TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

**MASTERARBEIT**

# COMPARISON BETWEEN A BRICK BUILDING AND A STRAW-BALE BUILDING IN TERMS OF ENERGY EFFICIENCY

**ausgeführt zum Zwecke der Erlangung des akademischen Grades einer Diplom-Ingenieurin**

unter der Leitung
**Univ. Prof. Dipl.-Ing. Dr.techn. Ardeshir Mahdavi**
E 259/3 Abteilung für Bauphysik und Bauökologie
Institut für Architekturwissenschaften

eingereicht an der
**Technischen Universität Wien**
Fakultät für Architektur und Raumplanung
von

**Bianka Szász**

Matrikelnr. 1026627

Wien, im Dezember 2013 Unterschrift

## ABSTRACT

This thesis uses a comparative method to analyse the differences between a straw-bale building and a brick building, located in Hungary, regarding their energy performance and impact on the environment. To get better and more realistic results, two virtual buildings are included in the analysis, one that has the same characteristics as the existing brick building but uses straw-bale walls and another that has the characteristics of the existing straw-bale building but employs conventional brick construction. Both are compared to their real-world counterparts. This shows that straw-bale buildings represent a better alternative to brick buildings in terms of energy performance, thermal performance, environmental impact as well as cost-efficiency.

The first chapter outlines some of the basic concepts e.g. how straw-bale buildings are constructed, what benefits and drawbacks they represent and how they compare to brick buildings.

Straw is a waste product of agriculture; it is green, affordable and has low embodied energy. The thermal properties of building elements and the factors required to determine their environmental impact are also discussed.

The second chapter analyses the structures and the two programs used. It also contains all essential data such as climate, orientation, zoning and internal conditions for each case. The choice of programs is also explained and the process of implementing the houses for the purpose of comparison. The goal of this thesis is to create energy certificates for these buildings and estimate their heating demands as well as transmission and infiltration losses in order to study their energy performance.

Simulations make it possible to determine environmental factors such as global warming potential, acidification potential and primary energy content.

The third part of this thesis is an analysis of the results, presented as a comparative study.

## ZUSAMMENFASSUNG (IN DEUTSCHER SPRACHE)

In dieser Arbeit werden die Unterschiede hinsichtlich thermischer, energetischer und ökologischer Performance zwischen Gebäuden in Strohballenbauweise und Bauwerken in traditioneller Ziegelbauweise untersucht. Um Unterschiede aufgrund unterschiedlicher Größe, Ausgestaltung und Morphologie auszuschließen wurden neben zwei realen Gebäuden (eines in Ziegelbauweise, eines in Strohballenbauweise) zusätzlich zwei virtuelle Gebäude erdacht, die auf den untersuchten realen Gebäuden basieren. Dabei wurde die Konstruktionsform getauscht (Strohballenkonstruktion statt Ziegelkonstruktion und umgekehrt). Damit war es möglich einen direkten Performancevergleich anhand dieser Bauwerke durchzuführen. Die Untersuchung zeigte, dass die Strohballenkonstruktion gegenüber der Ziegelkonstruktion einige Vorteile hinsichtlich Energie- und Ressourcenverbrauch, so wie auch hinsichtlich der Kosteneffizienz zeigt.

Die Arbeit gliedert sich in mehrere Abschnitte, im ersten Abschnitt werden der Hintergrund und die Motivation dieser Untersuchung präsentiert, sowie die in anderen wissenschaftlichen Publikationen bereits erreichten Erkenntnisse gezeigt. Stroh ist ein “Nebenprodukt” der Landwirtschaft, es ist nachhaltig, günstig und benötigt kaum Energie um als Baumaterial genutzt zu werden. Die Eigenschaften des Baumaterials Stroh zeigen ebenfalls sehr günstige Werte hinsichtlich Wärmedurchgang und Ökoeffizienz.

Im zweiten Abschnitt wird die Methodologie dieser Arbeit detailliert vorgestellt: Die verwendeten Berechnungs- bzw. Untersuchungsverfahren, Software mit der diese durchgeführt wurden, die verwendeten Bauwerke, deren Zonierung, die verwendeten Klimadaten und internen Bedingungen, die in dieser Untersuchung vorausgesetzt wurden. Auch die Modellierung der Gebäude wird präsentiert.

Im dritten Abschnitt werden die errechneten und simulierten Ergebnisse präsentiert: Diese umfassen Energieausweise und detaillierte thermische Simulationen der Bauwerke sowie eine umfassende ökologische Bewertung der in diesen Gebäuden verwendeten Baustoffe.

# ACKNOWLEDGEMENT

First I would like express my gratitude to Univ. Prof. Dipl.-Ing. Dr.techn. Ardeshir Mahdavi for his scientific guidance and his support which enabled me to carry out this research.

Furthermore I thank all the people from the Building Physics Institute for their great suggestions and their patience to help and solve issues that came up during my thesis. Special thanks to Ulrich Pont and Kristina Orehounig.

I would like to thank the architects who shared their data with me in order to make this study possible.

Above all, I would like to express my gratitude to my family who made it possible for me to study in Vienna and all of my friends for their encouragement and their support.

## LIST OF ABBREVIATIONS AND SYMBOLS

| Abbreviations and symbols | Explanation |
|---|---|
| ach | Air Change Rate |
| AP | Acidification Potential |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineering |
| °C | Celsius degree |
| cm | Centimeter |
| $CO_2$ | Carbon Dioxide |
| $CO_{2equi}$ | Carbon Dioxide Equivalent |
| CTA | Ceiling to attic |
| E | East |
| ECOBINE | Ecological Building Net |
| ED | Entrance door |
| EDSL | Environmental Design Solutions Limited |
| EPDs | Environmental Product Declarations |
| EPS | Expanded polystyrene |
| FTG | Floor to the ground |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| IBO | Austrian Institute for Building and Ecology |
| IPCC | Intergovernmental Panel on Climate Change |
| $kgm^{-3}$ | Kilogram per cubic meter |
| kW | Kilowatt |
| kWh | Kilowatt hours |
| $kWhm^{-2}a^{-1}$ | Kilowatt hours per square meter annually |
| $m^2$ | Square meter |
| $MJ_{equi}$ | Mega joule Equivalent |

| | |
|---|---|
| N | North |
| NE | North-East |
| N+F | Key and slot (Nut und Federbindung) |
| $NO_x$ | Nitrogen Oxides |
| NW | North-West |
| OIB-RL | Austrian Institute for Building |
| | Technology- Guidelines |
| OW | Outside wall |
| OW-NE | Outside wall orientated to North-East |
| PEI | Primary Energy Content |
| S | South |
| SE | South-East |
| $SO_2$ | Sulfur Dioxide |
| $SO_{2equi}$ | Sulfur Dioxide Equivalent |
| SW | South-West |
| TAS | Thermal Analysis Simulation |
| TD | Terrace door |
| VOC | Volatile Organic Compounds |
| WI | Window |
| $Wm^{-1}$ | Watt per meter |
| $Wm^{-2}K^{-1}$ | Watt per square meter Kelvin |
| XPS | Extruded polystyrene |
| 1_B | Brick building |
| 1_S | Virtual straw-bale building |
| 2_B | Virtual brick building |
| 2_S | Straw-bale building |

## Table of contents

ABSTRACT ........................................................................................................I

ZUSAMMENFASSUNG (IN DEUTSCHER SPRACHE) ................................ II

ACKNOWLEDGEMENT ................................................................................ III

LIST OF ABBREVIATIONS AND SYMBOLS .............................................IV

TABLE OF CONTENTS...................................................................................VI

LIST OF EQUATIONS ....................................................................................XII

LIST OF TABLES........................................................................................ XIII

1. INTRODUCTION ..................................................................................... 1

1.1 Overview ....................................................................................... 1

1.2 Motivation ..................................................................................... 3

1.3 Background..................................................................................... 4

1.3.1 History of straw-bale architecture................................................ 4

1.3.2 Technology ..................................................................................... 6

1.3.3 Advantages and disadvantages of the different constructions ...... 7

1.3.4 Thermal conductivity ..................................................................... 9

1.3.5 Moisture ........................................................................................ 11

1.3.6 U-Value (thermal transmittance) ................................................ 11

1.3.7 Embodied energy ........................................................................ 12

1.3.8 Climate’s effect ............................................................................ 13

1.3.8.1 Global warming and global warming potential........................... 14

1.3.8.2 Acidification potential................................................................. 17

1.3.8.3 Primary energy content ............................................................... 18

1.3.9 General definitions and calculations for energy metrics............. 19

2. METHODOLOGY ................................................................................... 23

2.1 Examined buildings ...................................................................... 23

2.1.1 Real buildings ........ 23
2.1.1.1 Brick building (1_B) ........ 23
2.1.1.2 Straw-bale building (2_S) ........ 24
2.1.2 Virtual buildings ........ 25
2.1.2.1 Virtual brick building (2_B) ........ 25
2.1.2.2 Virtual straw-bale building (1_S) ........ 26
2.1.3 Summary of buildings ........ 27
2.2 Applied evaluation methods ........ 28
2.2.1 Energy certificate ........ 28
2.2.1.1 Climate data ........ 28
2.2.2 Dynamic thermal simulation ........ 29
2.2.2.1 Weather data ........ 29
2.2.2.2 Zoning in EDSL TAS ........ 31
2.2.2.2.1 Zoning in the brick building and in the virtual straw-bale building 31
2.2.2.2.2 Zoning in the straw-bale building and the corresponding virtual brick building ........ 33
2.2.2.3 Internal conditions used for dynamic thermal simulation ........ 34
2.2.2.4 Thermal properties ........ 36
2.2.3 Environmental indicators ........ 38
3. RESULTS AND DISCUSSIONS ........ 39
3.1 Heating demand results ........ 40
3.1.1 Energy certificate result ........ 40
3.1.2 Dynamic thermal simulation result ........ 41
3.1.3 Comparison between the results of the two different methods ... 43
3.2 Dynamic thermal simulation results ........ 44
3.2.1 Transmission losses ........ 44
3.2.2 Natural infiltration losses ........ 45

3.2.3 Internal gains ........ 47

3.2.4 Solar gains ........ 48

3.3 Environmental indicators ........ 50

3.3.1 Global warming potential ........ 50

3.3.2 Acidification potential ........ 53

3.3.3 Primary energy content ........ 55

4. CONCLUSION ........ 57

5. FUTURE RESEARCH ........ 59

6. REFERENCES ........ 60

7. FURTHER RESOURCES ........ 64

8. APPENDIX ........ 65

## LIST OF FIGURES

Figure 1-1 Final energy consumption by sector in Hungary (2008) according to enerCEE 1

Figure 1-2 Share of energy consumption by end uses in total household consumption in Europe in percentage 2

Figure 1-3 Construction methods for straw-bale houses 6

Figure 1-4 Embodied energy of different materials according to Greenspec EPDs 13

Figure 1-5 Annual Greenhouse Gas Emissions by sector, 2000 15

Figure 1-6 Acidification potential 17

Figure 1-7 Categories of primary energy content 18

Figure 1-8 Thermal influences on a building 19

Figure 2-1 Simulation model and photo of the brick building 24

Figure 2-2 Simulation model and photo of the straw-bale building 25

Figure 2-3 Simulation model of the virtual brick building 26

Figure 2-4 Simulation model of the virtual straw-bale building 26

Figure 2-5 Hungary’s climate with the two examined buildings on it 29

Figure 2-6 Ground floor plans of the brick building and the virtual straw-bale building coloured by zones 31

Figure 2-7 Building elements shown by location in the brick building and in the virtual straw-bale building 32

Figure 2-8 Ground floor plans of the straw-bale building and the virtual brick building coloured by zones 33

Figure 2-9 Building elements shown by location in the straw-bale building and in the virtual brick building 34

Figure 3-1 Total annual heating demand of the examined buildings based on simple calculation methods 40

Figure 3-2 Total annual heating demand of the examined buildings based on dynamic thermal simulations 41

Figure 3-3 Reduction of total annual heating demand of the examined buildings based on dynamic thermal simulation and simple calculation method 42

Figure 3-4 Total annual heating demand of the examined buildings based on dynamic thermal simulation and simple calculation method 43

Figure 3-5 Monthly transmission losses based on dynamic thermal simulations in the brick building and in the virtual straw-bale building 44

Figure 3-6 Monthly transmission losses based on dynamic thermal simulations in the straw-bale building and in the virtual brick building 45

Figure 3-7 Monthly natural infiltration losses based on dynamic thermal simulations in the brick building and in the virtual straw-bale building 45

Figure 3-8 Monthly natural infiltration losses based on dynamic thermal simulations in the straw-bale building and in the virtual brick building 46

Figure 3-9 Monthly internal gains based on dynamic thermal simulations in the brick building and in the virtual straw-bale building 47

Figure 3-10 Monthly internal gains based on dynamic thermal simulations in the straw-bale building and in the virtual brick building 47

Figure 3-11 Monthly solar gains based on dynamic thermal simulations in the brick building and in the virtual straw-bale building 48

Figure 3-12 Monthly solar gains based on dynamic thermal simulations in the straw-bale building and in the virtual brick building 49

Figure 3-13 Global warming potential based on OI3 indicators in the four examined buildings 50

Figure 3-14 Global warming potential of different building elements based on OI3 indicators in the brick building and in the virtual straw-bale building 51

Figure 3-15 Global warming potential of different building elements based on OI3 indicators in the straw-bale building and in the virtual brick building 52

Figure 3-16 Acidification potential based on OI3 indicators in the four examined buildings 53

Figure 3-17 Acidification potential of different building elements based on OI3 indicators in the brick building and in the virtual straw-bale building 54

Figure 3-18 Acidification potential of different building elements based on OI3 indicators in the straw-bale building and in the virtual brick building 54

Figure 3-19 Primary energy content based on OI3 indicators in the four examined buildings 55

Figure 3-20 Primary energy content of different building elements based on OI3 indicators in the brick building and in the virtual straw-bale building 56

Figure 3-21 Primary energy content of different building elements based on OI3 indicators in the straw-bale building and in the virtual brick building 56

Figure 8-1 Plan of the brick building 65

Figure 8-2 Section of the brick building 66

Figure 8-3 Plan of the straw-bale building 70

Figure 8-4 Section of the straw-bale building 71

## LIST OF EQUATIONS


Eq. 1 U-value 20

Eq. 2 U-value for windows 20

Eq. 3 Heating load 20

Eq. 4 Heating demand 21

Eq. 5 Transmission gain 21

Eq. 6 Infiltration losses 21

Eq. 7 Solar gains 21

Eq. 8 Internal gains 22

## LIST OF TABLES


Table 1-1 Advantages and disadvantages of a straw-bale building 9

Table 1-2 Thermal conductivity for straw-bales according to different sources by the Danish Energy Agency 10

Table 1-3 U-value for stuccoed straw-bale walls provided by the Danish Energy Agency 12

Table 1-4 Global Warming Potential Values from the IPCC (Intergovernmental panel on climate change) for some key GHGs 16

Table 2-1 General data of the examined buildings 27

Table 2-2 Weather data, Budapest, Hungary 30

Table 2-3 Weather data, Győr, Hungary 30

Table 2-4 Zones in 1_B and in 1_S associated with floor areas and volumes 32

Table 2-5 Zones in 2_S and in 2_B associated with floor areas and volumes 33

Table 2-6 Internal conditions of the examined buildings- internal gains 35

Table 2-7 Internal conditions of the examined buildings- settings of the thermostat, schedule 35

Table 2-8 U-value limits according to the OIB-RL 6 36

Table 2-9 U-values in the four examined buildings 36

Table 2-10 U-value limits in passive houses according to ECOBINE (Ecological Building Net) 37

Table 8-1 Building elements of the brick building 67

Table 8-2 Thermal attributes of the building elements in the brick building 68

Table 8-3 OI3 values of the brick building 69

Table 8-4 Building elements of the straw-bale building 72

Table 8-5 Thermal attributes of the building elements in the straw-bale building 73

Table 8-6 OI3 values of the straw-bale building 75

# 1. INTRODUCTION

## 1.1 Overview

Architects in general have an ethical responsibility towards this planet to create and design structures that are sustainable. In Touson Saryon’s opinion in 80 years there will be no more oil left on the planet and in about 20-30 years it will be completely unaffordable to depend on oil. Consequently, we need to start thinking about how to reduce energy costs and build more sustainably. People need to find a way to live their life without exploiting and wasting the resources of the Earth. This is the responsibility of each and every country and small changes can sum up to significant positive effects on our environment (Hart 2013).

In Hungary, energy consumption increases year by year and building straw-bale homes could be a potential option to decrease this consumption and would also lessen the negative impact on the environment. Figure 1-1 shows the final energy consumption by sector in Hungary in 2008.

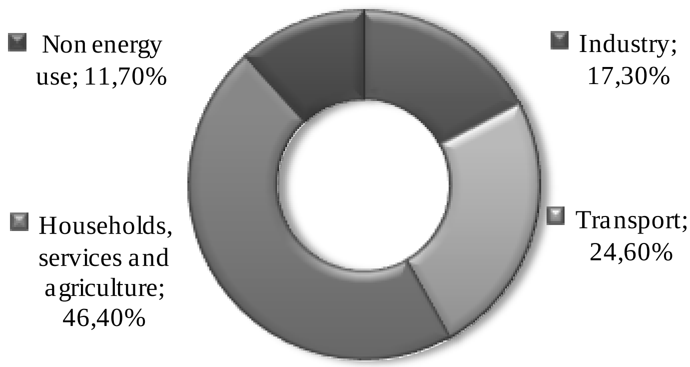


*Figure 1-1 Final energy consumption by sector in Hungary (2008) according to enerCEE (Austrian Energy Agency 2012)*

According to enerCEE in 2008 in Hungary 46,4 percent of the final energy demands came from households, services and agriculture, and therefore is building-related. Figure 1-2 shows the energy consumption by end uses in total household consumption in Europe.

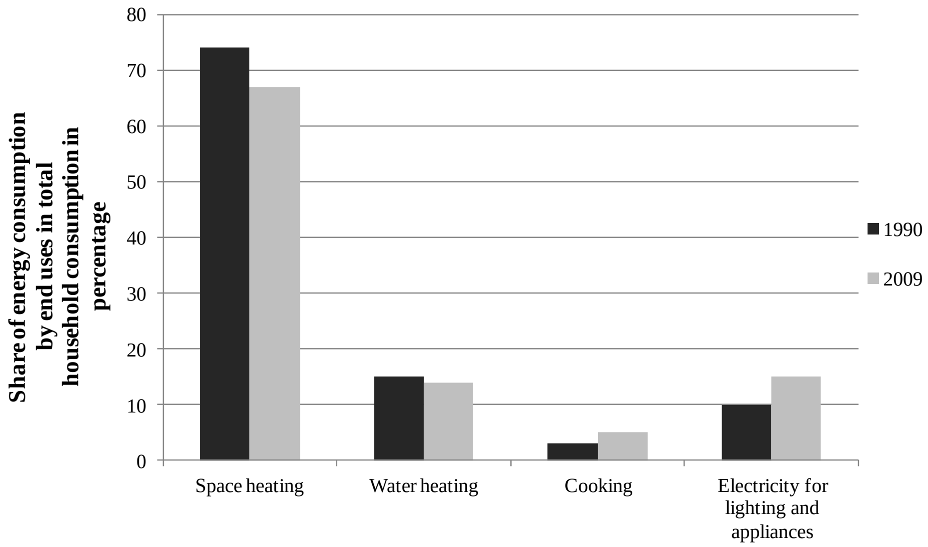


*Figure 1-2 Share of energy consumption by end uses in total household consumption in Europe in percentage (European Environmental Agency 2012)*

The highest percentage was used for space heating- approximately 75 percent- therefore this is the area where significant amounts of energy could be saved by decreasing the energy demand for space heating. Although this percentage got lower by 2009, it still represents more than two thirds of the overall energy consumption.

The goal of this research is to offer a way to reduce household energy consumption by using constructions that are more energy efficient. Thus, straw-bale constructions were compared to conventional brick constructions on two case study buildings. The comparison was performed with the help of computer-aided calculation and simulation of certain building performance indicators:

- The heating demand of the buildings was calculated with a standard suggested procedure as well as with a sophisticated dynamic thermal simulation application. Due to the constitutive impact of transmission losses, natural infiltration losses, internal gains and solar gains on the heating demand, these indicators were analyzed as well.

- An established indicator for environmental impact of building materials was also calculated (IBO 2011).

## 1.2 Motivation

There is a lot of waste straw available from wheat, oats and other grains, which is often burnt or composted, whereas, it could be easily used for the construction of new buildings. There are some pro-arguments for the use of straw in building construction mentioned in different works and sources:

- It has a certain insulating capacity, in most cases it can be sourced locally; it is fairly cheap and green. The cost of the building depends on different aspects such as design and size, but it is definitely cheaper than a conventional building (US Department of Energy 1995).
- Straw-bale buildings show high energy efficiency according to the big mass of the straw. Straw is a natural material; its thermal insulating capacity outperforms that of modern synthetic insulation materials. The preparation of the straw-bales does not require any mineral resources and energy source consumption (Pruteanu 2010).
- In straw-bale homes the temperature in summer is rather cool. One reason is the good thermal insulation capacity of straw, the other one is that as the result of the sunshine the moisture in the straw (approximately 14 percent) starts to evaporate, which comes with loss of heat. So in summer the inner temperature will always be lower than in the outer space. The straw absorbs the evaporated moisture at night again, so even on really hot summer days; the house is not overheated (Energia ès Környezet Alapítvàny 2012).

However in literature also potential problems are mentioned:

- For instance if the windows are open all the time in summer then the hot air comes in, which reduces the cooling effect of the straw (Energia ès Környezet Alapítvàny 2012).

In this thesis straw-bale constructions and their environmental aspects are analyzed as well. Modern buildings negatively impact the environment, contributing to climate change through high energy use (producing building materials, maintenance and demolition of the buildings). A substantial amount of energy can be saved and the negative impact of the buildings on the environment can be reduced by using green building materials. This possibility of reducing the negative impact of construction on the environment makes it important to discuss these issues and explore more environment-friendly building techniques.

This work is intended to study the energy and environmental related advantages of straw in building constructions.

## 1.3 Background

### 1.3.1 History of straw-bale architecture

The oldest known and still standing straw-bale building is in Nebraska, in the United States of America and it was built in 1901 as a residential house. There was a huge inner migration within the USA after the abolition of slavery; people began to wander between the differently developed parts of the country. Thus the free labor and the housing needs started to grow. They had a lack of wood, but they had big corn and grain producing fields, so it was given to use the side product of agriculture for something. The mechanization of the agriculture developed fast, they started to work with baling machines and reaping machines which were working with steam, vegetable oil and later on with diesel oil. The straw as a ridging was not so popular mostly because of the huge prairie fires. Therefore they started to build straw-bale buildings (Medgyasszay and Novak 2006).

The word of mouth says that the first straw-bale building was built by settlers as a temporary shelter for winter. The inside part of the straw was patched and after a while it turned out that it was not waterproof, so they patched the outside part too. Accidentally a spark came out of a steam-engine which started a fire and that is when they realized that straw was fireproof with enough clay on it.

In Hungary this type of construction emerged later than in the USA, because the big grain producing fields evolved in the late 19th century. Hungary had too much straw because of the agriculture, so it was destroyed by burning. This burning caused huge environmental contamination. Today this process is prohibited.

In the Hungarian economy, straw was used for livestock farming, but during the years a radical reduction took place in the livestock production, so the problem of straw remained unsolved. This is one of the reasons why straw-bale homes appeared. Another motivating factor was the low operational cost. Furthermore, straw as building material is known to be widely compatible for people with asthmatic and allergic illnesses (Medgyasszay and Novak 2006). Although straw-bale houses could have been built already at the end of the 19th century or the beginning of the 20th, the first straw-bale building in Hungary was completed in 2001 in a city called Sárospatak. This house was built because people realized that straw has less negative impact on the environment and the heating costs could be also reduced through the construction. The cost of heating for the whole heating season in this particular house in Sárospatak is approximately 200 Euros, which is substantially lower compared to the heating costs of other buildings (Medgyasszay and Novak 2006).

In the field of straw-bale buildings, it has to be mentioned that the resources are infinite, straw has a low negative impact on the environment and it has excellent building physical and building biological attributes (Amazon Nails 2001).

### 1.3.2 Technology

The following figure represents the three types of technology used for building a straw-bale building.

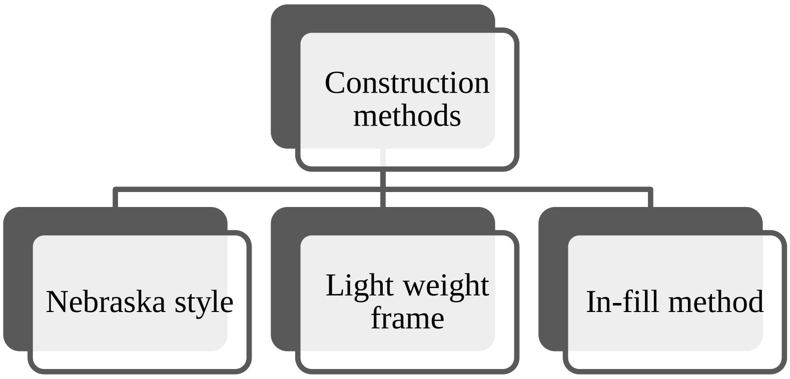


*Figure 1-3 Construction methods for straw-bale houses (Amazon Nails 2001)*

Amazon Nails is a company working with straw-bale housing. The firm also holds lectures at universities and schools, and has published a summary about the technology of building straw-bale.

One of the technologies is the so called ‘Nebraska- style’ where the straw is a load-bearing construction. There is no column or wall part where the weight of the roof runs down, it is only made from well-structured straw-bales with steel wires in it. This type of technology is recommended if the area of the building is not too large.

The other method is the light weight frame, where the house is constructed with a frame (usually from wood). However this is not sufficient for a load-bearing structure, therefore it works together with the straw to carry the weight of the roof and floors.

The third method is the in-fill method where there is a proper beam structure or frame from wood, which constitutes the load-bearing structure, and straw-bales play only a filling role in the walls. In the latter case the thermal insulation and other building physical properties become a priority. This type of technology has become really common lately, because the load-bearing structure used is similar to that of the conventional buildings, which means that during the planning process there are no new challenges.

It is obvious that frames made from wood seem to be more ecological, however due to constructive limitations; it would be more feasible to use steel structures. A number of steel structured warehouses covered by straw-bales have been constructed in the past.

There are different types of frames used for residential buildings. The most common one is the ladder frame, which holds the roof (normally this frame is hidden inside the walls), but there are cases where the frame is outside the walls, usually for aesthetic reasons.

In case of the in-fill method, there are prefabricated panels for straw-bale houses available on the market. Comparable to prefabricated concrete panels, wooden frame boxes are constructed and filled with straw-bales on the site. Sometimes clay is used as plaster and put on the construction already in the factory. This kind of technology makes the construction faster and the weather conditions do not obstruct the construction.

The prefabricated panels can also be used for subsequent insulation. This might be a great solution for an already built house which has an insufficient insulation.

The specific straw-bale home analyzed in this research has a pine ladder frame, which is located between the straw, and therefore, is not visible.

### 1.3.3 Advantages and disadvantages of the different constructions

One major advantage of a straw-bale building is that straw is a waste product of agriculture, so it is just given by the nature and is affordable. Furthermore:

- These buildings are highly energy efficient.
- They are well insulated due to the large mass of straw.
- This method does not have any heavy machine demand, because most of the machines needed, can be found in the agriculture.
- This construction method helps reduce air pollution ($CO_2$ and $SO_2$) .
- In case of demolition there is not much waste because demolition materials from the walls can be returned to the nature and the wood can

be recycled in the sense of being used for new buildings or chopped down and used for heating or bedding for animals (Waste Management World 2013).

- There is lower heating demand and no cooling demand during summer because the straw has a high heat capacity.
- The biological characteristics of the building are agreeable as well: breathable, permeable walls with good acoustic performance (Amazon Nails 2001).
- Another advantage of a straw-bale building is that it has low embodied energy, which means that the energy which is needed for the straw in its whole life-cycle is quite low. Actually energy is only used in the baling process and during the transportation, if necessary (Hollis 2005).
- Straw-bale buildings are very efficiently insulated, therefore, during the heating period they require less energy, which is favourable considering the growing concern of climate change. According to a Californian study straw-bale houses could save 75 percent on heating and cooling costs (Wanek 2012).
- The conductivity of straw, which is a key indicator influencing the transfer of heat through building elements, is quite low. Building elements using common straw technology usually have U-values that are lower than minimum requirements in most EU- countries. The required U-value (in Vienna according to the EURIMA) for outside walls is 0.35 $Wm^{-2}K^{-1}$ and the U-value of a straw-bale element is approximately between 0,10 and 0,20 $Wm^{-2}K^{-1}$.
- Straw-bale buildings are fire resistant, although there is a certain risk of fire during the storage and construction.

The advantages outweigh the few disadvantages that straw-bale homes come with. The straw has to be dry and should be protected against moisture during construction; otherwise, it will start to rot. Moisture has to be kept out of the wall, to prevent the growth of mold and fungus. There are a few constructive ways to prevent moisture intrusion in straw-elements: the building has to be raised above the ground, which makes it more difficult for water to penetrate walls. An overhang of the roof is necessary to protect the house from rain.

Straw is not fire resistant on its own, as such; plaster and stucco are required to ensure fire safety (Amazon Nails 2001).

Table 1-1 summarizes the pros and cons of straw-bale buildings.

*Table 1-1 Advantages and disadvantages of a straw-bale building (Medgyasszay and Novak 2006)*

| **Advantages of a straw-bale building** | **Disadvantages of a straw-bale building** |
|---|---|
| Side product of agriculture | No official regulations in Hungary regarding these buildings |
| Large quantity can be found | No industrial usage possible |
| Fairly cheap and green | Not recommended in high density areas |
| Easily executed constructions | Not recommended in a humid climate |
| Good quality of the wall element | |
| High thermal capacity | |
| Agreeable biological properties | |
| Environment-friendliness | |
| **Ecological aspects** | **Danger** |
| Low built-in energy content | Fire |
| No emission of pollutants | Water |
| Healthy building, breathing wall | Rodents |

### 1.3.4 Thermal conductivity

Commonly, buildings in Hungary today are made of brick or concrete, insulated with different types of materials such as polyurethane panels, XPS, EPS etc. The thermal properties of these materials might be better than those of straw, but the energy is needed for their production, transport and application and building construction has to be taken into account. If an energy efficient house is desired it is better to use green materials, because the primary energy needed for it, is usually lower (Pruteanu 2010).

The most essential attribute of a straw-bale construction is the thermal insulation. In order to define the thermal insulation, thermal conductivity of the layers (forming the construction) needs to be known. Thermal conductivity represents the amount of heat which goes through a material with a given thickness. Thermal conductivity of straw-bale also depends on the type of the straw, the density of the straw and straw orientation (if it is parallel to heat flow then the conductivity is higher, if it is perpendicular then the conductivity is lower). In order to reach low energy consumption in a new building, materials with high thermal resistance have to be used (Straube 2013). According to a research project in Denmark, the following values were assumed for straw construction:

*Table 1-2 Thermal conductivity for straw-bales according to different sources by the Danish Energy Agency (Munch-Andersen and Moller Andersen 2012)*

| | **Density** | **Thermal conductivity** | |
|---|---|---|---|
| | **[kg.m$^{-3}$]** | **[W.m$^{-1}$.K$^{-1}$.]** | |
| Reference | | Straw parallel to heat flow | Straw perpendicular to heat flow |
| Present study | 75 | 0,057 | 0,052 |
| Present study | 90 | 0,06 | 0,056 |
| Haus der Zukunft | 100 | | 0,038 |
| Christian et al. (1998) | 62 resp. 81 | 0,082 | 0,057 |
| McCabe (1993) | approx. 150 | 0,06 | 0,048 |
| Sandia National Lab. (1994) | 90 | 0,05-0,06[2] | 0,05-0,06 |

The straw-bale homes breathe through their walls, so there is a slow air exchange with the outside. This kind of air exchange ensures the appropriate quality of the inside air, however, due to the reverse flows the cold air molecules of the unconditioned outside air penetrate into the heated space (Medgyasszay and Novak 2006).

Aside from comfort considerations in winter, overheating protection should also be considered in summer to ensure summertime thermal comfort.

### 1.3.5 Moisture

It is no question that the biggest enemy of straw-bale homes is moisture. The damage made by water can cause major problems. According to Medgyasszay and Novak the weakest parts of a straw-bale wall are the top and the bottom parts of the walls. Moisture may appear on the inside surfaces, through condensation. It can also attack from the ground if the water present in the soil reaches the straw elements, or be absorbed by straw if it comes in contact with any moisture during the construction process. The most dangerous and lasting effects are caused if water comes from the sources such as rain, snow or melting snow.

Activities inside the building, such as cooking, showering, washing and drying of clothes generates water vapor, which migrates through the surrounding building elements to the outside. If this process is affected by a too large temperature drop inside the constructions, a danger of condensation damage is present. Preventive measures against this include:

- The right amount of natural ventilation.
- Use of plaster (loam or lime) in straw constructions to regulate the water vapor content in the air.

The vapour coming from the soil can be easily prevented by using appropriate waterproofing.

The most important rule in the climate of Hungary is the order of the layers of the outside wall. The vapour diffusion resistance of the materials from the inside to the outside has to decrease; therefore materials with decreasing moisture resistance are applied. This prevents large amounts of vapour from being trapped between the layers.

### 1.3.6 U-Value (thermal transmittance)

The U-value is the key indicator for thermal transmittance by conduction. It is expressed in $Wm^{-2}K^{-1}$. The lower the U-value is, the smaller the amount of energy transmitted through the construction will be.

Basically the U-value is used to express the capability of a material in the context of how well the building element transfers heat (Brennan 2013).

Table 1-3 shows a notable difference between a straw-bale wall and a brick wall. While the brick wall reaches approximately 1,5 $Wm^{-2}K^{-1}$, the straw-bale approaches only 0,2 $Wm^{-2}K^{-1}$. This could cause a huge difference in the energy consumption of the houses.

*Table 1-3 U-value for stuccoed straw-bale walls provided by the Danish Energy Agency (*Munch-Andersen and Moller Andersen 2012*)*

| **Straw orientation** | **Thickness of straw** | **Surfaces** | **U-value** |
|---|---|---|---|
| | **[mm]** | **[mm]** | **[$Wm^{-2}K^{-1}$]** |
| **Present study** | | | |
| parallel to heat flow | 385 | 34+42 mm stucco | 0,208 |
| perpendicular to heat flow | 365 | 26+26 mm stucco | 0,196 |
| **Christian et al. (1998)** | | | |
| parallel, with cavities | 470 | Stucco + 13mm board | 0,365 |
| parallel, without cavities | 480 | Stucco + 13mm board | 0,210 |
| **Watts et al. (1995), paralell** | 460 | Stucco + 13mm board | 0,210 |

### 1.3.7 Embodied energy

As mentioned before, the embodied energy is the energy used for the material in its whole life-cycle, in other words, the total primary energy consumed for the product. This includes extraction, manufacturing and transportation. In case of straw it is quite low, because energy is only used in the bailing process and during transportation if necessary (Greenspec 2013).

Contrary to straw, in the case of brick, energy is needed to mine clay, to create cuboids and then to bake and transport them to the site. These processes emit a lot of $CO_2$, while in the extraction of straw-bales the $CO_2$ contamination is rather low, because the grain uses $CO_2$ from the environment and produces oxygen while building the carbon atoms into its body (Medgyasszay and Novak 2006).

In table 1-4 the embodied energy of different common materials are illustrated according to the Greenspec EPDs.

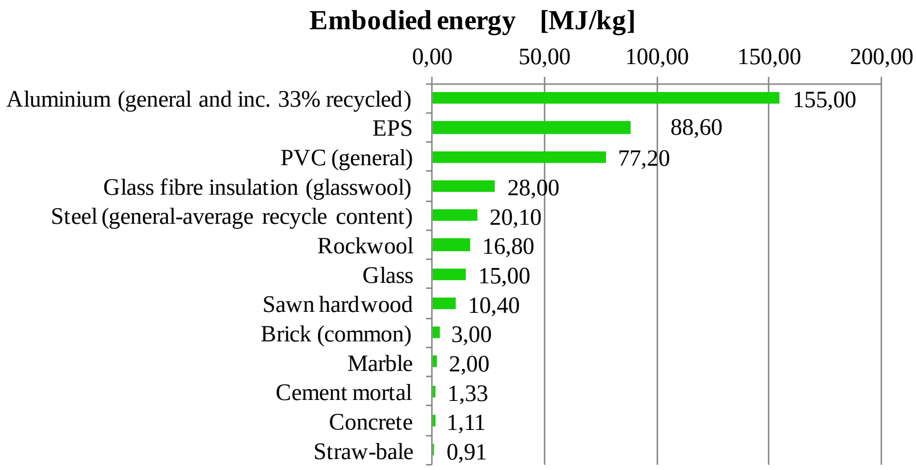


*Figure 1-4 Embodied energy of different materials according to Greenspec EPDs*
*(Greenspec 2013)*

### 1.3.8 Climate's effect

Local weather and micro-climate has to be taken into account in the planning of straw-bale building.

The climate's effect has to be mentioned on the straw-bale house and how the construction design can be adapted to the weather conditions. This has to be thought through during the design process. For instance if high precipitation is expected, which is the case in Hungary, it is better to design a roof overhang and a raised foundation. A second problem as mentioned before can be the humidity. The best solution against high humidity levels is a two sided approach: First, used materials have to have a high moisture regulating capacity (for instance certain plasters). Secondly, lime and soil-based materials can be put on the constructions additionally to keep the moisture level constant inside the walls. It is also possible to use mechanical solution, for instance an Energy Recovery Ventilator, which helps to keep the air fresh in the building and removes the excess moisture (Shepard and Bartels 2011).

Using organic materials can not only improve the carbon footprint, but can decrease the health risks to the people.

In conventional buildings we can often detect some chemicals or VOC's (Volatile Organic Compounds); common paint, lacquers, cleaning supplies, varnishes and waxes, pesticides, building materials and furnishings can emit these compounds. VOC's can lead to health issues such as asthma. Straw-bale buildings usually contain less of these chemicals than conventional buildings (United States Environmental Protection Agency 2013).

#### 1.3.8.1 Global warming and global warming potential

It is essential to talk about the impact of construction on the environment, especially with regards to climate change. First it has to be clarified what global warming means exactly. 'Climate change is any substantial change in Earth's climate that lasts for an extended period of time. Global warming refers to climate change that causes an increase in the average temperature of the lower atmosphere. Global warming can have many different causes, but it is most commonly associated with human interference, specifically the release of excessive amounts of greenhouse gases` (US EPA, 2006). The most common greenhouse gases are carbon-dioxide, methane and nitrous oxide (Lallanilla 2013).

Figure 1-5 shows the amount of man-made greenhouse gas emissions divided into eight sectors.

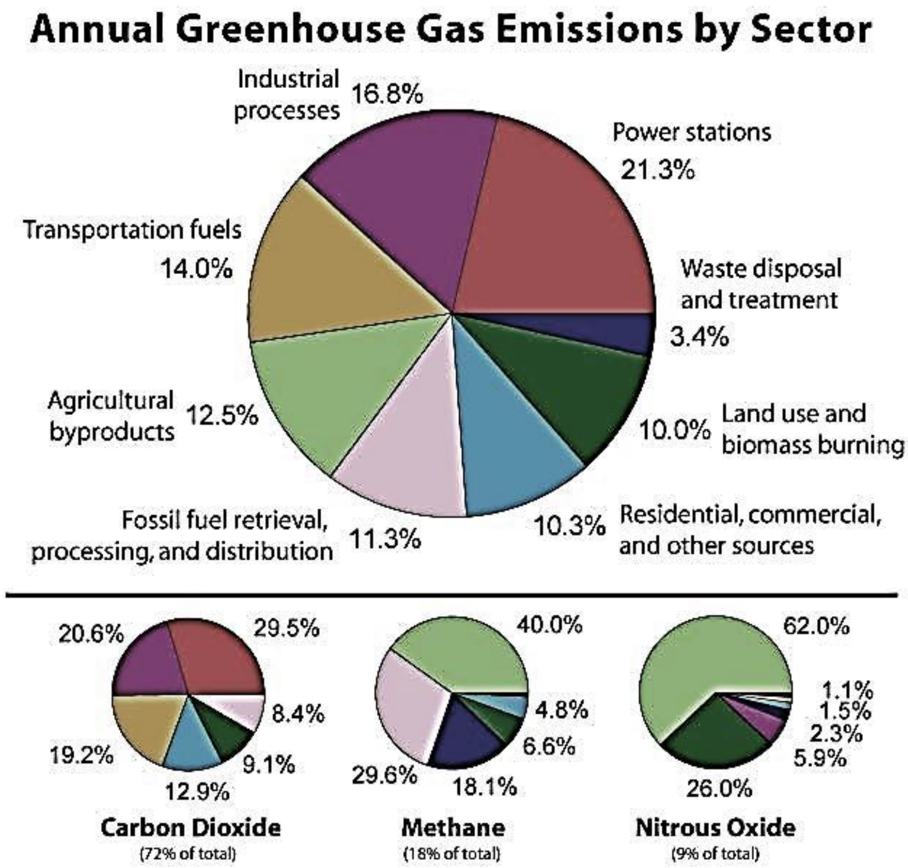


*Figure 1-5 Annual Greenhouse Gas Emissions by sector, 2000 (Rohde 2009)*

The highest percentage belongs to power stations (21,3 percent) and lowest percentage belongs to waste disposal and treatment (3,4 percent). Residential, commercial and other sectors are responsible for 10,3 percent of greenhouse gas emissions.

The figure on the top shows the total amount of greenhouse gases, weighted by the global warming potential over the next 100 years. This includes 72 percent of carbon-dioxide, 18 percent of methane, 9 percent of nitrous oxide and 1 percent of other gases.

'The global warming potential (GWP) is a value which compares the abilities of different greenhouse gases to trap heat in the atmosphere' (Greenhouse Gas 2011).

The GWP is calculated during a specific timeline like 20, 100 or 500 years. The GWP of the carbon-dioxide is standardized to 1. For instance if the GWP of

methane is 25 in 20 years, this means that the methane is 25 times more heat-absorptive than the carbon-dioxide per unit of weight, if the same amount of methane and carbon-dioxide were presented in the atmosphere (IBO-OI3 2011).
Gases with long atmospheric lifetime have high global concentration due to their lasting presence in the atmosphere. We use GWP values for these gases. Gases with short atmospheric lifetime perish quickly, so they do not represent a high GWP effect (Gillenwater 2010).
The table 1-4 presents the GWP values of different greenhouse gases.

*Table 1-4 Global Warming Potential Values from the IPCC for some key GHGs (Gillenwater 2010)*

| | **Lifetime (years)** | **GWP time in horizon** | | |
|---|---|---|---|---|
| | | 20 years | 100 years | 500 years |
| **Carbon-dioxide** | Complex | 1 | 1 | 1 |
| | | 1 | 1 | 1 |
| | | 1 | 1 | 1 |
| **Methane** | 12 | 72 | 25 | 7,6 |
| | 12 | 62 | 23 | 7 |
| | 12 | 56 | 21 | 6,5 |
| **Nitrous oxide** | 114 | 289 | 298 | 153 |
| | 114 | 275 | 296 | 156 |
| | 120 | 280 | 310 | 170 |

Lerner (2005) suggests that the alternative use of straw-bale construction (instead of traditional construction forms) might reduce $CO_2$ emissions by 0.6 - 1.2 tons per year per house (depending on house size and severity of the winter) (Lerner 2005).

#### 1.3.8.2 Acidification potential

'The acidification potential is given in sulphur dioxide equivalents ($SO_{2equi.}$). The acidification potential is described as the ability of certain substances to build and release H+ - ions.' (Eyerer et al. 2010, page 35).

The acidification potential is a kind of environmental phenomena caused by gases which produce acid when they come in contact with air humidity. Sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$) are some examples. Figure 1-6 shows the sources of these emissions such as combustion processes, transport and energy generation. Acidification has a negative effect not only on the environment but also on the buildings.

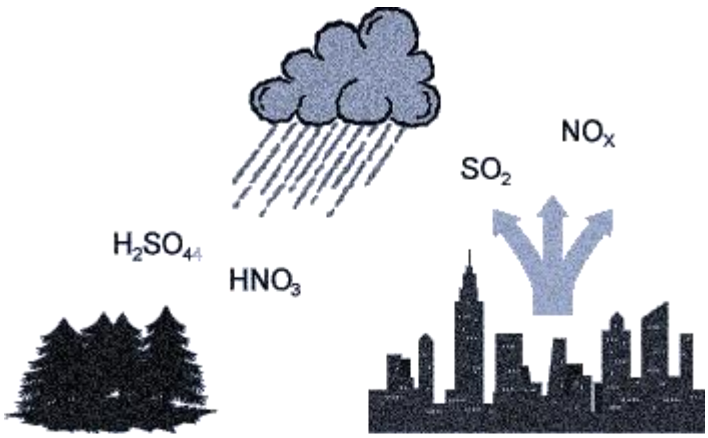


*Figure 1-6 Acidification potential (www.stiftung-mehrweg.de)*

#### 1.3.8.3 Primary energy content

‘The primary energy content is the overall consumption of energy resources required to manufacture a product or a service’ (IBO GmbH 2011).

Figure 1-7 represents two categories of primary energy content: renewable and non-renewable primary energy content.

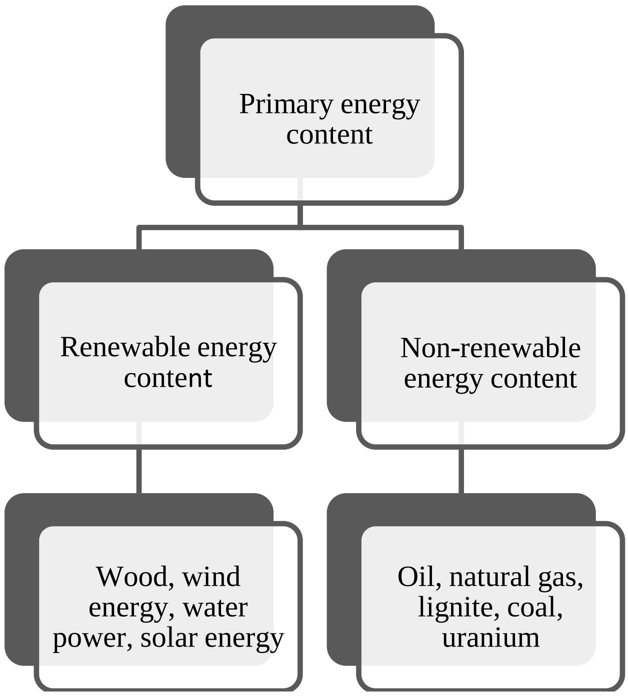


*Figure 1-7 Categories of primary energy content (IBO-OI3 2011)*

### 1.3.9 General definitions and calculations for energy metrics

Figure 1-8 describes the different thermal infulences on a building and how they effect our daily life.

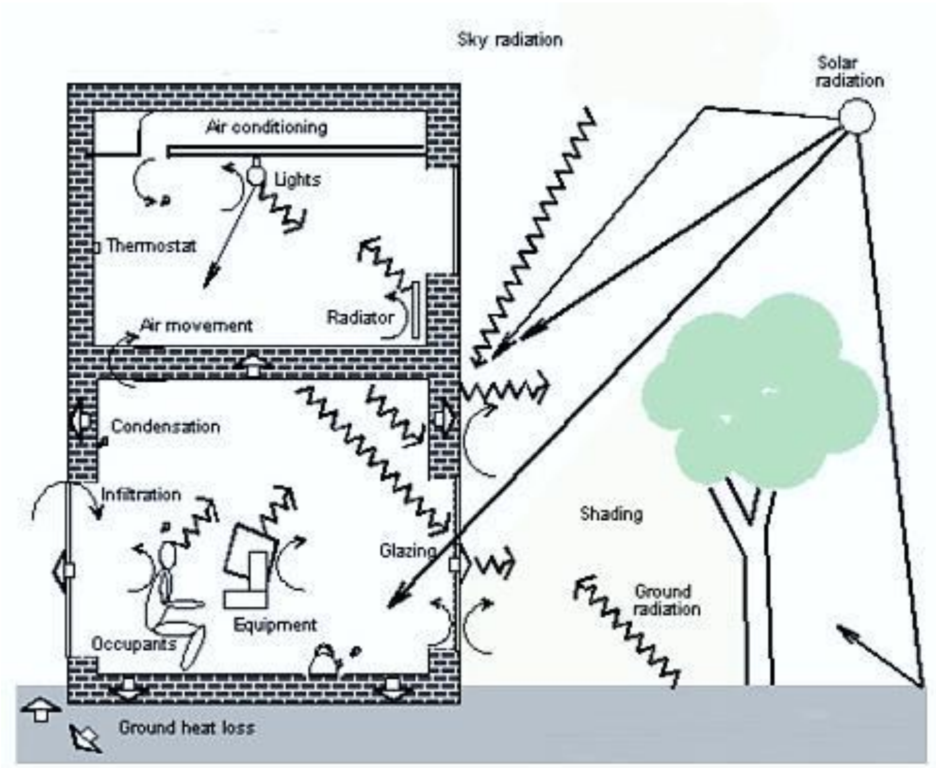


*Figure 1-8 Thermal influences on a building (EDSL 2010)*

Part of the solar radiation is reflected from the ground, the other part is reflected from the building, some parts are absorbed by opaque materials and the last part is transmitted through the transparent materials. The amount of heat gained through the solar radiation is the solar gain. The internal gains are also shown on Figure 1-8 in the form of heat produced by equipment, lighting and occupants.

The following formulas can be used for manual calculation of indicators. These formulas are the base of most computer-aided calculation tools, even if the different time-scales of input variables (climate, occupancy schedules etc) are used in these sophisticated applications (Mahdavi 2010).

**U-value** U [$Wm^{-2}K^{-1}$]:

U-value is the amount of heat loss per $m^2$ in a building element.

Formula: $U = \frac{1}{R_T} = \frac{1}{R_{SI}+R_{Scichten}+R_{SE}}$ , where (Eq. 1)

U is the U-value,

$R_T$ is the sum of thermal resistance of different layers in the constructions.

Formula for windows: $U_w = \frac{Ag*Ug+Af*Uf+lg*\Psi g}{Ag+Af}$, where (Eq. 2)

$U_w$ is the U-value of the window,

$A_g$ is the area of the glass,

$U_g$ is the heat transfer coefficient of the window,

$A_f$ is the area of the frame,

$U_f$ is the heat transfer coefficient of the frame,

l is the perimeter glazing,

Ψ is the linear thermal resistance.

**Heating load** $Q_h$ [kWh]:

The amount of energy we need in order to heat up the zone to a desired temperature.

Formula: $Q_h = (Q_T+Q_v) - \eta(Q_i+Q_s)$, where (Eq.3)

$Q_h$ is the heating load,

$Q_T$ is the transmission gains/losses,

$Q_v$ is the ventilation gains/losses,

$Q_i$ is the internal gains/losses,

$Q_s$ is the solar gains and

η is the efficiency factor (depends if the building is heavy constructed, middle or light constructed).

**Heating demand** [$kWhm^{-2}a^{-1}$]:

The amount of energy the building consumes in the whole year per $m^2$. It can be easily calculated from the heating load:

Formula: $Q_d = Q_h$*3600/3600000, where (Eq. 4)

$Q_h$ is the heating load.

**Transmission losses** $Q_T$ [kWh]:

The amount of energy gained or lost by conduction between two points.

Formula: $Q_T = 0{,}024 * L_T * HGT$ , where (Eq. 5)

$Q_T$ is the transmission/ conduction gain,

$L_T$ is the total conductance,

HGT is the heating degree days.

**Infiltration losses** $Q_v$ [kWh]:

The amount of loss during the infiltration between the outer and inner space.

Formula: $Q_V = 0{,}024 * L_V * HGT$, where (Eq. 6)

$Q_V$ is the natural infiltration loss,

$L_V$ is the guiding value for ventilation ($L_V = 0{,}33 * n * V_n$) and

HGT is heating degree days.

**Solar gains** Qs [kWh]:

The amount of heat gained through solar radiation.

Formula: $Q_s = \sum (A_{gi} * I_j * f_{si} * g_{wj})$, where (Eq. 7)

$Q_s$ is the solar gain,

$A_{gi}$ is the area of the glass,

$I_j$ is the intensity of the sun radiation depending on the building location and orientation,

$g_{wj}$is the effective transmittance (g-value).

**Internal gains** Qi [kWh]:

Internal gains are the amount of energy we gain in a zone from occupants, equipments and lighting.

Formula: $Q_i$= 0,024*$q_i$ *BGF* HT, where (Eq.8)

$Q_i$ is the monthly internal gain,

$q_i$ is the heat flow density,

$H_T$ is the heating days and

BGF is gross floor area.

# 2. METHODOLOGY

In this chapter the examined buildings are described followed by sections about the thermal properties used for examination. To make a comparison between the buildings possible, both real buildings were virtually reconstructed each with the other's construction. These reconstructions are referred to as virtual buildings in this study.

## 2.1 Examined buildings

For this study two real buildings were chosen: one building constructed with straw-bales and one constructed with traditional brick technology.
The original plans from the architects were acquired. These plans included site plans, floor plans, sections and 3D models. The buildings were visited and it was confirmed that the plans correspond closely to the actual buildings. Architects kindly agreed to the use of their work for this study.

### 2.1.1 Real buildings

#### 2.1.1.1 Brick building (1_B)

The first building is located in Piliscsaba approximately 26 km away from Budapest, designed by Hungarian architect András Fosztó. The house has a gross floor area of 112,27 $m^2$ and is of residential use (single family home).
It includes a heated ground floor and an unheated roof. The house is Southwest-Northeast orientated.
The entrance is oriented towards North-East; next to the entrance, the toilet and the laundry room are located on the right and a bedroom on the left. The living room which is on the other side of the building faces South with large glazed surfaces towards a terrace.
The foundation of the building is a monolith strip foundation. The load-bearing outside walls are made from POROTHERM 38N+F, the inside walls from POROTHERM 30 N+F and the partition walls from POROTHERM 10 N+F.

The fenestrations were individually fabricated from plastic, originally, passive house standard windows were intended but this plan was later abandoned. The windows have thus a U-value of 1.40 $Wm^{-2}K^{-1}$.
Figure 2-1 shows the simulation model and a photo of the brick building.

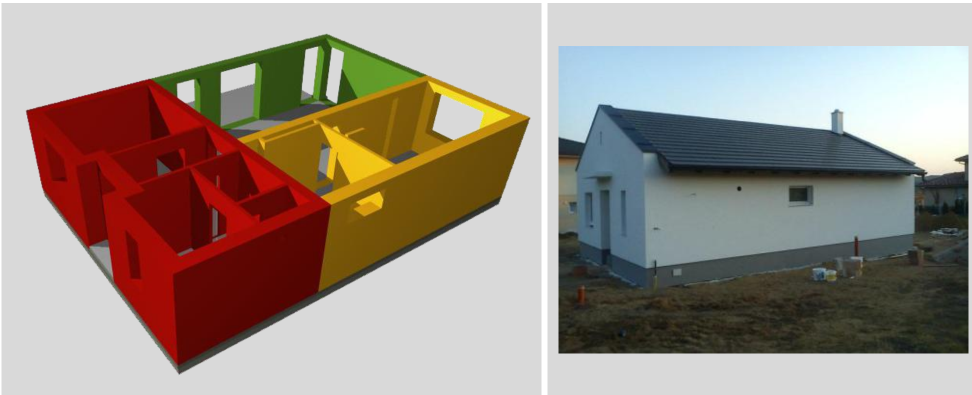

*Figure 2-1 Simulation model and photo of the brick building*

As Piliscsaba is a rather small city, there was no weather station data available, thus, climate information was acquired from Budapest, not far away.

#### 2.1.1.2 Straw-bale building (2_S)

The straw-bale building is located in Bozsok approximately two kilometers away from the Austrian - Hungarian border. It is a one-story family house designed by Tibor Jandrasits, which was completed in 2006.
The site is around 2100 $m^2$, the building is East-West orientated, the gross floor area is 199,30 $m^2$ only consisting of the heated ground floor.
The main entrance is on the South side, where the porch is located. At the entrance there is a small hall, an American-style kitchen and a living room on the left. The windows of the living room are oriented towards South and West. On the right side of the entrance hall there are several bedrooms, bathroom, working room and a wardrobe.

The foundation of the building is strip foundation and the load-bearing structure of the house is a ladder frame structure. The filling wall is composed of 50 cm thick straw-bales covered by 5 cm of clay on both sides. The partition walls were made of 10 cm thick Porotherm bricks. The roof is a traditional roof with collar beam. The roof slab is insulated by 35 cm of straw-bale, therefore the attic is unheated.

The windows were individually made; they are triple-glazed windows with wooden frames. However they were not intended to be passive windows, their U-value is 1 $Wm^{-2}K^{-1}$.

Figure 2-2 shows the simulation model and a photo of the straw-bale building.

*Figure 2-2 Simulation model and photo of the straw-bale building*

The nearest big city to this town is Győr in Hungary, so the climate data used in the simulations is from a weather station in Győr.

### 2.1.2 Virtual buildings

#### 2.1.2.1 Virtual brick building (2_B)

This building is a virtual building which was created based on the original straw-bale building by changing its building elements from straw construction to brick construction.

While the location, geometry and size of the building stayed the same, constructions were switched (corresponding to the real brick building).

Thermal properties of the fenestrations were changed to the values of the straw-bale building to allow in depth comparison.

Figure 2-3 shows the simulation model of the virtual brick building.

.

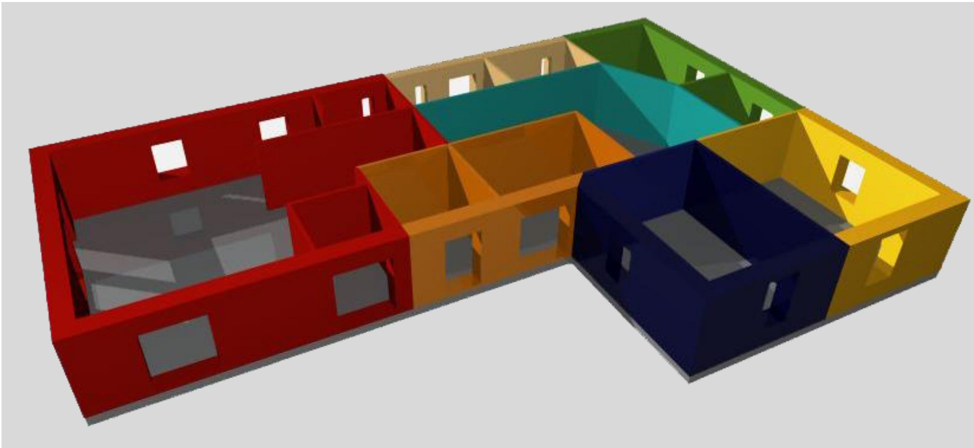

*Figure 2-3 Simulation model of the virtual brick building*

#### 2.1.2.2 Virtual straw-bale building (1_S)

This building is based on the same principle data as 1_B. This model is created based on the original brick building, but instead of the brick construction straw-bales are used.

Figure 2-4 shows the simulation model of the virtual straw-bale building.

.

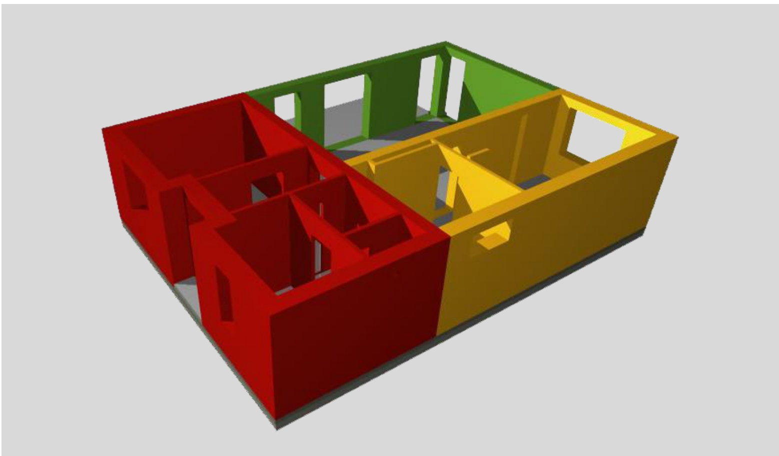

*Figure 2-4 Simulation model of the virtual straw-bale building*

### 2.1.3 Summary of buildings

Table 2-1 presents the general data of all the examined buildings in this study.

*Table 2-1 General data of the examined buildings*

| | **1_B** | **1_S** | **2_B** | **2_S** |
|---|---|---|---|---|
| Country | Hungary | | | |
| City | Piliscsaba | | Bozsok | |
| Floors | Ground floor + unheated roof | | | |
| Date of construction | 2011 | Virtual | Virtual | 2006 |
| Wall construction | Brick | Straw-bales | Brick | Straw-bales |
| Brutto heated floor area | 112,27m$^2$ | | 199,30m$^2$ | |
| Brutto heated volume | 345,81m$^3$ | | 673,65m$^3$ | |
| Envelope of the building | 386,38m$^2$ (100%) | | 646,98m$^2$ (100%) | |
| Sum of the areas of opaque elements of the building envelope | 367,18 m$^2$ (95,03%) | | 619,20 m$^2$ (95,71%) | |
| Sum of the transparent elements of the building envelope | 19,20 m$^2$ (4,97%) | | 27,78 m$^2$ (4,29%) | |
| Characteristic length | 0,90 m | | 1,04m | |

## 2.2 Applied evaluation methods

### 2.2.1 Energy certificate

Simple calculation method was used to create energy certificates with the help of Archiphysik, which is one of the most common calculation tools. Basically the building constructions (opaque and transparent) have to be modeled and their position in the building has to be determined by specifying the direction of the heat flow through the construction. There is also a possibility to make homogeneous or inhomogeneous building parts. After creating the building elements, specifying the thermal properties of the materials, and selecting the appropriate heating system, the program automatically calculates the heating demand based on current standards (ÖNORM B 8110-RL 6). The software also needs climate data, which can be either manually imported, or automatically retrieved by the software from the integrated weather data repository, according to the user provided location (e.g., postal code).

The energy certificate provides information regarding the heating energy demand. Energy certificates are widely used in Europe as an indicator of the energy performance of the building.

#### 2.2.1.1 Climate data

Once the location of the building is set in Archiphysik, the software automatically produces a climate data, which is based on the mean monthly temperatures and humidity. Figure 2-5 presents the two chosen buildings in Hungary located in the same climate zone.

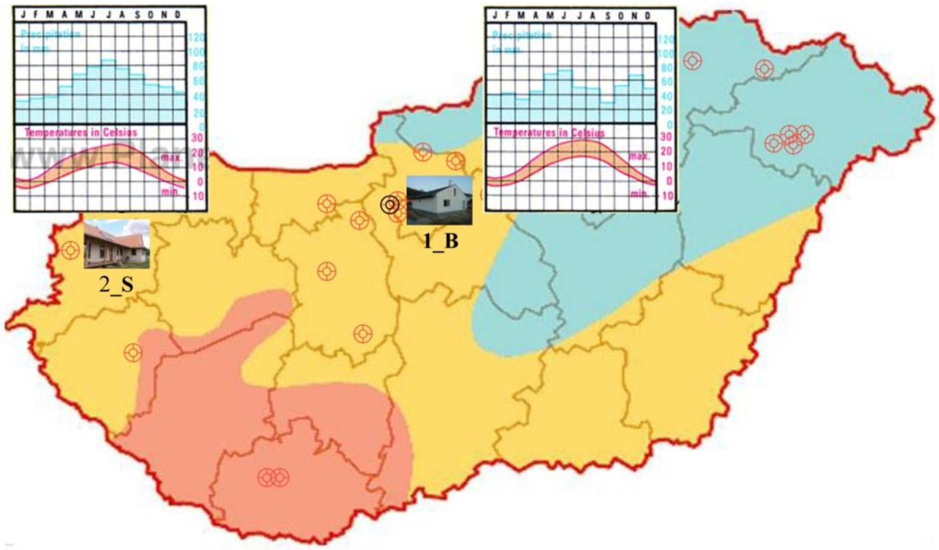


*Figure 2-5Hungary's climate with the two examined buildings on it (based on the diagram of Prof. Wolfgang Hassenpflug)*

### 2.2.2 Dynamic thermal simulation

TAS (Thermal Analysis Simulation) is a simulation tool, which is capable of performing dynamic thermal simulation and has a wide range of analysis capabilities. In addition to the heating demand, TAS is also capable of simulating other indicators such as heat transfer between elements.

TAS has three different parts; the first part is the 3D Modeler, where the envelope of the building is modeled and zones are created for different areas. The second part is the Building Simulator, where the building elements are defined, materials and their various attributes are determined, zones are assigned to the spaces, desired internal conditions are defined and the weather data is imported. After the second part, simulations can be processed and in the third part (Result Viewer) results can be analyzed.

#### 2.2.2.1 Weather data

Climate data for dynamic thermal simulation was acquired from weather station data stored in the database of the software meteonorm (METEOTEXT 2012). The locations of the weather stations are Budapest and Győr.

A weather station is a facility that examines the climate by using a number of sensors. It measures the essential attributes of atmospheric conditions such as temperature, global radiation, diffuse radiation, humidity and more.
The climate data from weather stations and the one from the tool of simple calculation method are very similar. Table 2-2 shows the climate data from Budapest, while table 2-3 shows the climate data from Győr.

*Table 2-2 Weather data, Budapest, Hungary (meteonorm.com)*

| **Month** | **Average temperature** | **Average global radiation** | **Average diffuse radiation** | **Average humidity** |
|---|---|---|---|---|
| | Monthly [°C] | [$Wm^{-2}$] | [$Wm^{-2}$] | [%] |
| January | -0,79 | 39,88 | 23,21 | 85 |
| February | 1,26 | 69,98 | 42,63 | 75 |
| March | 5,63 | 117,41 | 57,48 | 65 |
| April | 11,44 | 177,02 | 84,01 | 61 |
| May | 17,29 | 220,18 | 110,48 | 62 |
| June | 20,03 | 241,40 | 124,18 | 63 |
| July | 21,46 | 245,90 | 116,91 | 64 |
| August | 21,78 | 207,34 | 91,56 | 62 |
| September | 15,76 | 151,76 | 72,65 | 71 |
| October | 11,18 | 95,55 | 55,21 | 76 |
| November | 5,60 | 47,78 | 28,38 | 82 |
| December | -0,20 | 30,76 | 18,77 | 85 |

*Table 2-3 Weather data, Győr, Hungary (meteonorm.com)*

| **Month** | **Average temperature** | **Average global radiation** | **Average diffuse radiation** | **Average humidity** |
|---|---|---|---|---|
| | Monthly [°C] | [$Wm^{-2}$] | [$Wm^{-2}$] | [%] |
| January | -0,86 | 38,81 | 22,21 | 83 |
| February | 1,76 | 77,47 | 44,78 | 73 |
| March | 5,64 | 118,78 | 62,88 | 68 |
| April | 10,98 | 181,85 | 96,14 | 65 |
| May | 16,77 | 232,86 | 103,21 | 64 |
| June | 19,33 | 249,09 | 109,36 | 66 |
| July | 20,61 | 236,43 | 108,71 | 68 |
| August | 20,81 | 209,86 | 99,88 | 67 |
| September | 15,22 | 144,78 | 77,27 | 75 |
| October | 10,98 | 92,03 | 50,08 | 78 |
| November | 5,57 | 43,63 | 29,49 | 81 |
| December | 0,15 | 29,51 | 20,24 | 83 |

### 2.2.2.2 Zoning in EDSL TAS

TAS enables users to define thermal zones in the building. A zone is a volume that has specific properties with regard to occupancy, equipment, lighting, thermostat settings and ventilation (temperature, humidity and ventilation set points). If adjacent spaces have identical properties considering the mentioned domains, they can be represented as a single zone. However, the more zones are defined in a building, the more sophisticated and detailed thermal flow analyses can be conducted. Therefore, in this study, rooms with identical desired indoor conditions, but different orientations were also represented as different zones to allow in-depth analysis. Later on, in the building simulator internal conditions were defined and applied to zones.

#### 2.2.2.2.1 Zoning in the brick building and in the virtual straw-bale building

After modeling the buildings in TAS 3D Modeler, different zones were created in the house due to the properties of the spaces. Figure 2-6 shows the different zones in the brick building and also in the corresponding virtual straw-bale building.

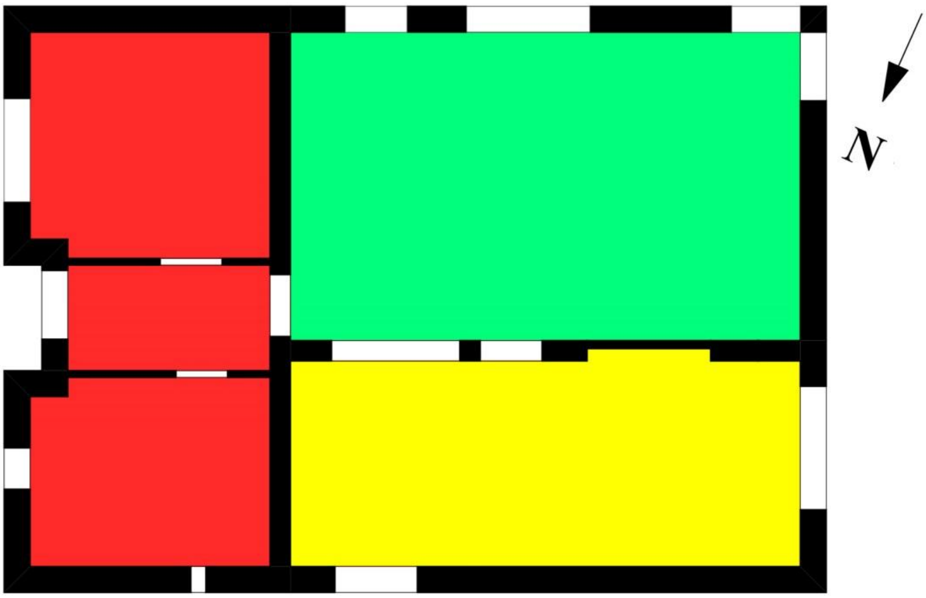


*Figure 2-6 Ground floor plans of the brick building and the virtual straw-bale building coloured by zones*

Table 2-4 describes the zones in the brick building associated with the floor areas and volumes.

*Table 2-4 Zones in 1_B and 1_S associated with floor areas and volumes*

| Name of the zones | Sign | Floor area [m$^2$] | Volume[m$^3$] |
|---|---|---|---|
| Room NE | | 26,04 | 80,19 |
| Room S | | 33,48 | 103,12 |
| Room NW | | 22,32 | 68,75 |

There are four different zones in the brick building, out of which three are heated; while the roof is unheated (the house is insulated on the ceiling slab).

In a second step all the building elements were modeled with the help of the Building Construction Database; thermal properties of the chosen materials were determined and applied to various building elements in the Building Simulator.

Figures 2-7 present the building elements shown by location in the brick building.

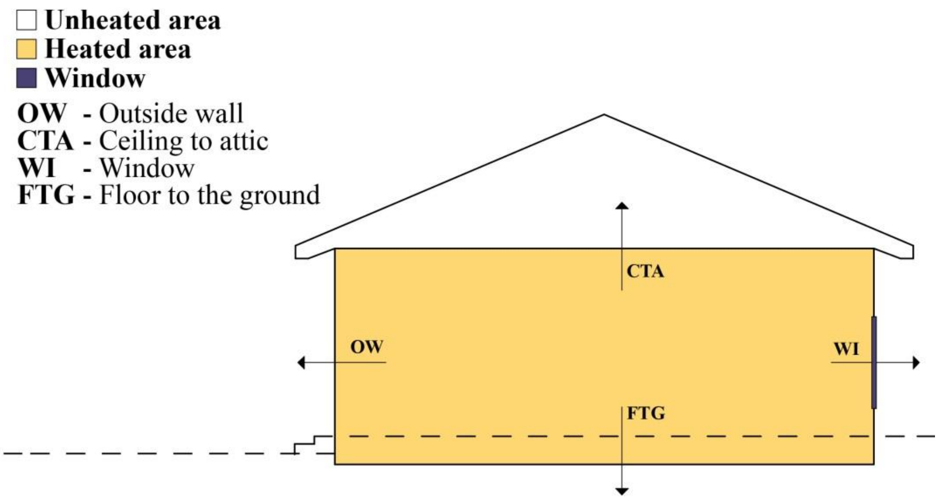


*Figure 2-7 Building elements shown by location in the brick building and in the virtual straw-bale building*

#### 2.2.2.2.2 Zoning in the straw-bale building and the corresponding virtual brick building

Figures 2-8 present the zones of the straw-bale building and also the corresponding virtual brick building.

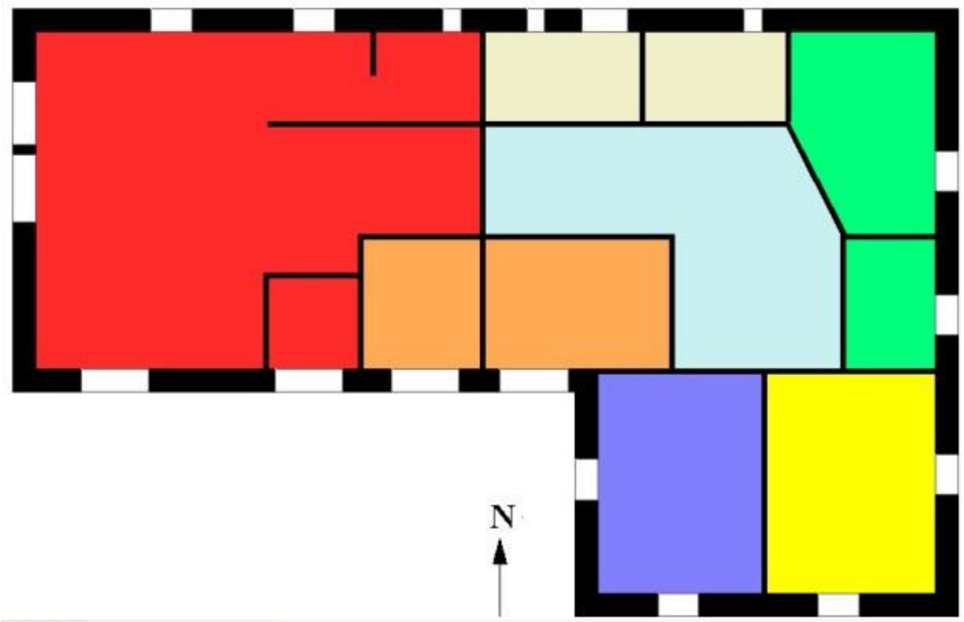


*Figure 2-8 Ground floor plans of the straw-bale building and the virtual brick building coloured by zones*

Table 2-5 describes the zones in the straw-bale building and in the virtual brick building associated with the floor areas and volumes.

*Table 2-5 Zones in 2_S and in 2_B associated with floor areas and volumes*

| Name of the zones | Sign | Floor area [m$^2$] | Volume[m$^3$] |
|---|---|---|---|
| Living room | | 58,79 | 198,73 |
| Room S | | 20,78 | 70,25 |
| Room SW | | 12,52 | 42,31 |
| Room SE | | 12,44 | 42,05 |
| Room E | | 15,92 | 53,81 |
| Room N | | 11,60 | 39,21 |
| Rooms inner | | 14,05 | 47,49 |

Eight different zones are defined in the straw-bale building, according to the properties of spaces. Seven of them are heated and the last one, the roof is unheated as the house is insulated on the ceiling slab similar to the brick building.

Figure 2-9 presents the building elements shown by location in the straw-bale building and in the virtual brick building.

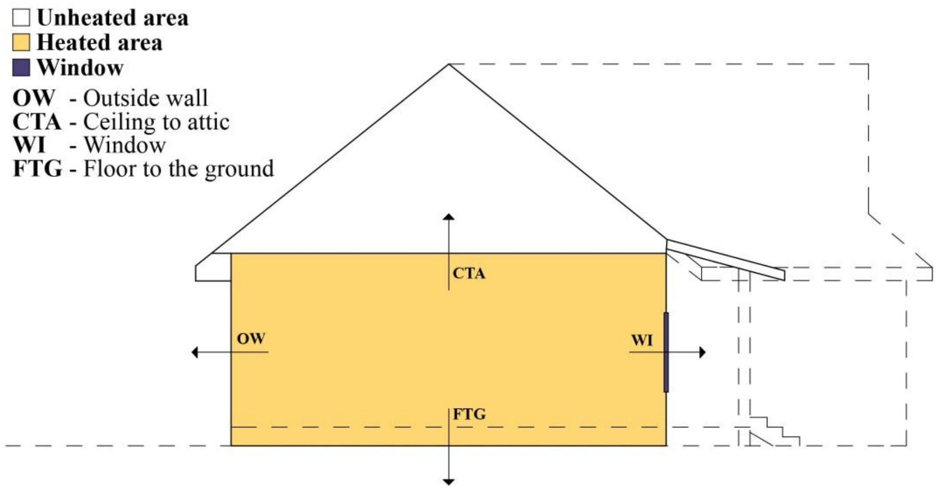


*Figure 2-9 Building elements shown by location in the straw-bale building and in the virtual brick building*

#### 2.2.2.3 Internal conditions used for dynamic thermal simulation

Both houses are detached houses. There is a family of five living in the straw-bale building (parents with three children). The brick building is occupied by a family of three. The families' daily rhythm is the same; they are only at home in the morning and in the evening. The parents work during the day and the children are at school or also working. The schedule is set, according to the families' life style and the rest of the details are based on ÖNORM (ÖNORM B 8110-5:2011). Archiphysik is based on different ÖNORMs, which means for a family house it takes 24 hours a day. This was one of the reasons why TAS was used for the energy performance simulations, as it enables more precise occupancy schedules. Table 2-6 describes the space properties of the four examined buildings.

*Table 2-6 Internal conditions of the examined buildings- internal gains*

| **INTERNAL CONDITIONS** | |
|---|---|
| ABBREVIATION | 1_B, 1_S, 2_B, 2_S |
| INFILTRATION | 0,4 ach |
| VENTILATION | - |
| LIGHTING GAIN | 1,75 $Wm^{-1}$ |
| OCCUPANCY SENSIBLE GAIN | 1,00 $Wm^{-1}$ |
| OCCUPANCY LATENT GAIN | - |
| EQUIPMENT SENSIBLE GAIN | - |
| EQUIPMENT LATENT GAIN | 1,00 $Wm^{-1}$ |

The values of the internal gains such as lighting gain, occupancy sensible gain and equipment latent gain are based on the ÖNORM B 8110-5:2011, $q_i$ =3,75 $Wm^{-2}$.

Table 2-7 presents the internal conditions of the examined buildings focusing on the schedule and set points.

*Table 2-7 Internal conditions of the examined buildings- settings of the thermostat, schedule*

| **INTERNAL CONDITIONS** | |
|---|---|
| ABBREVIATION | 1_B, 1_S, 2_B, 2_S |
| TEMP. UPPER LIMIT | 100 °C |
| TEMP. LOWER LIMIT | 20 °C |
| HUMIDITY UPPER LIMIT | 100 % |
| HUMIDITY LOWER LIMIT | 0 % |
| SCHEDULE | 23:00-6:00=0, 6:00-9:00=1, 9:00-16:00=0, 16:00-23:00=1 |

#### 2.2.2.4 Thermal properties

The most important thermal property is the U-value of different building elements. Table 2-8 shows the limits according to the OIB-RL 6 (2007).

*Table 2-8 U-value limits according to the OIB-RL 6*

| **Building elements** | **U-values [$Wm^{-2}K^{-1}$]** |
|---|---|
| Outside wall | 0,35 |
| Inside wall | 0,90 |
| Window | 1,40 |
| Windows in the roof | 1,70 |
| Ceilings to outside and not cond. roofs | 0,20 |
| Ceilings to unheated areas | 0,40 |
| Ceiling to flats | 0,90 |

Table 2-9 shows the U-values of the examined buildings.

*Table 2-9 U-values in the four examined buildings*

| **Building elements** | **1_B** | **1_S** | **2_B** | **2_S** |
|---|---|---|---|---|
| | [$Wm^{-2}K^{-1}$] | [$Wm^{-2}K^{-1}$] | [$Wm^{-2}K^{-1}$] | [$Wm^{-2}K^{-1}$] |
| **Outside wall** | 0,2 | 0,094 | 0,2 | 0,094 |
| **Floor to the ground** | 0,37 | 0,544 | 0,37 | 0,544 |
| **Ceiling to attic** | 0,168 | 0,101 | 0,168 | 0,101 |
| **Windows U-value** | 1,4 | 1,4 | 1,0 | 1,0 |
| **Windows g-value** | 0,55 | 0,55 | 0,55 | 0,55 |

All the calculated U-values are within the required limits of OIB-RL 6 (2007) except for the ground floor slab of the straw-bale buildings.

If we take a closer look at the outside walls, we realize that the U-values of the brick buildings are higher than those of the straw-bale buildings. The U-value of the outside wall in the brick buildings is approximately twice the U-value of the walls of the straw-bale houses (the lower the U-value, the better is the energy performance of the element).

Except for the ground floor slab, all the U-values are lower in the straw-bale buildings, thus it is expected that the straw-bale building performs better in terms of energy efficiency.

The ground floor slab in 1_S and 2_S are inhomogeneous parts, while 1_B and 2_B have a homogeneous floor construction. In the floor of the brick building the insulation has a thickness of 8cm and a 12 cm thick reinforced concrete slab forms the structure, while the floor of the straw-bale house is composed of only 5 cm of EPS insulation and 8 cm of reinforced concrete. These attributes obviously account for the difference in U-values of 1_B and 2_B.

Table 2-10 represents the U-value limits in passive houses according to ECOBINE.

*Table 2-10 U-value limits in passive houses according to ECOBINE (Ecological Building Net)*

| **Building elements in a passive house** | **U-values [$W.m^{-2}.K^{-1}$]** |
|---|---|
| Outside walls | 0,25 |
| Roof | 0,15 |
| Windows (including frames) | 0,8 |
| Basement ceiling | 0,3 |

Comparing the building elements of the examined buildings with the table reveals that in all four cases the outside walls meet the passive house standards. This also applies to the roof of the straw-bale building and the virtual straw building.

A complete list of the composing layers of each building element can be found in the appendix.

### 2.2.3 Environmental indicators

To examine the environmental performance of all four buildings, the OI3 calculation method was used. This is based on a catalogue, generated by Austrian Institute for Healthy and Ecological Building (IBO 2008) and was conducted with Archiphysik. It has to be mentioned that the IBO catalogue might not feature the exact properties of the used building materials; in these cases the properties of the most resembling available option were adapted from the catalogue. The OI3 indicator is mathematically derived from GWP, AP and PEI indicators. A detailed overview of the assigned environmental attributes for layered constructions can be found in appendix.

The calculated indicators such as global warming potential, acidification potential or primary energy content provide us with an overview of the environmental footprint of the house.

# 3. RESULTS AND DISCUSSIONS

In this chapter the results of the conducted calculations and simulations are presented and discussed.

The results are divided into three parts:

- In the first part, the overall Heating Demand Results, computed with the energy certification method and the detailed thermal simulation are presented and compared with each other. Differences between the results yielded by different methods are discussed as well.
- In the second part the results of the dynamic thermal simulation are presented and discussed in detail (thermal transmission losses, natural infiltration losses, solar gains, internal gains). This part is intended to show the most influential parameters on the thermal performance of the buildings.
- In the third part, the results of the environmental impact analysis of constructions of individual building elements are presented and discussed. These analyses are based on the OI3-Index (and thus on GWP, AP and PEI).

## 3.1 Heating demand results

### 3.1.1 Energy certificate result

Figure 3-1 presents the annual heating demand based on simple calculation method.

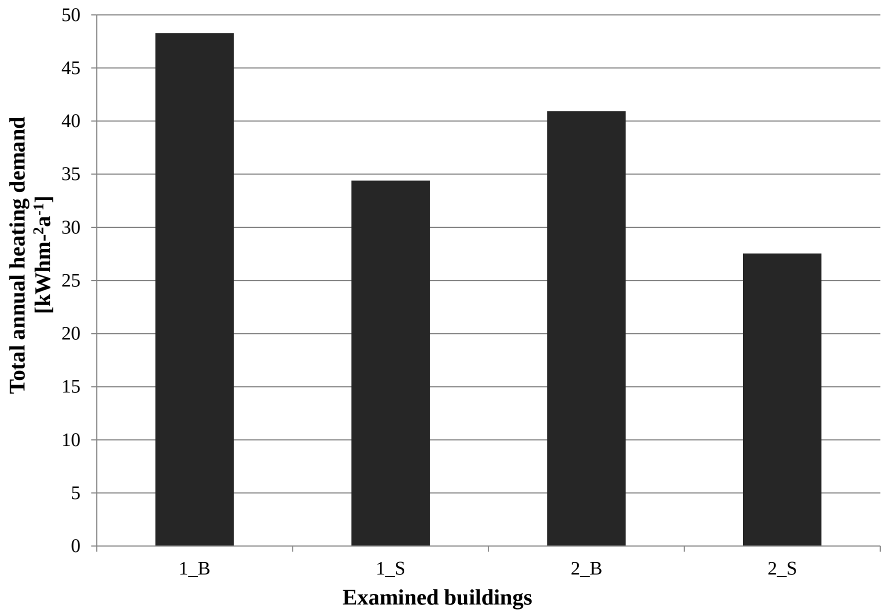


*Figure 3-1 Total annual heating demand of the examined buildings based on simple calculation methods*

Given the fact that the straw-bale constructions provide a better thermal envelope, a lower total annual heating demand was expected. Indeed, it can be observed that the straw-bale constructions perform better compared to their counter-parts. All four buildings are certified with class B performance level (between 25 and 50 kWhm$^{-2}$a$^{-1}$).

### 3.1.2 Dynamic thermal simulation result

Figure 3-2 illustrates the annual heating demand based on dynamic thermal simulation.

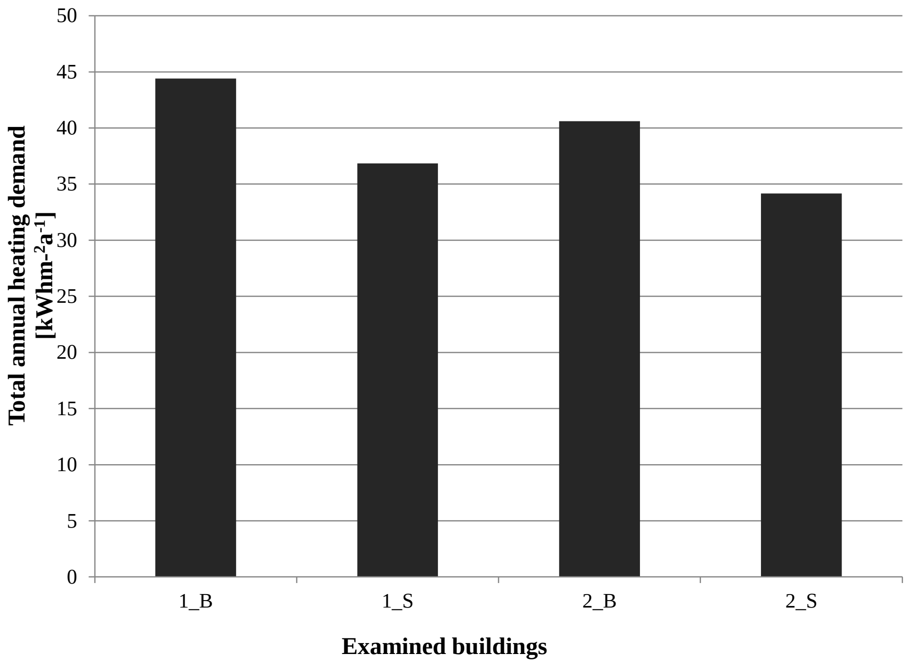


*Figure 3-2 Total annual heating demand of the examined buildings based on dynamic thermal simulations*

Results based on dynamic thermal simulations show the same pattern; the straw-bale constructions provide a lower annual energy demand.

For every building element different properties can be defined regarding what standard the program uses for the calculation (see chapter 3.1.3).

Figure 3-3 illustrates the reduction of total annual heating demand due to the different methods.

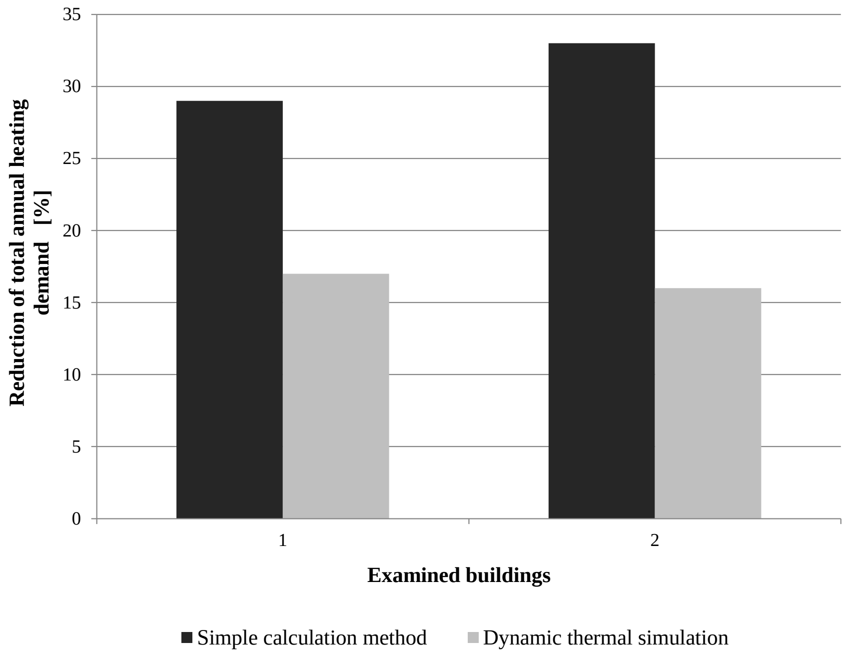


*Figure 3-3 Reduction of total annual heating demand of the examined buildings based on dynamic thermal simulation and simple calculation method*

It can be observed that the virtual straw-bale building needs 29 percent less heating demand than the original brick building according to the simple calculation method and 17 percent less according to the dynamic thermal simulation. The original straw-bale building also requires less heating demand than the virtual brick building; due to the simple calculation method 33 percent less and due to the dynamic thermal simulation 16 percent less. In conclusion the straw constructions perform better in terms of heating demand computed with both methods.

### 3.1.3 Comparison between the results of the two different methods

Figure 3-4 shows the differences in annual heating demand computed with dynamic thermal simulation and simple calculation method.

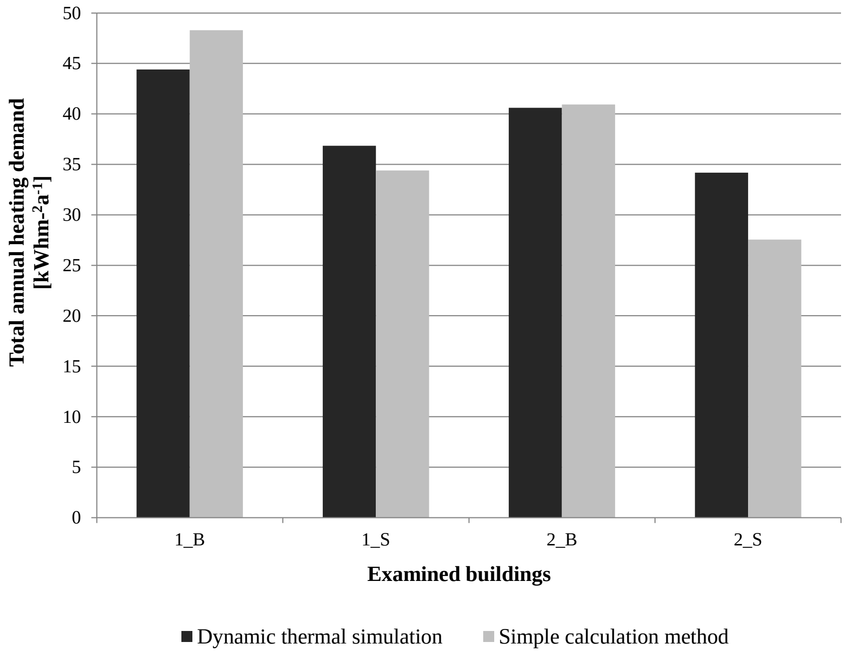


*Figure 3-4 Total annual heating demand of the examined buildings based on dynamic thermal simulation and simple calculation method*

In the tool of the dynamic thermal simulation most of the settings are adjustable, but there are a few parameters or values that cannot be changed. The dynamic thermal simulation tool is not able to set the levels of details in the simulations; however the tool of the simple calculation method requires giving these settings. As a consequence of that, it can be observed that the results of annual heating demand are not identical in the different methods; however the results are not extremely different.

The simple calculation method calculates regarding the Austrian standards ÖNORM, whereas, the dynamic thermal simulation uses the ASHRAE (LEED) standards. They do not always use corresponding formulas and they go into different levels of details in their calculations. Therefore dynamic thermal simulation was used to analyze the energy performance indicators and simple calculation method was used to analyze the environmental indicators.

## 3.2 Dynamic thermal simulation results

### 3.2.1 Transmission losses

Figures 3-5 and 3-6 illustrate the monthly transmission losses in the four examined buildings.

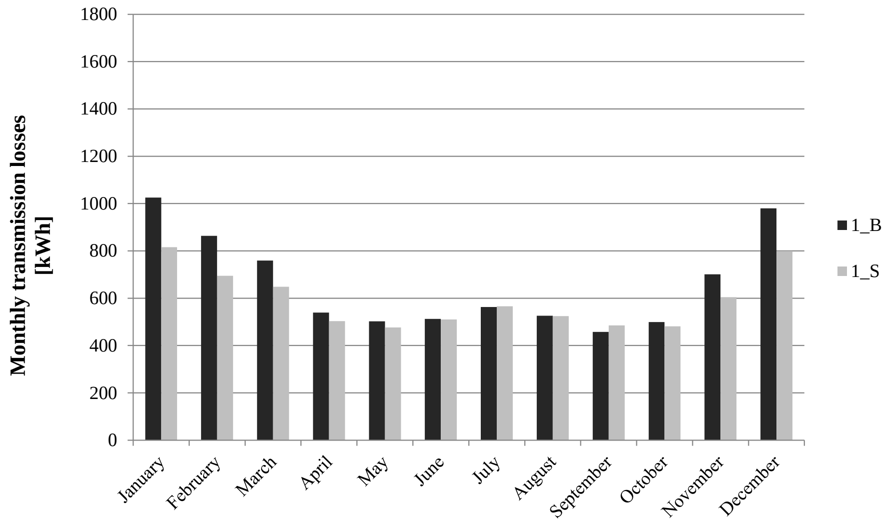


*Figure 3-5 Monthly transmission losses based on dynamic thermal simulations in the brick building and in the virtual straw-bale building*

Heat loss appears through conduction, through the walls, roofs, floor slabs etc. Transmission losses depend on several factors, for example: the composition of layers, the thickness of layers and the thermal conductivity of the constituting materials (see Eq. 5). Throughout the winter season transmission losses in the brick building are higher, while during the summer season both constructions show almost the same transmission losses. The ratio of the results between 1_B and 1_S varies between 1,0 and 1,2. The hotter the outside temperature is, the smaller this ratio is.

Comparing the materials in the outside walls, POROTHERM 38 N+F has a thermal conductivity of 0,17 $W.m^{-1}°K^{-1}$ while the straw-bale's thermal conductivity is much lower: 0,05 $W.m^{-1}°K^{-1}$. The higher the thermal conductivity, the higher the U-value is, leading to higher transmission losses.

The same behavior is observed regarding objects 2_B and 2_S in Figure 3-6. During winter time, the brick structured building loses substantially more heat, but during the summer the straw-bale building loses almost the same amount of energy.

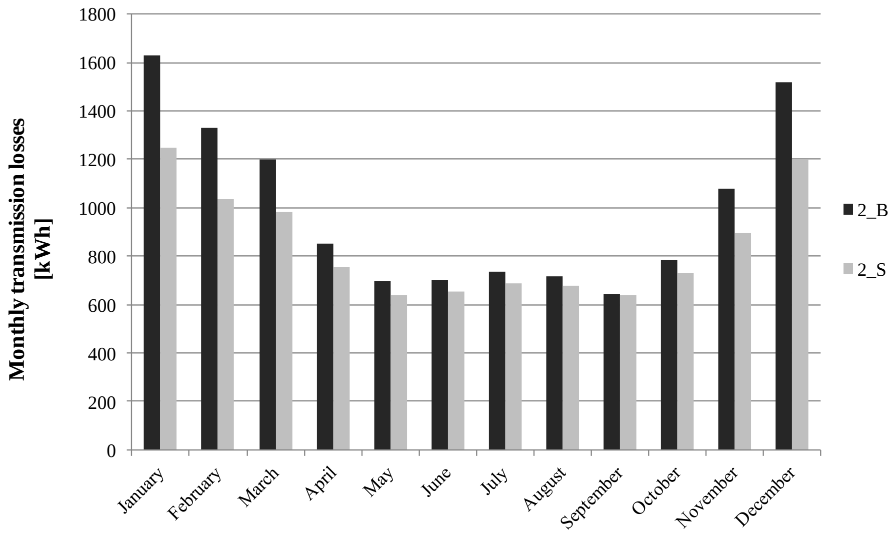


*Figure 3-6 Monthly transmission losses based on dynamic thermal simulations in the straw-bale building and in the virtual brick building*

### 3.2.2 Natural infiltration losses

Figures 3-7 and 3-8 illustrate the monthly infiltration losses based on dynamic thermal simulations in the brick building and in the virtual straw-bale building.

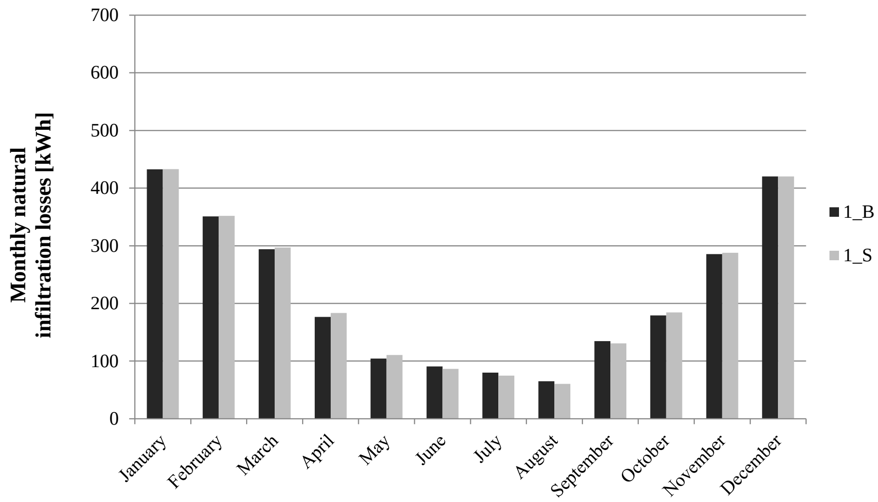


*Figure 3-7 Monthly natural infiltration losses based on dynamic thermal simulations in the brick building and in the virtual straw-bale building*

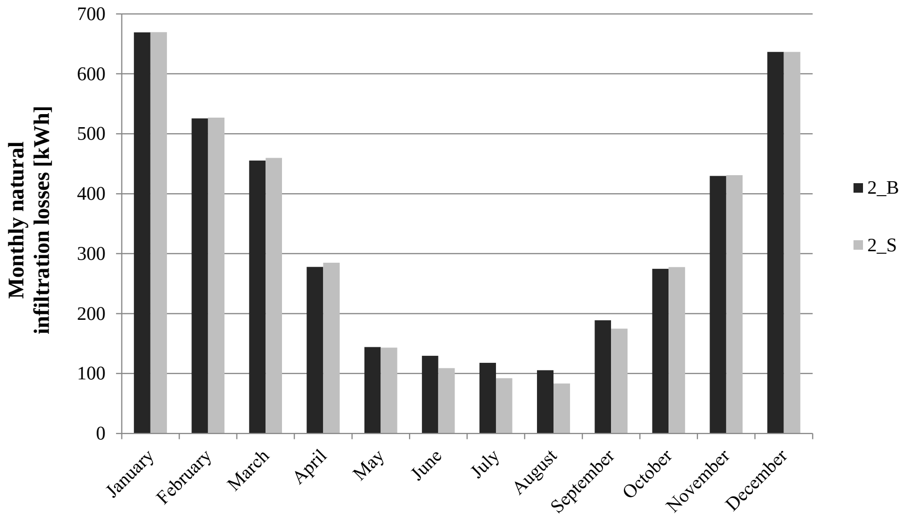


*Figure 3-8 Monthly natural infiltration losses based on dynamic thermal simulations in the straw-bale building and in the virtual brick building*

Infiltration stands for the unintentional air flow caused by the pressure or temperature differences between the inside and outside through cracks and gaps in the envelope (White 2013). Infiltration depends on the tightness of the building.

The above results are based on assumptions but they illustrate the impact of natural infiltration losses. The total annual infiltration loss in 1_B and 1_S is 2.620 kWh, with an air change rate assumption of 0,4 ach according to ÖNORM B 8110-5:2011.

Given the fact that 2_B and 2_S have a bigger volume, the natural infiltration losses also show us higher results (3900 kWh).

### 3.2.3 Internal gains

Figure 3-9 and 3-10 illustrate the monthly internal gains based on dynamic thermal simulations in the examined buildings.

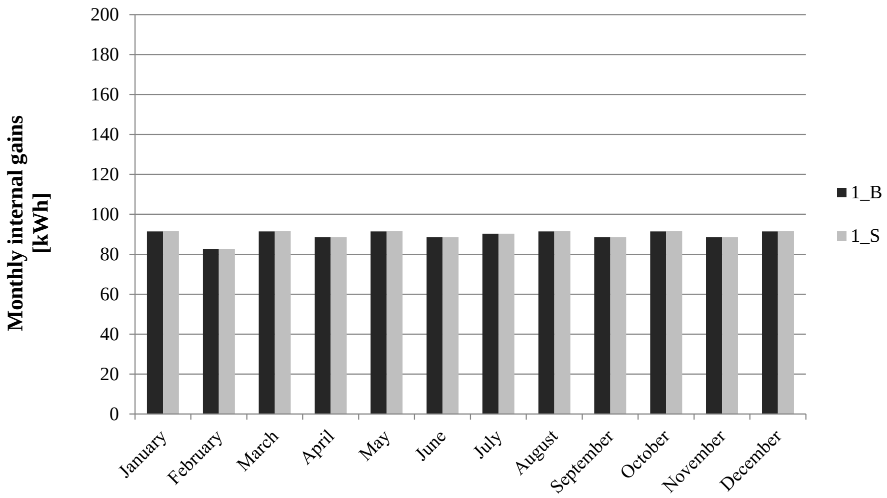


*Figure 3-9 Monthly internal gains based on dynamic thermal simulations in the brick building and in the virtual straw-bale building*

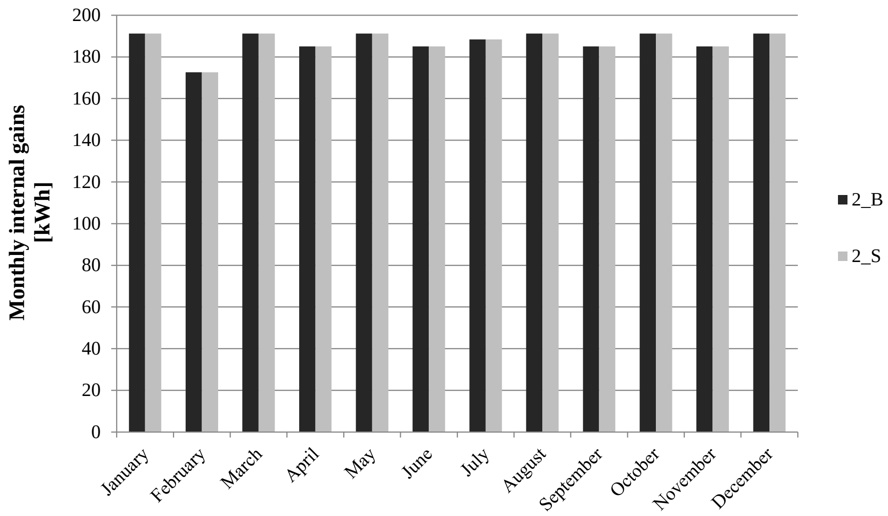


*Figure 3-10 Monthly internal gains based on dynamic thermal simulations in the straw-bale building and in the virtual brick building*

The internal condition assumptions were identical in 1_B and 1_S according to Table 2-6 and Table 2-7.

The total annual internal gain of 1_B and 1_S is 1.076 kWh according to dynamic thermal simulation.

The monthly internal gain varies between 83 and 91 kWh. The reason why the internal gain is not the same in every month- although the residents have exactly the same schedule- is the difference between the days of each month. Odd months have higher internal gains, because they have 31 days, even months have lower internal gains, because they only have 30 days.

Internal gains in 2_B and 2_S are higher than in 1_B and 1_S, because of the larger gross area and the number of residents.

The total annual internal gain is 2.248 kWh in 2_B and 2_S. The monthly value varies between 173 and 191 kWh depending on the number of days in a month.

### 3.2.4 Solar gains

Figures 3-11 and 3-12 illustrate the monthly solar gains based on dynamic thermal simulations in the four examined building.

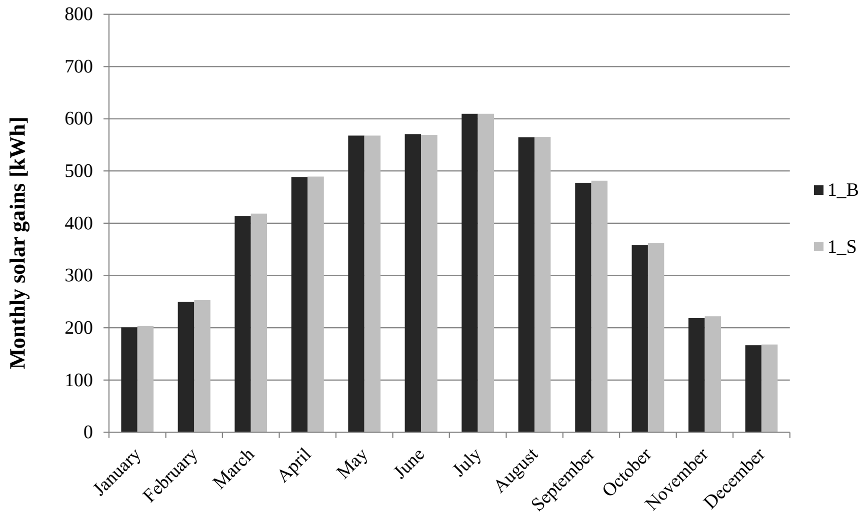


*Figure 3-11 Monthly solar gains based on dynamic thermal simulations in the brick building and in the virtual straw-bale building*

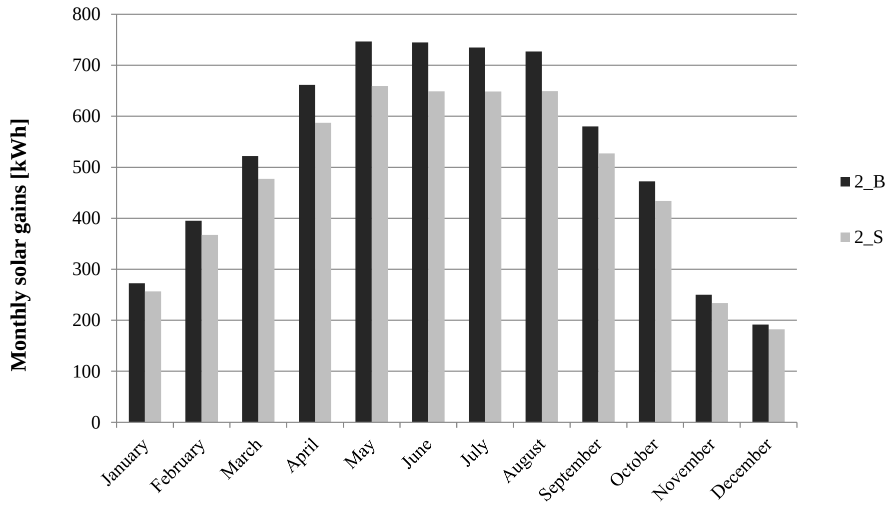


*Figure 3-12 Monthly solar gains based on dynamic thermal simulations in the straw-bale building and in the virtual brick building*

Solar gains were calculated for all four buildings. Same as the internal gain estimations, these computations are based on assumptions.

Solar gains are presented in Figure 3-11, which shows the highest solar gain value in July: 610 kWh and lowest value in December: 167 kWh. The solar gains of 1_B and 1_S are almost identical; the differences appear due the computation algorithms.

Figure 3-12 shows the monthly solar gain in the whole year for 2_B and 2_S. These buildings have higher solar gains than 1_B and 1_S.

As it was mentioned before, solar gain depends on several things. 1_B and 1_S are orientated to North-East-South-West, while 2_B and 2_S are orientated to West-East, which means that most of the windows face North and South. The total area of fenestration in the brick building is 19,20 $m^2$ and in the straw-bale building 46,62 $m^2$. The latter has more than twice as much fenestration surface as the former. Therefore, higher solar gains are reasonable.

As can be observed on Figure 3-12, the straw-bale construction has lower solar gains, than the brick construction. The reason is the slightly higher shading effect due to the thickness of the wall.

## 3.3 Environmental indicators

The following indicators help us better understand the environmental impact of the buildings.

For each material environmental property, such as $CO_2$ and $SO_2$ emissions were determined according to available repositories. The IBO 2008 edition database, integrated in the simple calculation method, has been used for the extraction of relevant values for various construction materials.

### 3.3.1 Global warming potential

Figure 3-13 presents the GWP based on OI3 indicators in the examined buildings.

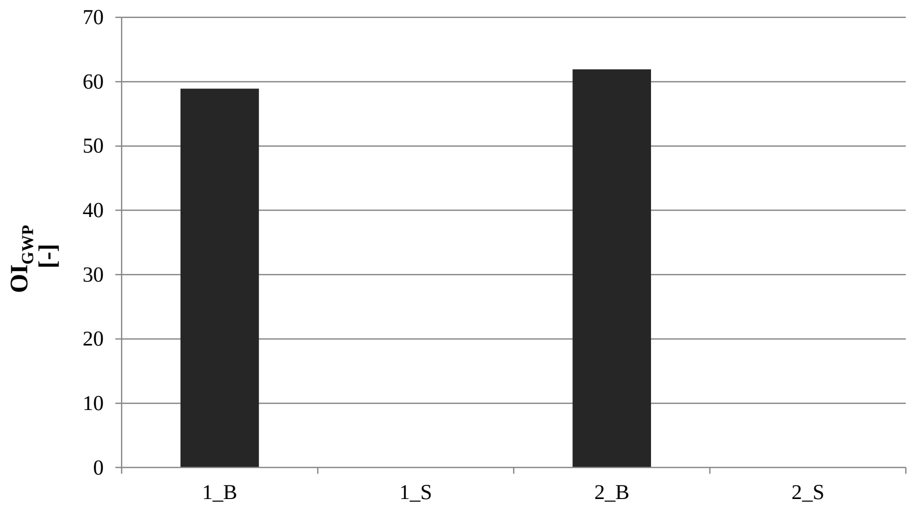


*Figure 3-13 Global warming potential based on OI3 indicators in the four examined buildings*

The conventional brick construction and the straw-bale structure display a significant dissimilarity.

1_B and 2_B have a value of approximately 60, which is the $CO_2$ equivalent per $m^2$ converted into $OI_{GWP}$ points. This emission contributes to global climate change. The straw-bale constructions have a GWP of 0, which means that they have less harmful impact on the environment.

Figure 3-14 represents the GWP of the different building elements in 1_B and 1_S.

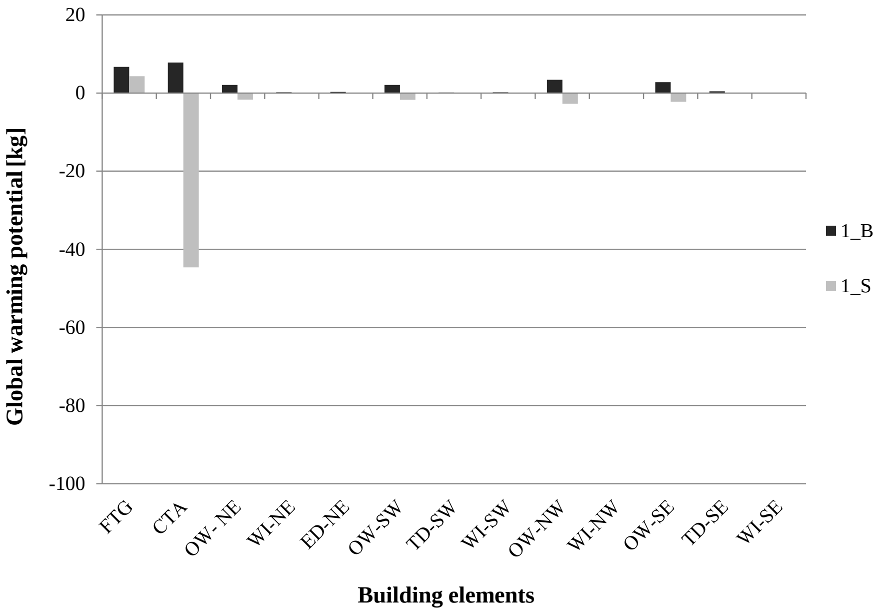


*Figure 3-14 Global warming potential of different building elements based on OI3 indicators in the brick building and in the virtual straw-bale building*

The values of GWP depend on the MJ, $CO_2$ and $SO_2$ equivalent of the materials. The first substantial dissimilarity noticed on Figure 3-14 is the $OI_{GWP}$ value of the ceiling to the attic in 1_S. It accounts to a minus value, because the materials which were used in this construction have lower gas equivalents, then in the brick building.

'As plants grow they absorb $CO_2$ molecules from the atmosphere. Through the process of photosynthesis, plants can separate the two-oxygen atoms form the single carbon atom. They return the oxygen to atmosphere, and keep the carbon to make complex sugars such as cellulose, the building blocks of plants. Carbon positive means that there is more $CO_2$ equivalent banked in the form of carbon in straw than is emitted through the process of planting, harvesting, baling and building a building using straw' (White 2013).

The values of the other building elements are quite similar correlated to each other. Deviation can be seen in the building elements which have disparity. All outside walls show some differences yet the straw-bale constructions always present lower results.

Figure 3-15 shows the GWP values of different building elements in 2_B and 2_S.

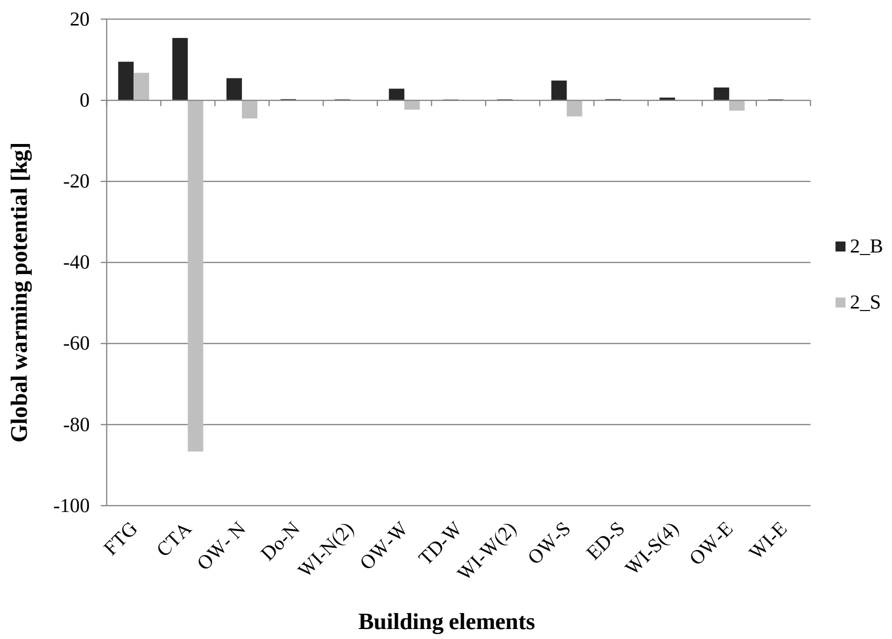


*Figure 3-15 Global warming potential of different building elements based on OI3 indicators in the straw-bale building and in the virtual brick building*

Figure 3-14 and 3-15 display almost the same results. The outcome proves the expected results that the straw-bale home is more in harmony with the environment due to its lack on negative impact on it, which is of no surprise because of the materials which were used. The biggest difference is at the ceiling to the attic again.

### 3.3.2 Acidification potential

Figure 3-16 describes the AP of the examined buildings.

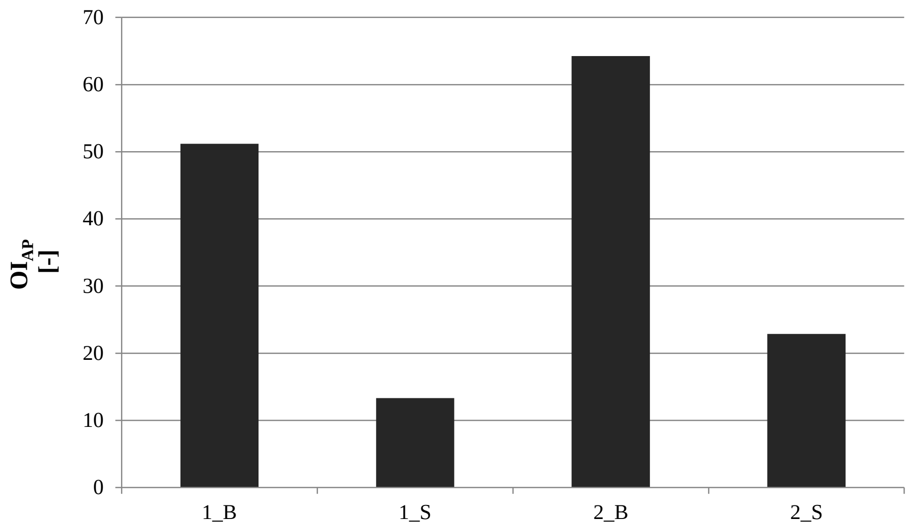


*Figure 3-16 Acidification potential based on OI3 indicators in the four examined buildings*

Results show exactly what was predicted. Straw-bale buildings have lower values of acidification potential. Figure 3-17 and 3-18 present AP values of different building elements in the examined buildings.

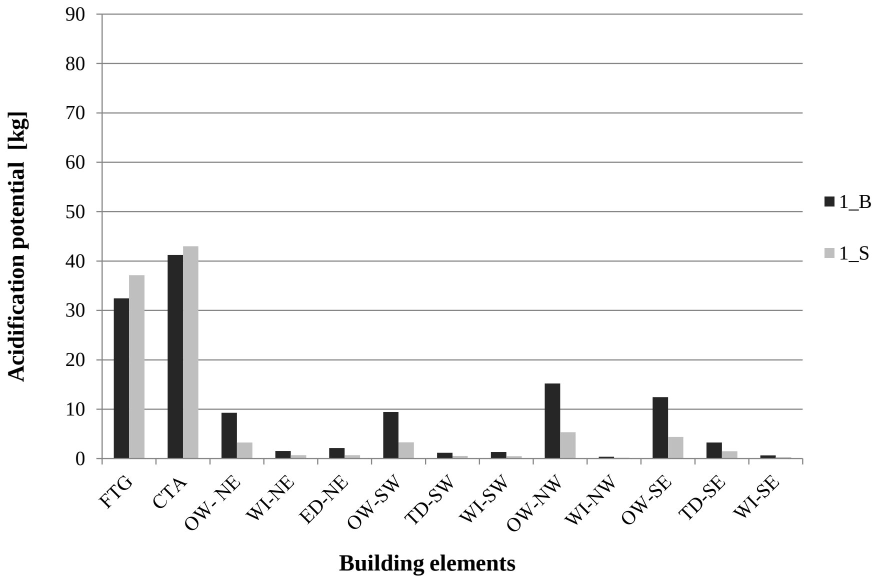


*Figure 3-17 Acidification potential of different building elements based on OI3 indicators in the brick building and in the virtual straw-bale building*

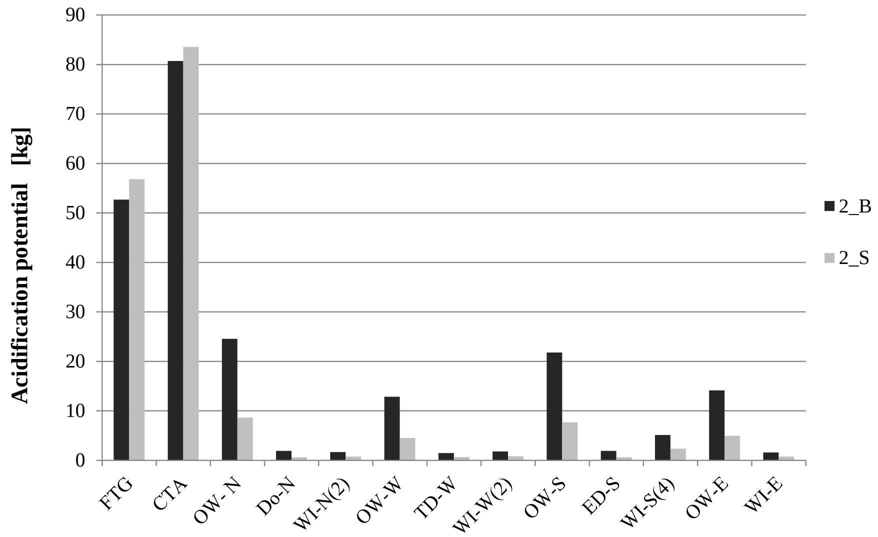


*Figure 3-18 Acidification potential of different building elements based on OI3 indicators in the straw-bale building and in the virtual brick building*

Generally the brick construction yields higher values, except for two construction elements: floor to the ground and ceiling to attic. The materials used in these two building elements have higher $SO_2$ equivalent (see appendix), which explains the higher acidification potential.

### 3.3.3 Primary energy content

Figure 3-19 presents the overall primary energy content in the examined houses with regard to non-renewable energy content.

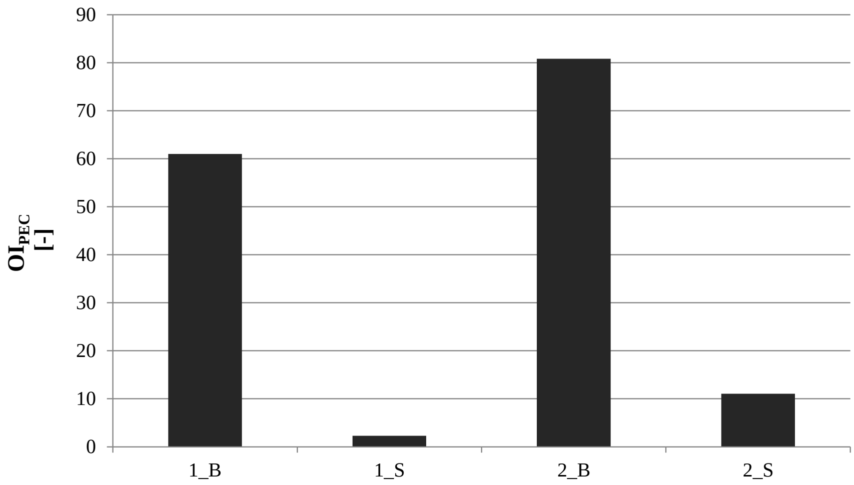


*Figure 3-19 Primary energy content based on OI3 indicators in the four examined buildings*

The difference between the brick and straw-bale constructions is very noticeable. The buildings with brick wall have a value of 60-80, while the straw-bale constructions' values vary between 2 and 11, which suggest that the manufacturing process of the latter is not at all energy intensive.

Figures 3-20 and 3-21 illustrate the PEI of the different building elements in the examined buildings.

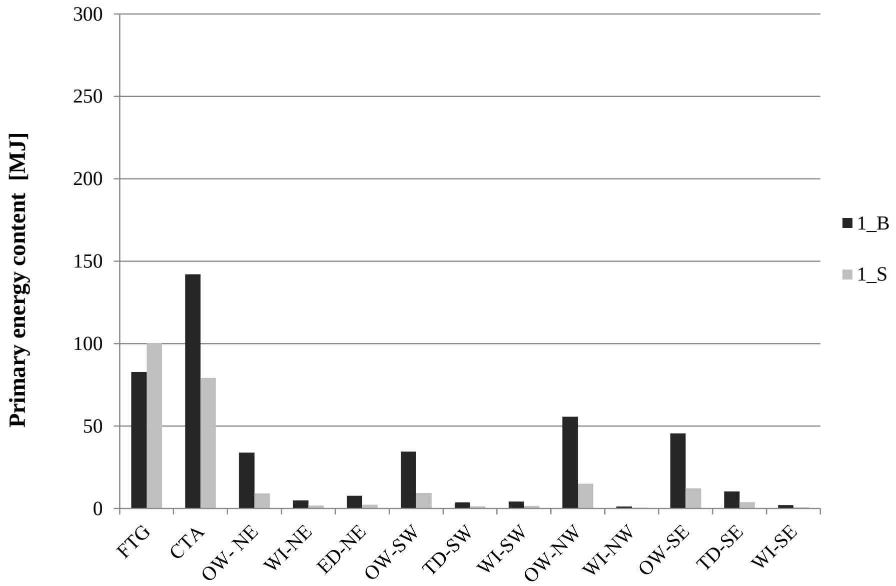


*Figure 3-20 Primary energy content of different building elements based on OI3 indicators in the brick building and in the virtual straw-bale building*

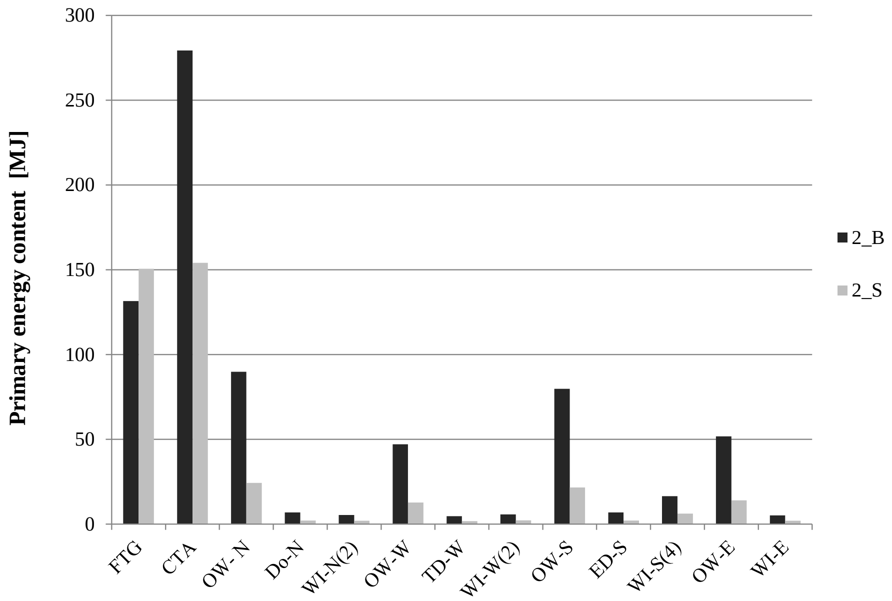


*Figure 3-21 Primary energy content of different building elements based on OI3 indicators in the straw-bale building and in the virtual brick building*

The diagrams perfectly show which part of the envelope have exhausted more energy resources during manufacturing. Generally the elements of a brick construction have higher PEI values in MJ, except for one the floor slab adjacent to the ground.

# 4. CONCLUSION

This work presents an attempt to validate the positive impact of the integration of green materials in the building industry, on the preservation of resources, which is becoming increasingly important in the light of the drastic recent climate change. Such materials can lead to better energy performance than is achieved through conventional methods.

Despite small dissimilarities in results obtained from different performance assessment software, straw-bale buildings perform generally better than conventional constructions with regard to energy efficiency.

The provided data was not highly detailed, but it was sufficiently fine to meet input requirements of both software. The results acquired from the implemented software, varied in resolution. Most parameters were adjustable; however there were some limitations to fine-tuning certain computation variables due to the underlying logics or standards. For instance, the norm-based calculation method adopted by Archiphysik does not allow personalized occupancy schedules and can only assume standard values hard-coded in the program. In EDSL Tas, certain geometries (e.g. curved surfaces) have to be approximated by simpler forms due to the limitations of the graphical user interface. It can be speculated that these computation tools need to be improved in order to better capture particular aspects of the building. These programs could be improved in order to provide the user with a higher degree of flexibility to work with various types of input, including the geometry of the building, composing materials or internal conditions.

Although geometries studied in this thesis were very simple, some problems occurred (e.g., with regard to internal conditions). Such problems are also detected in the results.

Comparing the buildings, the difference in the overall results is not as substantial as anticipated; a much larger difference in energy performance was expected. Nevertheless, obtained values indicate clearly the advantages of using straw as a building element; as it was expected due to the better thermal envelope of the straw- bale buildings.

Focusing on the environmental aspects, the results showed exactly what was predicted. Conventional homes have a negative impact on the environment, through different phases of production of materials, manufacturing and maintenance as well as demolition. Straw bale houses provide the preservation of natural resources and also reduce the greenhouse gas emissions. There are number of companies working with straw-bale buildings all around the world, yet people are still afraid of living in these homes. Hopefully this thesis will contribute to changing this mind-set and influence the society to consider more sustainable solutions for buildings in the future.

# 5. FUTURE RESEARCH

The purpose of this study was to analyze straw-bale buildings in the context of energy efficiency and show the results compared to conventional houses in order to raise public interest in this topic. One of the goals of this thesis was to help persuade architects to design sustainable structures, start caring about future and adopt more efficient life styles.

It is interesting to further investigate the energy performance of a straw-bale building compared to a conventional building, in which eco-friendly insulation is used. Recently new eco-friendly insulations are developed, which merit to be studied in view of thermal and environmental performance. Thermal attributes of these eco materials would be compared with the straw-bale as well as the impact on the environment.

There are several eco-friendly insulations available, such as mineral wool, loose-fill cellulose, expanded cork board stock insulation, etc.

All insulations help save energy, but a reduction in energy demand does not necessarily imply sustainability. Environmental impact of these materials should also be considered.

Global warming has become a pressing concern, demanding immediate action through reduction of greenhouse gas emissions. Materials, which store carbon in the fabric of the building, support this goal. According to the team of Superhomes the most friendly insulation materials are made out of cellulose or other natural materials, which absorb carbon from the atmosphere as they grow (Thorpe 2013).

It would be useful to conduct a comparative analysis of such materials to establish their potential advantages over conventional materials.

# 6. REFERENCES


Amazon Nails. 2001. *Information guide to straw-bale building.* Amazon Nails.

Armagh City and District Council. 2011. *Energy Performance*. Internet. Available from: http://www.armagh.gov.uk/building-control/energy-performance-certificates; accessed 23 November 2012.

Atlas Property Portugal, 2013. Internet. Available from http://www.atlaspropertyportugal.com/pages/energy_12; accessed 10 September 2013.

Austrian Energy Agency. 2012. *Final energy consumption by sector in Hungary (2008*). Internet. Available from: http://www.enercee.net/hungary/energy-demand.html; accessed 27 July 2012.

Battisti K. 2011. *Archiphysik 9.1 Handbuch*. Available from http://www.archiphysik.at/

Brennan J., 2013. *U-Values*. Internet. Available from : http://www.architecture.com/SustainabilityHub/Designstrategies/Earth/1-1-1-10-Uvalues(INCOMPLETE).aspx; accessed 5 February 2013.

Ecobine (Ecological Building Net). 2013. *The Different Types of Low-Energy Buildings*. Internet. Available from; http://www.ecobine.de/indexc.php?SESSID=&id=2.6.3&kurs=9&l=en; accessed 11 January 2013.

Energia és Környezet Alapítvány. 2012. *Szalmabála építészet ('Straw-bale architecture')*. Internet. Available from http://energiaeskornyezet.hu/index.php/szalmabala-epiteszet; accessed 22 July 2012.

European Environment Agency. 2012. *Energy efficiency and energy consumption in household sector.* Internet. Available from http://www.eea.europa.eu/data-and-maps/indicators/energy-efficiency-and-energy-consumption-5/assessment; accessed 12 December 2012.

Eyerer P., Weller M. and Hübner C., 2010. *Polymers- Opportunities and Risks II.- Sustainability, Product Design and Processing, Springer- Verlag Berlin Heidelberg.* Page 35. 5.8.15. Acidification potential (AP). Springer.

Gillenwater M., 2010. *What is global warming potential? And which one do I use*? Internet. Available: http://ghginstitute.org/2010/06/28/what-is-a-global-warming-potential/, GHG Management Institute; accessed 13 February 2013.

Green Passiv Solar Magazine. 2012. *Orientation/ South facing windows*. Internet. Available from: http://greenpassivesolar.com/passive-solar/building-characteristics/orientation-south-facing-windows/; accessed 13 February 2013.

Greenspec, 2013. *Embodied energy*. Internet. Available from: http://www.greenspec.co.uk/embodied-energy.php; accessed 16 January 2013.

Hart K. and Hart R., 2013. *Straw-bale*. Internet. Available from http://www.greenhomebuilding.com/strawbale.htm; accessed 19 February 2013.

Hollis M., 2005. *Practical straw-bale building*. Landlinks Press.

IBO GmbH, 2011. *IBO- Guidelines to calculating the OI3 indicators for buildings*, IBO- Austrian Institute for Healthy and Ecological Building.

Koko S., 2010. *Straw-bale vs. Cob. Internet*. Available from: http://buildnaturally.blogspot.co.at/2010/12/strawbale-vs-cob.html; accessed 23 June 2013.

Lallanilla M., 2013. *What is global warming?* Internet. Available from: http://www.livescience.com/37003-global-warming.html; accessed 15 January 2013.

Lerner K., 2005. *Energy Efficient Straw-bale Housing Project*. Internet. Available from : http://www.worldhabitatawards.org/winners-and-finalists/project-details.cfm?lang=00&theProjectID=292; accessed 10 June 2013.

Mahdavi A., 2010. *Fundamentals in Building Science*, Department of Building Physics and Building Ecology- Vienna University of Technology.

Medgyasszay P. and Novak A., 2006. *Föld- es szalmaépítészet* ( 'Earth- and straw-bale buildings'). TERC.

Munch-Andersen J. and Moller Andersen B. 2012. *Straw Bale Houses- design and material properties.* Internet. Available from http://www.baubiologie.at/download/jma_slides_halmhuse.pdf; accessed 26 November 2012.

Prutenau M., 2010. *Investigations regarding the thermal conductivity of straw*. Publication of Universitatea Tehnică „Gheorghe Asachi" din Iaşi.

Rohde R. A., 2009. *Annual Greenhouse Gas Emissions by Sector*. Internet. Available from: http://www.globalwarmingart.com/wiki/File:Greenhouse_Gas_by_Sector_png; accessed 15 December 2012.

Shepard K. and Bartels L., 2011. *Straw-bale home basics*. Internet. Available from http://www.ecobroker.com/userdef/articles/Straw.Bale.Homes/StrawBaleHomeBasics.pdf; accessed 3 December 2011.

Straube J., 2013. *Moisture Properties of Plaster and Stucco for Straw-bale Buildings*. Internet. Available from: http://homegrownhome.co.uk/pdfs/Straube_Moisture_Tests.pdf; accessed 5 February 2013.

Thorpe D., 2013. *Opening doors to low energy refurbishment*. Internet. Available from: http://www.superhomes.org.uk/resources/whats-best-insulation-material/; accessed 25 June 2013.

United States Environmental Protection Agency, 2013. Internet. Available from http://www.epa.gov/iaq/voc.html; accessed 15 September 2013.

US Department of Energy. 1995. *House Straw- Straw-bale construction comes of age*. US Department of Energy.

US Department of Energy, 1997. *What's New in Building Energy Efficiency*. U.S Department of Energy.

US EPA (United States Environmental Protection Agency), 2006. *Global warming potential.* Internet. Available from http://web.mit.edu/12.000/www/m2010/finalwebsite/background/globalwarming/definition.html; accessed 15 September 2013.

Wanek C. 2012. *Straw-bale construction*. Internet. Available from http://www.epsea.org/straw.html; accessed 18 October 2012.

Waste Management World, 2013. Internet. Available from http://www.waste-management-world.com/articles/print/volume-13/issue-6/features/sawmills-chopping-down-waste.html; accessed 20 September 2013.

White C., 2013. *Straw-bale construction*. Internet. Available from: http://www.architecture.com/SustainabilityHub/Designstrategies/Earth/1-1-1-8-Strawbaleconstruction.aspx; accessed 15 February 2013.

## 7. FURTHER RESOURCES


EDSL 2010

IBO 2008

IBO 2011

OIB-RL 6 (2007)

ÖNORM B 8110-5:2011

TAS Theory Manual

www.meteonorm.com

# 8. APPENDIX

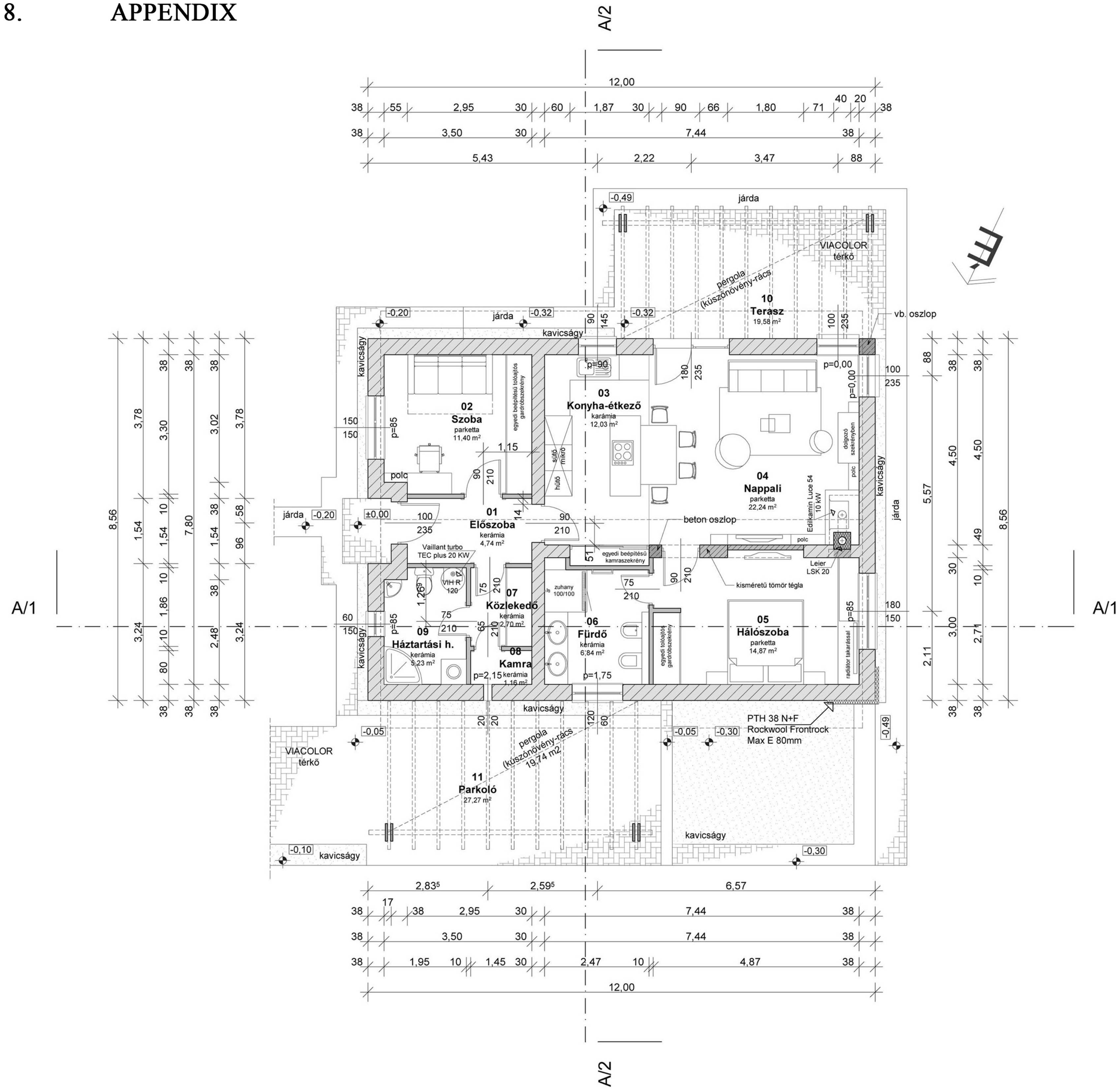

Figure 8-1 Plan of the brick building

# A/2 SECTION

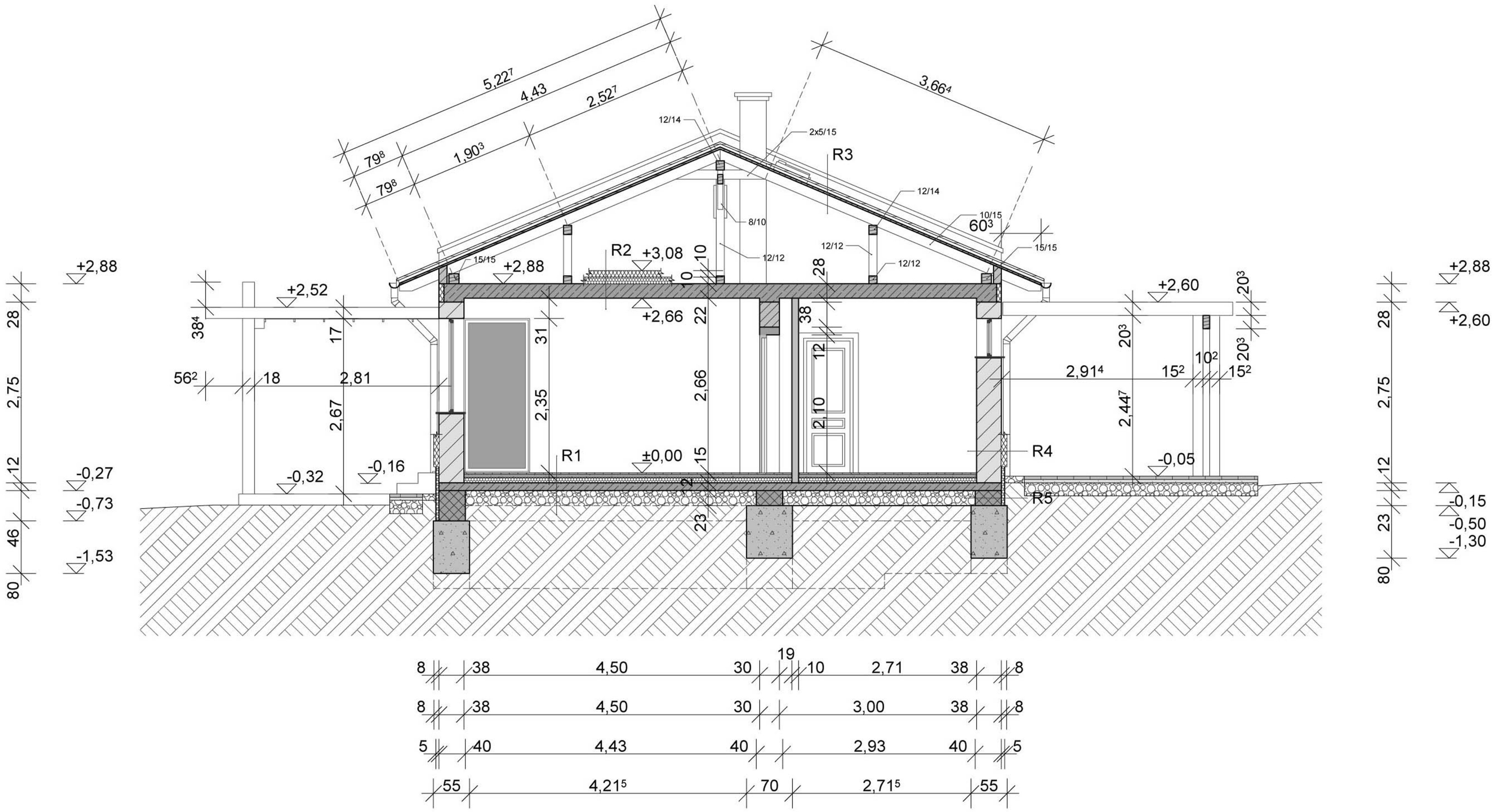


Figure 8-2 Section of the brick building

*Table 8-1 Building elements of the brick building*

| Building: 1_B | Brick building | Piliscsaba, Hungary |
|---|---|---|
| **Building elements** | **Layers of construction** | **Thickness [cm]** |
| **OUTSIDE WALL** | Baumit silicon plaster | 1,0 |
| | Baumit universal basis | 1 layer |
| | Baumit glassfiber net | 1 layer |
| | Baumit star contact glue | 1 layer |
| | Austrotherm grafit insulation | 10,0 |
| | Porotherm 38 N+F | 38,0 |
| | Inside plaster | 1,5 |
| **FLOOR TO THE GROUND** | Laminated parquet | 1,2 |
| | Barrier layer | 0,5 |
| | Estrich | 5,0 |
| | Austrotherm AT-N 100 insulation | 8,0 |
| | VILLAS E-G 4F/K waterproofing | 1 layer |
| | Promex Rapid tion due | 1 layer |
| | Reinforced concrete slab | 12,0 |
| | Gravel fill | 20,0 |
| | Natural ground/original soil | |
| **CEILING TO ATTIC** | Rockwool Airrock LD insulation | 10,0 |
| | Austrotherm AT-N 100 insulation | 10,0 |
| | Prefabricated Porotherm slab | 17+5 |
| | Plaster | 1,2 |
| | Paint | 1 layer |
| **PITCHED ROOF** | Creaton Domino ceramic roof tiles | |
| | Battens spaced for rooftiles-pine | 5/5 |
| | Battens spaced for rooftiles-pine | 3/3 |
| | Creaton Uno roof foil-polypropilen | 3 layers |
| | Rafter | 10/15 |
| | Ventilated attic | |
| **WINDOWS** | Weltstar Blue Evolution 4-16 Arg4-16Arg-4UltraN | 4,4 |

*Table 8-2 Thermal attributes of the building elements in the brick building*

| LAYER | M-CODE | WIDTH | INT. EMISSIVITY | CONDUCTIVITY | CONVECTION COEFFICIENT | VAPOUR DIFFUSION FACTOR | DENSITY | SPECIFIC HEAT |
|---|---|---|---|---|---|---|---|---|
| **BRICK BUILDING_OUTSIDE WALL** | | | | | | | | |
| [ - ] | [ - ] | [ mm ] | [ - ] | [ W/m°C ] | [ W/m°C ] | [ - ] | [ kg/mł] | [ J/kg°C ] |
| Inner | Plaster | 15 | 0,9 | 0,57 | 0,001 | 9999,0 | 1300,0 | 1000,0 |
| 2 | Porotherm 38 N+F | 380 | 0,9 | 0,17 | 0,001 | 9999,0 | 750,0 | 1000,0 |
| 3 | EPS 100 | 100 | 0,9 | 0,04 | 0,001 | 9999,0 | 15,0 | 1300,0 |
| Outer | Plaster | 10 | 0,9 | 0,57 | 0,001 | 9999,0 | 1300,0 | 1000,0 |
| **BRICK BUILDING_FLOOR TO THE GROUND** | | | | | | | | |
| Inner | Wood, parquette | 12 | 0,9 | 0,18 | 0,001 | 9999,0 | 700,0 | 1500,0 |
| 2 | Concrete | 50 | 0,9 | 0,96 | 0,001 | 9999,0 | 1800,0 | 1000,0 |
| 3 | EPS 80 | 80 | 0,9 | 0,04 | 0,001 | 9999,0 | 15,0 | 1300,0 |
| 4 | Bitumen | 4 | 0,9 | 0,17 | 0,001 | 9999,0 | 1050,0 | 1000,0 |
| 5 | Reinforced concrete | 120 | 0,9 | 2,50 | 0,001 | 9999,0 | 2400,0 | 1000,0 |
| 6 | Gravel 1/2in (RG01) | 200 | 0,9 | 2,00 | 0,001 | 9999,0 | 881,0 | 1674,0 |
| **BRICK BUILDING_CEILING TO ATTIC** | | | | | | | | |
| Inner | Plaster | 10 | 0,9 | 0,57 | 0,001 | 9999,0 | 1300,0 | 1000,0 |
| 2 | Porotherm 17+5 | 220 | 0,9 | 0,53 | 0,001 | 9999,0 | 1455,0 | 1000,0 |
| 3 | EPS 100 | 100 | 0,9 | 0,04 | 0,001 | 9999,0 | 15,0 | 1300,0 |
| 4 | Glasswool | 100 | 0,9 | 0,04 | 0,001 | 1,0 | 12,0 | 750,0 |

*Table 8-3 OI3 values of the brick building*

| LAYER | M-CODE | WIDTH | MJ equi. | PEI | $CO_2$ equi. | GWP | $SO_2$ equi. | AP | Assigned material |
|---|---|---|---|---|---|---|---|---|---|
| **BRICK BUILDING_OUTSIDE WALL** | | | | | | | | | |
| | | [mm] | [$kgm^{-2}$] | [-] | [$kgm^{-2}$] | [-] | [$kgm^{-2}$] | [-] | |
| Outer | Plaster | 10 | 1,56 | 37,44 | 0,15 | 3,67 | 0,00056 | 0,01 | Kalkzementputz |
| 2 | EPS 100 | 100 | 49,8 | 637,44 | 2,26 | 28,92 | 0,01600 | 0,20 | Glaswolle MW-PT Fassadenplatte |
| 3 | Porotherm 38 N+F | 380 | 2,49 | 706,81 | 0,17 | 49,95 | 0,00055 | 0,15 | Vollziegel |
| Inner | Plaster | 15 | 1,56 | 37,44 | 0,15 | 3,67 | 0,00056 | 0,01 | Kalkzementputz |
| **BRICK BUILDING_FLOOR TO THE GROUND** | | | | | | | | | |
| Outer | Gravel 1/2in (RG01) | 200 | 0,07 | 30,03 | 0,00 | 1,63 | 0,00005 | 0,01 | Sand, Kies feucht 20% |
| 2 | Reinforced concrete | 120 | 1,22 | 351,36 | 0,16 | 48,09 | 0,00055 | 0,15 | Stahlbeton in WU-Qualität |
| 3 | Bitumen | 4 | 51,80 | 6,21 | 0,39 | 0,04 | 0,00529 | 0,00 | Bitumen |
| 4 | EPS 80 | 80 | 102,00 | 122,40 | 3,45 | 4,14 | 0,02230 | 0,02 | Polystyrol expandiert Trittschall-dämmung |
| 5 | Concrete | 50 | 0,87 | 91,87 | 0,10 | 10,71 | 0,00027 | 0,02 | Estrichbeton |
| 6 | Wood, parquette | 12 | 8,04 | 67,53 | -1,25 | -10,57 | 0,00341 | 0,02 | Brettschichtholz, verleimt, Innenanvendung |
| **BRICK BUILDING_CEILING TO ATTIC** | | | | | | | | | |
| Outer | Glasswool | 100 | 49,80 | 747,00 | 2,26 | 33,90 | 0,01600 | 0,24 | Glaswolle MW-WF |
| 2 | EPS 100 | 100 | 102,00 | 0,00 | 3,45 | 0,00 | 0,0 | 0,00 | Polystyrol expandiert -Dämmplatte |
| 3 | Porotherm 17+5 | 220 | 2,49 | 370,81 | 0,17 | 26,20 | 0,0 | 0,08 | Porotherm 17-50 Plan |
| 4 | Plaster | 10 | 1,56 | 29,95 | 0,15 | 2,93 | 0,0 | 0,01 | Kalkzementputz |

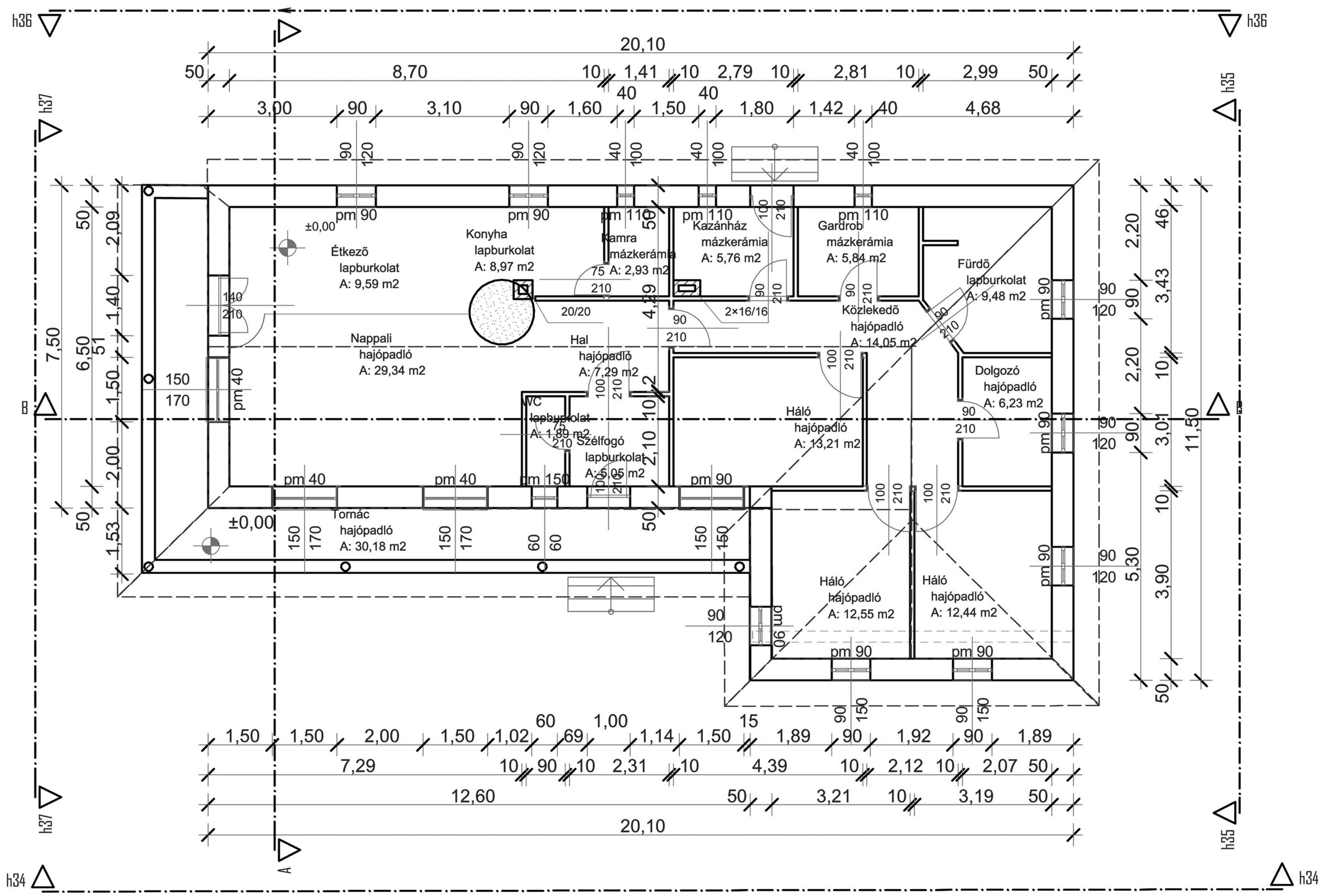


Figure 8-3 Plan of the straw-bale building

A-A SECTION

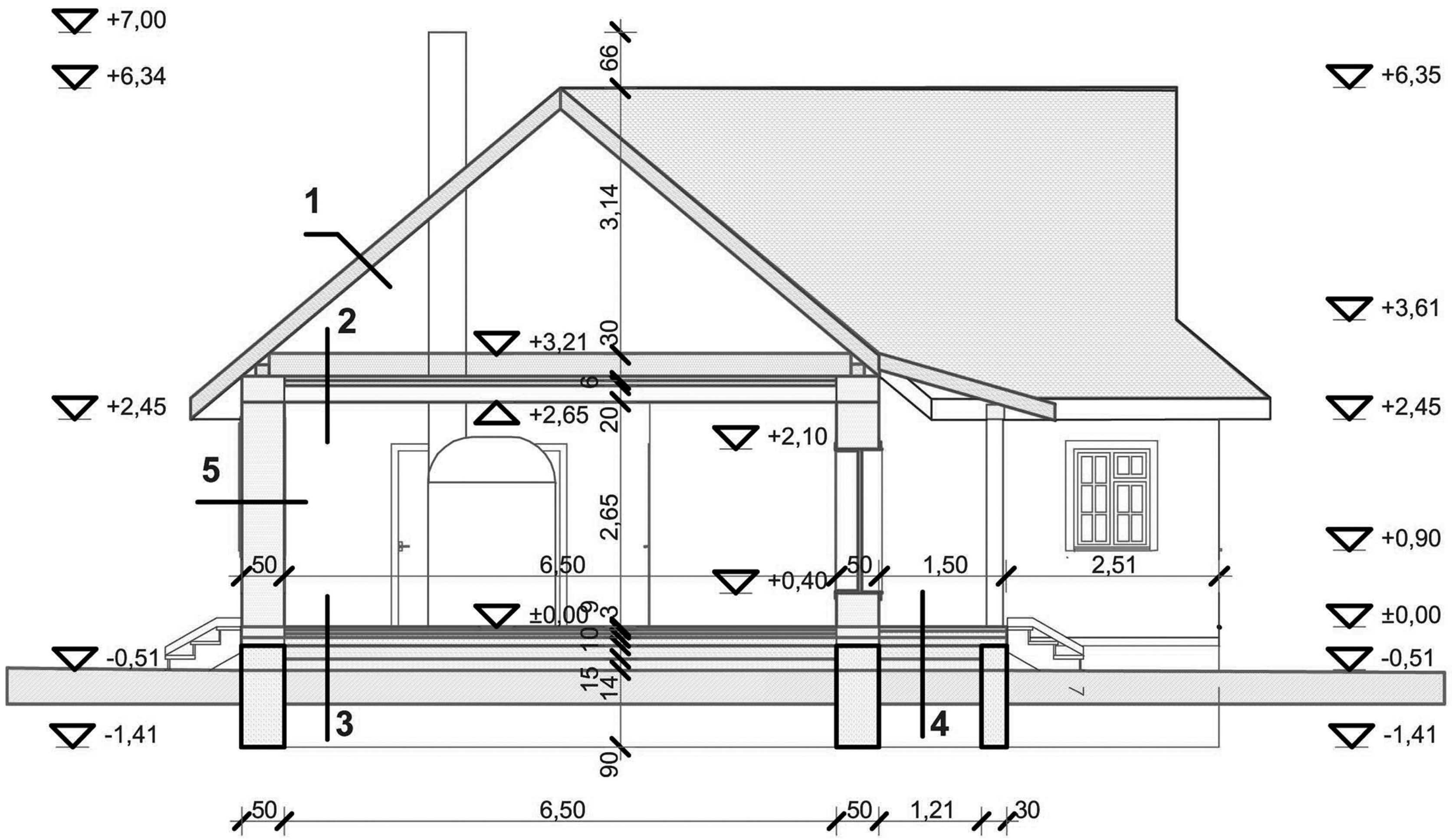


Figure 8-4 Section of the straw-bale building

*Table 8-4 Building elements of the straw-bale building*

| Building: 1_S | Straw-bale building | Bozsok, Hungary |
|---|---|---|
| **Building elements** | **Layers of construction** | **Thickness [cm]** |
| **OUTSIDE WALL** | Lime wash with kazein | 3 layers |
| | Clay | 5,0 |
| | Steel fabric (net) | 1 layer |
| | Straw-bale | 50,0 |
| | Steel fabric (net) | 1 layer |
| | Clay | 5,0 |
| | Inside lime wash | 2,0 |
| **FLOOR TO THE GROUND** | Parquett- timber boarding | 3,0 |
| | Floor slab | 5,0 |
| | Stepproof Nikecell | 5,0 |
| | Waterproofing | 1 layer |
| | Reinforced concrete | 8,0 |
| | Gravel fill | 15,0 |
| | Backfill | 14,0 |
| | Natural ground/soil | |
| **CEILING TO ATTIC** | Thinned boards (spaces between them) | 5,0 |
| | Clay | 5,0 |
| | Straw-bale | 35,0 |
| | Clay | 3,0 |
| | Boards (transmission lines) | 5,0 |
| | Squared timber, rails- pine | 20/20 |
| **PITCHED ROOF** | Roof tiles- plain tile | 3,0 |
| | Battens spaced for roof tiles- pine | 5/5 |
| | Battens spaced for roof tiles- pine | 3/3 |
| | Foil | 1 layer |
| | Rafter | 20,0 |
| **WINDOWS** | Unique wooden windows | |

*Table 8-5 Thermal attributes of the building elements in the straw-bale building*

| STRAW-BALE BUILDING_OUTSIDE WALL | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| LAYER | M-CODE | WIDTH | INT. EMISSIVITY | CONDUCTIVITY | CONVECTION COEFFICIENT | VAPOUR DIFFUSION FACTOR | DENSITY | SPECIFIC HEAT |
| [ - ] | [ - ] | [ mm ] | [ - ] | [ W/m°C ] | [ W/m°C ] | [ - ] | [ kg/mł] | [ J/kg°C ] |
| Inner | Plaster | 20 | 0,9 | 0,7 | 0,001 | 6,0 | 1400,0 | 850,0 |
| 2 | Clay | 50 | 0,91 | 0,14 | | 0,001 | 500,0 | 1,0 |
| 3 | Straw | 500 | 0,9 | 0,05 | | 9999,0 | 25,0 | 610,0 |
| 4 | Clay | 50 | 0,91 | 0,14 | | 0,001 | 500,0 | 1,0 |
| 5 | Plaster | 20 | 0,9 | 0,21 | | 6,0 | 900,0 | 850,0 |
| **STRAW-BALE BUILDING_FLOOR TO THE GROUND 1 (80%)** | | | | | | | | |
| Inner | Wood, parquette | 30 | 0,9 | 0,13 | 0,001 | 9999,0 | 593,0 | 2510,0 |
| 2 | Flooring screed | 50 | 0,9 | 0,41 | 0,001 | 9999,0 | 1200,0 | 1000,0 |
| 3 | EPS 50 | 50 | 0,9 | 0,04 | 0,001 | 9999,0 | 15,0 | 1300,0 |
| 4 | Bitumen | 8 | 0,9 | 0,17 | 0,001 | 9999,0 | 1050,0 | 1000,0 |
| 5 | Reinforced concrete | 80 | 0,9 | 2,50 | 0,001 | 9999,0 | 2400,0 | 1000,0 |
| 6 | Gravel 1/2in (RG01) | 150 | 0,9 | 2,00 | 0,001 | 9999,0 | 881,0 | 1674,0 |
| 7 | Soil 140 | 140 | 0,9 | 1,50 | 0,001 | 9999,0 | 1250,0 | 2500,0 |

| STRAW-BALE BUILDING_FLOOR TO THE GROUND 2 (20%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| LAYER | M-CODE | WIDTH | INT. EMISSIVITY | CONDUCTIVITY | CONVECTION COEFFICIENT | VAPOUR DIFFUSION FACTOR | DENSITY | SPECIFIC HEAT |
| [ - ] | [ - ] | [ mm ] | [ - ] | [ W/m°C ] | [ W/m°C ] | [ - ] | [ kg/mł] | [ J/kg°C ] |
| Inner | Wood, parquette | 30 | 0,9 | 0,13 | 0,001 | 9999,0 | 593,0 | 2510,0 |
| 2 | Wooden beams | 50 | 0,9 | 0,18 | 0,001 | 9999,0 | 721,0 | 1255,0 |
| 3 | EPS 50 | 50 | 0,9 | 0,04 | 0,001 | 9999,0 | 15,0 | 1300,0 |
| 4 | Bitumen | 8 | 0,9 | 0,17 | 0,001 | 9999,0 | 1050,0 | 1000,0 |
| 5 | Reinforced concrete | 80 | 0,9 | 2,50 | 0,001 | 9999,0 | 2400,0 | 1000,0 |
| 6 | Gravel 1/2in (RG01) | 150 | 0,9 | 2,00 | 0,001 | 9999,0 | 881,0 | 1674,0 |
| 7 | Soil 140 | 140 | 0,9 | 1,50 | 0,001 | | 1250,0 | 2500,0 |
| **STRAW-BALE BUILDING_CEILING TO THE ATTIC** | | | | | | | | |
| Inner | Wooden beams | 200 | 0,9 | 0,13 | 0,001 | 9999,0 | 593,0 | 2510,0 |
| 2 | Wooden beams | 50 | 0,9 | 0,13 | 0,001 | 9999,0 | 593,0 | 2510,0 |
| 3 | Clay | 30 | 0,91 | 0,14 | 0,001 | 0,0 | 500,0 | 1,0 |
| 4 | Straw | 350 | 0,9 | 0,05 | 0,001 | 9999,0 | 25,0 | 610,0 |
| 5 | Clay | 50 | 0,91 | 0,14 | 0,001 | 0,0 | 500,0 | 1,0 |
| 6 | Wooden beams | 50 | 0,9 | 0,13 | 0,001 | 9999,0 | 593,0 | 2510,0 |

*Table 8-6 OI3 values of the straw-bale building*

| STRAW-BALE BUILDING_OUTSIDE WALL | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LAYER | M-CODE | WIDTH | MJ equi. | PEI | $CO_2$ equi. | GWP | $SO_2$ equi. | AP | Assigned material |
| | | [mm] | [$kgm^{-2}$] | [-] | [$kgm^{-2}$] | [-] | [$kgm^{-2}$] | [-] | |
| Outer | Plaster | 20 | 1,56 | 37,44 | 0,15 | 3,67 | 0,00056 | 0,01 | Kalkzementputz |
| 2 | Clay | 50 | 3,07 | 122,80 | -0,05 | -2,04 | 0,00066 | 0,02 | Lehm-Leichtlehm 600-800kg/$m^3$ |
| 3 | Straw | 500 | 0,84 | 50,76 | -1,25 | -75,00 | 0,00087 | 0,05 | Strohballen-Wärmefluss normal zur Halmrichtung |
| 4 | Clay | 50 | 3,07 | 122,80 | -0,05 | -2,04 | 0,00066 | 0,02 | Lehm-Leichtlehm 600-800kg/$m^3$ |
| 5 | Plaster | 20 | 1,56 | 49,92 | 0,15 | 4,89 | 0,00056 | 0,01 | Kalkzementputz |
| **STRAW-BALE BUILDING_FLOOR TO THE GROUND 1 (80%)** | | | | | | | | | |
| Outer | Gravel 1/2in (RG01) | 150 | 0,07 | 21,02 | 0,00 | 1,14 | 0,00005 | 0,01 | Sand, Kies feucht 20% |
| 2 | Reinforced concrete | 80 | 1,22 | 234,24 | 0,16 | 32,06 | 0,00055 | 0,10 | Stahlbeton in WU-Qualität |
| 3 | Bitumen | 8 | 51,80 | 6,21 | 0,39 | 0,04 | 0,00529 | 0,00 | Bitumen |
| 4 | EPS 50 | 50 | 9,35 | 11,68 | 0,47 | 0,61 | 0,00165 | 0,00 | Thermo Floor |
| 5 | Flooring screed | 50 | 1,02 | 122,40 | 0,12 | 15,36 | 0,00029 | 0,03 | WU-Beton |
| 6 | Wood, parquette | 30 | 18,70 | 415,14 | 0,28 | 6,26 | 0,00627 | 0,13 | Parkett-Hartholzklebeparkett |

| STRAW-BALE BUILDING_FLOOR TO THE GROUND 2 (20%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LAYER | M-CODE | WIDTH | MJ equi. | PEI | $CO_2$ equi. | GWP | $SO_2$ equi. | AP | Assigned material |
| | | [mm] | [$kgm^{-2}$] | [-] | [$kgm^{-2}$] | [-] | [$kgm^{-2}$] | [-] | |
| Outer | Gravel 1/2in (RG01) | 150 | 0,07 | 21,02 | 0,00 | 1,14 | 0,00005 | 0,01 | Sand, Kies feucht 20% |
| 2 | Reinforced concrete | 80 | 1,22 | 234,24 | 0,16 | 32,06 | 0,00055 | 0,10 | Stahlbeton in WU-Qualität |
| 3 | Bitumen | 8 | 51,80 | 6,21 | 0,39 | 0,04 | 0,00529 | 0,00 | Bitumen |
| 4 | EPS 50 | 50 | 9,35 | 11,68 | 0,47 | 0,61 | 0,00165 | 0,00 | Thermo Floor |
| 5 | Wooden beams | 50 | 2,26 | 68,01 | -1,69 | -50,73 | 0,00149 | 0,04 | Schnittholz Fi rauh, lufttrock. |
| 6 | Wood, parquette | 30 | 18,70 | 415,14 | 0,28 | 6,26 | 0,00627 | 0,13 | Parkett-Hartholzklebeparkett |
| **STRAW-BALE BUILDING_CEILING TO THE ATTIC** | | | | | | | | | |
| Outer | Wooden beams | 50 | 2,26 | 68,01 | -1,69 | -50,73 | 0,00149 | 0,04 | Schnittholz Fi rauh, lufttrock. |
| 2 | Clay | 50 | 3,07 | 122,80 | -0,05 | -2,04 | 0,00066 | 0,02 | Lehm-Leichtlehm 600-800kg/$m^3$ |
| 3 | Straw | 350 | 0,84 | 35,53 | -1,25 | -52,50 | 0,00087 | 0,03 | Strohballen-Wärmefluss normal zur Halmrichtung |
| 4 | Clay | 30 | 3,07 | 73,68 | -0,05 | -1,22 | 0,00066 | 0,01 | Lehm-Leichtlehm 600-800kg/$m^3$ |
| 5 | Wooden beams | 50 | 2,26 | 68,01 | -1,69 | -50,73 | 0,00149 | 0,04 | Schnittholz Fi rauh, lufttrock. |
| 6 | Wooden beams | 200 | 2,26 | 272,04 | -1,69 | -202,93 | 0,00149 | 0,17 | Schnittholz Fi rauh, lufttrock. |