Design of Earthship for Climate Conditions in Macedonia

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Abstract. The Earthship, as a sustainable nearly zero house, built of natural and recycled materials, represents one of the solutions for the numerous environmental issues. A specific location is chosen by the Lake Ohrid in Macedonia. The house is designed for a single family, with dimensions and materials selected according to recommendations in the literature. It is not connected to the public infrastructural network, reducing its dependence on public services and the use of fossil fuels. It is built of natural and recycled materials, having thermal solar heating and cooling, collection and storage of rain water, controlled wastewater treatment, power from sun or wind and food self-production. Static and dynamic analysis has been performed and stability in this highly seismic region is confirmed, followed by the analysis of the energy efficiency and bill of quantities. This design meets the passive house criteria and the planned investment is considerably lower in comparison to a passive house built of “standard” building materials. The potential benefits of this designed Earthship might have an impact in the future building construction and architecture in Macedonia, especially for suburbs. They might help raise people’s awareness of the benefits of sustainable architecture: reduction of the greenhouse gas emission, saving fresh water reserves by harvesting rainwater and reusing it as grey water, controlling the micro climate of the suburban areas by using energy efficient materials and choosing the right location for building.

1. Introduction

1.1. Earthship building
Responsible behaviour towards nature will be one of the most important challenges in the future. Construction of energy efficient buildings incorporates harmonious design of the building, solar orientation, precise positioning of glass surfaces in the building envelope, adequate volume of the building according to the planned built area, durability of materials, use of natural and local materials, reuse of already used materials and economic viability.

Republic of Macedonia has great potential for using renewable energy sources, according to the Strategy for energy development, [7]. Namely, the unused potential of renewables, which can be utilized by 2030, is 1565 GWh annually for heat generation and 3795 GWh annually for electricity production. In the past, Macedonian traditional houses were built with local materials, characteristic for the surroundings where the houses were to be built.

Earthship is a passive solar house built of natural and recycled materials. The specific location for this building is chosen in the settlement of Lagadin, along Lake Ohrid. Buildings built on a location along water surface are exposed to abrupt climate change, wind, sunshine, extreme heat, water damage, etc. In addition, these site types are sometimes not connected to an electricity grid, waste,
pipeline or plumbing. The construction of passive houses at such locations is a combination of the necessary solutions of the natural conditions of the site, with technologies that maximize energy efficiency and minimize the impact of the building on the environment. This house is designed to create conditions for forming a sustainable community, which will offer opportunities for further development. As Freney et al [3] states, each of the houses of that community creates its own electricity, supplies it with its own water, has its own sewerage and treatment of wastewater, produces bio fuel, and raises a good portion of the food needed on a daily basis. Furthermore, the buildings are heated and cooled naturally and independently. Since Earthship houses are designed as structures that exist in harmony with their surroundings, it is important to have their own independent systems and to use materials that are sustainable and ready to use. These houses, in order to be completely self-sustaining, need to manage the three main systems: Water, Power and Climate.

The first Earthship house was built over forty years ago in Taos, New Mexico by Michael Reynolds, [9]. Design is constantly evolving and improving, opposing the conventional architectural concept. The first Earthship in Europe was built in 2004 at Kinghorn Loch in Fife, Scotland, while the second one was built in 2005 in Stammer Park, Brighton, England, both in UK, [6]. Following the recommendations in the literature [1], [4], [6], [9], a design for an Earthship at a specific location near the Ohrid Lake is proposed in this paper. The advantages and potential benefits of the proposed house are summed and pointed out.

1.2. State of the art in energy in Macedonia

Total electricity production of 5646 GWh in Macedonia in 2015, divided regarding to the source, is presented in figure 1, according the official statistics of the Macedonian Energy Agency, [2]. Additional 2656 GWh were imported, and negligible 143 GWh were exported in the same period. The domestic energy production in Macedonia is insufficient to satisfy the increasing energy consumption.

Regarding the renewables, due to the hydrological conditions in the region, hydroelectricity is the most harvested among the renewable sources, following by biomass, whilst solar power offers a minimal contribution. Hydropower can cover 10% to 20% of the total demand for electricity. There are 9 big hydropower plants with total production of 1392 GWh per year, [2]. According to the energy balance, the biomass participates with 6% of the total primary energy in the Republic of Macedonia, i.e. 9.5% of the total energy consumption. The wood is the most used resource from biomass. Biomass, of wood or coal, is almost exclusively used in the domestic sector. Local geothermal waters are of insufficient temperature, and they are not used for electricity generation. Currently, there are 18 known geothermal fields, with more than 50 geothermal sources with total outflow of 1000 l/s with temperature of 20°C - 78°C. Macedonia was the first country in the Western Balkan region to put into operation a sizeable wind facility, wind farm of 36.8 MW at Bogdanci. Solar PV capacity is also the highest compared to neighbouring countries, but the potential is hardly used, [2]. The energy consumption in the Macedonian residential sector, according to the official statistical data for the period of 1996 to 2006, grew by 0.47% annually. However, the growth of the household energy consumption is assessed at nearly 2% annually, taking into account the unrecorded consumption of firewood and electricity, [7]. Figure 2 represents the final consumption of electricity in the residential sector as 47.4% of the total final consumption of electricity in 2015 in Macedonia, according to IEA. On the other hand, the annual growth of construction of new homes in the last six years is 5.25%, [7]. The average consumption by types of energy commodities per household and per capita at the national level, as well as average energy consumption in households that consumed the particular energy commodity in 2014 are: fuel, wood and other plants with 61.59%, electricity 28.5%, LPG 0.44%, derived heat 8.33%, coal 0.07%, heating oil 0.1%. Regarding the CO2 emissions, 3.48 tons per capita were calculated in 2015.

Given the current environmental problems and the increase of energy consumption in Macedonia, it is of great importance that adequate actions are taken. They include preservation of the vegetation, implementation of renewable sources of energy, construction of energy efficient buildings, building with local and sustainable building materials etc.
2. Design of Earthship house

2.1. Location and climate conditions

The location chosen for this Earthship house is in the settlement of Lagadin, with geographical coordinates of 41.1ºN 20.8ºE. The house is located by the Ohrid Lake and is 9 km away from the Ohrid city centre. The settlement of Lagadin has been developed in the second half of the 20th century and its construction is still on-going. The building plot has an area of 1200 m², while the maximum building area is 216 m², with maximum permitted height of 9 m. All the houses are designed to have south-west orientation, receiving maximum solar gains and visibility to the lake. Figure 3 represents the solar radiation in Ohrid during the year; south, west and horizontal directions only, as the most representative ones. The climate in Macedonia is mixed, continental with Mediterranean, cold in winter and hot in summer. The country has no outlet to the sea and it is separated from the Adriatic and Aegean Seas by mountain ranges. The monthly average temperatures in °C for Ohrid are given in figure 4. Location of the building and its orientation in the neighbourhood is presented in figure 5, while its designed 3D view fitted in the environment is shown in figure 6.
2.2. Materials for the Earthship

One of the ways to integrate sustainable architecture in buildings is through the use of recycled and natural building materials. Given the already mentioned energy problems, as well as the energy used in the manufacturing process of conventional building materials, air and water pollution, the use of these materials is an imperative in the house like Earthship.

The most impressive material used, which represents the main bearing part of the Earthship, are actually used car tires filled with rammed earth, cans and tins as partition walls, glass bottles as fillers and decoration of exterior walls. In addition to these materials, due to the stability and durability of the building, natural materials are used in a certain parts, such as wood, glass, and also conventional materials such as concrete for buttresses on the supporting wall of tires and other segments, materials for thermal and hydro insulation etc.

2.3. Geometry of the building

The gross dimensions of the base are 26.2 m x 11 m, including the thermal layer of 10 cm expanded polystyrene with air barrier and 100 cm thick fill of earth, figures 7 and 8.

One row of the wall of tires, filled with a compacted soil, consists of 46 tires R15 in total. Tires’ dimensions are taken as d = 76 cm and height h = 24 cm for the analysis. It has 11 rows, with a total height of 264 cm, which does not exceed the recommended Earthship Biotecture of 300 cm, [9]. The recommendations of Reynolds [9] and Griepentrog [4] are followed regarding the adopted dimensions of the other elements, as well.

2.4. Solar and wind energy

The sunbeams fall at a 22.8° angle on the shortest day of the year - December 21th, dictating the slope of the wooden structure oriented to the southwest side to be at a 67.2° angle, see figure 9. In this way, the total solar insulation is gained during the winter, while the hot summer sun is prevented to enter the house.

The particular building has unfavourable position in terms of generating wind energy; the mean wind speed in this region is relatively low, 3.4 m/s, while the minimum required for the turbine to start
generating energy is 3.5 m/s. Furthermore, the wind has no constant continuity, and Ohrid is located in the geographical zone I regarding the intensity of wind (area of moderate winds).

Therefore, in terms of energy supply, the total energy is designed to be provided with solar photovoltaic systems. The biggest solar radiation in the Republic of Macedonia is determined in the south-west part of the state as 1530 kWh/m². Produced electricity can be used directly or stored in batteries and used according to the needs. Six modules of photovoltaic of 240 W, with dimensions 980 x 1660 x 32 mm are provided for this Earthship house. Their produced energy is stored in 6V (325 Ah) batteries, grouped into two groups of 5 batteries mutually connected, which manage to meet the minimum needs of 5 kWh per day designed by the architect. Similar recommendations are given by the group of architects which originally created Earthship house.

2.5. Collection and storage of water
Earthship houses are designed to be autonomous, both in terms of water supply and communal networks. Therefore, water is provided by taking, directing and storing rainwater through the roof. Table 1 represents the average annual and monthly precipitation (in mm) in the Ohrid valley (National plan for management with National park Galichica 2011).

| Months | Per year |
|--------|----------|
| I      | 76.4     |
| II     | 72.6     |
| III    | 59.8     |
| IV     | 50.3     |
| V      | 36.3     |
| VI     | 23.2     |
| VII    | 21.1     |
| VIII   | 47.4     |
| IX     | 71.9     |
| X      | 98.4     |
| XI     | 78.9     |
| XII    | 708.3    |

In the vicinity of Lake Ohrid, where the building is estimated to be, the annual amount of precipitation is slightly larger than the Ohrid valley and it is 759 l/m². On the other hand, estimated water consumption was 270 l per day per resident for 2015. Given that the Earthship house uses the water four times, it is calculated that 70 l per day per inhabitant have to be provided (270 l : 4 ≈ 70 l).

The roof area is 150 m², and then the total amount of water is about 114 000 liters per year, which meets 70 l of the total quantity of water needed per day per inhabitant, for a family of four members.

Regarding the installation of the entire system, 3 tanks of 6000 l are provided. The water is gravitationally directed from the tanks in a water organization module, whereby filters are used to purify the rainwater from bacteria and other pollutants. Then, the water is brought into a standard pressure vessel in order to achieve water pressure as in a conventional housing building. This water is further used for any activity in the household, except for the rinsing of the toilet, where grey water is used, which is actually waste water from the bathtub or sinks in the house that also passes through a particle filter and continues into the botanical garden in the front of the house. In some cases, at the request of the investor, the water from the sink in the kitchen is directed directly to the black water in order not to affect the grease of the filter from the botanical garden. When passing through the botanical garden, the water is filtered through the gravel and through the roots of the plants, whereby oxygen is added and the nitrogen is taken off the water. In addition, the water flowing through the plants and evaporating from them, maintains the humidity of the air in the room.

2.6. Controlled wastewater treatment
The waste water problem is solved independently of the city sewerage system, like other systems within the Earthship house. The grey water, after being used to flush the toilet, becomes black water that is directed to a septic tank for anaerobic bacteria decomposition. The septic tank is dug into the ground, it is coated with additional insulation and has a south-oriented window through which the pit is additionally heated by the sun and thus accelerates the anaerobic process. When the black water comes to the septic tank, the liquid part is separated from the solid, and then the treated water is directed through an external filtration and trenching field to the outer cell with decorative plants, similar to the inner botanical cell.
3. Analysis of the building

3.1. Static analysis

The analysis of the supporting wall is made in correlation with the paper of Zimmerman [12], which offers explanation of the problem through a more comprehensive analysis.

A realistic model has been used for static analysis, with 3 tires in length and 8 in height, filled with earth and connected to each other. The modification regarding the standard method of stacking and compacting the tires with earth, consists of cutting off the side of the tire from the open sides facing to the upper part, thus facilitating the fulfilment and compacting of the ground.

The coefficient of friction between two tires filled with soil and between tires and the ground, has been determined. For the R15 type of tires, the coefficient of friction “tire – tire” is 0.588, and “tire – ground” is 0.697. Its effect has been simulated by application of a force at the centre of the earth pressure diagram. The results of the analytical analysis include analysis of the stability of the structure, in terms of overturning and slipping, ground - tire and tire-tire, as well as in relation to the height of the wall, and expressed through the allowed active earth pressure.

The analysis has been performed for two types of structure:

- without inclusion of the bearing simulated by the reinforced concrete connecting beam, on which the roof beams are mounted, which additionally increases the stability, and
- with its inclusion (laterally restrained tire walls).

The incorporation of the roof into overall stability substantially better reflects the real behaviour of the wall when used specifically in Earthship, although it is noted that the results obtained by the analysis are quite conservative and on the side of reliability, since they do not include the buttresses and the placement of the structure in П-form, which also additionally increases stability.

This wall is the most magnificent element of the Earthship, regarding the insulation characteristics. About 800 car tires R15 are needed to build the wall of this house. Tires are organized and placed in the same way as bricks, with each row of tires being set 3.5-4 cm behind the row below it. In that way, the wall is tilted to the outside and supported by the compacted ground. Galvanized tubes are placed in two places above the third row of tires, presenting ventilation ducts, coated with 5 cm of EPS, through which the natural ventilation of the interior is carried out. A small mesh is placed at each end of the tube for protection against insects and small animals. Expanded polystyrene thick 10 cm for thermal insulation on a surface coated with a vapour membrane is placed behind the back side along the entire length of the tire wall at a distance of 100 cm, figure 10. The rainwater collection tanks are placed behind the thermal insulation and are completely insulated with 5 cm EPS.

The roof is designed as a timber structure, with external roofing of metal panels that enable maximum collection of the rain water. Its cross section is given in figure 11. On the top of the house, there are ventilation openings that improve the natural movement of the air together with the ventilation pipes. The heat transfer coefficient for the roof structure is calculated as 0.13 W/m²K.

Figure 10. Cross section of wall with rammed earth.
Figure 11. Cross section of roof.
Thermal barrier, made up of the wall of tires, compacted earth and expanded polystyrene foam have the greatest role in maintaining the thermal comfort and maintaining the desired indoor temperature. It has the best thermal insulation characteristics compared to other structural elements. Calculated U-value for this wall is 0.12 W/m²K, which is a value typical for passive houses.

The partition walls between the bedrooms and between the bedroom and the bathroom are built of two layers of cans (0.33 l) with cement and 5cm thermal insulation between the layers. The use of cans helps to form a wall mass and reduces the necessary amount of cement. The wall of cans is easy to build, and on the other hand recycling of the cans helps in the waste reduction. The partition wall between the bathroom and the living room, and the walls in the corridor of the house are built in the previously described manner with cans in the lower part, and in the upper part with "glass bricks" connected with cement. One glass brick is made of two glass bottles of the same kind, cut into the throat, washed and glued with adhesive tape. All the walls are plastered and painted. The U-value of the wall made of cans is calculated as 0.09 W/m²K.

Only the floors in the house are designed of reinforced concrete slab, placed on a levelled ground soil and the vapour barrier on it. Given the climatic conditions at the location where this house is planned, a 10 cm thermal insulation should be installed above the vapour barrier. Above it there is another layer of vapour barrier, on which the mesh reinforcement is arranged and concrete is placed. The floor in the rooms is with finishing of brown wooden flooring, with U-coefficient of 0.21 W/m²K; while the flooring in the toilet, kitchen and at the entrance hall is made of stone tiles and its U-coefficient is U=0.23 W/m²K.

3.2. Energy consumption analysis

After determining the coefficients of thermal conductivity of all elements of the building envelope, the ENSI Key Number software is used to calculate the energy consumption of the building. The software includes the location of the building and the type of building, [11].

The schedule of using the premises in the house is entered as 16 h/day per working day, according to the standard working hours of 8 hours, and 20 h per weekend days, because an absence of a part or all members of the family of 4 hours a day is assumed. The Earthship house does not use electricity for further heating, but a value greater than zero must be entered in the heating schedule fields, even though it is not necessary. Furthermore, regarding the systems for heating, cooling, ventilation and sanitary hot water, most of the input values are zero, because the Earthship house uses natural ventilation, generates its own electricity through solar energy, uses solar energy to heat water and uses the thermal properties of the earth. Finally, the calculated energy consumption for heating and cooling of the house is 12.5 kWh/m² annually. The results obtained with the ENSI Key Number Software for the total annual energy consumption of the house, including the lighting, electrical equipment and pumps, is about 45 kWh/m². The electricity used in the house is the energy obtained through the photovoltaic panels, and without the use of electricity from the city's electricity system. The additional heating of the water from the solar collectors, if required, is carried out with the aid of a gas, and the additional heating of the premises is done with a fireplace or a wood / pellet stove.

Unlike the ENSI Key Number software, a simple 3D model of the building is drawn in Design Builder software. Materials of each constructive element are input data, as well as the calculated U values and structural characteristics of each of the elements. The model is divided into zones according to the activities taking place in each room and the respective parameters are entered for each zone. Results from the conducted analysis show the thermal balance during the year and adequate comfort in the house.

4. Conclusions

The Earthship designed for a specifically chosen location in the settlement of Lagadin, along Lake Ohrid, is a sustainable passive solar house. Built of natural and recycled materials, it represents one of the solutions for the numerous environmental issues. The house is designed for a single family, with dimensions and materials selected according to the recommendations in the literature. The house is an
off grid house, i.e. it is not connected to the public infrastructural networks, reducing its dependence on public services and the use of fossil fuels. It is built of natural and recycled materials, having thermal solar heating and cooling, collection and storage of rain water, controlled wastewater treatment, power from sun or wind and food production. Static and dynamic analysis of the building determined the dimensions of the structural bearing members. All the necessary checks were performed and controlled.

The results of the conducted analysis for energy consumption of the building show that the Earthship house meets the passive house criteria, [8]. Heating energy demand is 12.5 kWh/m² and it does not exceed 15 kWh per square meter of net living space. Its total energy consumption to be used for all domestic applications (heating, cooling, domestic hot water, lighting and electricity for household appliances) is 43.5 kWh/m², i.e. less than 120 kWh per square meter of treated floor area per year. Furthermore, according to the results from the Design Builder Software, the thermal comfort in the house is met for all living areas during the all seasons, with not more than 10% of the hours in a given year over 25 °C. The financial estimations show that the construction of the Earthship house requires 20% less investment funds for construction compared to a passive house built of reinforced concrete in an urban area, with the same living space, with classical HVAC systems incorporated, [10]. The main advantage of the Earthship house is that it is an off-grid house.

According to the conducted research, the appropriate location for the construction of the Earthship house is in the suburbs or periphery of the larger cities, due to its construction and because of the space it occupies. There is an opportunity to build buildings for collective living of this type, but they will still have the same limit in terms of space and number of floors. Finally, these types of houses are environmentally friendly, affordable and energy efficient alternative to conventional houses, without reduction of the living comfort.

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