the ground to perform the heat transfer process [16]. Its geometry was here implemented into a 2D domain, schematizing a vertical cross-section of heat exchangers and ground laid under the building, as shown in Figure 5. For the purpose of saving simulation time, only half of the building façade was considered (6.75m), thus assuming symmetric the performance.

Flat-panels were considered to be 3m high, vertically installed in a trench 40cm wide and running for the full depth of the plot area of 30 metres. The spanning distance between one trench and another was 1.7m, respectively, according the methodology reported in [17] compared with the very small footprint available. Thermal properties of soil were selected according to [18], taking into account the most widespread shallow lithology of Malta (globigerina limestone) and Ferrara (silty loam). Similarly, the backfill materials were assumed to be of similar material, but partially modified to represent sand (Malta) and sieved loam (Ferrara). All properties are reported in Table 2.

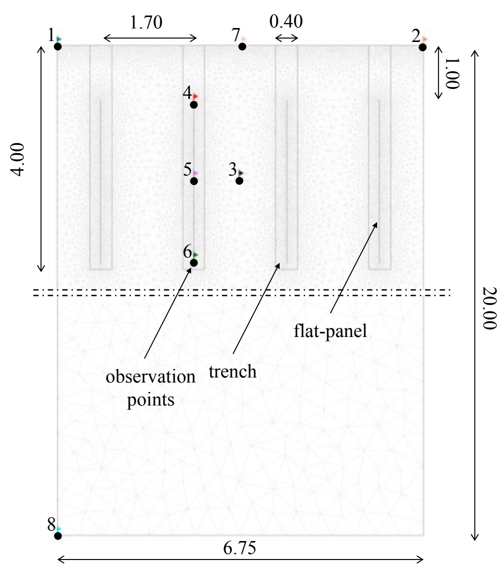

Figure 5. 2D domain and mesh

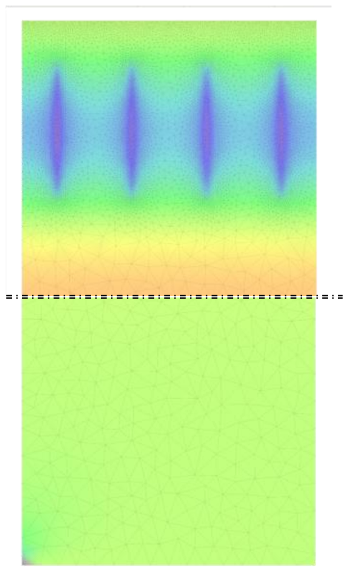

Figure 6. Representative thermal field in winter

Table 2. Ground material characteristics data

Parameter	Malta		Ferrara	
	soil	backfill	soil	backfill
Porosity, [%]	0.1	0.3	0.3	0.3
Density,[kg m^{-3}]	2500	2000	1800	1800
Thermal conductivity, [W m^{-1} K^{-1}]	2.7	2.0	0.8	1.0
Specific heat, [MJ m^{-3} K^{-1}]	2.2	1.6	1.5	1.6
Hydraulic conductivity, [m $year^{-1}$]	10	3000	10	100

To minimize numerical errors and reduce the computational time, the size of the finite elements was chosen to be fine for the area surrounding the foundation and coarse for the area far from it. The mesh independence of the full final mesh (20,000 finite elements, Figure 5) was checked by doubling the number of elements, without observing significant differences in the resulting temperatures at selected observation nodes.

The vertical sides of the domain were considered adiabatic, because of the symmetry and the adjacent abutting buildings, which were assumed to have the same underground system. Two cases were considered for the top part of the domain, which represents the bottom side of the foundation slab:

– an adiabatic condition, which represents the shaded configuration of the heat exchangers, when installed under the building's footprint, and
– a 1° kind boundary condition; which represents a simplified unshaded condition, similar to a standard installation outdoors. In this case, the hourly time series of the local air temperature (Malta, Ferrara) was assigned, as an approximation of the seasonal weather conditions that only partially affect the heat transfer process on shallow ground heat exchangers, as reported in [16].

The groundwater level was considered 2.0 m deep for the soil surface only for Ferrara, whereas dry condition was assumed for Malta. Finally, the average local air temperature (Malta: 20.3°C; Ferrara: 15.6°C) was assigned to the far bottom side of the building's ground at a depth of 20m.

In order to control the switching between air and ground heat sources/sinks, an user-defined sub-routine was programmed in C^{++} and uploaded as a plug-in module in FEFLOW. The working logic was controlled by the air and average flat-panel temperatures. The average of the panel temperature was taken as the mean of the observation points 4, 5, 6 (see Figure 5). When the flat-panel temperature was energetically more advantageous than the outdoor air temperature, the plug-in sub-routine switches the DSHP to utilize the geothermal resource. The actual energy requirement of the building was then used as a heat flux (boundary condition of 2nd kind). Otherwise, the plug-in triggered the usage of the air source for the DSHP, and in this case, the above boundary condition was removed.

The heat flux ($\dot{h}$) applied at the flat-panels was calculated by dividing the building's thermal requirement ($\dot{H}$) by the full heat transfer surface, taking into account the symmetry of the domain (*2*), the number (n), the length (L) and the height (h) of the flat-panels, as follows:

$$\dot{h} = \frac{\dot{H}}{2 \cdot n \cdot L \cdot h} \tag{1}$$

3. Results

Based on the DesignBuilder simulation outputs for Malta and Ferrara, it is clear that the heating and cooling loads are not balanced for both sites, as shown in Figure 7. Malta requires more cooling than heating, while Ferrara needs more heating than cooling.

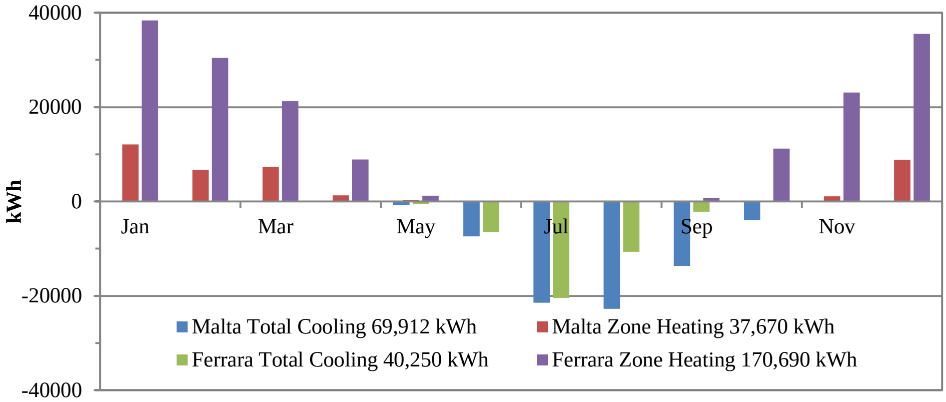

Figure 7. Monthly thermal energy demand for the building block in Malta and Ferrara (cases 1,2).

Four cases were simulated in FEFLOW, taking into account the following heat flux at the flat-panel system:

– the full energy requirement as calculated by DesignBuilder, and applied at the flat-panels (3 m) in *unshaded* conditions taken (*case 1, reference unshaded case*);

- the full energy requirement as calculated by DesignBuilder, and applied at the flat-panels (3m) in the *shade* (*case 2, full shade case*);
- Meeting 50% of the full load energy requirement, and applied at the flat-panels width (3m) in *shaded* conditions (*case 3, shade case with reduced energy load at flat-panel*);
- Meeting 50% of the full load energy requirement, and applied at reduced flat-panels width (1m) in *shaded* conditions (*case 4, shade case with reduced energy load and heat transfer surface at the flat-panel*).

The first case represents a standard installation (*unshaded*), which is taken as the benchmark for comparison purposes. The second case represents the equivalent installation in urban conditions, whereby the flat-panel is buried under the building's footprint (*shaded*). The third case represents the case of reduced energy demand, which could be achieved if the building block was built to higher energy efficiency standards. The fourth case was proposed to evaluate the extent to which the reduction of heat transfer surface would affect the performance of the system, because of a smaller and therefore a cheaper installation (*shaded, reduced energy load, reduced heat transfer surface*). All cases were run for four consecutive years starting from an undisturbed initial condition, until the ground reaches steady temperature trend and thus one would check for any thermal drift in the ground.

The results are summarized in Table 3 and Figure 8 for the cooling season, and Table 4 and Figure 9 for the heating season, where:

- *System average load* is the average thermal power for air conditioning;
- *System max load* is the maximum thermal power for air conditioning;
- *Seasonal energy* is the overall thermal energy for air conditioning;
- *Average specific load FP* is the average heat flux at the flat-panel;
- *Max specific load FP* is the maximum heat flux at the flat-panel;
- *FP energy* is the overall energy exchanged per square metre of flat-panel;
- *FP load energy factor* is the energy share for air conditioning covered by the flat-panel;
- *AIR-FP hour degrees* is hourly seasonal sum of the difference between the temperature at the flat-panel and the air, when the flat-panel is operating;
- *Tmed FP when FP is ON* is the average temperature at the flat-panel when in operation;
- *Tmed AIR when FP is ON* is the air average temperature when the flat-panel is operating;
- *FP time ON* are the operational flat-panel hours;
- *System time ON* are the air conditioning system hours operating;
- *FP share* is the share of the flat-panel operating hours.

For Malta, the share of thermal energy required is 35% for heating and 65% for cooling of the overall energy demand for air conditioning (Tables 3 and 4); for the case of Ferrara, the heating share is 81%, and the cooling share is 19%.

Taking into account the results shown in Figures 8 and 9, Malta shows an enviable mild climate, having on average air temperature between 15°C and 30°C, whereas a harsh continental climate is depicted for Ferrara, where the temperature moves from less than 5°C to more than 30°C. The case 1 is always the worst condition in terms of average working fluid temperature, because it is unable to preserve the thermal energy storage of the summer season for its exploitation during the winter season, and vice versa. On the other hand, the underground thermal energy storage carried out by the adiabatic condition over the soil surface is well depicted by the straight slopes of all other cases, both in spring and in autumn for Malta. For Ferrara, that is clearly only occurring in spring because the low cooling requirement during summer (low operational hours of the heat pump) does not transfer sufficient energy to the ground to be utilized in winter. Moreover, the heating season starts as early as October in Ferrara and this means that the little stored energy from summer would be quickly depleted.

For Ferrara, the winter operating time of the FP system does not change significantly among the four cases (34%, 36%, 38%, 33%), even if the average energy load per square metre of FP is quite

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different (64, 64, 32, 96 W/m^2). That happens because the energy exploitation of the ground starts early in autumn and the beginning of winter, when the ground temperature is still high. As a consequence, the FP's high performance in heat transfer can be the cause for the fast depletion of the ground thermal storage. After that, the ground-source is only used by the DSHP when hard weather conditions occur (very low ambient air temperature). With regards to this winter behaviour, the case no.4 would seem to be the most profitable, because of the smaller FP surface area installed. During the summer season, case no.4 suffers due to the quick overheating of the ground surrounding the FPs, and therefore, the temperature reaches the same worst conditions as case no.1, within a span of one month only.

Table 3. FEFLOW cooling season results.

COOLING		*Malta*				*Ferrara*			
		Case 1	*Case 2*	*Case 3*	*Case 4*	*Case 1*	*Case 2*	*Case 3*	*Case 4*
System average load	*kW*	32.5	32.5	16.2	16.2	25.7	25.7	12.9	12.9
System max load	*kW*	96.1	96.1	48.1	48.1	95.2	95.2	47.6	47.6
Seasonal energy	*kWh*	69912	69912	34956	34956	40251	40251	20125	20125
FP load energy factor	-	35%	34%	46%	30%	53%	68%	90%	60%
Average specific load FP	*W/m^2*	45.1	45.1	22.5	67.6	35.7	35.7	17.9	53.6
Max specific load FP	*W/m^2*	133.5	133.5	66.7	200.2	132.3	132.3	66.1	198.4
FP energy	*kWh/m^2*	34.1	33.3	22.4	43.6	29.9	38.3	25.2	50.5
AIR-FP hour degrees	*°C*h*	1964	3629	4252	2999	5398	9693	14937	7439
Tmed FP when FP is ON	*°C*	24.0	21.3	21.6	21.7	19.8	16.3	14.1	17.8
Tmed AIR when FP is ON	*°C*	26.4	25.6	25.8	25.6	26.5	26.3	26.2	26.3
FP time ON	*hours*	806	851	1027	763	805	965	1231	881
System time ON	*hours*	2153	2153	2153	2153	1564	1564	1564	1564
FP share	-	37%	40%	48%	35%	51%	62%	79%	56%

Table 4. FEFLOW heating season results.

HEATING		*Malta*				*Ferrara*			
		Case 1	*Case 2*	*Case 3*	*Case 4*	*Case 1*	*Case 2*	*Case 3*	*Case 4*
System average load	*kW*	17.7	17.7	8.8	8.8	46.2	46.2	23.1	23.1
System max load	*kW*	83.1	83.1	41.6	41.6	137.8	137.8	68.9	68.9
Seasonal energy	*kWh*	37670	37670	18835	18835	170690	170690	85345	85345
FP load energy factor	-	57%	57%	76%	47%	34%	36%	38%	33%
Average specific load FP	*W/m^2*	24.6	24.6	12.3	36.9	64.1	64.1	32.1	96.2
Max specific load FP	*W/m^2*	115.5	115.5	57.7	173.2	191.3	191.3	95.7	287.0
FP energy	*kWh/m^2*	29.7	29.7	19.8	36.9	81.7	84.4	45.5	115.7
AIR-FP hour degrees	*°C*h*	2358	4484	7182	3224	3439	4194	4322	3439
Tmed FP when FP is ON	*°C*	15.8	18.5	19.5	17.7	9.0	10.0	9.9	9.6
Tmed AIR when FP is ON	*°C*	13.1	13.5	13.6	13.4	6.3	6.9	6.9	6.8
FP time ON	*hours*	899	886	1205	743	1266	1348	1422	1249
System time ON	*hours*	2129	2129	2129	2129	3698	3698	3698	3698
FP share	-	42%	42%	57%	35%	34%	36%	38%	34%

In Figure 10 and figure 11 are shown the temperatures at the mid-point of the flat-panel (point. no.3), that is representative of the working fluid of the geothermal closed-loop. In comparison with the air temperature when the FP is operating, the average temperature of the working fluid between the unshaded (case 1) and shaded case (case 2) improves by up to 5.0°C for Malta in the heating season, and 3.1 °C for Ferrara. In the cooling season, the improvement is 4.3°C for Malta and 10.0°C for Ferrara. The last high performance in Ferrara is strictly related to the long heating season, which decreases substantially the ground temperature.

Given that no thermal drift occurs in all cases, the energy balance is compensated by the other boundary condition applied in the 2D domain, that is the fixed ground temperature at 20 metres below the ground.

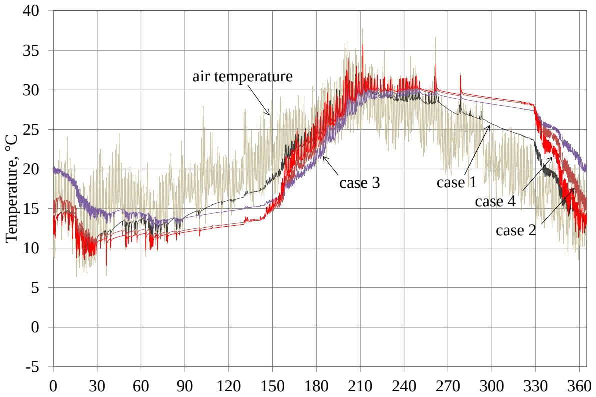

Figure 8: Flat-panel temperature, Malta.

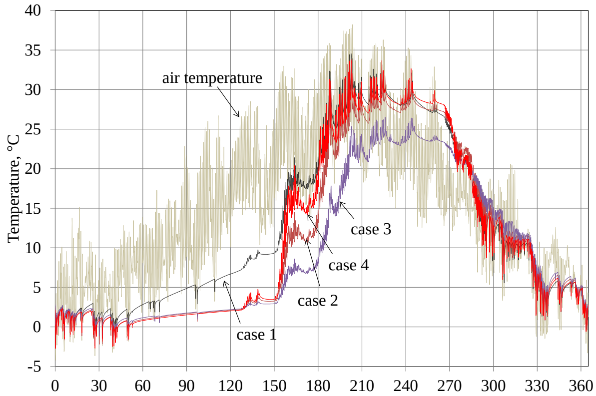

Figure 9: Flat-panel temperature, Ferrara.

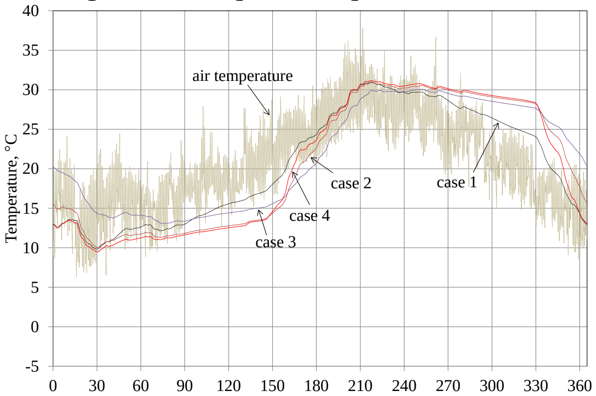

Figure 10. Temperature at mid-point n.3, Malta.

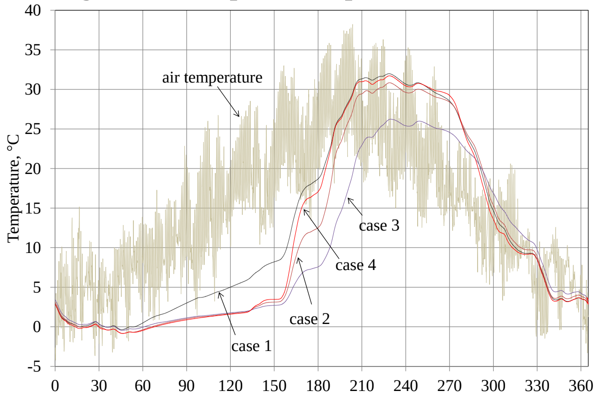

Figure 11. Temperature at mid-point n.3, Ferrara.

4. Conclusions

This paper has attempted to answer the question of whether it is possible to place the shallow ground heat exchangers of a ground-coupled heat pump (GCHP) in the shade, and more specifically under the basement of high rise buildings, without suffering adverse effects such as freezing of the water in the pipes.

The analysis was numerically carried out in two steps. Firstly, the energy requirement for space heating and cooling of a building block was calculated implementing an EnergyPlus model by mean of DesignBuilder; then, the resulting thermal loads were imposed as boundary conditions in FEFLOW, to evaluate the heat transfer carried out by flat-panels in the ground. Two different urban areas were considered to analyse the behaviour according a mild (Malta) and a continental climate (Ferrara, Italy). The building block used purposely a high energy demand for heating and cooling, due to high U-values for walls, windows and floors. As a consequence, preliminary simulations showed that so high thermal loads were not endurable by a common GCHP with shallow ground heat exchangers, and hence it was foreseen a dual-source heat pump (DSHP), which makes use of two thermal energy sources, namely the air and the ground.

With regards of four different scenarios solved, the DSHP was capable of taking up the induced thermal stress in the ground, both in summer and in winter, and to benefit by at least 35% and up to 79% in terms of energy share covered by the geothermal system, according the climate, the energy demand and the sizing of the flat-panels. Moreover, over an extended simulation of four years, the geothermal system suffered no thermal drift in terms of yearly trend, even though the flat-panels were in the shade and the thermal requirement was not balanced over the year.

Therefore, if well controlled, the underground thermal energy storage could be improved and therefore to provide an additional source of renewable energy besides the traditional systems of solar thermal and solar photovoltaic systems.

5. References

[1] Hart, D. P. and Couvillion, R., Earth-coupled Heat Transfer. National Water Well Association, Dublin, OH, USA, 1986.

[2] Luo, Z. and Asproudi, C., Subsurface urban heat island and its effect on horizontal ground-source heat pump potential under climate change *Applied Thermal Engineering* **90** 530-537, 2015.

[3] Bottarelli, M., A preliminary testing of a flat panel ground heat exchanger *International Journal of Low-Carbon Technologies* **8** 2 80-87, 2013.

[4] Vocale, P., Morini, G. L. and Spiga, M., Influence of outdoor air conditions on the air source heat pumps performance *Energy Procedia*, **45** 653-662, 2014.

[5] Jang, Y. J., Bae, H. B., Lee, J. S. and Ha, Y. M.,Continuous heating of an air-source heat pump during defrosting and improvement of energy efficiency *Applied Energy* **110** 9-16, 2013.

[6] U.S. Department of Energy (DOE), Energy Savings from Dual-Source Heat Pump Technology. DOE/EE-0220, 2000. http://www.eren.doe.gov/femp

[7] Chiasson, A., A feasibility study of a multi-source hybrid district geothermal heat pump system. *GHC Bullettin* 9-14, 2011.

[8] Wang, H., Liu, X., Feng, G., Kang, Z., Luo, Y., Bai, B. and Chi, L., Simulation analysis of air-ground dual source heat pump operating efficiency *Procedia Engineering* **121** 1413-1419, 2015.

[9] EnergyPlus Documentation, http://nrel.github.io/EnergyPlus

[10] Fumo, N., Mago, P. and Luck, R. Methodology to estimate building energy consumption using EnergyPlus benchmark models, *Energy and Building* **42** 12 2331-2337, December 2010.

[11] Crawley, D. B., *et al*, EnergyPlus: Creating a new-generation building energy simulation program, *Energy and Buildings*, **33** 4 319-331, April 2001.

[12] DesignBuilder software, http://www.designbuilder.co.uk

[13] Building Industry Consultative Council (BICC), Malta, *Technical Guidance F, Conservation of Fuel, Energy and Natural Resources: Minimum Requirements on the Energy Performance of Buildings Regulations 2006*, http://www.bicc.gov.mt/bicc/files_folder/ Cons%20Fuel%20Energy%20Doc%20F%20new.pdf.

[14] Yousif, C., *Assessing Energy Efficiency in Maltese Dwellings*, a Ph.D. Thesis, Universidad de Valladolid, Spain, April 2015.

[15] Diersch, H.-J. G., *FEFLOW Finite Element Subsurface Flow and Transport Simulation System*, Reference Manual, User’s Manual and White Papers Vol. I, II, III, IV”, Institute for Water Resources Planning and Systems Research, 2005.

[16] Bortoloni, M., Bottarelli, M., Su, Y., A study on the effect of ground surface boundary conditions in modelling shallow ground heat exchangers, *Applied Thermal Engineering*, **111** 1371-1377, 2017

[17] Bortoloni, M., Bottarelli, M., On the sizing of a flat-panel ground heat exchanger, *International Journal of Energy and Environmental Engineering* **6** 2 185-195, 2015.

[18] UNI 11466: Heat pump geothermal systems: design and sizing requirements (2012).