Design and Simulation of an Energy-Positive Building

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Abstract—**This article presents the results from a simulation work regarding the analysis of energy balance of an positive energy building. To meet the criteria for an energy-positive house, a high priority was given to the performance of the thermal envelope, such as high insulation of walls, roofs, floors and windows, thermal bridge-free construction and air tightness. Due to the required air tightness, special attention was also paid to indoor air quality through proper ventilation. We have simulated the building and the heating/cooling system which in our case is a water source heat pump connected with U-pipes vertical boreholes. With the geothermal system, along with solar thermal system used to produce the domestic hot water demand and along with the photovoltaic-PV system we managed to obtain a positive energy construction. The multi-source system is simulated with multiple specialized software. The installed PV system produces 5379 kWh/year while the energy consumption of the house is 4856 kWh/year. During summer, in order to avoid overheating a set point of 27°C was considered. For the entire simulation year, the interior temperature in all the zones was between 19°C and 27°C. This article presents the modeling and simulation of the multi-source systems and illustrates interesting insights about the right measures to obtain a high energy efficient house with optimum indoor comfort.**

Keywords-positive energy house; dynamic simulations; multi-source system.

I. INTRODUCTION

European Union (EU) has agreed a forward-looking political agenda to achieve its core energy objectives of sustainability, competitiveness and security of supply, by reducing greenhouse gas emissions by 20%, by increasing the share of renewable in the energy consumption to 20% and improving energy efficiency; all these, by 2020 [1].

The energy spent to heat the occupied spaces in the residential sector represents more than 40% from the total energy demand [2], which includes electricity, hot-water and air-conditioning. In this area, a major energy reduction can be achieved if a building is correctly designed by engineers and architects, and even more if, renewable energy systems are integrated to the construction. Installing multiple renewable sources on the same site is even more appealing when substantial energy savings could be made if the advantages of each source are associated. In the near future, more and more the renewable energy sources will cohabit with fossil energy source systems and research has to be pointed towards solutions that are energy efficiently, economical viable and environmental friendly. The goal of a multi-source system is to decrease at maximum the primary energy consumption by generating the needed demand by renewable sources like solar, wind or wood energy. The use of several sources on the same construction site will be applied for new, but also for buildings which, are on the way to be renovated. Coupling a heating system with a renewable energy system along with a multi-criteria decision analysis was realized by Catalina et al. [2]. The benefits of such a use is that the constructions can be closer to Zero Energy Buildings (ZEB) or even positive energy buildings since only by means of a multi-energy system we can arrive to such ambitious purpose. The renewable energy systems will produce locally the energy needed for the building and the extra energy, which is not necessary, will be sent to the overall urban energy infrastructure (i.e., the case of photovoltaic power energy or wind energy). A comparison of different ZEB in terms of thermal behavior was studied by Nazif and Altan [3]. The use of a ground to air heat exchanger for energy efficient houses in South of Europe was found to be an attracting solution in order to achieve a ZEB [4]. Compared to the other studies, in this article, a new multi-source system along with the design parameters to be taken into consideration for the envelope is presented. Moreover, if most of the studies are focused only on how to reduce the energy consumption, we found that first of all a building should provide a healthy and comfortable environment for the occupants. With this project it is showed that is possible to achieve a ZEB with a good comfort for the occupants. This is also the main advantage of the proposed system and approach. The structure of the article is divided several sections that are meant to present the study case building, the HVAC (Heating, Ventilation, Air-Conditioning) system, the results of the simulations and finally, the conclusions. During the next chapter we will present the building design of the study case, along with thermal modeling. Afterwards, it is shown the modeling of the HVAC system. At the end of the article are illustrated the results and the corresponding conclusions.

II. BUILDING DESIGN

The house selected for the study is located in Chambery, France. It is a detached two storey building and it is occupied all year long, with a difference between weekdays and weekends. The architectural plan of the building is illustrated

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in Fig. 1. By its shape and space configuration, the house has to achieve, besides comfort and regular architectural image, the premises of an energy-positive house. Based on efficiency concept, the house is wrapped with a „thick skin", to allow an efficient thermal insulation and to have neglectable heat losses from thermal bridges. The envelope of the house will be plastered with the same material, in order to ensure air tightness.

A key factor in this house is the relation with the solar radiation, captured both directly (windows) and indirectly (solar collectors). Large windows are mainly oriented south, increasing the useful solar gains during winter and using efficiently the natural light during the year. Furthermore, the main areas are oriented south, east and west, while the small areas are oriented north side.

The house presents highly insulated facades and roof; in addition, the triple-glazed windows, with specially insulated frames, are based on a 6 chamber system, that keeps out draughts, dust and water. The total window U-value is 0,73 W/m^{2}K. The other elements of the house are presented in Table I.

TABLE I. HOUSE BUILDING MATERIALS AND INSULATION LEVELS

Type	Building structure materials and U-value
Exterior walls	Interior plaster (15 mm) POROTHERM 30 STh clay blocks (300 mm) Thermal insulation compound system (300 mm) out of polystyrene hard foam EPS, plastered on the outside **U=0.09W/m^{2}K**
Interior walls	Interior plaster (15 mm) Thermokron 24 TK blocks (115 mm) Interior plaster (15 mm)
Roof	Clay tiles (20 mm) ISOVER VARIO KM membrane – vapour retarder and air tightness layer Mineral wool (350 mm) Plaster board (15 mm) **U=0.0977 W/m^{2}K**
Ground floor	Oak wood flooring (30 mm) Concrete slab (200 mm) Rigid polyurethane foam (350 mm) Vapour retarder and air tightness layer Cement (50 mm) **U=0.094 W/m^{2}K**
First floor	Concrete slab (100 mm) Interior plaster (15 mm) Oak wood flooring (30 mm)
Attic floor	Interior plaster (15 mm) Concrete slab (100 mm) Thermal insulation (400 mm) Concrete (50 mm) **U=0.0966 W/m^{2}K**
Attic wall	Wood (100 mm) Thermal insulation (400 mm) Exterior plaster (20 mm) **U=0.0911 W/m^{2}K**

The building has been introduced and modulated in TRNBuild, a component of TRNSYS 16 program [2]. The TRNBuild module allows users to define a number of building parameters including the orientation, envelope construction, glazing and infiltration rate. Once the building has been fully defined, it can be imported into the Simulation Studio to be linked with the weather file and HVAC system. We have used for the building the Type 56 component, a detailed multi-zone building model. This component models the thermal behavior of a building divided into different thermal zones.

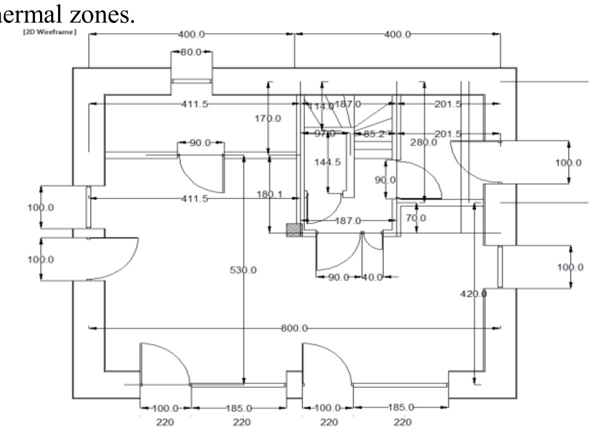


Figure 1. First floor plan of the energy positive house

The thermal zones are very important if we want to simulate the energy consumption of the building. These zones can include a room or several rooms that may have similar heat gains, similar profiles (temperature, occupancy, etc.) or they are provided by the same HVAC system. In our case, the house was divided in 10 different zones, presented in Table II.

TABLE II. THERMAL ZONES OF THE HOUSE

Zone	Space	S [m^2]	V [m^3]
1	Kitchen+Dining Room+Living Room	30,58	84,17
2	Hall	3,88	10,67
3	Storeroom	4,83	13,29
4	Staircase	5,3	15,36
5	Room 1	11,08	29,79
6	Room 2	10,83	29,1
7	Room 3	10,83	29,1
8	Bathroom	5,01	13,45
9	Attic	39,73	54,21
10	Sanitary void	46,81	49,15

The heat gains for people are very important and must be considered in the energy balance. They have a great influence on the energy consumption and the overheating of the rooms during the summer season. Occupancy profiles were created specific to each area and divided into periods of the week (weekdays and weekends). The power dissipation of a person is estimated to 100 W (60 W sensible heat and 40 W latent heat) for casual activities and the percentage of heat gains by convection and radiation to 33% radiation and 67% convection [3]. The artificial lighting is not constant and doesn't depend necessarily on the occupied area. The following control strategy was used: the lighting is on if horizontal solar radiation <120 W/m^2 and off if >200 W/m^2, taking into account the occupied area.

There is no need to heat the entire building day and night at 19^{o}C, while the rooms are empty during the day and some areas are empty during the night. If the house is not occupied, the temperature is set to 16°C. During the weekend, the temperature profile is linked to the occupancy profile in order to provide thermal comfort for every person.

III. HVAC SYSTEM MODELING

In recent years, the design requirements for the primary energy consumption of dwellings has been radically reduced, making it difficult, if not impossible, to meet the required levels using only a combination of construction measures and fossil fuel-based heating systems. This has set in motion a transition to alternative energy systems within domestic construction. Ventilation systems, heat pump systems and solar collector systems form an often-used alternative to provide heating and hot water in dwellings as they reduce the use of fossil energy sources.

The house has a ventilation system with built-in heat exchanger to recover heat, which can be operated by the occupants. There is no room which is not clearly integrated into the ventilation concept. The supply air is shared and areas with stagnant air do not exist. All living and sleeping rooms are planned as supply air zones, while the exhaust air rooms are the kitchen, storeroom and bathroom. The hallway and staircase act as overflow zones. The system is located in the building services room under the roof; supply and exhaust air are extracted or blown out directly above the roof.

A compact solution that combines the ventilation system and the space heating provides better efficiency and opportunities for different system solutions that can be adapted to different conditions and applications. The solution consists in linking a GSHP (Ground Source Heat Pump) to the heat recovery unit (see Fig. 2). A piping loop is buried in the ground, which is considerably warmer than the outdoor air in the winter. Water is circulated through the loops and into the building where the heat pump removes the heat from the water and delivers it to the air. The heat pump covers the whole heating demand with forced air heating, due to its distribution system, which transfers heat to the building. The process is reversed in cooling. Heat is removed from the inside air and delivered it to the water loop which rejects this heat to the ground. The GSHP also provides high cooling efficiency since the ground is much cooler than the air during the summer [4-8].

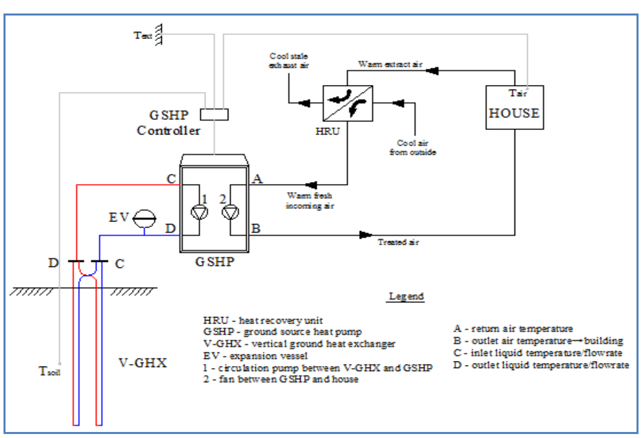


Figure 2. Ground source heat pump for heating/cooling

The production of domestic hot water is ensured by a thermal solar system, which provides heat through a solar collector. The collector transfers the heat to a storage tank, which is connected with an internal heat exchanger and a thermostatic valve for DHW (Domestic Hot Water) temperature control (see Fig 3). The STC (Solar Thermal Collector) is operating in series with the storage tank, which allows for an improvement in collector efficiencies due to the lower temperature fluid entering the collector. An efficient control strategy is implemented to regulate the system. The indoor temperature of the house is regulated by a thermostat, which controls the fan speed in the space heating circuit. Based on the temperature difference, the thermostat switches on/off or remains in its current state. The humidity control in the house is ensured by the GSHP's controller, which dehumidifies the space at reduced cooling capacity. The circulation pump in the solar circuit is controlled based on the temperature difference between the upper side of the STC and the bottom of the hot water tank. If the temperature difference is greater than (5-8)^{0}C, the pump is switched on, but when the difference is (1-3)^{0}C, the pump is switched off, due to the lack of heat that can be transferred to the tank. This difference can not drop below 1^{0}C, because the risk of cooling the tank will appear. The thermostat located in the upper area of the tank protects the equipment from temperatures higher than 90^{0}C. Otherwise, the pump is switched off and, for example, the pressure relief valve will be on. The production of on-site energy is ensured by a photovoltaic system. An analysis by numerical simulations of a system of photovoltaic modules is intended, in order to assess its potential to cover the electricity consumption of the house. The photovoltaic system was designed and analyzed with the PVSyst V6.0 program [12].

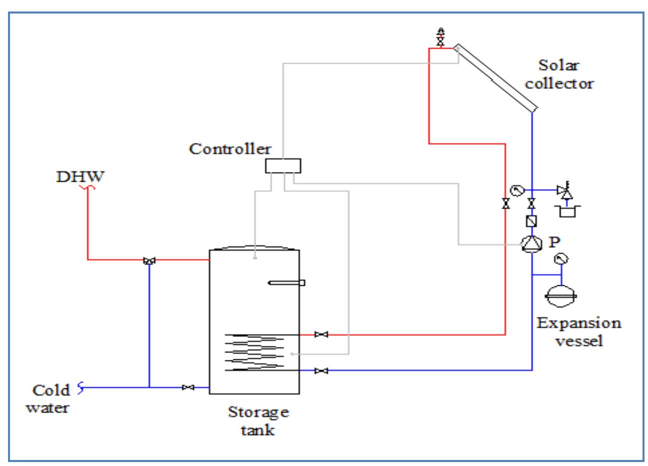


Figure 3. Domestic hot water production using solar panels

For the modeling and simulation of the entire system it was necessary the introduction of multiple parameters. The heat recovery has a sensible effectiveness of 0.95 and a power consumption of 500W. The heat pump is a water source based and provides a maximum air flow of 1250 m3/h and a maximum heating production of 5.5 kW with a COP of 4.8 when the entering liquid temperature is 10 ^{o}C.

TABLE III. VERTICAL U-TUBES PROPRIETIES

Borehole depth	100 m
Number of boreholes	2
Header depth	2 m
Borehole radius	0,1016 m
Storage thermal conductivity	2,423 W/mK
Storage heat capacity	2016 kJ/m³/K
Outer radius of U-tube pipe	0,01664 m
Inner radius of U-tube pipe	0,01372 m
Fill thermal conductivity	8,722 kJ/hmK
Pipe thermal conductivity	1,5122 kJ/hmK
Reference borehole flow rate	1000 kg/h

The proprieties of the boreholes used for the simulations resumed in Table III.

IV. RESULTS

For an appropriate analysis of the system, a dynamic simulation is necessary. The numerical simulation is made throughout the year, for 8760 hours. The thermal comfort is acquired for the entire occupational period as the air temperature, during winter time, is not passing below 19^{o}C and during summer period is always lower than 27^{o}C. Fig. 4 illustrates the air temperature for the thermal zones 1 to 8. Zone 1 has higher temperatures, up to 22^{o}C because in that zone we have the highest internal heat gains (kitchen, occupants, and other appliances). Zone 2 and Zone 3 with the lowest temperatures, close to 19^{o}C represent the Entrance hall and the storage room. It can be concluded that the HVAC system is well designed and the indoor environment is comfortable.

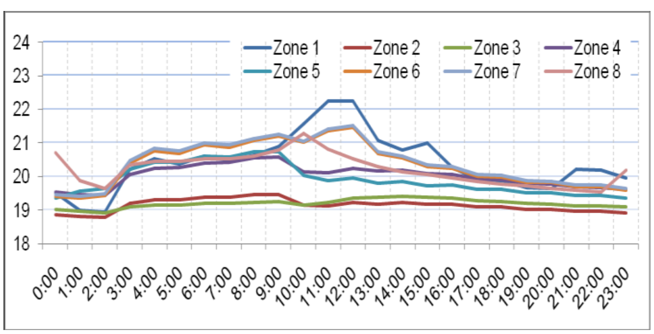


Figure 4. Air temperature during the coldest day of the year

The heat pump transfers to the introduced air a certain amount of energy, when it is needed. Figure 4 shows the total heat transfer to air and the heating controller during the coldest week of the year. The maximum value is around 5500 W and the lowest air temperatures are -12^{o}C. As it can be noticed from Fig. 5, the functioning hours are low because of the high level of insulation of the house and of the internal heat gains that covers most of the heating demand.

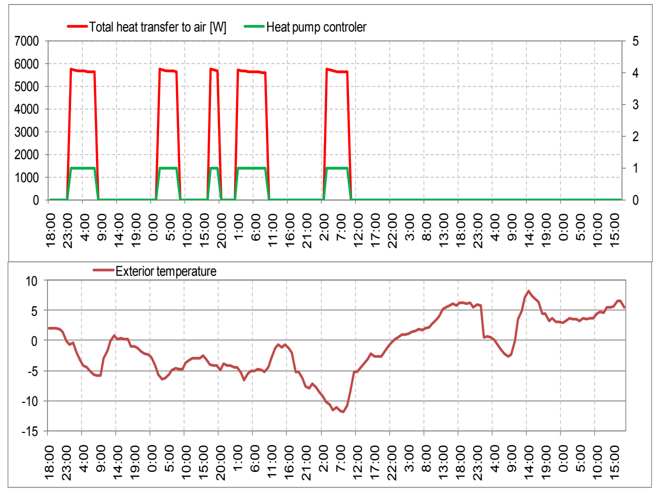


Figure 5. GSHP functioning during the coldest week of the year

As concerns the cooling energy demand, during the warmest week of the year the heat pump transfers to the introduced air around 7000 W (see Fig. 6). This energy is required to avoid the overheating of the zones. Compared to the winter situation, it can be clearly noticed that the functioning hours of the GSHP are more. The reason for that is because the solar radiation heat gains and internal heat gains have high values. Moreover, the outdoor air temperatures during the summer period are around 35^{o}C.

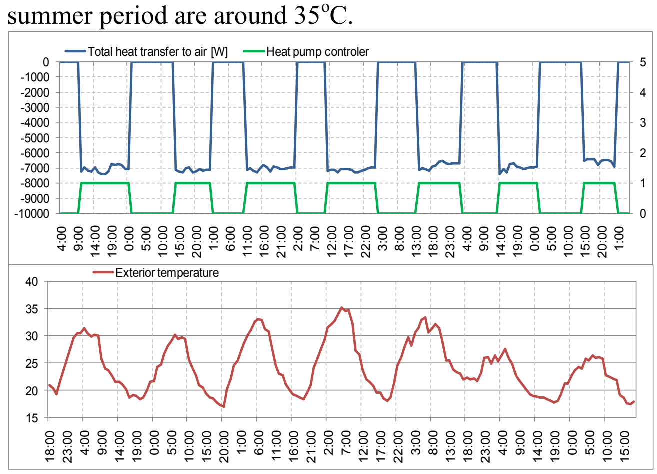
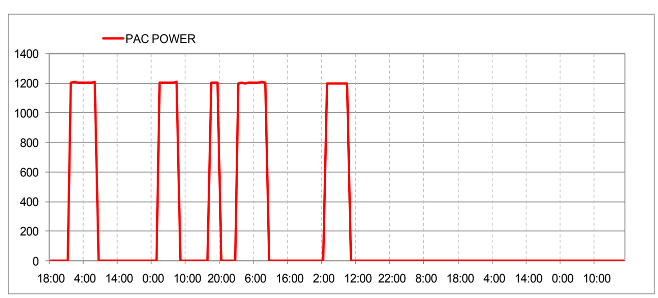


Figure 6. GSHP functioning during the warmest week of the year



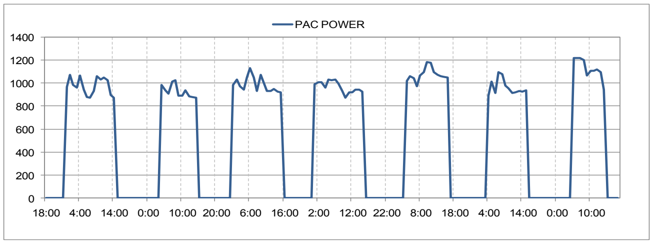


Figure 7. GSHP power consumption during the coldest/warmest week

The power consumption of the heat pump is important for an energy efficient building. From Fig. 7, it can be noticed that during the winter/summer period the maximum needed energy is 1200 W. This energy consumption comprises the compressor, the controller and the blower. For the entire year period we have a consumption of 1853 kWh.

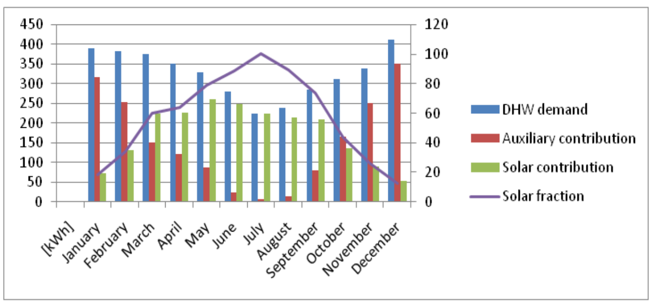


Figure 8. Energy balance of the DHW solar production

The DHW energetic demand is 3932 kWh/year. As it can be observed in Fig. 8, the largest amount of energy from solar contribution is provided during May, when the value of 250 kWh/month is exceeded. The lowest amounts of solar contribution are during the months when outdoor temperatures and solar radiation intensity have lower values. The solar energy is not enough to cover the DHW energetic demand; therefore an auxiliary heating device is necessary. The auxiliary contribution covers entirely the demand and the value is 1833 kWh.

As concerns the photovoltaic system this one is oriented south and is located on the roof of the house. The panels are polycrystalline silicon cells, for the best performance. The input data are: tilting angle: 30^{o}; Azimuth: 0^{o}; Number of PV modules: 17; The module power: 0.255 kWp, The total PV system power: 6 kWp; Module type: Polycrystalline; Modules efficiency: 15.7%. The energy produced by the PV system is 5266 kWh. The necessary energy for the appliances is estimated at 2.66 kWh/day = 971 kWh/year and the electrical lighting at 200 kWh/year. The energy balance of the house is positive because we have 1853 kWh (Heat pump) + 1833 kWh (Auxiliary heating DHW) + 970 kWh (Appliances) + 200 kWh (Electrical lighting) = 4856 kWh (Total consumption) and the produced energy is 5372.9 kWh.

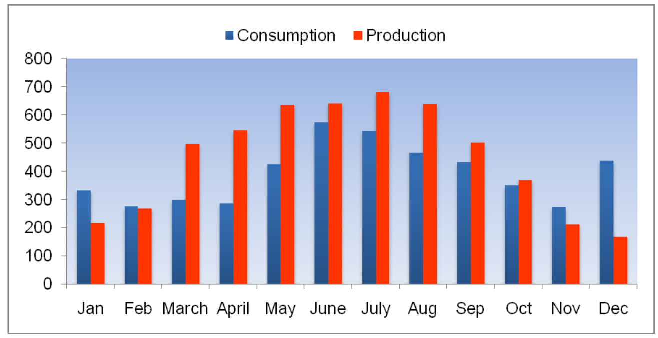


Figure 9. Energy production of the PV system and energy consumption

The maximum energy consumption is found in June with 580 kWh, while the maximum production is July with 685 kWh (see Fig. 9).

V. CONCLUSIONS

In this study, we analyzed a single family house and the possibility to obtain an energy positive balance. Using a ground source heat pump the indoor comfort conditions were reached while the energy consumption had low values. A solar thermal system coupled with an auxiliary heating system produced the domestic hot water demand of the four occupants. An energy positive house would not have been possible without the use of photovoltaic panels that is why 17 modules of 0.255 kWhp/module were installed. With this amount of PV panels the energy production was of 5372.9 kWh over passing the energy consumption by 516.9 kWh. It is concluded that the proposed multi-source system was correctly designed and that the simulations were the perfect way to analyze the house and the HVAC system.

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REFERENCES

[1] Memo: EU energy security and solidarity action plan: 2nd strategic energy review, Online reference : http://ec.europa.eu/energy/strategies/2008.
Retrieved: February , 2011

[2] Catalina T., Virgone J., and Blanco E., Multi-source energy systems analysis using a multi-criteria decision aid methodology, Renewable Energy, Volume 36, Issue 8, August 2011, pp. 2245-2252.

[3] Nazif G. and Altan H., Zero energy house design for cyprus: enhancing energy efficiency with vernacular techniques, Proceedings of Building Simulation 2013 conference, August 2013, pp. 2978-2984.

[4] Pagliano L. and Zangheri P., Design of nearly zero energy buildings coupled with an earth to air heat exchanger in mediterranean climate: development of an analytic model and validation against a monitored case study, Proceedings of Building Simulation 2013 conference, August 2013, pp. 3705-3711.

[5] Trnsys 16, A Transient System Simulation Program, Solar Energy Laboratory, 2005, University of Wisconsin Madison, USA.

[6] ASHRAE Handbook, HVAC Applications, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., Atlanta, GA, 1995.

[7] S. Kavanaugh and K. Rafferty, Ground-Source Heat Pumps, ASHRAE Transactions, 1997.

[8] J.E. Bose, M.D. Smith, and J.D. Spitler, Advances in ground source heat pump systems an international overview, Proceedings of the Seventh International Energy Agency Heat Pump Conference, May 19-22 2002, Beijing, pp. 313-324.

[9] J.D. Spitler, S.J. Rees, and C. Yavuzturk, Recent Developments in Ground Source Heat Pump System Design: Modelling and Applications. Proceedings of CIBSE/ASHRAE conference, Dublin, September 2000, Session 9a, Paper A28, pp. 1-34.

[10] IGSHPA, Closed-Loop/Ground-Source Heat Pump Systems – Installation Guide, International Ground-source Heat Pump Association, Oklahoma State University, Stillwater, Oklahoma, USA, 1988.

[11] P.K. Kavanaugh and K. Rafferty, Ground-source Heat Pumps – Design of Geothermal Systems For Commercial and Institutional Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, N.E., Atlanta, GA, USA, 1997.

[12] Online reference : http://www.pvsyst.com/en/, Retrieved: October, 2013

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