ANALYSIS OF THE ENERGY PERFORMANCE OF EARTH-SHELTERED HOUSES WITH SOUTHERN ELEVATION EXPOSED

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ABSTRACT

In the article the authors present the results of heating and cooling energy usage of earth-sheltered houses with exposed southern elevations. The results were then compared to a conventional above-ground building. Simulations were focused on the influence of soil cover and the thermal insulation of building envelope thickness and were done for Polish climate conditions.

The large thermal inertia of soil surrounding earth-sheltered houses causes smaller winter heat losses from a building which means smaller heating energy loads, whereas during summer heat losses to the ground are greater which naturally helps to cool down the air temperature in a building.

As could be expected, the simulation results indicate that earth-sheltered buildings outperform above-ground buildings with respect to annual heating and cooling energy consumption.

INTRODUCTION

In recent years, the concept of sustainability has attracted increasing attention within building science, for energetic, ecologic and economic reasons. The decreasing fossil fuel reserves warrant a minimized consumption of energy and maximized application of renewable energy sources.

A potential method to fulfill these requirements for dwellings is the concept of earth-sheltered buildings, which may be simply described as concrete constructions partially covered with soil. The large thermal inertia of the soil cover causes the temperature in the surrounding soil to be higher/lower than the outdoor air temperature during winter/summer. This way, the temperature differences between the interior and exterior are reduced, which means that the heat transmission is lower compared to conventional above-ground houses. The application of soil cover thus potentially cuts the required heating and cooling loads.

The authors have undertaken the analysis of the influence of soil cover thickness, thermal insulation thickness, glazing area of exposed elevations and type of soil on heating and cooling loads of earth-sheltered builidings with one or two elevations exposed. The results were then compared to the respective above ground buildings. Building energy simulations were done for Polish climate conditions. In this article the authors present the results of simulations done for the earth-sheltered buildings with one (southern) elevation exposed, glazed with 60 % of wall area.

SIMULATIONS INPUT DATA

Buildings

The analyzed buildings are one-storey residential houses built on a slope, with one (southern) elevation exposed and respective above-ground buildings as shown in picture 1.

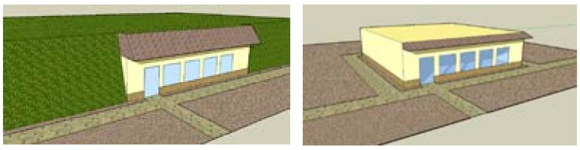

a) earth-sheltered *b) above-ground*

Figure 1 The analyzed schemes of: a) earth-sheltered and b) above-ground buildings

Buildings have a floor area of a square with internal dimensions of 12x12 m (144 m^2). Room height is set at 2,8 m, heated volume is then 403,2 m^2. Because of high soil pressures, buildings have a concrete construction with walls and a thickness of up to 30 cm and slab on the ground of 15 cm. Thermal insulation thickness is set equal on all external building partitions. Both earth-sheltered and above-ground buildings have the same window area, equal to 60% of the exposed elevation area, which gives 20 m^2. Material parameters are presented in table 1.

Table 1
Material characteristics

MATERIAL	VOLUMETRIC HEAT CAPACITY [J/(m^{3}K)]	HEAT CONDUCTION [W/(mK)]
Concrete	1,764*10^6	1,700
Thermal insulation	0,025*10^6	0,045
Soil (sand)	2,000*10^6	2,000

Simulations of energy performance were done for several thermal insulation thicknesses: 5 cm, 10 cm and 20 cm and 30 cm.

Soil

Soil parameters are shown in table 1. Simulations of energy performance of earth-sheltered buildings were done for several soil thickness covers: 0,5 m, 1,0 m, 1,5 m, 2,0 m and 2,5 m.

Climate

Energy simulations were done for Poznan, Poland (Central Europe; temperate/mesothermal, climate type Dfb - following Koppen climates classification). Basic climate informations are presented in table 2.

Table 2
Climate conditions

Latitude (N):	52º25’
Longitude (E):	16º49’
Maximum air temperature:	+ 35,6°C
Annual air temperature:	+ 9,8°C
Minimum air temperature:	- 16,0°C
Annual direct sun radiation:	1 865 [Wh/m^2]
Annual diffusive sun radiation:	1 679 [Wh/m^2]
Annual total sun radiation:	2 692 [Wh/m^2]
Annual air humidity:	78 %
Annual wind speed:	3,3 [m/s]
Annual clouds cover:	0,61 [-]

Interior conditions

The heating and cooling systems are turned on when the interior air temperature reaches one of two temperatures. If the temperature goes below the minimum value the heating system is turned on. When the internal air temperature rises above the maximum temperature the cooling system is turned on. For wintertime minimum and maximum air temperatures are 19 °C and 22 °C, respectively and for summertime are 20 °C and 24 °C.

NUMERICAL MODEL

As most building energy simulation models do not allow to incorporate soil cover accurately, an integrated strategy is used: soil heat transfer was calculated with the finite-element package FlexPDE (with energy balance at the soil surface as a boundary condition), and building energy consumption was calculated with EnergyPlus software.

First the temperature of a building’s envelope is calculated in FlexPDE. Then the results are exported to EnergyPlus, where the building energy consumption is calculated. All simulations were performed with one hour time step. Boundary conditions of a model of temperature distribution around the building are set as shown in picture 2.

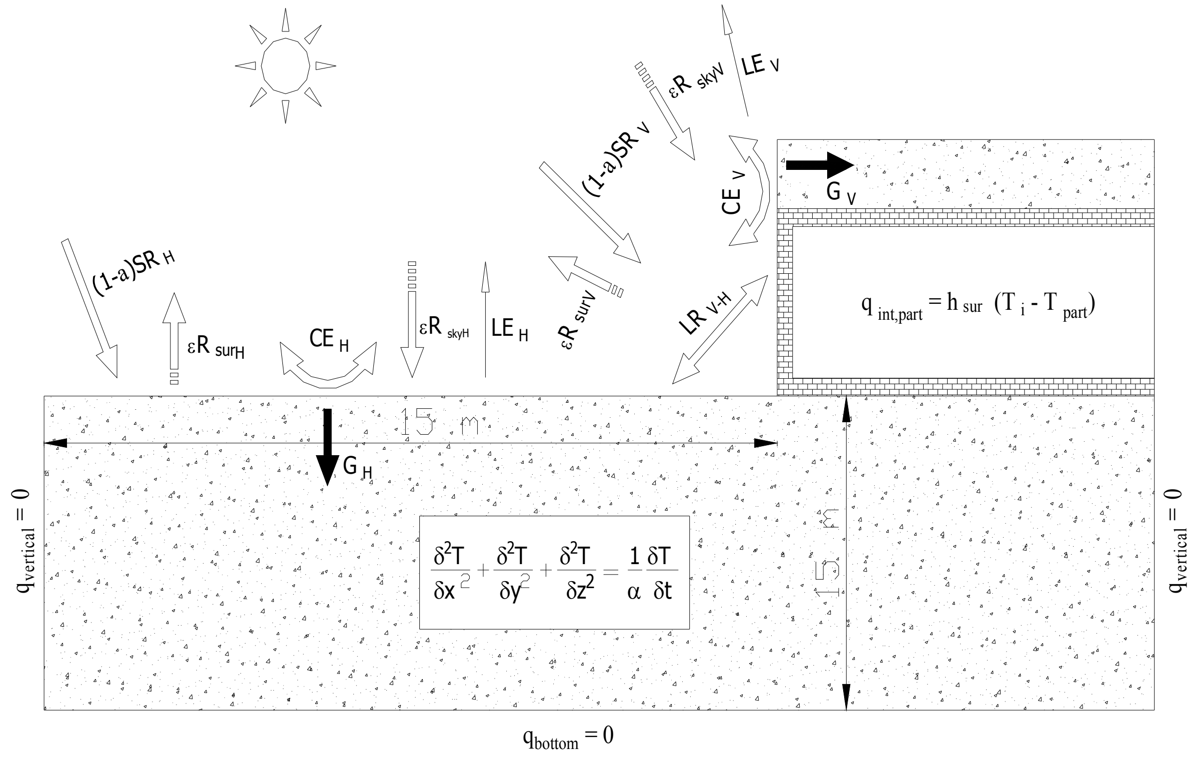


Figure 2 Boundary conditions of the domain (not in scale)

Heat balance at the soil surface

Soil surface, both horizontal and vertical, boundary conditions are set as an energy balance at the soil surface, where energy absorbed by soil is equal to the sum of an absorbed incoming shortwave sun radiation and longwave sky radiation, outgoing longwave soil surface radiation, energy due to convection and latent evaporation plus longwave radiation between both horizontal ($_H$) and vertical ($_V$) surfaces. The formulation of the top boundary condition is based on the equation of the conservation of energy at the soil surface [3] [4]:

$$G = R + CE - LE \tag{1}$$

which takes a form:

$$G_{H(V)} = SR_{H(V)} + R_{skyH(V)} - R_{surH(V)} + \\ + CE_{H(V)} - LE_{H(V)} + LR_{H-V} \tag{2}$$

where:

$G_{H(V)}$ - energy absorbed by horizontal (vertical) soil surface, W/m^2,

$SR_{H(V)}$ - shortwave sun radiation energy absorbed by horizontal (vertical) soil surface, W/m^2,

$R_{skyH(V)}$ - longwave sky radiation energy on horizontal (vertical) soil surface, W/m^2,

$R_{surH(V)}$ - longwave horizontal (vertical) soil surface radiation, W/m^2,

$CE_{H(V)}$ - energy due to convection on horizontal (vertical) surface, W/m^2,

$LE_{H(V)}$ - energy due to latent evaporation of horizontal (vertical) surface, W/m^2,

LR_{H-V} - longwave radiation between both horizontal and vertical surfaces, W/m^2.

Bottom and vertical boundary condition

Bottom and vertical boundary conditions of a domain are set as an adiabatic ones (perfect insulators), thus heat flow is equal to zero [2]:

$$q_{bottom} = q_{vertical} = 0 \tag{3}$$

Bottom and vertical boundary conditions were set at the edges of a domain 15 m under a slab and next to the walls. It follows the hints of the European Standard EN ISO 13370 “Thermal performance of buildings – Heat transfer via the ground – Calculation methods”.

Internal boundary condition

In this work the internal air temperature is not constant in time, but is dependent on time (one hour time step). Following Hagentoft [1] internal boundary conditions may be represented by a simplification (4) which is the heat flow through building partitions to the ground:

$$q_{\mathrm{int},part} = h_{sur}\left(T_i - T_{part}\right) \tag{4}$$

depending on the heat flow direction, where:

q - heat flux on a inside face surface, W/m^2,

h_{sur} - heat transfer coefficient of a surface, W/m^2 K,

T_{air} - inside air temperature, K,

T_{sur} - surface temperature, K.

Heat transfer in a soil domain

Heat transfer in a soil domain is represented by the equation of 3D transient heat conduction equation in a isotropic body, known as the Fourier’s equation:

$$\frac{\lambda}{\rho c_p}\left(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2}\right) = \frac{\delta T}{\delta t} \tag{5}$$

Mesh grid

In numerical analysis the basic key is mesh density. FlexPDE sotfware uses the adaptive mesh refinement method. First a domain is divided into triangle elements. Next a problem is solved and then the accuracy of the results is checked. If the mistake is larger then set at the beginning, mesh is densified and the whole process is repeated. The mesh is denser at the borders where heat flux change is rapid, these are: at the soil surface, and at the interial walls, ceiling and floor. The analized domain was divided into triangle elements, which produces about 11700 grids.

SIMULATIONS RESULTS

The first point (paragraph) concerns heat losses to the ground from the analyzed buildings. The second section concerns heating and cooling loads of earth-sheltered and above-ground buildings.

Heat losses/gains

Figure 3 shows heat losses/gains from analyzed earth-sheltered and above-ground buildings for annual values and seperatly for heating and cooling seasons. Because of linear dependence heat losses to the ground from buildings, they are presented for 0,5 m, 1,5 m and 2,5 m of soil cover thickness. Results are presented for 5 cm, 10 cm and 20 cm of thermal insulation.

Analysing annual values of heat losses/gains of earth-sheltered and above-ground buildings it may be noticed that the differences between them are not significant. A clear difference is seen when analysing values separately for heating and cooling season. It is caused by the fact that heat losses from earth-sheltered buildings are smaller than from above-ground ones but only during winter (heating season).

The temperature of soil is then higher that of external air, what causes lower heating loads for earth-sheltered buildings.

During summer – cooling season, heat losses from earth-sheltered buildings are higher, as the temperature of soil is lower that of external air, which naturally cools down a building. That’s why earth-sheltered buildings require less cooling energy than above-ground ones.

During heating season heat losses from earth-sheltered builings are about 14 %, 8 % and 5 % smaller for: 5 cm, 10 cm and 20 cm of thermal insulation thicknesses. Increasing soil cover thickness over 0,5 m decreases heat losses about 20÷25 %, 10÷15 % and 5 % for 5 cm, 10 cm and 20 cm of thermal insulation comparing to buidlings with 0,5 m of thermal insulation.

Heat gains during heating season are abot 40 % higher in earth-sheltered houses than in above-ground ones.

In above-ground houses heat gains are 3 % of heat losses. In earth-sheltered houses heat gains are up to about 15 % of heat losses during heating season.

During cooling season heat losses from earth-sheltered builings are about 20 ÷ 35 % greater than from above-ground buildings, while heat gains are nearly 80 % lower. In the summertime each 5 cm of thermal insulation lowers the heat losses by about 20 %.

In above-ground buildings heat gains during heating season are comparable in the range of analyzed thermal insulation thiknesses. It may be concluded then, that in above-ground buildings the thickness of thermal insulation does not have a significant influence on heat gains. In the earth-sheltered houses heat gains are greater with increasing thermal insulation thickness. Each 5 cm of thermal insulation increases heat gains about 40 %.

In above-ground houses heat gains are 35 % of heat losses, while in earth-sheltered houses ratio of heat gains to heat losses is smaller. If heat losses are 100 % then heat gains are only 5 %. Which is why earth-sheltered buildings need less cooling energy.

Heating and cooling energy

The simulation's results concerning heating and cooling energy consumption are presented in monthly values (Fig. 4) and annual values (Fig. 5) for 5 cm, 10 cm and 20 cm of thermal insulation thicknesses.

They concern all analysed soil cover thicknesses, these are: 0,5 m, 1,0 m, 1,5 m, 2,0 m and 2,5 m. Figure 6 shows annual heating and cooling energy savings compared to above-ground building. Accurate values of savings are presented in table 3.

Monthly values

Because the interpretation of the results presented in monthly values would be very complicated, annual values are discussed, while monthly values are shown for general view.

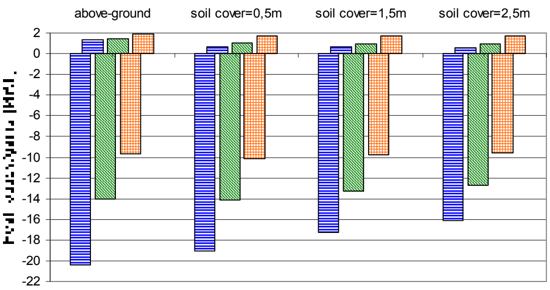
It can be easily noticed that the heating and cooling consumption of analysed earth-sheltered buildings is definitively smaller that of above-ground ones. The difference between them gets smaller with the increase of the thermal insulation thickness.

When analysing the monthly values it can be noticed that earth-sheltered buildings require longer heating periods than conventional above-ground ones, while total heating loads are still smaller. This is due to the lower temperature of the soil surrounding earth-sheltered houses. The cooling period is nearly the same.

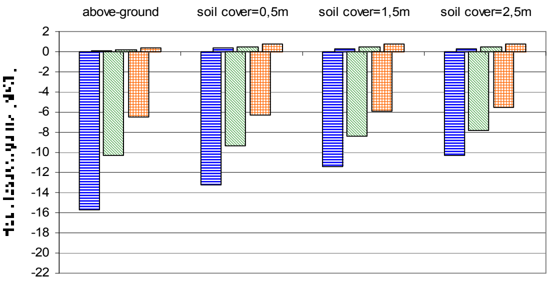
Annual values – heating energy

When analysing the heating energy consumption it can be noticed that the largest difference in heating consumption of an above-ground building and an earth-sheltered one is noticed for 0,5 m soil cover (Fig. 5.a). Further increasing of the soil cover thickness doesn't produce such large differences. This relation is also smaller with increasing thermal insulation thickness. First 0,5 m of soil cover reduces heating consumption by about 25 % compared to a conventional above-ground building.

a) annual values



b) heating season



c) cooling season

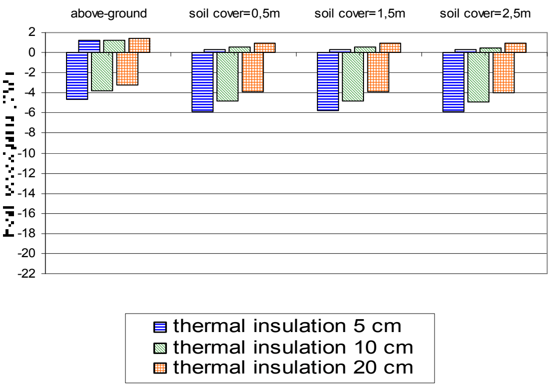
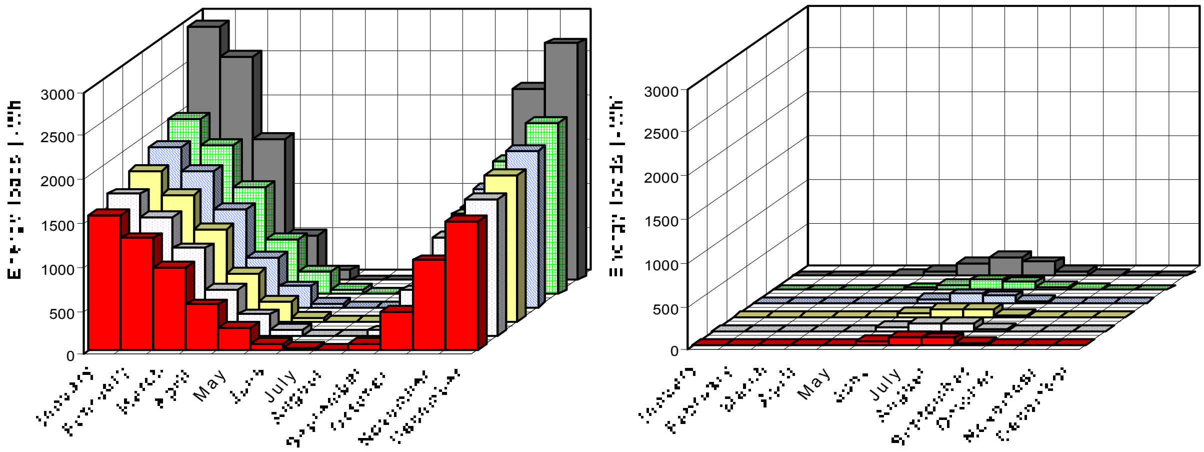


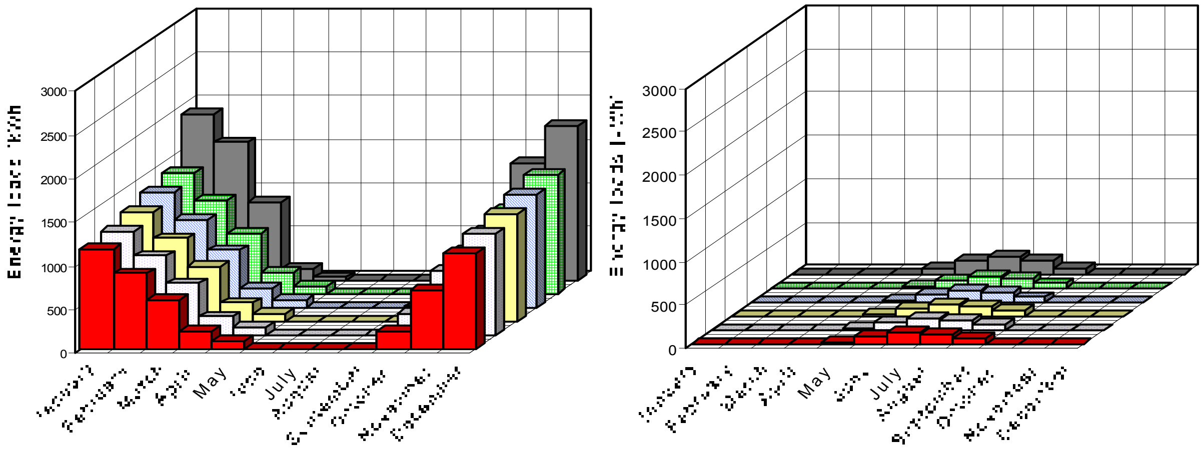
Figure 3 Heat losses/gains from analyzed earth-sheltered and above-ground buildings, with 5, 10 and 20 cm of thermal insulation, presented for: a) annual values, b) heating season and c) cooling season

Heating energy *Cooling energy*

a) 5 cm of thermal insulation



b) 10 cm of thermal insulation



c) 20 cm of thermal insulation

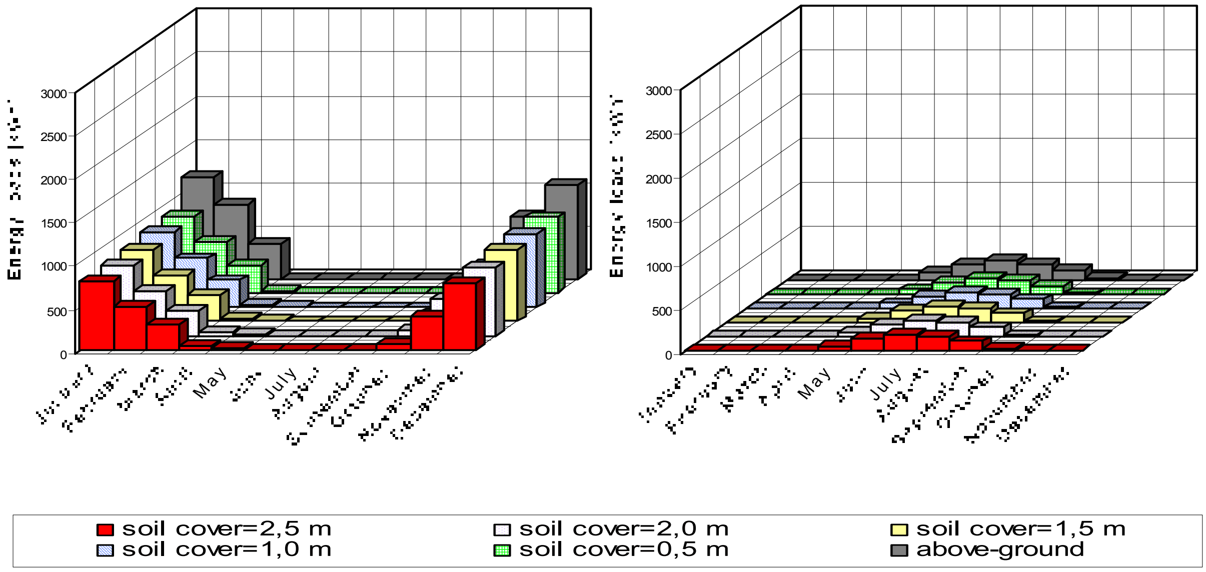
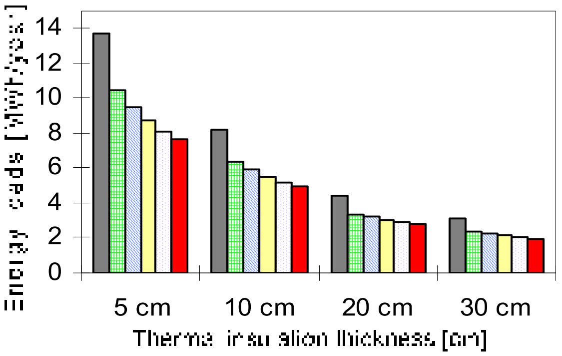


Figure 4 Monthly values of heating and cooling loads of earth-sheltered and above-ground buildings, with 5, 10 and 20 cm of thermal insulation

Each next 0,5 m of soil cover reduces heating consumption about 4 ÷ 10 % compared to a conventional building (table 3).

For 5 cm of thermal insulation heating energy consumption of analyzed earth-sheltered buildings covered with: 0,5 m, 1,5 m and 2,5 m of soil, compared to the consumption of above-ground building is about 24 %, 36 % and 44 %. Thermal insulation of 10 cm gives heating energy consumption about 23 %, 32 % and 40 % lower than of the respective above-ground buildings.

a) heating loads



b) cooling loads

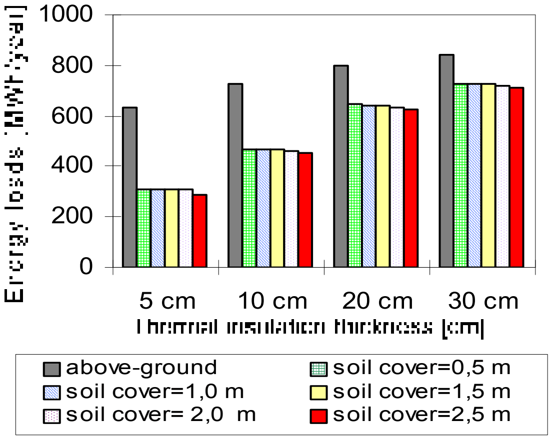


Figure 5 Annual heating and cooling energy loads of earth-sheltered and above-ground buildings, with 5, 10 and 20 cm of thermal insulation

For 20 cm of thermal insulation heating energy consumption of the analyzed earth-sheltered building, covered with respective: 0,5 m, 1,5 m and 2,5 m of soil is about 24 %, 31 % and 37 % lower that of the conventional buildings. It can be noticed that the differences become smaller with increasing thermal insulation thickness. For 30 cm of thermal insulation heating energy consumption of earth-sheltered buildings is about 24 %, 30 % and 34 % lower.

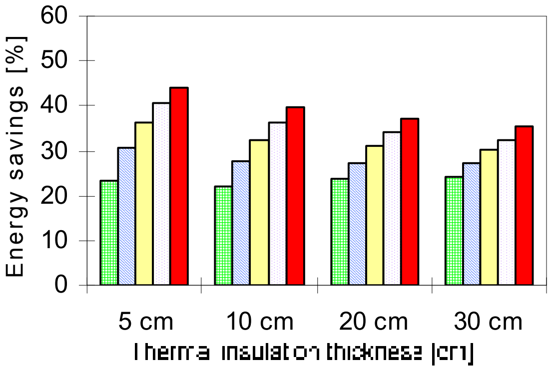
Analyzing the above values one may come to the conclusion that the thicker the thermal insulation is, the lower heating energy savings can be obtained. This is due to the fact that by increasing thermal insulation thickness, the influence of soil is reduced.

It can be also noticed that heating energy loads rise faster by increasing the soil cover thickness than by the thermal insulation thickness.

Annual values – cooling energy

Covering a building with 0,5 m of soil cover reduces cooling loads about 52 %, 36 %, 20 % and 15 % for respective 5 cm, 10 cm, 20 cm and 30 cm of thermal insulation (table 3). Increasing soil cover thickness does not significantly influence cooling energy consumption.

a) heating energy savings



b) cooling energy savings

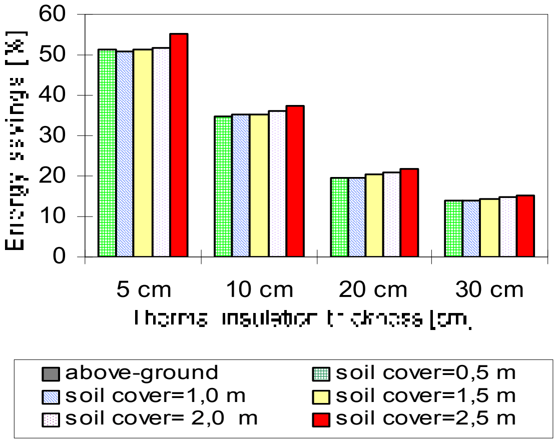


Figure 6 Annual heating and cooling energy savings compared to above-ground buildings, with 5, 10 and 20 cm of thermal insulation

For all analyzed soil cover thicknesses thicker than 0,5 m, the values of cooling eneregy consuption differ with by 2 %. Thus it can be concluded that the influence of soil cover thicker than 0,5 m on cooling energy consumption can be neglected.

Cooling energy savings are reduced with increasing thermal insulation thickness (Fig. 5.b). This is due to the fact, that thermal insulation does not allow gathered heat in a builing to flow to the ground and naturally cool down internal air temperature.

Table 3

Annual heating and cooling energy savings

SOIL COVER THICKNESS	THERMAL INSULATION THICKNESS			
	5 CM	10 CM	20 CM	30 CM
HEATING ENERGY SAVINGS [%]				
0,5 m	24	23	24	24
1,0 m	31	28	27	27
1,5 m	36	32	31	30
2,0 m	41	36	34	33
2,5 m	44	40	37	34
COOLING ENERGY SAVINGS [%]				
All	52	36	20	15

CONCLUSIONS

It may be noticed that from the heating energy load's point of view, the thicker soil cover and insulation are, both above-ground and earth-sheltered buildings naturally consume less heating energy. But also with increasing thermal insulation thickness the influence of soil gets smaller, which causes insignificant differences between above-ground and earth-sheltered buidlings for large insulation thickness.

For cooling loads, the soil cover thickness does not have a significant influence. Both kinds of buildings consume more cooling energy with increasing thermal insulation thickness. Thus the thinner the thermal insulation is the greater the cooling energy savings are compared to the above-ground ones. This is due to the fact that thermal insulation acts like a coat, and during wintertime protects a buidling from colder outside soil temperatures but during summertime does not allow the soil to naturally cool a building down.

The earth-sheltered buildings with exposed southern elevations, which are covered with a soil cover of 0,5 m have heating energy consumption reduced by about 25 % compared to the respective thicknesses of above-ground builidings. Each next 0,5 m soil cover thickness reduces heating loads about:

- 8 % for 5 cm of thermal insulation,
- 7 % for 10 cm of thermal insulation,
- 5 % for 20 cm of thermal insulation,
- 4 % for 30 cm of thermal insulation.

The earth-sheltered buildings with southern elevation exposed, which are covered with a soil cover of 0,5 m have cooling energy consumption reduced by about:

- 52 % for 5 cm of thermal insulation,
- 36 % for 10 cm of thermal insulation,
- 20 % for 20 cm of thermal insulation,
- 15 % for 30 cm of thermal insulation.

Although it has been many years since earth-sheltered houses have been built, they are still not included in sustainable design strategies. Moreover there are few numerical programs which allow a user to perform detailed building annual energy simulations of earth-sheltered buildings.

With the method the authors have undertaken, it was shown that eatrth-sheltered buildings with one (southern) elevation exposed consume less heating and cooling energy that above-ground houses.

With this paper the authors want to spread knowledge about earth-sheltered houses among researchers, professionals and students.

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NOMENCLATURE

a – soil surface albedo, [-],

c_v – volumetric heat capacity, [J/m^{3}K],

ε – soil surface emissivity, [-],

q – heat flow, [W/m^{2}K],

h_{sur} – thermal transmittance, [W/m^{2}K],

λ – thermal conductivity, [W/mK],

t – time, [s],

CE – energy by convection, [W/m^{2}K],

G – heat flow into the soil, [W/m^{2}K],

LE – energy by latent evaporation, [W/m^{2}K],

LR – long wave radiation, [W/m^{2}K],

R – heat flow by radiation, [W/m^{2}K],

SR – shortwave radiation, [W/m^{2}K],

T_i – temperature of an internal air, [K],

T_{part} – temperature of internal surface of building's partitions, [K].