NUMERICAL SIMULATION OF A HYBRID SOLAR GEOTHERMAL ENERGY SYSTEM USED FOR AN ENERGY POSITIVE BUILDING

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Abstract. This article is intended to be a clear demonstration of the benefits of implementation of multiple renewable energy sources to cover the energy needs of a residential building. The simulated building in this article is the EFDeN Signature building and represented Romania at SolarDecathlon Dubai 2018 competition. By using a double U heat exchanger inside a 100 m borehole and connected to a 5kW heat pump, the total CO₂ emission reduction was calculated to be 3786 kg/year, while the 62.1 m² solar photovoltaic panels produced 11522 kWh/year covering entirely the building energy demands.

Keywords: geothermal heat pump, nZEB building, EfDeN Signature, SolarDecathlon competition.

1. Introduction

According to the latest reports, the energy consumption in the European Union (EU) continued to increase for the third consecutive year, thus moving away from energy efficiency targets. Among the main energy consumers, buildings’ operation represents one of the most important ones with a share of almost 40%. It is clear than EU policies and directives are focused on this particular field that can make a huge difference for the coming years. Multiple guidelines and standards were elaborated to promote the use of renewable energy resources (RES) or to build constructions with nearly zero energy consumptions and entitled nZEBs (Nearly Zero Energy Buildings) or even energy positive ones. The main energy consumption of a building is needed to ensure a comfortable indoor environment, thus heating & cooling represents almost 50%, while the rest is divided between appliances (11-13%), lighting (10-12%), domestic water heating (12-14%), computers and electronics (3-4%) and other (10-11%). To reach the goal of nZEB the need to better insulate the building or to use RES in no longer optional but mandatory. The use of numerical simulations or accurate measurements are needed when converting or better said upgrading an existing building to the nZEB standards [1]. Not only the purpose is to reduce the energy consumption but finally to reduce the carbon emissions and the need of dynamic life cycle assessment is one of best options.
to have a global view on the nZEB solutions [2]. During a study [3] made in Hong Kong, the authors proposed the use of building integrated photovoltaics, wind turbines and thermal energy storage to reach the nZEB goal. Paduos and Corrado [4] analysed 107 retrofit solutions for existing buildings suitable for the nZEB target and found out that there are buildings that cannot respect the minimum use of RES requirements imposed by the standards. An interesting evaluation of different solutions to improve the energy efficiency was made for a Greek residential building [5] using energy simulations. It was found that correct insulation, windows, and shading devices can decrease the energy consumption by 30% and enable the reduction of the annual energy demand to less than 50 kWh/m²/year. The use of RES plays a major role in achieving the nZEB standard and among the most used RES geothermal and solar energy are mentioned. Shallow geothermal energy is one of the promising solutions that will attract funding for the next decade [6]. The use of simulations to predict the performances of geothermal heat pumps is preferred by many researchers including the one mentioned in [7] where the authors found out that a geothermal solution can reduce up to 43% the energy consumption of an office building and also reduce the CO₂ emission by 7 kg/m²/year.

![Schematic illustration of a HVAC system for a nZEB building](image)

**Fig. 1 – Schematic illustration of a HVAC system for a nZEB building [8]**

The use of a geothermal source heat pump (GSHP) combined with solar thermal or photovoltaic panels is one of the combinations which allows reaching the nZEB standard. Figure 1 presents the proposed system [8] for a multi-family building located in Athens and it was found out that this is an efficient RES combination.
2. Study case presentation

The evaluated building in this paper is the EFDeN Signature building and it represented Romania during the largest competition of solar houses SolarDecathlon in Dubai, UAE in 2018. The building structural system combines prefabricated modules for slabs, load-bearing walls, and beams for added resistance. It was specially tailored to an open and continuous architectural space. The solution was to use a mix of three structural systems: Cross Laminated Timber, Timber Frame and Glued Laminated Wood. The house was constructed as a cell structure, designed as a multi-layered skin envelope which acts as a protective barrier from the harsh environment. The building respects all the nZEB standards in terms of thermal insulation, as all opaque envelope elements were insulated with top quality mineral wool with a thermal conductivity of 0.035 W/mK. Avoiding thermal bridging was also a key-point of the structure and building insulation as Passive House certified joineries system were used. The wooden structure - unlike concrete or steel ones - was found to be an excellent solution for thermal insulation, and it helped reducing thermal bridging.

As windows are in most cases the weak thermal points of a building, special focus was needed and finally the EFDeN Signature project was equipped with triple glazing panels Cool-lite Xtreme 60-28 II with 90% Argon buffers, a “g” solar factor of 0.28 and a U-value of 1.0W/m²K. As indoor air quality is also an important criterion in nZEB
buildings, fresh air is supplied through a heat and humidity recovery unit. The mechanical ventilation is monitored and controlled by air quality sensors, to ensure that the CO₂ concentration is below 800 ppm and that humidity is between 30% and 60%. Unlike typical enthalpic recovery units, the model used in the EFDeN Signature house is a plate heat exchanger made of desiccant fibbers, thus the sound power is considerably reduced. The use of Renewable Energy Sources (RES) - like solar energy - is another key point of the building. The solar-powered photovoltaic system is designed to meet the consumption requirements of the house to reach a positive energy balance. This target is achieved by planning the energy strategies and by thoroughly using passive and active systems. The house system consists of 4 photovoltaic strings with 8 polycrystalline solar modules of 280 Wp each, which makes a total peak power of 8.96 [kWp]. These four strings enter 2 by 2 into the string inverters. During daytime, when solar production reaches the highest levels, the produced electricity is used on-site to fuel the heat-pump, the house appliances and other smaller electric consumers (e.g. laptop or building management system). The over production of electricity is not injected in the network but stored in batteries using LiFePO₄ as technology with highest discharge capacity (almost 100%), so that the storage capacity (13.8 kWh) can be used almost entirely. Logically, the main strategy adopted is self-consumption, which is the act of consuming only the energy you have produced. This strategy works best when one has a positive balance and, in general, for the whole year, the energy balance is positive, which is in line with the project strategy. Based on numerical simulations the main energy consumptions of the house are represented by the heating energy - 4195 kWh/ year, the pumping energy - 1711 kWh/year and the mechanical ventilation energy - 65 kWh/year.

3. The Hybrid solar geothermal system

While during the SolarDecathlon competition the main solution for air-conditioning was the use of a classic air-to-air heat pump, for the new improved version the proposed heating/cooling system for the EFDeN Signature house is composed of a 5 kW geothermal heat pump and a single 100 m borehole with an estimated thermal production of 50 W/m. The system was defined for 4 people in a 150 m² built area and 74 m² usable area, with a daily consumption of 200 litres/day of domestic hot water in a house with low energy consumption, located in Bucharest Pache Protopopescu Street no. 66. The total energy requirement, excluding domestic hot water, is 4195 kWh, and the room temperature is set at 20°C during winter period and 26°C during summer. The 5 kW heat pump is mounted inside the heated area, with a heat loss of approximately 5% and a nominal seasonal coefficient of performance (COP) of 4.3. As concerns the shallow geothermal heat exchanger, this one is composed of a 32 mm double U heat exchanger in a single borehole drilled at a depth of 100 m. The ground heating potential is 0.08°C and a temperature gradient of 0.03 K/m. The borehole is filled with bentonite to allow better heat transmission between the ground heat exchangers and the ground,
but also to maintain temperature uniformity and structural resistance of the borehole. The heat pump is connected to a buffer tank of 700 litres. The heating&/cooling terminals are air fan coils with a heating power of 1700 W and a cooling power of 1100 W.

4. Numerical simulations

Nowadays the building is in the construction phase in the courtyard of the Faculty of Building Services Bucharest and the assembly process will reach its final stages during October 2020. As numerical simulations are excellent solutions to predict the potential of energy production and system design, the research team decided to use the well-known Swiss energy modelling software called PolySun. For this project, the numerical tool was found to be a reliable and professional platform for simulating renewable energy systems like geothermal or solar. The system was configured and assembled using predefined elements like the heat pump, borehole, buffer tank or solar PV panels. Figure 2 presents a schematic view from the PolySun simulation platform for the proposed system of the EFdeN Signature house.

![Schematic view of the main systems elements in PolySun Simulation Tool.](image)

The energy reduction has a clear impact on the CO₂ savings and these ones were calculated based on the Romanian standards (conversion factor 2.62 from final energy to primary energy for the electricity and afterwards multiplied by the emission factor 0.299 kg CO₂/kWh). From Table 1 it can be concluded that the solar PV panels have a
net production of 11522.5 kWh and thus the CO\textsubscript{2} emissions reduction are near to 9 tonnes CO\textsubscript{2}/year. As concerns the geothermal heat pump the calculated seasonal factor was found to be 3.7, with an electricity consumption of 1797 kWh and a total reduction of CO\textsubscript{2} of almost 4 tonnes CO\textsubscript{2}/year.

### Table 1

*Overview photovoltaics (annual values)*

| Characteristic                  | Results       |
|---------------------------------|---------------|
| Total gross area                | 62.1 m\textsuperscript{2} |
| Energy production DC            | 12388.5 kWh   |
| Energy production AC            | 11522.5 kWh   |
| Total nominal power DC          | 8.96 kW       |
| Performance ratio               | 79.6\%        |
| Specific annual yield           | 1.286 kWh/kWp |
| Total reduction in CO\textsubscript{2} emissions | 9026 kg |

The double U ground source heat exchanger, as mentioned previously, has a length of 100 m, an inlet temperature during operation of 2.7°C and an outlet temperature during operation of 5°C. It is responsible for an energy withdrawal from the ground-source loop of 4844 kWh, thus completely ensuring the building heating energy demand of 4195 kWh.

### Table 2

*Overview heat pump (annual values)*

| Characteristic                             | Results       |
|--------------------------------------------|---------------|
| Seasonal performance factor (without pump energy) | 3.7           |
| Total electricity consumption when heating | 1797 kWh      |
| Ground loop length                         | 100 m         |
| Energy withdrawal of the ground-source loop | 4844 kWh      |
| Total energy savings                       | 4833 kWh      |
| Total reduction in CO\textsubscript{2} emissions | 3786 kg |

The pump for the space heating loop has a flow rate of 321 l/h and a final electricity consumption of 73.5 kWh. On the other hand, the pump of the heat source has an energy consumption of 61.4 kWh. The storage tank buffer is made of steel and insulated with 80 mm rigid PU foam and thus the heat losses are 330 kWh. As concerns the monthly distribution of the energy production (see Figure 3) it can be noticed that the highest energy production is supplied in August with a value of 1246 kWh while the minimum in December with 501 kWh. The total energy consumption of the building in terms of HVAC system (heat pump, circulation pump, BMS) without appliances are covered 100% for the whole year. In fact, the PV system produces more energy than needed with a value of 9566 kWh/year and hence the building not only reached the nZEB standard but even the energy positive standard.
Fig. 4 – Photovoltaic solar energy production versus total energy consumption

As the main energy consumption of the building is needed for heating the building, the GSHP supplies the demanded energy for heating and DHW purposes. It can be seen from Figure 4 that the maximum heating demand is found for January with 1408 kWh.

Fig. 5 – Energy to the system provided by the GSHP (kWh)
4. Conclusions

In this paper it was presented a solar house called EfDEn Signature supplied with a geothermal heat pump to cover the heating/DHW energy demand of the building. The 5kW heat pump and a 100 m double U ground source heat exchanger were found out to be the right combination to ensure full coverage of the energy demand. The numerical simulations proved that the solar house has an energy production from the solar photovoltaic panels of 11522 kWh/year, thus not only covering the total energy consumption of the building, but moreover over-producing by 9566 kWh/year. The total CO₂ emission reduction obtained from the use of the two RES systems (geothermal heat pump and solar photovoltaic panels) is almost 13 tonnes CO₂/year classifying this building as one of the best in Romania in terms of environment protection. The building itself is currently under construction and in October 2020 it will be monitored and the experimental results will serve as validation for the numerical simulations.

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