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The potential of hemp buildings in different climates

A comparison between a common passive house and the hempcrete building system

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Johan Ahlberg
Elza Georges
Mikael Norlén

UPPSALA
UNIVERSITET

Teknisk- naturvetenskaplig fakultet
UTH-enheten

Besöksadress:
Ångströmlaboratoriet
Lägerhyddsvägen 1
Hus 4, Plan 0

Postadress:
Box 536
751 21 Uppsala

Telefon:
018 – 471 30 03

Telefax:
018 – 471 30 00

Hemsida:
http://www.teknat.uu.se/student

Abstract

The potential of hemp buildings in different climates

Johan Ahlberg, Elza Georges, Mikael Norlén

The aim of this bachelor thesis was to study the potential of hemp buildings in different climates. The report examines and models two different energy efficient building concepts – the more common passive house and the environmental friendly hempcrete building system. These two buildings thermal performances were then simulated and compared in different climates followed by a brief discussion about their economic and environmental impact.

The simulation was performed with the energy calculating program VIP-energy v 2.1.1 with the two models located in Kiruna, Sundsvall, Malmo, Berlin and Rome to represent the different climates. Simulations for different wall sizes and a sensitivity analysis of some significant parameters were also made.

The hempcrete building system showed to have a thermal performance similar to that of passive houses in more southern climates. In the north of Sweden however the hempcrete building required up to 20 % more energy than the passive house to maintain comfortable indoor temperatures. This deficit could be compensated for with hemp fibre insulation to augment the building envelope and U-value. Furthermore the hygrothermal material properties that were not included in the simulation can be expected to have a significant positive impact on hemp buildings relative thermal performance.

With a passive house thermal performance, a healthy indoor environment and an economically viable and environmental friendly production process hemp building demonstrated great potential in all the fields studied.

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Table of Contents

1. Introduction

Today sustainable development is under close scrutiny by most nations in the industrialized world. One of the major challenges for the environment is climate change which is no longer something to be anticipated in the future – it has already started. The evidence is in our backyard: Higher temperatures, melting glaciers, tropical storms, droughts and rising sea levels are just some of the consequences and we are running out of places to hide.[1] The past decades of development have led us into a new epoch, the Anthropocene, where humans constitute the dominant driver of change to the earth system. This realization requires us to take responsibility for the sake of future generations and life systems as a whole, complying with planetary boundaries.[2]

In 2011 the residential sector used 18%[3] of the total world energy use and contributed with as much as one third of the total global greenhouse gas emissions, primarily through the use of fossil fuels during their operational phase.[4] In the European Union the numbers are different; nearly 40% of the final energy consumption is used by buildings in the public and private sector which results in 36% of all greenhouse gas emissions.[5] Despite all previous efforts, the energy consumption in the residential sector increased from 3200TWh to 3600TWh between years 1990 – 2010, a growth of 12% which implies much work still has to be done.[6]

One way for the household sector to save energy is by utilizing passive houses. Passive houses are designed to "passively" regulate the energy demand and can be viewed as the opposite of "active" regulation through the heating system. Commonly they are built with a highly insulating building envelope to establish a controlled indoor environment. However there are other things than a materials insulating capacity that contribute to thermal performance such as thermal storage and hygroscopicity.

Hempcrete is an example of a vapour permeable or "breathable" building material that utilizes a combination of thermal and hygroscopic attributes to enable a good thermal performance as well as a healthy indoor climate. The material is a bio composite mainly consisting of hemp and lime and is also amongst other things sound- and fire resistant. Hemp is an organic, non-fossil and carbon negative product that can often be grown without herbicides, fungicides or other pesticides. It has been used for over 10,000 years[7] for its strong fibres and has been estimated to have over 25,000 industrial uses.[8]

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[1] Europa – Summaries of EU legislation. *Tackling climate change.* http://europa.eu/
[2] Rockström, Johan et al. Ecology and Society. *Planetary Boundaries: Exploring the Safe Operating Space for Humanity* (2009): p. 2-19.
[3] U.S. Energy Information Administration. *Frequently asked questions* (2014) http://www.eia.gov/
[4] United Nations Environment Programme - Sustainable Buildings & Climate Initiative. *Building and climate change – Summary for Decision-Makers* (2009): p. 2.
[5] Technical Guidance – Financing the energy renovation of buildings with Cohesion Policy funding. *Final report- A study prepared for the European Commission DG Energy* (2014): p. 21.
[6] JRC Scientific and policy report. *Energy Efficiency Status Report* (2012): p. 10.
[7] Hemp Industries Association. *Facts.* http://www.thehia.org
[8] North American Industrial Hemp Council, INC. *Hemp Facts* (1997) http://naihc.org/

Due to the incorporation of hemp in the building material it also captures a lot of greenhouse gas emissions when carbon is locked into the building walls. $1m^3$ of hempcrete stores up to 130kg CO_2 resulting in a negative carbon footprint.[9]

1.1 Purpose

The purpose of this report is to study the potential of hemp buildings in different climates by primarily comparing the thermal performance, but also the economic and environmental impact with a more common passive house building technique in use today.

1.2 Methodology overview

The following will be addressed:

- An informative study of the two different building techniques will be presented.
- The energy consumption for a hempcrete house and a common passive house with identical dimensions will be modelled and simulated over a one-year period in different climates.
- The impact of different wall thicknesses will be tested to study the factors contributing to the thermal potential of the different building systems in the different climate zones.
- How climate affects the two building systems energy consumption as well as the impact of the different wall thicknesses will be studied.
- The thermal, environmental and economic potential of hemp building will be discussed based on the background information and simulation results.

Simulations

In order to simulate the energy consumption for the different building systems, VIP-energy v 2.1.1 was used.[10] The software is created by the Swedish software manufacturer StruSoft AB and uses dynamic calculation methods to calculate the energy use per hour for a modelled building over a given time period. The energy flow is being calculated with consideration taken to climate factors such as temperature, radiation from sun, humidity and wind. The different model designs were based on a small one family house example model from VIP energy and then adjusted to passive house and hempcrete building standards respectively. To evaluate the simulation results they were compared with norms and previous reports.

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[9] Abott, Tom. The Limecrete company LTD. *Hempcrete Factsheet* (2014) http://www.limecrete.co.uk/
[10] VIP-energy. http://www.vipenergy.net

1.3 Delimitations

The different models used in the simulations were adjusted to represent single-family homes based on the two different building concepts. To compare different climate zones in Europe, central cities have been chosen as representatives. Most of the cities where chosen in Sweden, due to the simulation program's default geographical limitations and the availability of regulation information.

This report uses the same definition of the household energy consumption as the Swedish energy agency and hence does not include operational electricity use or various household electricity. The discussion about environmental and economic costs will be focused on the production phase and CO_2 emissions. Hygroscopic performance and its impact on household energy consumption could not be properly taken into account in the simulations but will be discussed based on previous reports.

1.4 Structure of the report

The report begins with a background section (Ch. 2) containing important concepts and definitions (Ch. 2.1) and a brief summary of the total energy consumption and the impact of the building industry (Ch. 2.2). Energy consumption regulation codes will be reviewed in Sweden to allow for benchmarking of the different houses. This is followed by an introduction to passive houses; their construction and standards (Ch. 2.3). Afterwards information about hemp follows regarding its properties and farming process (Ch. 2.4). The final part of the background covers the hempcrete building system (Ch. 2.5).

The methodology section explains the motivation behind the household model and simulation design in VIP-energy (Ch. 3). Finally, in the last sections of the report the simulation results will be featured (Ch.4) together with a sensitivity analysis (Ch. 5) and a comparative discussion (Ch. 6) regarding the climates effect on the relative thermal performance of the two building systems. The economic and environmental costs are also discussed with focus on CO_2 emissions followed by a conclusion about the hempcrete building systems potential (Ch. 7) and an evaluation of its future prospects (Ch.8).

1.5 Source criticism

The main sources used in the report are:

- The International Passive House Association (IPHA)[11] and their Passipedia[12] which functions as a tool where new Passive House findings from around the world are presented, as well as where the highlights of more than 20 years of research on Passive Houses are being posted.

[11] International Passive House Association. http://passivehouse-international.org/
[12] Passipedia – The Passive House Encyclopedia. http://passipedia.org/

- The International Hemp Building Association (IHBA)[13], its director Steve Allin and his book Building with Hemp.
- Lime Technologies from the UK who have estimated the properties for their tradical hemcrete®[14] product which was used to represent the hempcrete material in the simulation.
- Scott Simpson (2014)[15]. An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames. MSc thesis, Graduate School of the Environment, Centre for Alternative Technology, University of East London.

A few references used in the background come from less profound sources. However the information is used in an informative way and has no impact on the simulation results.

[13] International Hemp Building Association. http://internationalhempbuilding.org/
[14] Lime Technology. http://lime-technology.com/
[15] Simpson, Scott. University of East London. *An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames*. (2004): p. 16.

2. Background and theory

To understand the method and what will be simulated in the report, one must first understand some essentials ideas and what defines the different building concepts. Through this section the reader will be given an introduction to these important concepts and definitions and a brief explanation of the physical principles that affect the energy balance of a building. Afterwards there will be a review of the current energy use of the building sector in Europe, some key targets for future climate goals as well as some of the building codes in Sweden. This is followed by a deeper explanation of the passive and hemp house building concepts.

2.1 Important concepts and definitions

To understand what influences the energy balance of a building it is necessary to know the basics of thermodynamics as well as some other physical laws. This chapter provides an explanation of these concepts. All underlying formulas are included in this section to give a more complete understanding to the interested reader but will not necessarily be of importance to the general understanding of the report.

2.1.1 Thermal conductivity

Thermal conductivity (k value or λ) indicates the ability of a given material to conduct heat. Heat transfer by conduction occurs when energy flows within a material without any motion of the material. When a temperature gradient exists in a solid medium the conductive heat flow occurs in the direction of decreasing temperature. This is because energy is transferred when neighbouring molecules collide and higher temperature equates to a higher molecular energy, or more molecular movement.[16]

> "Thermal conductivity is defined as the quantity of heat (Q) transmitted through a unit thickness (L) in a direction normal to a surface area (A) due to a unit temperature gradient (ΔT) under steady state conditions and when the heat transfer is dependent only on the temperature gradient." (see Equation 1)

$$\lambda = \frac{Q\,L}{A\,\Delta T} \qquad [\mathrm{W\,m^{-1}\,K^{-1}}] \tag{1}$$

Lower values equal less conductivity and a better insulating value for the material.

2.1.2 U-value

The U-value[17] measures the amount of heat loss in watts (W) per square meter of material of set thickness when the outside temperature is at least one degree lower. It is commonly used in buildings to determine if a building element such as walls, floors and

[16] NDT Resource Center. *Thermal Conductivity.* http://www.ndt-ed.org/
[17] Brennan, John. Royal-Institute of British Architects. *U-value.* http://www.architecture.com/

roofs has a good measure of heat loss and how well they transfer heat. A component with a low U-value has a better insulation and improves the thermal performance of the building envelope. The U-value is useful because of its way of predicting the insulation performance of an entire building with set component thicknesses so one does not have to take into account the properties of all individual materials.

To calculate the U-value firstly the Thermal resistance $R_{Th} = \frac{d}{\lambda}$, is calculated, where d is the material thickness and λ the thermal conductivity.

Later the U-value is calculated by Equation 2.

$$U = \frac{1}{R_i}, i = 1,2,3 \dots \quad [W\ m^{-2}\ K^{-1}] \qquad (2)$$

Where R_i, $i = 1,2,3$ ... is the sum of all the resistances of the building material in the chosen building part. For example, to reach a U-value of 0.13W $m^{-2}\ K^{-1}$ for the outer wall you will need 15.8meters of concrete with a thermal conductivity of 2.1W $m^{-1}K^{-1}$ or 6 meters of solid brick with a thermal conductivity of 0.8W $m^{-1}\ K^{-1}$.

2.1.3 Heat capacity

Heat capacity is also known as thermal capacity (C) or thermal mass. Heat capacity is defined as the amount of heat units (ΔQ) that under specified conditions must be applied to a system to increase the temperature (ΔT) of a body by one degree.[18] The formula is shown in Equation 3.

$$C = \frac{\Delta Q}{\Delta T} \quad [J\ K^{-1}] \qquad (3)$$

2.1.4 Specific heat capacity

Physical properties are often described as an intensive property because it has many experimental and theoretical advantages. Heat capacity is describes as an intrinsic character by expressing it in relation to mass. This is then called the specific heat capacity (c) and is described as the amount of heat required to raise the temperature of 1 kg of a substance by one degree.[19] Specific heat capacity is given by Equation 4:

$$c = \frac{\partial C}{\partial m} = \frac{\text{Volumetric heat capacity}}{\text{density}} \quad [J\ kg^{-1}\ K^{-1}] \qquad (4)$$

2.1.5 Volumetric heat capacity

Volumetric heat capacity (VHC) describes the ability of a material at a given volume to store internal energy. Because it measures the capacity per volume it can sometimes be

[18] Swedish National Encyclopedia. *Heat capacity.* (2014) http://www.ne.se/
[19] Swedish National Encyclopedia. *Specific eat capacity*. (2014) http://www.ne.se/

a better indicator of a material's thermal storage capacity than specific heat capacity as is often the case for more lightweight insulation materials.[20] See Equation 5.

$$\mathrm{VHC} = \frac{\partial \mathrm{C}}{\partial \mathrm{V}} = \text{Specific heat capacity} \times \text{density} \quad [\mathrm{J\ m^{-3}\ K^{-1}}] \tag{5}$$

2.1.6 **Heat flow rate**

Energy and heat flow exist whenever there exists a temperature difference in a system because all systems strive to meet thermodynamic equilibrium. The heat flow rate describes how much energy that flows between two systems per second. It is a measure of power and can be derived from Fourier's law as seen in Equation 6:[21]

$$\mathrm{q} = \frac{\Delta \mathrm{Q}}{\Delta \mathrm{t}} = \frac{-\lambda\ \mathrm{A}\ \Delta \mathrm{T}}{\Delta \mathrm{s}} \quad [\mathrm{J\ s^{-1}} = \mathrm{W}] \tag{6}$$

Q	Heat
t	Time
λ	Thermal conductivity
A	Area of cross section
$\mathrm{T_1} - \mathrm{T_2}$	Temperature difference from one side to another
s	Thickness of the material

2.1.7 **Relative humidity**

Relative humidity (RH) is the ratio of the partial pressure of water vapour in an air-water mixture to the saturated vapour pressure of water at a prescribed temperature. The relative humidity of air depends on the temperature and pressure of the system of interest and has a non-linear relationship according to Equation 7.[22]

$$\text{Relative humidity} = \frac{\text{vapour pressure (actual water vapour in the air)}}{\text{sauration vapor pressure (max the air can hold at this temp}} \tag{7}$$

2.1.8 **Hygroscopy**

Hygroscopy is the ability of a substance or material to attract or hold water molecules from the air or surrounding environment. Materials with this property allow water vapour to condense on their surface and pores at less than 100% RH. This is due to vapour being attracted by electro-static forces.[23] A hygroscopic material can also be called "breathable".

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[20] Simpson, Scott. University of East London. *An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames*. (2004): p. 17

[21] The Engineering ToolBox. *Conductive Heat Transfer. (*2014) http://www.engineeringtoolbox.com

[22] Simpson, Scott. University of East London. *An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames*. (2004): p. 16

[23] Simpson, Scott. University of East London. *An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames*. (2004): p. 15

2.1.9 **Latent heating/cooling**

When a substance changes state it either releases or absorbs energy in the form of heat while the temperature is unchanged. Latent heat[24] describes the amount of heat released or absorbed during a phase transition. It is expressed as the amount of heat per unit mass of the substance undergoing the phase transition, without change of temperature. In a breathable building these effects can occur in the building envelope and latent cooling[25] then measures the amount of energy necessary to dehumidify the air in the building regardless the humidity outdoors.

2.1.10 **Thermal diffusivity and thermal inertia**

Thermal diffusivity (α) describes the rate at which heat spreads in a material. This affects how far heat will penetrate and a lower diffusivity results in heat penetrating the material slower and more shallow.[26]

Thermal diffusivity is also derived from Fourir's law and is described in Equation 8:

$$\alpha = \frac{\lambda}{c_p \cdot \rho} \quad [\mathrm{m^2\,s^{-1}}] \tag{8}$$

Where c_p is the specific heat capacity at constant pressure.

A low diffusivity means the material has a high thermal inertia due to the slow movement of heat inside the material.

2.1.11 **Thermal effusivity**

Thermal effusivity (e) describes the surface heat flux – the rate at with material absorbs or emits heat through its surface. Higher effusivity results in heat flowing faster into a surface from its environment and is described in Equation 9.

$$e = \sqrt{\lambda\,\rho\,c_p} \quad \left[\mathrm{J\,m^{-2}\,K^{-1}\,s^{-\frac{1}{2}}}\right] \tag{9}$$

λ = thermal conductivity, ρ = density, c = specific heat capacity

For example rock-wool has low effusivity and shows resistance to heat. When in contact with materials with different effusivities they will feel relatively warmer or colder to you even if they are at thermal equilibrium; the one with the high effusivity is just taking heat away faster.

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[24] Encyclopedia Britannica. *Latent heat.* (2014) http://www.britannica.com/

[25] The Engineering ToolBox. *Cooling Loads – Latent and Sensible Heat.* http://www.engineeringtoolbox.com/

[26] Venkanna, B.K. New Delhi: PHI Learning. *Fundamentals of Heat and Mass Transfer*. (2010). p. 38

2.1.12 **Energy balance**

A system in thermodynamic equilibrium is a system where there it is no (net-) flow of heat or energy between the various parts of the system. This means that the temperature is the same in all parts and that this temperature is unchanged if the system is isolated.[27]

Thermodynamic equilibrium can only be achieved when the system reaches its maximum entropy. This is derived from the second law of thermodynamics, which states entropy can only increase until the maximum entropy is reached and then the system is in thermodynamic equilibrium.[28]

For residential houses, this implies that the entropy will always increase as the temperature will always strive to be the same as the outside temperature. The law of conservation of energy also states that energy can neither be created nor destroyed, it can only change form. So the only way the energy has to go, in order to reach equilibrium and maximum entropy, is to flow through the building envelope. To keep the temperature at pleasant levels, heat must be supplied to compensate the energy loss in cold climates. This means that the sum of heats losses is equal to the sum of heat gains.[29]

In an ordinary house in a cooler climate, the energy losses appear as shown in Figure I.

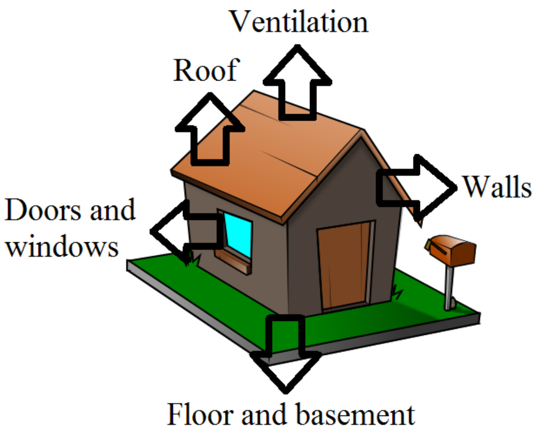

Figure I. Energy loss in an ordinary house.

The indoor climate in a house is determined by four parameters:[30]

- The structure and design of the building
- The activities inside the building
- The outdoor climate
- The technical system that have to provide the required indoor climate.

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[27] Swedish National Encyclopedia. *Thermodynamic equilibrium.* (2014) http://www.ne.se/
[28] HyperPhysics. *Second Law of Thermodynamics.* (2014) http://hyperphysics.phy-astr.gsu.edu/
[29] Passipedia. *Energy balances – Background.* http://passipedia.passiv.de/
[30] Nilsson, Per. *Achieving the desired indoor climate: energy efficiency aspects of systems design* (2003): p. 299

The last parameter is only necessary if the other three are insufficient for an acceptable climate. If that is the case then the system might handle heating, ventilation and/or air conditioning (HVAC) to adjust the indoor climate. The main goal for the HVAC system is therefore to compensate heat deficit and heat surplus. However without the HVAC system the indoor temperature is determined mainly by the relationship between heat transport and generation. These are influenced by:[31]

1) *Transport of heat through the envelope of the building*. Heat is transported through the envelope of the building via heat transmission due to temperature differences, thermal bridges and air flows.

2) *Storage of heat in the building structure.* Due to thermal inertia heat is stored in the building structure when the room temperature rises. When the building is heated the structure slowly absorbs heat and eventually enters thermal equilibrium. Later, when the building cools down again this heat is transmitted and thereby compensates the negative fluctuation. Radiated heat from lights, people and equipment is also absorbed by the building, stored in the structure and emitted afterwards to restore equilibrium. This leads to a delay in both heating and cooling effects.

3) *Internal generation of heat in the building.* Can either be solar irradiation through windows heating up the floor and walls, heat from people and activities in the room and heat generated by lighting and equipment.

[31] Nilsson, Per. *Achieving the desired indoor climate: energy efficiency aspects of systems design* (2003): p. 301

2.2 Building energy use

The household energy consumption refers to the energy used for heating, cooling, tap water and operating installations such as pumps and ventilation.[32] In the European Union nearly 40% of the final energy consumption is used by buildings in the public and private sector which results in 36% of all greenhouse gas emissions.[33] Reducing the energy use in Europe is vital and the current policy for energy saving measures is based on the Kyoto Protocol from 1998. Three goals regarding energy efficiency were set up by the EU in 2007:[34]

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency.

These targets are known as the “20-20-20” targets and are key objectives for the year 2020. In March 2014 a continuation on the 20-20-20 targets were made to the year 2030. Only the first two targets were given new specific goal values, reducing greenhouse gas emissions by 40% and increasing the share of renewable energy to at least 27%. The last goal regarding energy efficiency has not got a specific goal; the EU parliament has only stated that EU must continue to improve its energy efficiency.[35]

It is understandable that EU would not give specific new goals on the improvement energy efficiency considering the previous growth of EU building energy consumption by 12% in 1990 – 2010.[36] The potential for energy savings in the building sector is estimated to be one of the largest factors for reducing our total energy consumption, see Figure II.

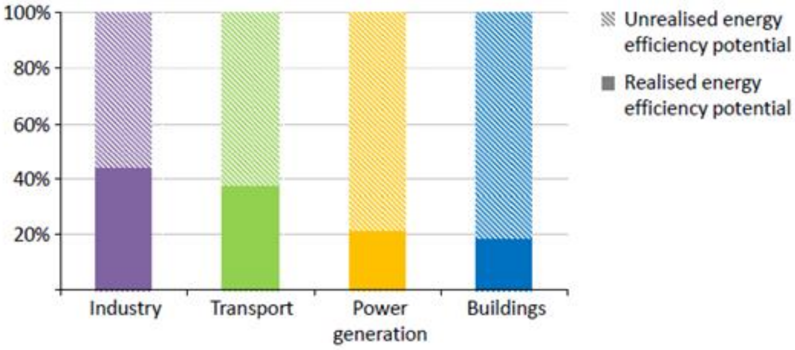

Figure II: The potential for energy savings in different sectors.

[32] Levin, Per et al. Svebyprogrammet. *Brukarindata bostäder*. (2012): p. 31. http://www.sveby.org/
[33] Paulou, Julien et al. European Commission, Directorate – General for Energy. *Financing the energy renovation of buildings with Cohesion Policy funding.* (2014): p. 21. http://ec.europa.eu/
[34] European Commission. *The 2020 climate and energy package.* (2014) http://ec.europa.eu/
[35] European Commission. *2030 framework for climate and energy policies.* (2014) http://ec.europa.eu/
[36] Bertoldi Paolo et al. Joint Research Centre Scientific and policy report. *Energy Efficiency Status Report 2012.* (2012): p. 10. http://iet.jrc.ec.europa.eu/

To get an understanding of the building codes regarding building energy consumption in the industrialized world the current situation in the author's home country Sweden will be reviewed. The reasoning behind this more specific location is the benchmarking difficulties imposed by the great regulation and climate variability in the EU as a whole.

In 2011 the total Swedish national energy use reached approximated 337.5 TWh accordingly to the Swedish energy agency. The household sector accounted for 86.3 TWh, which corresponds to 22.8 % of the total energy use.[37] Two years earlier, in 2009, Statistics Sweden (SCB) made an evaluation on the average Swedish house energy consumption:[38]

- Living area: $149 \mathrm{m}^2$
- Total energy use: 23 980 kWh per year
- Total energy use per area per year: 160.9 $\mathrm{kWh\ m^{-2}\ yr^{-1}}$.

2.2.1 Swedish building codes

Today the Swedish national board of housing, building and planning (Boverket) is responsible for the Swedish building codes for building energy use. As ordered by the Swedish government, they have come up with limitations for energy use such as space heating, domestic hot water heating and common electricity. The daily average temperature in Sweden differs from the south to the north. In the northern town Kiruna the yearly mean temperature is -1.96°C and in the southern town Malmo the yearly mean temperature is +8.08°C.[39] Since the mean temperature is this different the energy demand will also be different. To accommodate this variability Boverket divided Sweden into three different climate zones, see Figure III.[40]

Figure III: Swedish climate zones by Boverket.

[37] Energimyndigheten. Total energianvändning – Total slutlig energianvändning i Sverige. *Hushåll.* (2012) http://www.energimyndigheten.se/
[38] Energimyndigheten. *Ditt hus och din uppvärmning*. (2012) http://www.energimyndigheten.se/
[39] World Meteorological Organization, World weather information service for Malmo and Kiruna, http://www.worldweather.org/
[40] Boverket. *Regler om byggande*. (2013) http://www.boverket.se/

The latest report from Boverket is BBR20 (Boverkets building regulations 20). The maximum energy use for residential buildings is defined in Table 1.

Table 1: Maximum allowed total energy use in residential buildings in Sweden. [41]

kWh $m_{A_{temp}}^{-2}$ yr^{-1}	**Climate zone I**	**Climate zone II**	**Climate zone III**
Max non electrically heated	130	110	90
Max electrically heated	95	75	55

In BBR20 the heated area, A_{temp}, is defined as the total internal floor area heated above 10°C.[42] The U_{mean} value must not exceed 0.4W m^{-2} K^{-1} for all climate zones.

2.3 Passive house

A passive house is a building with a primary goal to be energy efficient. The basic idea is to utilize a well-insulated, airtight building envelope with mechanical ventilation similar to a thermos. The passive houses are primarily heated by passive solar gain and by internal gains from people and activities inside the house, see Figure IV. It is a comprehensive system where "passive" refers to the opposite of "active" where heat sources like radiators are in use.[43]

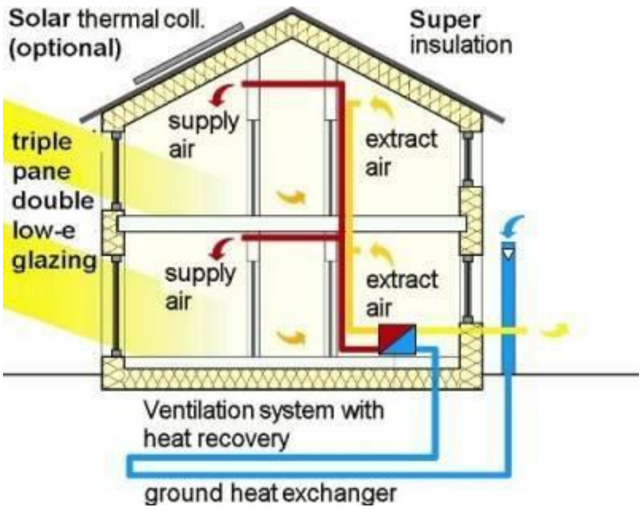

Figure IV: Passive house thermal system

A Passive House is highly sustainable and uses up to 90% less energy than typical Central European buildings. The investment in higher quality building components can be compensated by the elimination of expensive heating and cooling systems and seen from the entire life cycle a passive house is cheaper than an ordinary building because

[41] Boverkets författningssamling. *BFS 2013:14 BBR 20.* (2013): p. 37. https://rinfo.boverket.se/

[42] Boverket. *Vad är Atemp för något?* http://www.boverket.se/

[43] Passipedia. *What is a Passive House?* http://passipedia.passiv.de/

of the low energy use during its operational phase. The construction of a passive house can be quite similar to that of an ordinary house and no special construction type is required.[44, 45]

There are also other energy efficient standards similar to the passive houses. Some with even better energy classifications called zero-energy houses and plus-energy houses. These are houses that meet all requirements for a passive house and also have the sum of the delivered weighted energy to the building equal to the sum delivered from the building during one year. If the energy delivered to the building is less than the energy from the building it is a plus energy house.[46]

2.3.1 History of the passive house

The passive solar building design is not a new concept.[47] The ancient Greeks and Chinese utilized this method thousands of years ago. But the modern idea of the passive house came from Professor Bo Adamson from the Department of Building Science at Lund University in the late 80s. By improving the building envelope and interchanging the space heating system to a passive solar system Adamson saw that a good "passive design" for a house also worked in cold climates, with no auxiliary heating or cooling. With help from his colleague Wolfgang Feist the full concept of passive houses was realized in 1988 and the first version was later built in Darmstadt Kranichstein, Germany in 1990.[48] The first international certified passive house in Sweden was built in 2008. Although other buildings should have been defined as passive houses a few years earlier but they did not get an international certification.[49]

The number of passive houses in the world has grown rapidly and proven to be a reliable system in many different climates. In 2013 it was estimated that there were 50.000 units built worldwide, most of them in Germany, Austria and Switzerland.[50]

2.3.2 Definition

A Passive House is not energy standard but a fundamental concept to reduce the ecological footprint. The idea is to have a house use the least amount of energy and still have the highest level of comfort. The Passive House Institute has made the following definition of a Passive House: [51]

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[44] Passive House Institute, International Passive House Association. The Passive House – comfortable, affordable, sustainable. (2012) http://passivehouse-international.org
[45] Passipedia. *What is a Passive House?* http://passipedia.passiv.de/
[46] Erlandsson, Martin et al. Sveriges Centrum för Nollenergihus. *Kravspecifikation för nollenergihus, passivhus och minienergihus FEBY.* (2012): p. 4 http://www.nollhus.se/
[47] Passipedia. *The Passive House – historical review.* http://passipedia.passiv.de/
[48] Feist, Wolfgang. Passive House Institute. *15th Anniversary of the Darmstadt – Kranichstein Passive House*. (2006) http://passivhaustagung.de/
[49] Passipedia. *Sweden's first certified Passive House kindergarten.* http://www.passipedia.org/
[50] Passive House Institute, International Passive House Association. The Passive House – comfortable, affordable, sustainable. (2012) http://passivehouse-international.org
[51] Passipedia. *The Passive House – definition.* http://passipedia.passiv.de/

“A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air.”

The definition is valid for all climates and thermal comfort is achieved to a maximum extent through passive measures using insulation, heat recovery, passive use of solar energy and internal heat sources.[52]

To achieve a functional passive house there are 5 principles, see Figure V:[53]

- All opaque building components of the exterior envelope of the building must be very well-insulated.
- To utilize the sun’s energy the windows should be strategically positioned and well insulated.
- In a well-insulated house ventilation is very important, so efficient heat recovery ventilation systems are mandatory that provide fresh air.
- The building must be airtight, uncontrolled leakage through gaps must be limited.
- Avoid all thermal bridges. All edges, corners, connections and penetrations must be planned and executed with great care.

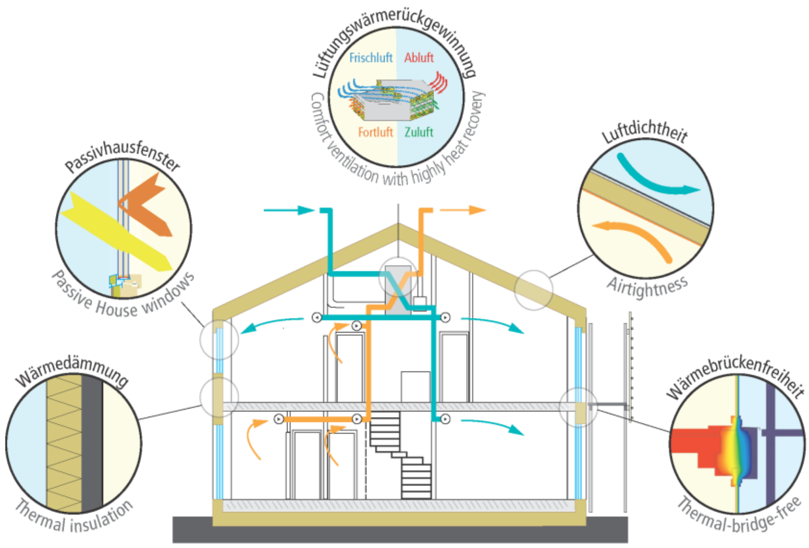

Figure V: Passive house principles

The properties of these principles vary depending on the climatic conditions, e.g. passive house buildings in Scandinavia, Canada or Russia will require greater insulation than passive houses in Mediterranean climates and therefore increased wall thickness.

[52] Passipedia. *The Passive House – definition.* http://passipedia.passiv.de/
[53] Passive House Institute. *Passive House Requirements.* (2012) http://www.passiv.de/

Heat recovery through ventilation is a key component of a passive house. It works by having the ingoing and outgoing airlines exchange their energy through the separating plates in the heat exchanger, see Figure VI. Systems with 75% to 95% efficiency (η) are available.[54] A similar method can also be used for drain water heat recovery.[55]

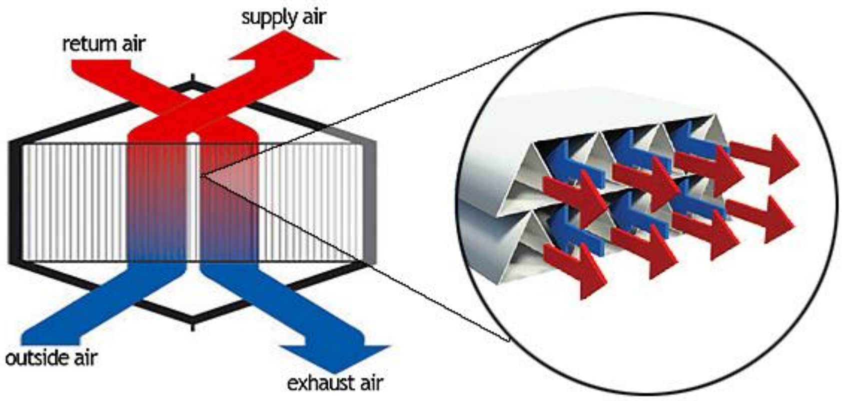

Figure VI: Heat recovering ventilation

Although active geothermal heat pumps are generally not included in the passive house concept, in cooler climates such as Sweden many passive houses use a geothermal system to preheat the incoming ventilation air.[56] The materials often used for passive houses are concrete, wooden or steel frames and synthetic mineral wools for insulation.[57] Some of these materials can lead to significant carbon emissions during production. Concrete is estimated to release between 100-300kg CO_2 eq m^{-3} and rock wool about 1.01kg of CO_2 eq kg^{-1}.[58, 59]

Although the passive house is a concept and not standardization, some criterions have been developed to define them. The criterions are set by the International Passive House Association together with the German Passivhaus Institute and are meant for a mid-European climate but can be adapted to local conditions and climate.[60]

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[54] Passive House Institute. *Why a mechanical ventilation system is recommended – at least in Passive Houses.* (2006) http://www.passivhaustagung.de/
[55] U.S. department of Energy. *Drain Water Heat Recovery.* (2012) http://energy.gov/
[56] Canadian Passive House Institute. *FAQ.* http://www.passivehouse.ca/faq/
[57] Boqvist, Albert. Division of Structural Engineering, Lund Institute of Technology. *Passive House Construction – Symbiosis between Construction Efficiency & Energy Efficiency.* (2010): p. 14-15. http://www.sbuf.se/
[58] Flury, Karin et al. ESU-services. *Life Cycle Assessment of Rock Wool Insulation*. (2012): p. 16. http://www.esu-services.ch/
[59] National Ready Mixed Concrete Association. *Concrete CO_2 Fact Sheet*. (2008): p. 7-8. http://www.nrmca.org/
[60] Passive House Institute, International Passive House Association. The Passive House – comfortable, affordable, sustainable. (2012) http://passivehouse-international.org

2.3.3 **Certification specification.**

The Passive house demands have been adjusted from mid-European climate to suit the Swedish climate conditions by SCNH (Sveriges Centrum för Nollenergihus) from an earlier expert group appointed by FEBY (Forum för Energieffektiva Byggnader). Their newest specific criteria is from 2012, called FEBY12. A passive house in Sweden must not only follow the FEBY12 but also the Swedish National Board of Housing building regulations (BBR20).[61]

Below are the requirements for a building to be considered a passive house in Sweden, mid-Europe and Mediterranean when the minimum indoor temperature is set to 21 degrees. To meet the requirements for passive houses, you must either meet the heat load or heat demand criteria. All the requirements for Sweden are taken from FEBY12.[62]

Energy demand and peak load for space heating (heating load):
The German Passive House Institute illustrates the heating load with following calculations and assumptions. The supply air must be heated, but only to 51°C to avoid scorching of the dust. To ensure a good indoor air quality the ventilation system must deliver $30\mathrm{m}^3\,\mathrm{h}^{-1}$ of fresh air per person. Air has the specific heat capacity of $1.01\mathrm{kJ}\,\mathrm{kg}^{-1}\,\mathrm{K}^{-1}$ and density of $1.2\mathrm{kg}\,\mathrm{m}^{-3}$ at ca. 21°C. This is equivalent to $0.33\mathrm{Wh}\,\mathrm{m}^{-3}\,\mathrm{K}^{-1}$. Then the power demanded can be calculated according to Equation 10.

$$P_{\mathrm{pers}} = 30\mathrm{m}^3\,\mathrm{h}^{-1}\,\mathrm{pers}^{-1} \times 0.33\,\mathrm{Wh}\,\mathrm{m}^{-3}\mathrm{K}^{-1} \times (323 - 293)\mathrm{K} = 300\mathrm{W}\,\mathrm{pers}^{-1} \quad (10)$$

Assuming that one person takes up $30\mathrm{m}^2$ of living area the maximum heating load at a given point may not exceed $10\mathrm{W}\,\mathrm{m}^{-2}$ according to Equation 11.

$$\frac{300\mathrm{W}\,\mathrm{pers}^{-1}}{30\mathrm{m}^2\,\mathrm{pers}^{-1}} = 10\mathrm{W}\,\mathrm{m}^{-2} \quad (11)$$

This limit works as a starting point all around the world for energy demand for passive houses since the calculations is independent of climate and temperature, so a passive house will require different levels of insulation depending on climate zone in order to meet this criterion.[63]

But the world is not as perfect as a mathematical formula and in Sweden the peak-heating load is regulated by SCNH and it follows the three climate zones set up by Boverket, see Figure III. The peak load for space heating, P_{max}, for residential buildings may be higher as the average temperature drops, see Table 2.

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[61] Sveriges Centrum för Nollenergihus. *Om FEBY12.* (2012) http://www.nollhus.se/
[62] Ibid, Kravspecifikation för nollenergihus , passivhus och minienergihus, (2012)
[63] Passipedia. *Heating load in Passive Houses.* http://passipedia.passiv.de/

Table 2: Limit peak load for space heating for passive house in Sweden.

Energy demand	**Climate zone I**	**Climate zone II**	**Climate zone III**
P_{max} [W $m^{-2}_{A_{temp}}$]	17	16	15

Additions for buildings smaller than $400m^2$: +2W $m^{-2}_{A_{temp}}$.

In a mid-European and Mediterranean climate the heating load criterion is lower. There P_{max} is defined through Equation (2).

Maximum yearly delivered energy to buildings (heating demand):
Energy demand and peak load for space heating is correlated with the yearly delivered energy to the building. The buildings heating loads are sometimes hard to simulate or calculate; therefore there exist a maximum limit on the delivered energy aka heating demand. In Sweden SCNH has given the maximum delivered energy, see Table 3.

Table 3: Maximum yearly delivered energy to buildings in Sweden

[kWh $m^{-2}_{A_{temp}}$ yr^{-1}]	**Climate zone I**	**Climate zone II**	**Climate zone III**
Max non electrically heated	58	54	50
Max electrically heated	29	27	25

With electric heated building means all electrically heated systems, including heat pumps for heating and hot water. Addition for:

- Non-electrically heated buildings less than $400m^2_{A_{temp}}$: +5W $m^{-2}_{A_{temp}}$.
- Electrically heated buildings less than $400m^2_{A_{temp}}$: +2W $m^{-2}_{A_{temp}}$.

Internationally, the heating demand is regulated by the Passive House Institute. The maximum limits in mid-European and Mediterranean climates are shown in Table 4.[64]

Table 4: Maximum yearly delivered energy to buildings in Europe

[kWh $m^{-2}_{A_{temp}}$ yr^{-1}]	**Mid-European climate (reference value Berlin)**	**Mediterranean climate (reference value Rome)**
Max heating demand	15	10

The Passive House Institute has not given any additions for buildings with different A_{temp}.

64 Passipedia. *Heating load in Passive Houses.* http://passipedia.passiv.de/

2.4 Hemp

The word cannabis refers to the whole plant genus containing one main species, *Cannabis sativa L*,[65] which in turn has three commonly identified subspecies, *sativa*, *indica* and *ruderalis*, see Figure VII.[66]

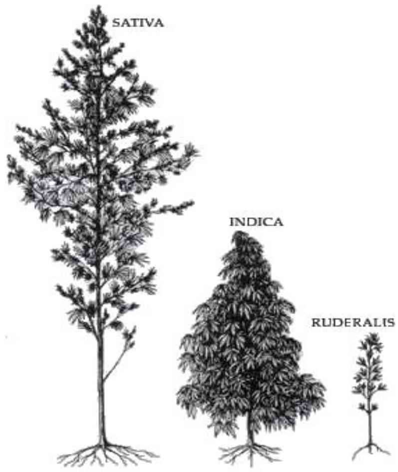

Figure VII: Cannabis plant subspecies

Cannabis as a product is one of the oldest parts of human industry.[67] It grows vigorously in most temperate and subtropical climates, see Figure VIII, has been used for over 10,000 years and been a dominant driver of commerce throughout the civilized world.[68]

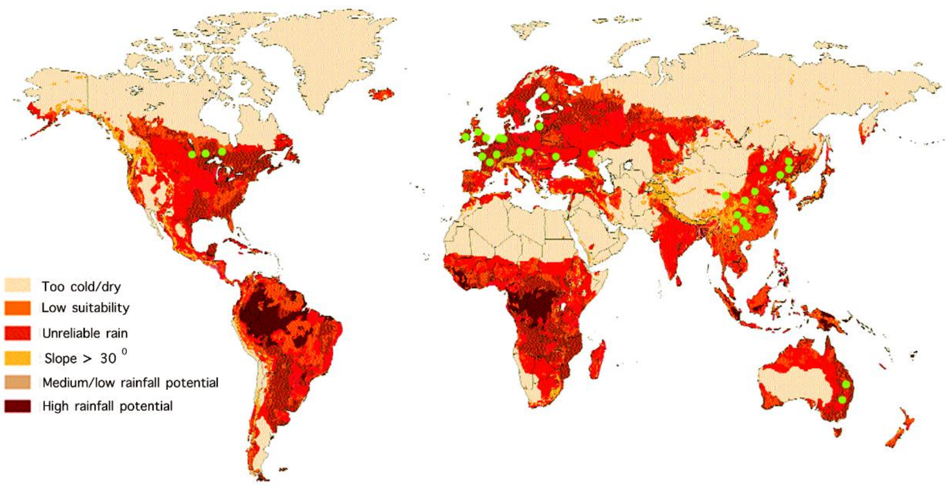

Figure VIII: The areas suitable for hemp cultivation with the current large-scale production sites marked with green dots

[65] United States Department of Agriculture. *Cannabis satvia L.* (2011) http://www.ars-grin.gov/
[66] Hash, Marihuana & Hemp Museum. *The Plant.* http://hashmuseum.com/
[67] Hemp Industries Association. *Facts.* http://www.thehia.org/
[68] Cherett, Nia el at. BioRegional Development Group, WWF Cymru and Stockholm Environment Institute. *Ecological Footprint and Water Analysis of Cotton, Hemp and Polyester.* (2005): p. 5. http://www.sei-international.org/

In 1938 it was estimated in the US that it existed over 25 000 industrial uses for the plant and that is about to become the new billion-dollar crop. However legislative action against the plants propagation was already in action and later spread to most of the world.[69] One milestone treaty with global reach was the UN Single Convention on Narcotic Drugs in 1961.[70]

Hemp, although technically a synonym for cannabis, commonly refers to the industrial varieties of the plant.[71] The cultivation of these specific breeds have now been approved in the EU, similar to most of the industrialized world, so long as they contain less than 0.2 % of the psychoactive substance THC.[72] These small amounts makes any sensation of a high impossible.[73]

Nearly all hemp grown for industrial purposes is from the subspecies *Cannabis Sativa*. As it is the tallest variety, it also produces the longest stalks and therefore has the greatest production efficiency and widest range of industrial uses, see Figure IX.[74]

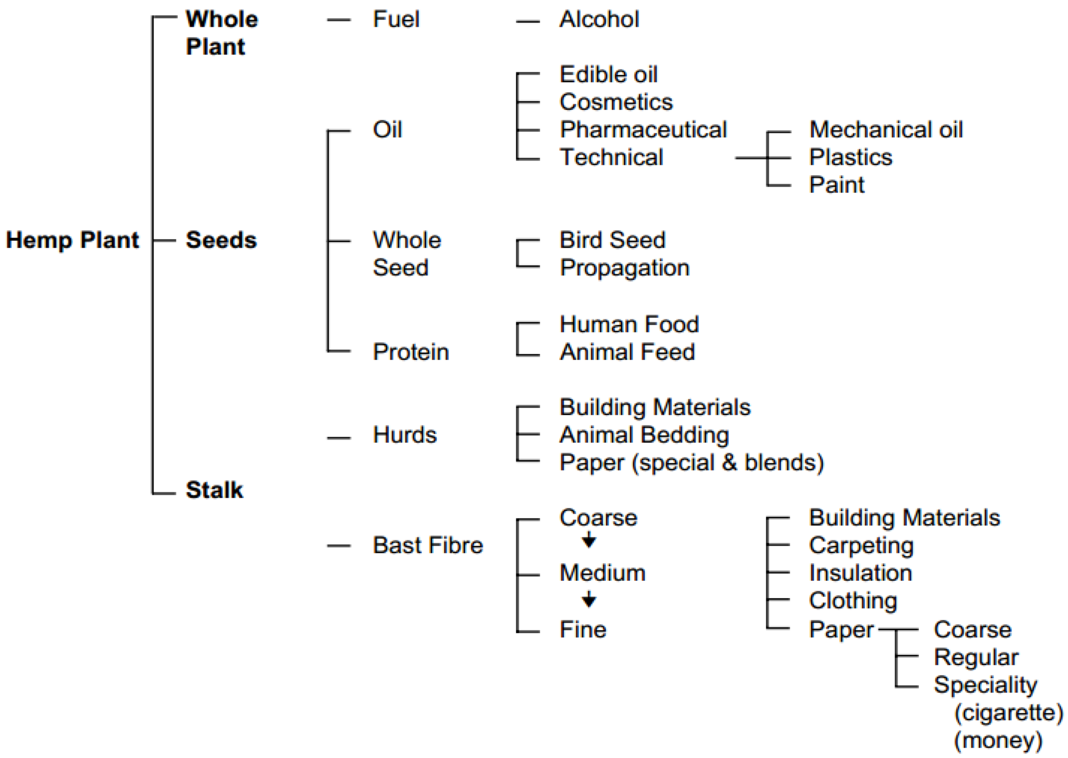

Figure IX: Industrial uses of hemp

[69] Schaffer Library of Drug Policy. *New billion-dollar crop.* (1938) http://www.druglibrary.org/
[70] International Narcotics Control Board. *Single Convention on Narcotic Drugs.* (1961) https://www.incb.org/
[71] Hash, Marihuana & Hemp Museum. *The Plant.* http://hashmuseum.com/
[72] Food Standards Australia New Zealand. *Supporting Document 6 – International Hemp Regulations.* http://www.foodstandards.gov.au/
[73] West, David. North American Industrial Council. *Hemp and Marijuana: Myths & Realities.* (1998) http://www.naihc.org/
[74] Hash, Marihuana & Hemp Museum. *The Plant.* http://hashmuseum.com/

Depending on the use, hemp will be grown in different ways. The growth cycle is 70 to 140 days and from one hectare you can get an average of 800 kg of gain, which is equivalent to 200 litres of hemp-oil and 600 kg of meal. The same hectare yields 6 tons of straw which is approximately equivalent to 1.5 tons of hemp fibre.[75] The more densely hemp is planted the finer the stems get and the growth is simultaneously stimulated at the same time due to competition of sunlight. The growth rate can reach speeds of up to 100-300 mm per week.[76] Hemp does not demand special herbicides because other plants cannot keep up with hemps growth rate and the canopies block the sun light making hemp to a natural weed suppressor.[77] The shading from the canopies also helps to protect the soil from dehydration and the soil is held together as well as aerated by the roots after harvest.[78] Also up to 70 % of the nutrients used during the growing process are returned to the soil through fallen leaves, roots, retting and harvest trimmings.[79]

Because of these crop attributes, hemp can often be grown without herbicides, fungicides or other pesticides with minimal nutrient additives.[80] It is also more than twice as productive and about three times less water intensive than cotton.[81]

2.4.1 **Hemp building materials**

Hempcrete is bio-composite building material developed in the 1980s[82] consisting of hemp shives (the chopped stem core) and lime-based binder mixed with water. It's consistency and application is similar to concrete, although it's less runny it is usually applied as a mass in between shuttering, surrounding a structural timber frame. After a short drying period the shuttering is then removed leaving a massive wall, which can then be rendered or plastered. This whole procedure is illustrated in Appendix C. The monolith application style and the similarity between timber and hempcrete thermal properties also make the system less prone to causing thermal bridges.[83]

However there are also alternative application techniques with different types of prefabricated bricks[84], see Figure X, and boards as well as spray application which are more common when used in renovation projects.[85] Another interesting development is the introduction of carbon negative hemp fibre insulation with a low conductivity

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75 Agriculture and Agri-Food Canada. *Industrial Hemp.* (2013) http://www.agr.gc.ca/
76 Allin, Steve. *Building with Hemp.* (2012): p. 23
77 Hemp Industries Association. *Facts.* http://www.thehia.org/
78 Allin, Steve. *Building with Hemp.* (2012): p. 27
79 British Columbia Ministry of Agriculture and Food. *Industrial Hemp.* (1999) http://www.agf.gov.bc.ca/
80 Hemp Industries Association. *Facts.* http://www.thehia.org/
81 Cherett, Nia el at. BioRegional Development Group, WWF Cymru and Stockholm Environment Institute. *Ecological Footprint and Water Analysis of Cotton, Hemp and Polyester.* (2005): p. 16 – 21 http://www.sei-international.org/
82 Allin, Steve. *Building with Hemp.* (2012): p. 34
83 American Lime Technology. *The Thermal Performace of Tradical® Hemcrete®.* (2006): p. 8 http://americanlimetechnology.com/
84 Cannabric. *Catalogue.* http://www.cannabric.com/
85 Allin, Steve. *Building with Hemp.* (2012): p. 71

similar to traditional mineral wools that could be adopted into the building system where the climate is colder and greater insulation is required, see Figure X.[86]

Figure X: (a) Picture of a cannabric, (b) picture of hemp isolation

The binder constituents and proportions of different types of limes may vary as well as the inclusion of cement and other additives.[87]

There are also different mixing proportions and compactness's adjusted for the different properties preferred in different parts of the building. The main difference between the mixes is the balance between structural strength and insulation. For example the amount of binder is generally increased to about 25% of the mix volume to make the walls stronger, while maintained at a lower 10% for less rigid, more insulating roof fillings.[88]

To understand how the mix gets its strength and "sets" it is necessary to understand the basics of the lime cycle.

2.4.2 The limestone cycle

Limestone is created when particles of shells, bones or coral deposited on the sea bed for about a million years get pressured into carbonate rock, $CaCO_3$. Some of these limestone quarries also contain impurities that allow the final product called hydraulic lime to set underwater, or in humid walls. The quarries are mined and the material is burned, releasing CO_2 to create quicklime, CaO. Water is then added to create slaked lime, $Ca(OH)_2$, during an exothermic process. If the final product is dry it is called hydrated lime which together with hydraulic lime is the two main components of the hempcrete binder. The slaked lime then reabsorbs the same amount of CO_2 it one released in the atmosphere and starts to harden and return to its initial form. This

[86] Zampori, Luca et al. ACS Publications Environmental Science & Technology. *Life Cycle Assessment of Hemp Cultivation and Use of Hemp-Based Thermal Insulator Materials in Buildings.* (2013) http://pubs.acs.org/doi/
[87] Allin, Steve. *Building with Hemp.* (2012): p. 41
[88] Ibid: p. 45

reabsorption of CO_2 is also why lime has a low greenhouse gas emission and thus low global warming impact[89], see Figure XI.

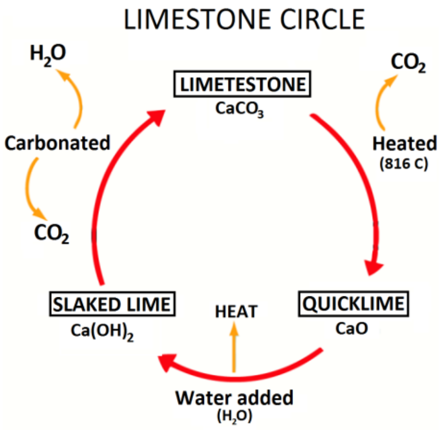


Figure XI: Lime cycle

2.4.3 **Hempcrete technical properties**

The estimated values for a standard mix of the common tradical hempcrete mix, called hemcrete®, can be seen in Table 5. Some values are given an interval depending on the relative humidity in the material and density, which will be discussed further in the hempcrete building system section. In addition to the monolith mass the building often gets finished with hemp plaster which properties can be found in Table 6. The values from Table 5 and 6 are later used to in the model for simulations.

Table 5: Properties of hempcrete at ρ=275$kg\ m^{-3}$.[90]

Density (ρ)	275kg m^{-3}
Flexural strength	0.3-0.4N mm^{-2}
Thermal conductivity at 10 C (λ)	0.06W $m^{-1}\ K^{-1}$
Heat Capacity (c)	1500-1800J $kg^{-1}K^{-1}$
Thermal diffusivity (α)	$\sim 1.4 \cdot 10^7 m^2\ s^{-1}$
Fire Rating	1 h BS EN 1365-1:1999
Carbon capture	130kg $CO_2\ m^{-3}$
Airtightness (q_{50})	$< 2m^3\ m^{-2}\ h^{-1}$ @ 50pa $\leftrightarrow < 0.55\ell\ s^{-2}\ m^{-2}$

[89] Allin, Steve. *Building with Hemp.* (2012): p. 38 ff.
[90] Abbott, Tom. The Limecrete Company LTD. *Hempcrete Factsheet.* (2014) http://limecrete.co.uk/

Table 6: Properties of hemp plaster[91, 92]

Density (ρ)	700 to 950 $\mathrm{kg\ m^{-3}}$
Thermal conductivity at 10 C (λ)	0.12-0.13 $\mathrm{W\ m^{-1}\ K^{-1}}$
Heat Capacity (c)	1378-1871 $\mathrm{J\ kg^{-1}}\ K^{-1}$

These properties of hempcrete lead to some material attributes that can be summarized according to the following:

- High thermal inertia[93]
- High thermal insulation[94]
- High sound insulation[95]
- Medium density and high thermal capacity[96]
- Breathable nature, and ability to act as moisture buffer[97]
- Nature of application minimises thermal bridges[98]
- Low effusivity that can improve thermal comfort[99]
- Inherently airtight structures[100]
- Fire and pest resistant[101]
- Can significantly reduce CO_2 emissions[102]
- Low waste[103]
- Competitive economic[104]
- Easily recyclable[105]

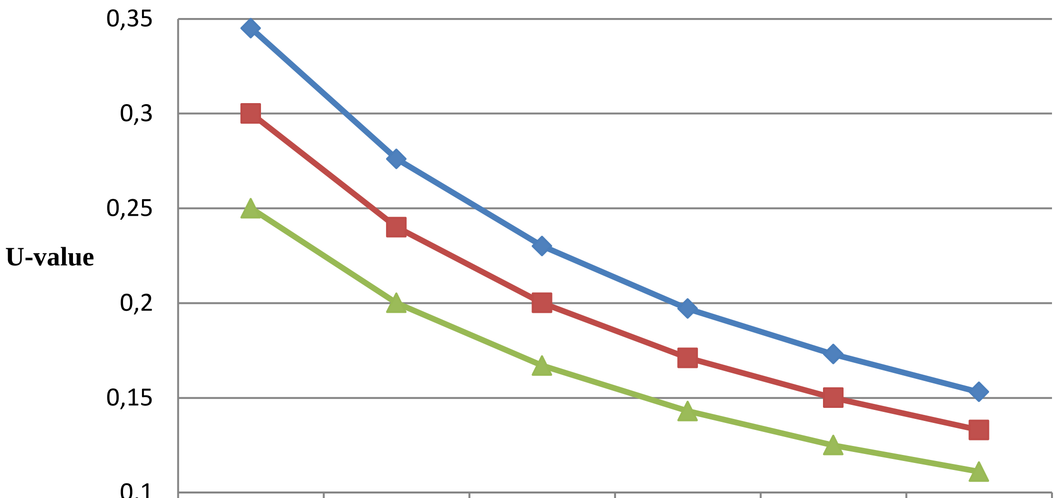
2.4.4 **The hempcrete building system interaction**

The hempcrete building system works with a different logic than most common passive houses. Instead of using an insulating envelope that does not transfer moisture vapour, the material is breathable. This is not to be confused with air permeability which is relatively low in hempcrete. This vapour permeability of hempcrete means the thermal properties vary with the relative humidity of the atmosphere. It also utilizes higher

[91] Lhoist UK. Tradical Building lime innovation. *Renders/plasters.* http://www.tradical.com/
[92] Allin, Steve. *Building with Hemp.* (2012): p. 60
[93] Mawditt, Ian. Living Space Sciences. *Unique thermal performance of Tradical Hemcrete.* (2008): p. 16. http://www.limetech.info/
[94] Tradical. Hemp Lime Technology. *Tradical Information Pack.* p. 3. http://www.lhoist.co.uk/
[95] Ibid p. 3.
[96] Ibid p. 12 ff.
[97] Ibid p. 47.
[98] Ibid p. 47.
[99] Ibid p. 47.
[100] Ibid p. 47.
[101] Ibid p. 3
[102] Ibid p. 3
[103] Ibid p. 3
[104] Ibid p. 15
[105] Hempcrete Australia. *FAQ.* (2012) http://www.hempcrete.com.au/

levels of thermal capacity and inertia than the average passive house. To complicate things further the mix ingredients, the proportions used and the application technique also play an important role in the thermal performance. Several studies have been released on how some of these parameters affect the thermal performance of hempcrete. In the following an overview of these results will be illustrated to give a better understanding of the system and its potential.

The thermal conductivity and U value are mainly related to the density of the mix as shown in Figure XII.[106]



	200	250	300	350	400	500
330kg/m3	0,345	0,276	0,23	0,197	0,173	0,153
275kg/m3	0,3	0,24	0,2	0,171	0,15	0,133
220kg/m3	0,25	0,2	0,167	0,143	0,125	0,111

Hempcrete thickness (mm)

Figure XII: Hemcrete® U values for different mixes

The density is in turn affected by the amount of humidity trapped in the walls as well as how hard hempcrete is packed during construction. It would appear that a high relative humidity, an increase in density, would also lead to increased heat fluxes through the wall. However due to hempcretes breathability and voluminous moisture handling the effects of latent heating has to be taken into account as well. Hemp has also been found to have an unusual porous system that contributes to these latent heating effects.[107] Recently some studies have shown remarkable results indicating that the heat flux may actually decrease when relative humidities are increased. However these tests were not able to confirm how much of the heat flux suppression that was actually caused by latent heating. Research on hemps phase changing properties is ongoing.[108] Figure XIII

[106] Lime Technology. *Tradical® Hemcrete® Thermal Performance.* (2006): p. 7 http://www.limetechnology.co.uk/

[107] Simpson, Scott. University of East London. *An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames*. (2004): p. 62

[108] Ibid p. 137

shows a summary for the volumetric heat capacity for some different building materials as well how hempcrete is affected by a change relative.

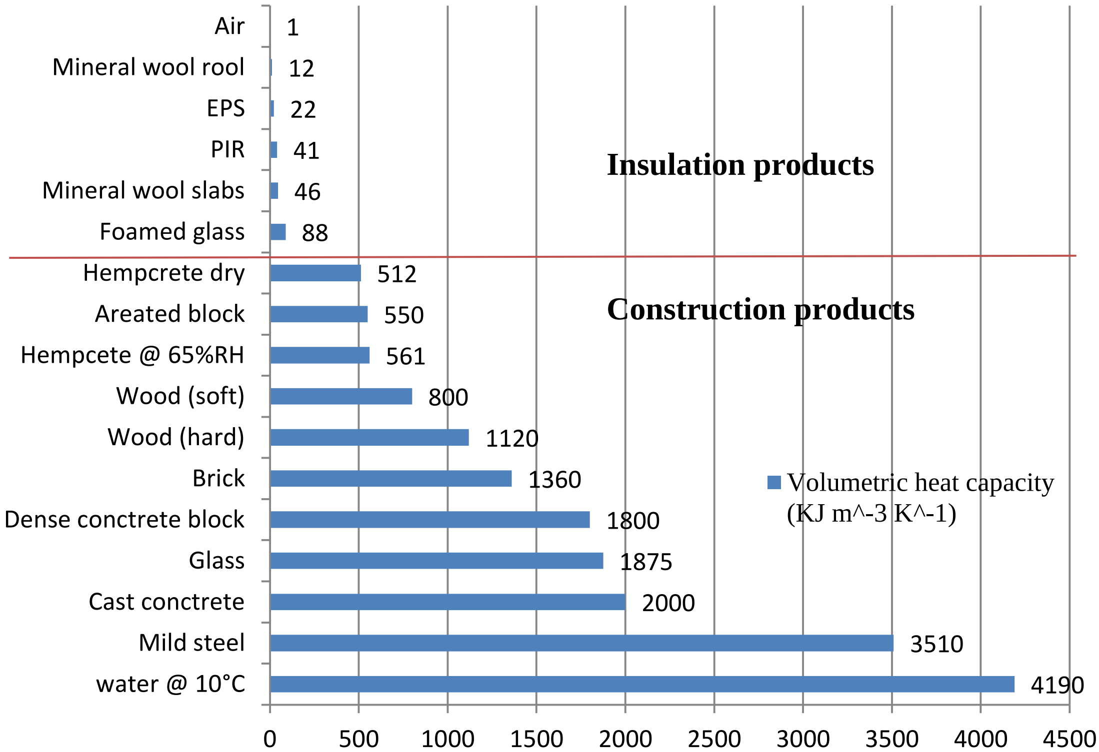


Figure XIII: A comparison of volumetric heat capacity for hemp and other common building materials.

A high thermal capacity and a low conductivity lead to a low thermal diffusivity which is why hempcrete has a high thermal inertia.[109] The effusivity is also relatively low, which means heat has a hard time getting into the material through its surface.[110] This also contributes to the feeling of comforting warmth when in proximity to the walls.

Hempcrete with its good thermal and moisture buffers effectively stabilize the indoor temperature as well as relative air humidity leading to lower overall heat fluxes and a healthier and safer indoor environment (see Figure XIV).[111] Under a dynamic load the Hempcrete heat flux can even become lower than mineral wool despite mineral wool having a much better insulation value.[112] These delays of heating and cooling transfer can also help optimize the latent energy effects to help cooling during the day and heating at night.[113]

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[109] Lime Technology. *Tradical® Hemcrete® Thermal Performance.* (2006): p. 8 http://www.limetechnology.co.uk/
[110] Simpson, Scott. University of East London. *An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames*. (2004): p. 44
[111] Lime Technology. *Tradical® Hemcrete® Thermal Performance.* (2006): p. 10 ff. http://www.limetechnology.co.uk/
[112] Ibid p. 12
[113] Simpson, Scott. University of East London. *An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames*. (2004). p. 61

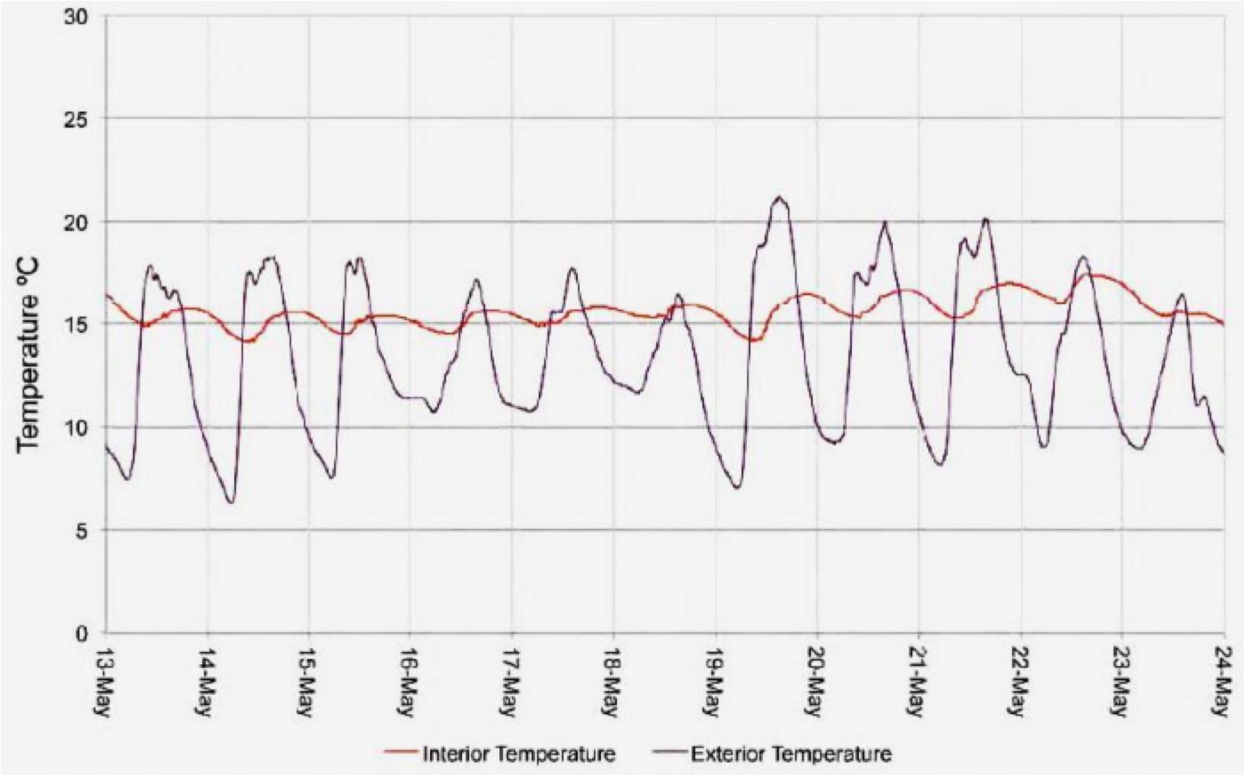


Figure XIV: Dampened and delayed interior temperatures (red) relative to exterior temperatures (purple) in a light timber framed building with lime-hemp

From these results we can see that the traditional U values alone only express part of a material's thermal performance ability. Other factors such as thermal storage, thermal inertia, hygroscopicity and moisture storage can all help reduce heating, cooling and ventilation energy demands. These properties also contribute to a comfortable and healthy living environment for occupants by attenuating temperature and relative humidity fluctuations.[114]

[114] Simpson, Scott. University of East London. *An investigation of hygrothermal properties of lime-hemp and clay-hemp blocks retrofitted onto light-timber frames*. (2004): p. 137

3. Method

To estimate and compare the energy use of different buildings in different climates the dynamic simulation program VIP-energy v2.1.1 was used. The software is created by StruSoft AB which is a Swedish software manufacturer specialized in software applications for the building industry. The program uses dynamic calculation methods to calculate the energy use per hour for a specific building over a given time period. VIP-energy is validated by IEA-BESTEST, ASHRAE-BESTEST, CEN-15265 and 20 years of research and practical work.[115]

3.1 Input

The base of the modelling process was an example house model from VIP's own website.[116] Since it was a modern one family house (see Figure XV and Figure XVI) built with common passive house materials and a regular structure it was considered suitable as a benchmark to evaluate the hempcrete building systems potential. To create the second model most of the materials in the house were then replaced to simulate a traditional hemp house while leaving the dimensions unchanged. These two models' wall thicknesses were then modified as well as relocated to different parts of the world to allow for a comparative study of both building techniques and their performance in different climates. A thorough presentation of the input variables is listed in Appendix A. This section however will feature a brief overview of the different models used to discuss the motivations behind their design.

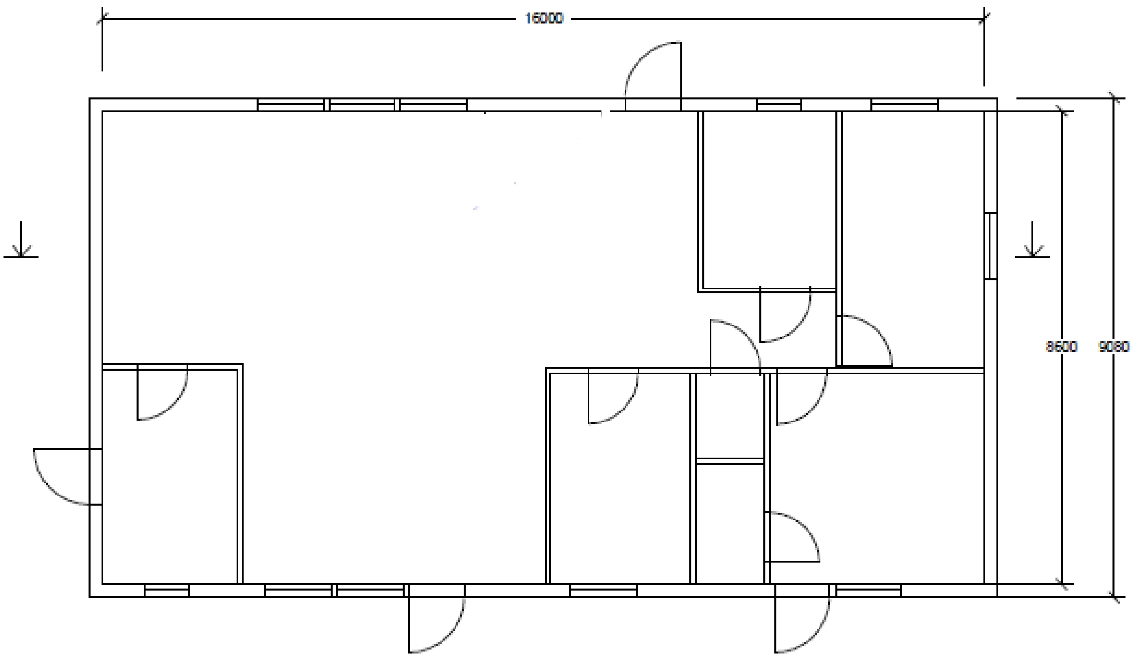
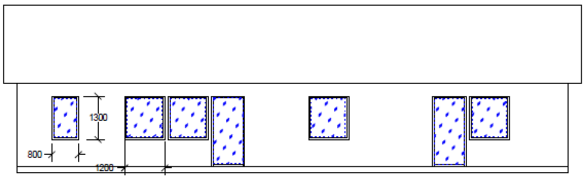
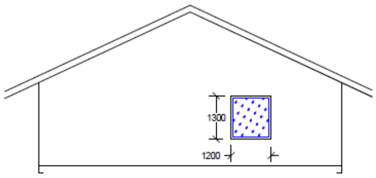


Figure XV: Model building layout design

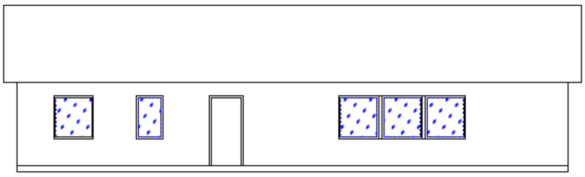
[115] Structural Design Software in Europe AB. *VIP-Energy*. http://www.strusoft.com/
[116] VIP-energy, *Calculation example 3 – Family house*, www.vipenergy.net/Villa-2.htm



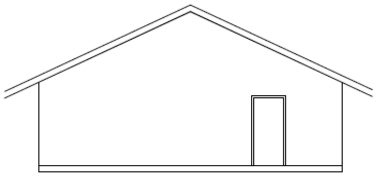
Façade facing south



Façade facing east



Façade facing north



Façade facing west

Figure XVI: Model building facades

3.1.1 **Heat recovery, temperatures and location**

Initially the example house model was adjusted to compatibility with passive house norms and updated to modern standards. This was done primarily by setting the ventilations air flow to $0.35\ell\ s^{-2}\ m^{-2}$ to satisfy the BBR20 codes[117]. Because systems with a ventilation heat recovery of η = [75%,95%] were available the model got the mean value, η =85%, for both in- and outgoing air flow. A drain line heat recovery was chosen with η =50%[118] and a geothermal heat pump were also added to the model. Although such heat pumps are generally not included in the passive house concept we used it as a more sophisticated solution to make up for VIP's limitations of geothermal preheating systems of the incoming ventilation air. Using a geothermal heat pump has also been done before in Swedish passive houses.[119]

The minimum indoor temperature was set to 21°C and the maximum to 27°C to meet the BBR20 code for measuring energy use.

The locations of the two houses were first set to three different Swedish cities, Malmo, Sundsvall and Kiruna, one from each climate zone as defined in Figure III. This simplified the comparison between the models' performances and passive house criteria, which is otherwise vaguely defined in the EU as a whole with its widely differing climates. Afterwards the building models were moved to Berlin and Rome to give an understanding of the potential of hempcrete houses in central Europe as well as around the Mediterranean. The different locations are shown in Figure XVII.

[117] Boverkets byggregler, BBR. Del 2 Regelsamling för byggande. *6 Hygien, hälsa och miljö.* (2012): p. 217 ff. http://www.boverket.se/
[118] Enviromental Building *News, Recovering Heat from Wastewater* (1997), http://buildinggreen.com
[119] Thelin, Björn. Ekofektiv. *Advanced BTES solution for passive house in Haninge.* (2011) http://ekofektiv.com/

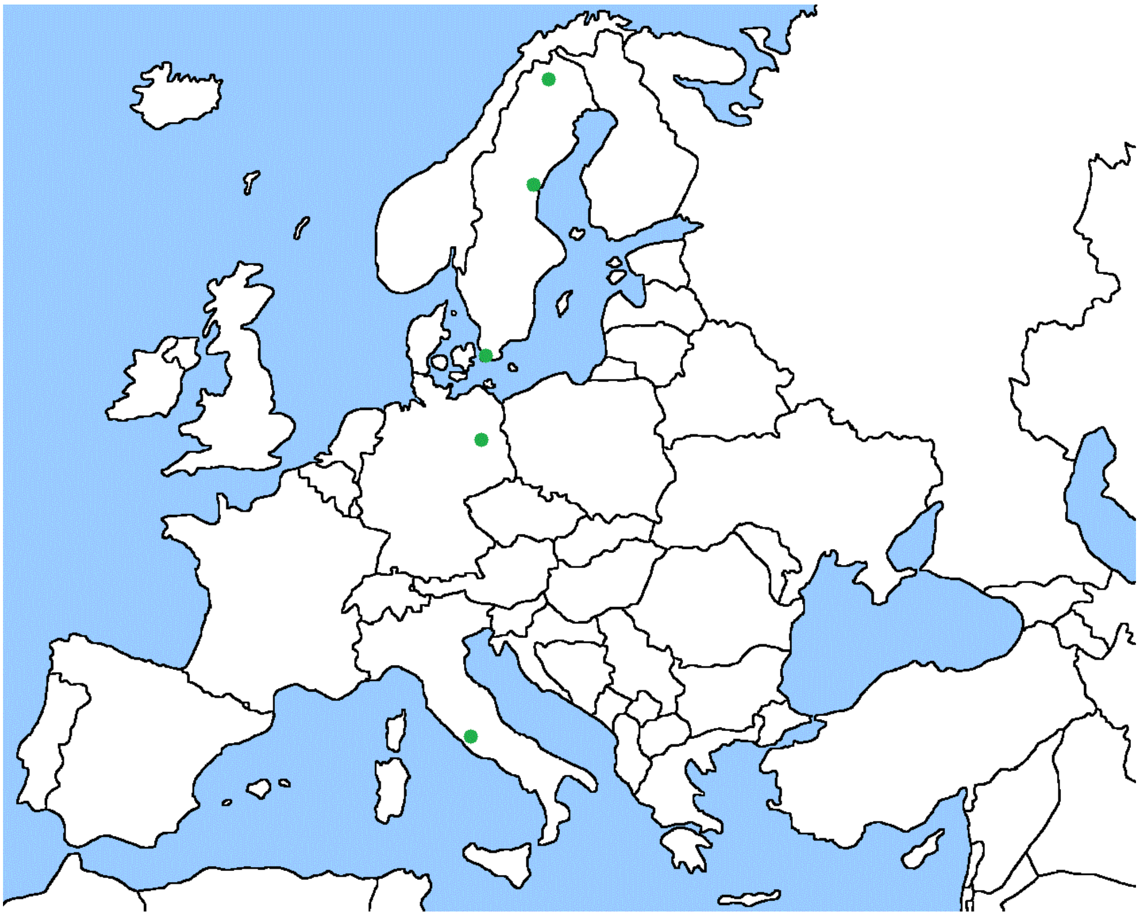


Figure XVII: Map of the locations for the simulations

3.1.2 **Building envelope**

The building in the example house model was first simplified by the removal of a cellar which led to recalculations of the floor as well as inner walls area to 136.7m^2. Then the walls and their 2D connection parts were all adjusted to a thickness of 200, 300 and 400 mm respectively in different versions of the model to study the impact on thermal performance. The windows and doors were adjusted to clear passive house recommendations with a U-value of 0.80.[120] The window solar transmission values were derived from an existing product with a glass U-value set to 0.70 compensating for the total U-value increase after installation of the full window unit.[121]

The hempcrete model was then adjusted to the same dimensions leaving windows, doors and all gravel material as well as the wooden interior for the roof and floor unchanged. The other materials however were replaced with different density hempcrete mixes for roof (225kg m^{-3}), walls (275kg m^{-3}) and floor (325kg m^{-3}), the latter

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[120] International Passive House Association. *Passive House Guidelines.* http://www.passivehouse-international.org/

[121] Feist, Wolfgang. Passive House Institute. *Window – Heat Transfer Coefficient U_w and Glazing – Heat Transfer Coefficient U_g.*(2006) http://www.passivhaustagung.de/

coated with hemp plaster according to described situations of use[122]. We also used the same plaster as rendering for the external parts of the wall although this is slightly less common[123]. The different mix densities and conductivities used in the model were derived from Figure XII.

Different density mixtures have different specific heat capacities. In Figure XIII the volumetric heat capacity is shown to be 512kJ m^{-3} K^{-1} for dry hemp and by using different hemp densities in the wall were given a natural improved U-value and better insulation while still utilizing the heat capacity. The different densities for the wall were chosen to ρ=225kg m^{-3}, 275kg m^{-3} and 330kg m^{-3} and the hemp plaster were chosen to ρ=700kg m^{-3}. The different specific heat capacities for the walls are shown in Table 7 and could be calculated by using Equation 4 and for plaster using Table 6.

Table 7: The relationship between density and specific heat capacity

Density (ρ)	225 kg m^{-3}	275 kg m^{-3}	330kg m^{-3}	700kg m^{-3}
Heat capacity (c)	2275.5J kg^{-1} K^{-1}	1861,8J kg^{-1} K^{-1}	1551,5J kg^{-1} K^{-1}	1871J kg^{-1} K^{-1}

In reality embedded timber frames are also required to maintain the hempcrete building structure. This as well as the practical difficulty to produce perfect mix compactness has been included in the model through a slightly higher adjusting ΔU-value set to 0.02, despite the building system giving little room for thermal bridges. A comparative study from Limetech reviewing a timber frames impact on the walls combined thermal performance was also considered.[124]

3.1.3 Time schedule and operating case

The time schedule and internal operation and generation of heat and moisture is adjusted to the SVEBY (Standardisera och verifiera energiprestanda i byggnader) from the Swedish Energy Agency. Table 8 shows the calculated time schedule and operating cases, SVEBY model is shown in Appendix B.

[122] Allin, Steve. *Building with Hemp.* (2012): p 45
[123] Ibid, p 103
[124] Mawditt, Ian. Living Space Sciences. *Unique thermal performance of Tradical Hemcrete.* (2008): s 6 ff. http://www.limetech.info/

Table 8: Time schedule and operating case

Time period	Activity energy: To room air [W m^{-2}]	Activity energy: External [W m^{-2}]	Personal energy [W m^{-2}]	Hot water [W m^{-2}]	Room temperature [°C]
00:00-06:00	1.49	0.64	2.05	1.85	21-27
06:00-07:00	2.26	0.97	2.05	2.81	21-27
07:00-17:00	2.26	0.64	0	2.81	21-27
17:00-18:00	2.26	0.64	2.05	2.81	21-27
18:00-24:00	4.52	1.94	2.05	5.61	21-27

4. Results

This section covers the simulation results. The main focus is to illustrate the energy performance of the two building concepts.

4.1 Energy balance

The energy balance from the simulations of the 40 cm passive and hempcrete house is shown below. The 40 cm wall model results can be considered most interesting since they represent a more realistic passive house wall width and therefore also give a more realistic demonstration of the potential of both building concepts. Figure XVIII show the simulations of the passive house in all locations and Figure XIX show the simulations for the hempcrete house.

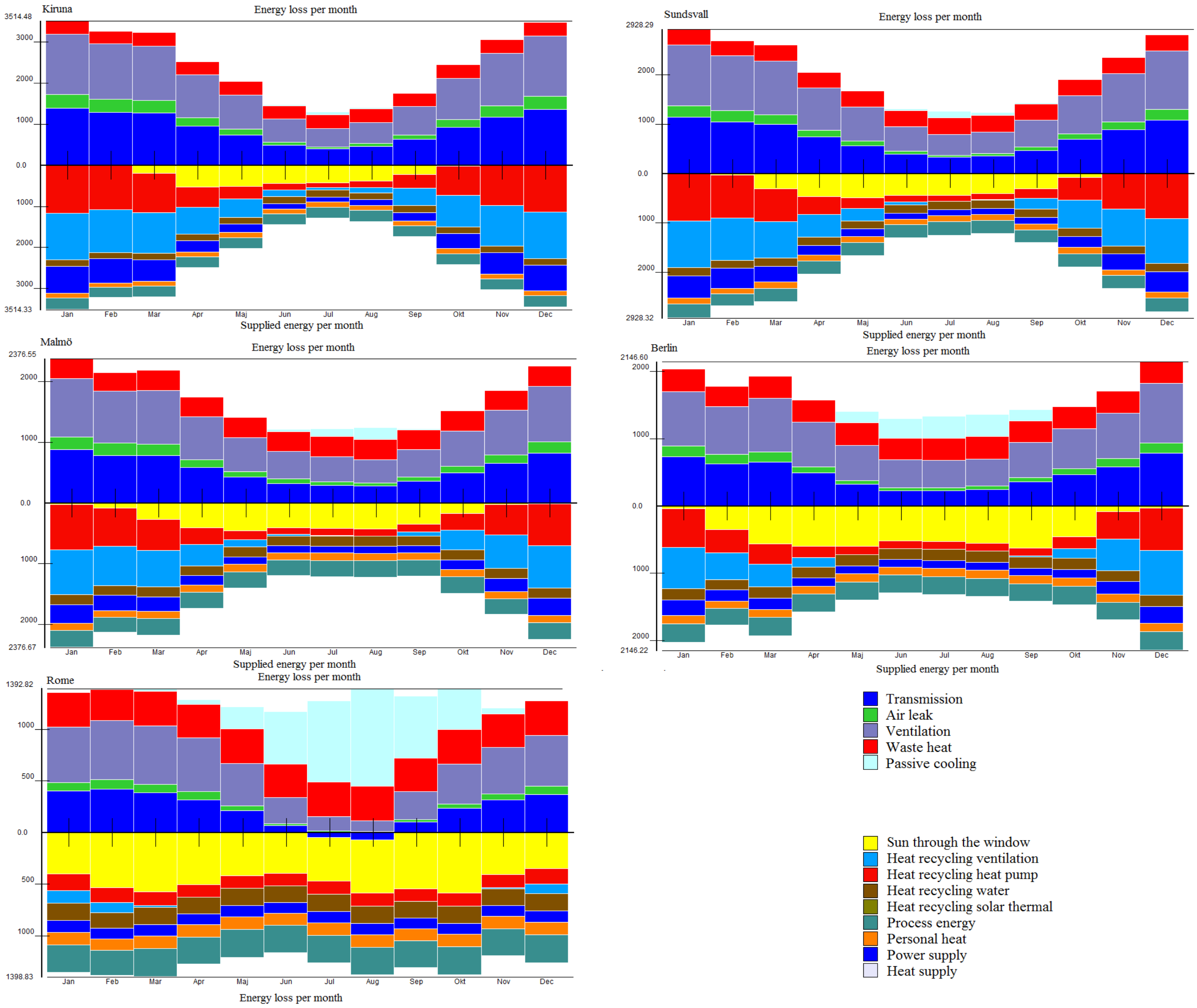

Figure XVIII: Difference in energy balance for the 400 mm passive house in different locations

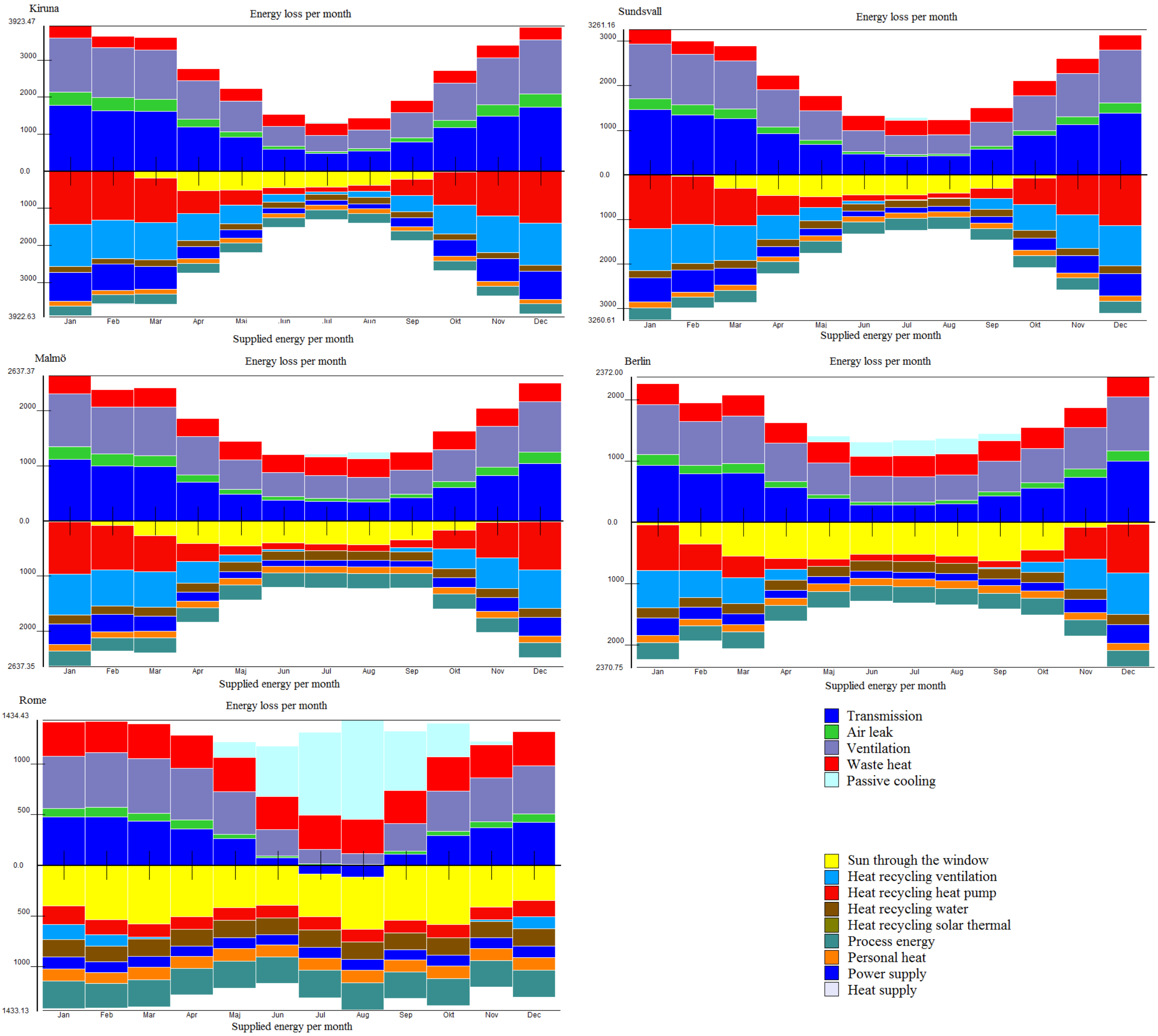

Figure XIX: Difference in energy balance for the 400 mm hempcrete house in different locations

The graphs show that the houses behave similarly at the different locations. In the supplied energy area one can see that the passive solar gain increases when the houses are moved further south while passive cooling increases to eliminate the excess heat during the summer months.

In both the passive house and hemp house the main heat loss it due to ventilation and transmission for all locations. Even though the passive house is specifically built to have low heat transmission this is still one of the main losses.

4.2 Space heating demand

In this section the results of space heating demand will be shown but since VIP-energy does not calculate the energy load this variable has been left out. However to achieve the passive house criterion one could either reach the energy load criterion or the energy demand criterion so this limitation does not affect the general results.

The energy demand is compared to the passive house space heating demand, see Table 3 and Table 4. Because the simulated house is electrically heated and have 136.7$m^2_{A_{temp}}$ which are less than 400$m^2_{A_{temp}}$, so an addition of +2 W $m^{-2}_{A_{temp}}$ can be added to the limitation for every climate zone in Sweden which gives the limitations in Table 9:

Table 9: The passive house space heating demand for the simulated houses for the different cities

	Kiruna	**Sundsvall**	**Malmo**	**Berlin**	**Rome**
Max electrically heated [kWh $m^{-2}_{A_{temp}}$ yr^{-1}]	31	29	27	15	10

In Table 10 and Figure XX the energy demand is shown. In the table the green cells indicate that the house clears the respective space heating demand.

Table 10: U-value and energy demand in different climates with different wall thicknesses

Unit		200mm Passive	Hemp	300mm Passive	Hemp	400mm Passive	Hemp
U-value	Wall	0.231	0.300	0.149	0.200	0.110	0.150
	Building	0.189	0.238	0.168	0.215	0.158	0.204
Energy demand	Kiruna	35.7	43.0	32.8	39.2	31.4	37.3
	Sundsvall	24.3	28.3	22.4	26.1	21.8	25.3
	Malmo	17.4	19.7	16.3	18.4	15.9	17.9
	Berlin	14.2	15.6	13.5	14.8	13.2	14.5
	Rome	9.39	9.47	9.31	9.36	9.30	9.38

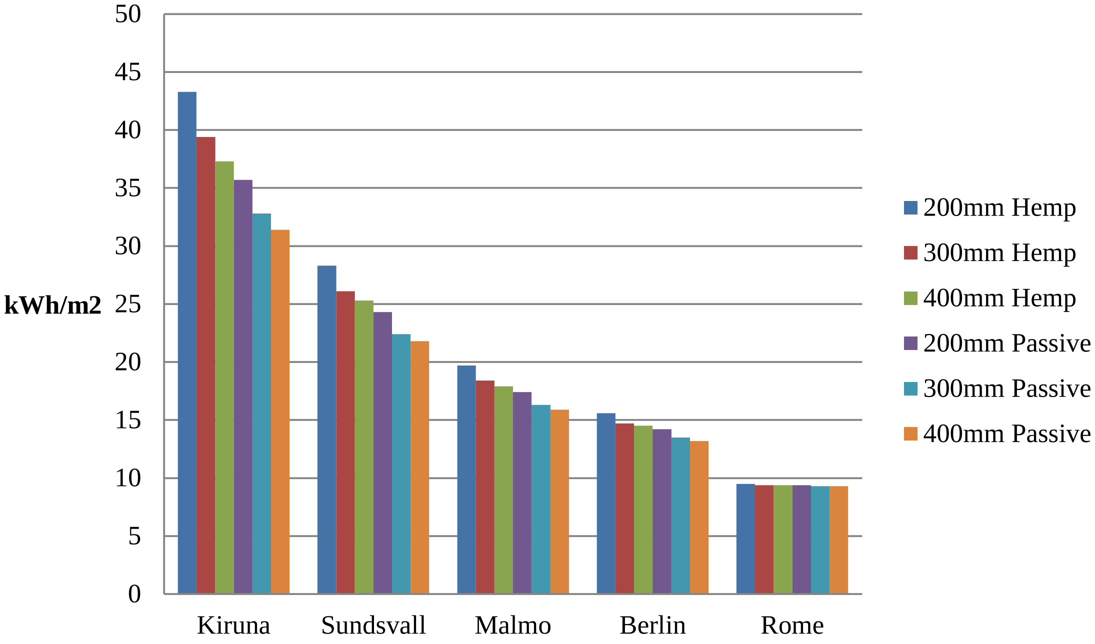

Figure XX: Difference in energy demand

In Table 10 one can see that the passive house clears more of the energy demand criterions than the hempcrete house. The passive house clears 13/15 of the energy demands while hempcrete house clears 11/15. The Figure XX shows that the passive house is thermally outperforming the hempcrete house in every location. An illustration of the relative thermal performance ratio between the two models is shown in Table 11 below. The relative thermal performance ratio was calculated by dividing the energy demand for the hempcrete house with the energy demand for the passive house.

Table 11: Energy demand for hemp house in relation to passive house (hemp/passive)

Location	200mm	300mm	400mm
Kiruna	120%	120%	120%
Sundsvall	116%	117%	116%
Malmo	113%	113%	113%
Berlin	110%	110%	110%
Rome	101%	100%	101%

Table 11 shows how much percent energy the hempcrete houses consume at the different locations compared to the respective passive house. One can see that hempcrete houses consume about 20% more energy than passive houses in Kiruna but that the difference is only about 1% in Rome.

4.3 Sensitivity analysis.

The impact on the result from some of the different simulations inputs will be studied in this section. This is done to evaluate the models sensitivity and reliability. The sensitivity analysis was chosen to only evaluate the 400 mm wall of the two building concepts since a more massive wall should lead to a greater impact when changing parameters.

4.3.1 **Specific heat capacity**

The first parameter to be evaluated in the sensitivity analysis was the specific heat capacity. In Table 12 the energy performance is shown when the specific heat capacity of all materials was set to 0.01 J kg^{-1} K^{-1} to study its effects on thermal performance.

Table 12: Energy demand when specific heat capacity is set to 0.01 $J\ kg^{-1}\ K^{-1}$ for all building materials with 400 mm walls

Locations	Passive	Hemp
Kiruna	31.6	37.5
Sundsvall	21.9	25.5
Malmo	16.0	18.2
Berlin	13.5	14.9
Rom	9.44	9.62

The relative thermal performance can be calculated from Table 12 and 10 and the performance ratio can be seen in Table 13

Table 13: The ratio of the energy performance between the original model and when specific heat capacity was set to 0.01 $J\ kg^{-1}\ K^{-1}$ in all building materials for 400 mm walls (changed heat capacity/original heat capacity)

Locations	Passive	Hemp
Kiruna	101%	101%
Sundsvall	100%	101%
Malmo	101%	102%
Berlin	102%	103%
Rom	102%	103%

These results indicate that the thermal capacity has a small but noticeable effect on the thermal performance. The ratio is greater for the hempcrete house than the passive house and the biggest difference is in the Mediterranean. Since hempcrete utilizes thermal mass to a higher degree it should have a more significant impact on the heat flux with the delayed heating and cooling effects in southern climates.

4.3.2 Air tightness

The next parameter in the sensitivity analysis to be modified is the building air tightness, q_{50}, to see how it affects the energy performance. Table 14 shows the resulting heat demand when the air tightness is at first set to an exaggerated high value of $1\ell\ \mathrm{s}^{-2}\ \mathrm{m}^{-2}$ and later to $0.1\ell\ \mathrm{s}^{-2}\ \mathrm{m}^{-2}$ for all building components. The previous values were $0.5\ell\ \mathrm{s}^{-2}\ \mathrm{m}^{-2}$ for the passive house and $0.55\ell\ \mathrm{s}^{-2}\ \mathrm{m}^{-2}$ for the hempcrete building.

Table 14: Energy demand when air tightness is set to 1 and 0.1 respectively for all building materials with 400 mm walls

Location	Passive		Hemp	
	q_{50}=1	q_{50}=0.1	q_{50}=1	q_{50}=0.1
Kiruna	36.8	27.6	44.0	33.1
Sundsvall	24.5	19.7	28.7	22.9
Malmo	17.8	14.5	20.0	16.3
Berlin	14.4	12.4	15.8	13.5
Rom	9.42	9.24	9.52	9.32

To visualize the air tightness impact on the thermal performance of the houses the ratio is given in Table 15.

Table 15: The ratio of the energy performance between the original model and when air tightness is changed to 1 and 0.1 respectively in all building materials for 400 mm walls (changed air tightness/original air tightness)

Location	Passive		Hemp	
	q_{50}=1	q_{50}=0.1	q_{50}=1	q_{50}=0.1
Kiruna	117%	87.9%	118%	88.7%
Sundsvall	112%	90.4%	113%	90.5%
Malmo	112%	91.2%	112%	91.1%
Berlin	109%	93.9%	109%	93.1%
Rom	101%	99.4%	102%	99.4%

Table 15 shows that the building air tightness is more important in northern climates than in the Mediterranean. The reason is that a higher air tightness value leads to a higher level of heat exchange which has greater impact where outdoor and indoor temperatures differ greatly.

5. Discussion

The simulation results show an increase in the hempcrete buildings relative thermal performance for locations further south in Europe. Since the increasing wall thicknesses didn't have as much effect in the southern climates the lesser significance of low U-values can be considered the main reason for the relative reduction in energy demand. In the sensitivity analysis the heat capacity of the material also showed to have a slightly increased significance in southern climates. According to theory the delayed heating and cooling effects should be more substantial when the outdoor temperatures fluctuate below and above the desired indoor temperatures. In the northern climates the temperatures seldom reach high enough for stored heat emissions to occur at night and little cooling is required. This corresponds to previous reports as well.[125] However the relatively low significance of thermal mass in this simulation could be explained by the placement of the windows. In the example house model the total northern window area was set to 7.3m^2 and the southern to 9.4m^2. In Scandinavian passive houses for example north facing windows are not very strategical in regards to the movement of the sun and this might have inhibited the effects of passive solar heating and the internal thermal mass. If done correctly the internal mass could also have been more strategically placed and increased at certain locations.

[125] Holladay, Martin. Green Building Advisor. *All About Thermal Mass.* (2013) http://www.greenbuildingadvisor.com/

Since the simulation program does not take hygroscopic material properties into account the calculated hemp house energy demand is probably higher than in reality. This is because the northern parts of Europe have a high relative humidity and the breathable hemp material has its porous system that contributes to these effects.[126] The hygrothermal interaction has also showed potential to outweigh the effects of thermal mass even when utilized correctly.[127] These factors suggest a significant reduction in the hemp buildings energy demand.

The calculated building air tightness is also higher than what is recommended for passive houses. Changing these values had a small impact on the energy demand, at least when within a realistic interval.

Since insulation has shown to be the single most important attribute, especially in the north, hemp fibre insulation could be incorporated in the hempcrete building to adjust its properties accordingly. This in combination with the vapour breathability and the latent heating effects that follow could give the system a lowered heat flux on par with more traditional passive houses even in colder climates. However a slightly thicker wall might be necessary. Also it is important to remember that the average Swedish household has an energy demand of 160 kWh m^{-2} yr^{-1} which is far higher than both of the households studied in this report. This is another indication of the great potential improvements that could be done in the building sector.

Beyond thermal performance hemp houses also have other benefits. The high thermal inertia and moisture buffering effects of the material help stabilize the temperatures and indoor humidity levels. The low effusivity also lowers the surface heat transmission which gives a feeling of warmth in proximity to the walls and potential toxic emission from the materials are practically zero due to their natural composition. In combination with the sound resistance all these attributes can lead to a more healthy and comfortable indoor environment.

The earth environment as a whole can also benefits from the use of these hemp based building materials. Due to the carbon sequestering of the organic hemp as well as the lime carbon reabsorption the materials net carbon emissions are negative even when the production phase is taken into account. The production process is efficient, low on waste and toxins and can even be environmentally beneficial since hemp as an agricultural crop is highly sustainable and regenerates the soil. Lime production also involves relatively low impact processing although the quarries can be considered damaging to the landscape.

Hemp houses are also economically competitive to produce and if the market and production processes are allowed to develop in the industrialized world, it can probably

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[126] The Board of Regents of the University of Wisconsin System. Atlas of the Biosphere. *Average Annual Relative Humidity.* (2002) http://www.sage.wisc.edu/
[127] Schnieders, Jürgen. The Passive House Institute. *Passive Houses in South West Europe.* (2009). http://www.passivhaustagung.de/

become even cheaper with hemp materials in general. Especially since the crop has an abundance of industrial uses.

The breathability and ability to act as moisture buffer also reduces the risk of damage from trapped humidity and the application technique prevents thermal bridges. This in combination with the fire resistance can lead to houses lasting for centuries; and afterwards they can even be recycled.[128]

The short history and time for development of the materials also suggests room for further improvements of the hemp building system in the future.

6. Conclusion

The thermal performance of a hempcrete building relative to a more common passive house increases in more southern climates. In the Mediterranean climate zone the building systems performed equally well. This is primarily because of the lowered significance of high insulation values in these climates. Air tightness and thermal mass both had a small impact on the results. The latter however could probably have a more significant effect if utilized correctly, especially in southern climates. The hygrothermal properties that VIP does not take into consideration could also be significant factor to increase the thermal performance in the hemp building simulation results. Furthermore the addition of hemp fibre insulation can provide the system with better U-values.

The hemp based materials used for a hemp building are all carbon negative, low on toxins, long lasting and recyclable. The production process is also highly sustainable and economically competitive and could probably be developed further when the technology has had more time to grow. With all this in consideration the hemp building system has potential to reach a passive house thermal performance in most climates if adjusted correctly. It could also contribute to the regeneration of the soil, healthier indoor environments and reverse the effects of global warming on a grand scale.

7. Further studies

More research can be done in most areas regarding hemp building. However some of the more important factors related to this report are the hygrothermal performance, the efficiency of thermal mass and how to adjust the material composition in order optimize these properties in different climates. Another major area of improvement could also be the simulation programs used to calculate the thermal performance of these breathable buildings since VIP has some significant limitations. The environmental impact could also be expanded to larger systems.

[128] American Lime Technology. *What is Hempcrete?* http://www.americanlimetechnology.com/

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9. Appendix A

In Appendix A there will be a review over the simulation input. Since the only thing that changes during the simulations is location and wall thickness these changes will be shown when necessary.

This is one of six different VIP energy simulations to evaluate the potential of hemp buildings in different climates in comparison to passive houses.
The simulations consist of tree passive houses and tree hemp houses each with 200mm, 300mm and 400mm thick walls. The different houses will also be moved to Kiruna, Sundsvall, Malmo, Berlin and Rome to evaluate how different climate impact the building.

Allmänt

Calculation period – Day	1 - 365
Solar reflection from ground	20.00 %
Wind velocity % of climate data	S:70 SV:70 V:70 NV:70 N:70 NO:70 O:70 SO:70
Air pressure	1000 hPa
Horizontal angle to ground	S:20 SV:20 V:20 NV:20 N:20 NO:20 O:20 SO:20 °
Form factor for wind pressure	0:0.70 45:0.50 90:-0.60 135:-0.50 180:-0.50 TAK:-0.00
’South facade’ angle to south	0 °
Activity	Bostad
NO of apartment	1
Ventilation volume	0.0 [m³]
Heated floor area	137.6 [m²]
Ground properties Heat conductance: Slit, Undrained sand and gravel, moraine	2.3 [W/m*K]

Climate data

KIRUNA 1996-2005	Latitud	67.8	degrees	
	Highest value	Average value	Lowest value	
Outside temperature	25.7	-0.1	-31.3	°C
Wind velocity	13.8	3.5	0.0	m/s
Solar radiation	831.0	91.0	0.0	W/m²
Relative hunidity	100.0	73.3	14.0	%

SUNDSVALL 1996-2005	Latitud	62.5	degree	
	Highest value	Average value	Lowest value	
Outside temperature	24.7	4.6	-22.5	°C
Wind velocity	16.9	2.5	0.0	m/s
Solar radiation	831.0	102.3	0.0	W/m²
Relative hunidity	100.0	80.2	28.0	%

MALMO 1996-2005	Latitud	55.6	degree	
	Highest value	Average value	Lowest value	
Outside temperature	26.7	8.4	-9.6	°C
Wind velocity	18.1	4.8	0.0	m/s
Solar radiation	931.0	112.7	0.0	W/m²
Relative hunidity	100.0	82.1	0.0	%

BERLIN-2008	Latitud	52.6	degree	
	Highest value	Average value	Lowest value	
Outside temperature	29.0	10.4	-6.3	°C
Wind velocity	10.5	4.3	0.3	m/s
Solar radiation	923.3	179.1	0.0	W/m²
Relative hunidity	99.8	81.1	51.6	%

ROME-2008	Latitud	41.9	degree	
	Highest value	Average value	Lowest value	
Outside temperature	30.4	17.1	1.3	°C
Wind velocity	12.7	3.6	0.1	m/s
Solar radiation	981.8	208.8	0.0	W/m²
Relative hunidity	95.8	76.4	51.3	%

Energy price

Price group	Week days	Day number	Time	Heat supply kr/kWh	Proc. energy kr/kWh	El supply kr/kWh	Distr cooling kr/kWh
CO2 Faktor	MÅND-SÖND	1 - 365	0 - 24	0.34	0.35	0.35	0.17

House parts

In this sector the building part is shown for hemp400mm and later passive400mm. The only thing that changes when changing wall size is Hempcrete 270 in the Hempcrete house and Beams s600x600 in the Passive house. The hempcrete275 is 180mm in the 200mm wall, 280mm in the 300mm wall and 380mm in the 400mm wall and in the Passive house the beam is first 122mm, then 222mm and 322mm.

Building part Hemp 1-dimensionella - Catalog

Building part	Material from outside to inside	Layer thickne s m	Heat conduct. W/m,K	Density kg/m³	Heat capacity J/kgK	U-value W/m²K	Delta- U-value W/m²K	Infiltratio n q50 l/s,m²	Solar-absorp-tion %
Ext. wall hempcrete	Hempcrete 700	0.010	0.120	700	1871	0.200	0.020	0.55	50.00
	Hempcrete 275	0.380	0.060	275	1500				
	Hempcrete 700	0.010	0.120	700	1871				
Floor hempcrete	Drained gravel	0.100	1.400	1800	1000	0.147	0.020	0.55	70.00
	Hempcrete 330	0.450	0.070	330	1550				
	Wood fir	0.020	0.140	500	2300				
Int. wall hempcrete	Hempcrete 700	0.010	0.120	700	1871	0.475	0.020	0.55	70.00
	Hempcrete 275	0.106	0.060	275	1500				
	Hempcrete 700	0.010	0.120	700	1871				
Roof hempcrete	Wood fir	0.020	0.140	500	2300	0.118	0.020	0.55	70.00
	Hempcrete 225	0.403	0.050	225	1450				
	Hempcrete 700	0.010	0.120	700	1871				

Building part Passive house 1-dimensionella - Katalog

Building part	Material from outside to inside	Layer thickn es m	Heat conduct. W/m,K	Density kg/m³	Heat capacity J/kgK	U-value W/m²K	Delta-U-value W/m²K	Infiltratio n q50 l/s,m²	Solar-absorp-tion %
Ext. wall	Wood fir	0.020	0.140	500	2300	0.149	0.010	0.50	50.00
	Beams s600x600	0.322	0.042	87	961				
	Beams s600x600	0.045	0.042	87	961				
	Gypsum board	0.013	0.220	900	1100				
Floor	Drained gravel	0.100	1.400	1800	1000	0.098	0.010	0.50	70.00
	Cellular plastic 36	0.300	0.036	25	1400				
	Concrete normal RH	0.100	1.700	2300	800				
	Cellular plastic 36	0.050	0.036	25	1400				
	Wood florr	0.020	0.140	500	2300				
Int. wall	Gypsum board	0.013	0.220	900	1100	0.376	0.020	0.80	70.00

	Beams s600x600	0.100	0.042	87	961				
	Gypsum board	0.013	0.220	900	1100				
Roof	Wood fir	0.020	0.140	500	2300	0.104	0.010	0.50	70.00
	Light sprayed wool	0.255	0.042	40	800				
	Light wool beams s1200	0.145	0.046	59	862				
	Gypsum board	0.013	0.220	900	1100				

Building part Hemp 2-dimensionella – Catalog

Building part	Psi-value W/mK	thickness m	Infiltration q50 l/s,m²	Solar-absorption %	Building part	Psi-value W/mK	thickness m	Infiltration q50 l/s,m²	Solar-absorption %
Window flanning hemp	0.074	0.200	0.00	0.00	Outer corner hempcre	0.103	0.400	0.55	50.00
Roof angle hempcrete	0.181	0.400	0.55	50.00					

Building part Passive 2-dimensionella – Catalog

Building part	Psi-value W/mK	thickness m	Infiltration q50 l/s,m²	Solar-absorption %	Building part	Psi-value W/mK	thickness m	Infiltration q50 l/s,m²	Solar-absorption %
Window flanning	0.068	0.200	0.00	0.00	Outer corner	0.087	0.400	0.80	50.00
Roof angle	0.074	0.400	0.80	50.00					

Buldings parts Hemp - Walls

Name	Building part type	Orientation	Amount Area m² Length m	Lowest level m	Highest level m	Adjacent temperature °C	Share of total heat power %	U- Psi- Chi-value With ground and D-U
	Ext. wall hempcrete	South	23.3m²	0.0	2.5		0	0.170 W/m²K
	Ext. wall hempcrete	North	20.3m²	0.0	2.5		0	0.170 W/m²K
	Ext. wall hempcrete	East	16.2m²	0.0	2.5		0	0.170 W/m²K
	Ext. wall hempcrete	West	15.4m²	0.0	2.5		0	0.170 W/m²K
	Floor hempcrete	PPM 0-1m	20.4m²	0.0	0.0		0	0.153 W/m²K
	Floor hempcrete	PPM 1-6m	38.9m²	0.0	0.0		0	0.131 W/m²K
	Floor hempcrete	PPM >6 m	72.2m²	0.0	0.0		0	0.125 W/m²K
	Roof hempcrete	Roof	127.8m²	2.5	2.5		0	0.138 W/m²K
	Int. wall hempcrete	Inner	240.0m²				0	
	Window flanning hemp	South	15.4m	0.0	2.5		0	0.076 W/mK
	Window flanning hemp	North	30.4m	0.0	2.5		0	0.076 W/mK
	Window flanning hemp	West	6.2m	0.0	2.5		0	0.076 W/mK
	Window flanning hemp	East	5.0m	0.0	2.5		0	0.076 W/mK
	Outer corner hempcre	South	2.5m	0.0	2.5		0	0.125 W/mK
	Outer corner hempcre	West	2.5m	0.0	2.5		0	0.125 W/mK
	Outer corner hempcre	North	2.5m	0.0	2.5		0	0.125 W/mK
	Outer corner hempcre	East	2.5m	0.0	2.5		0	0.125 W/mK
	Roof angle hempcrete	Roof	24.6m	2.5	2.5		0	0.188 W/mK
	Roof angle hempcrete	South	8.0m	2.5	2.5		0	0.188 W/mK
	Roof angle hempcrete	North	8.0m	2.5	2.5		0	0.188 W/mK
	Roof angle hempcrete	West	4.3m	2.5	2.5		0	0.188 W/mK
	Roof angle hempcrete	East	4.3m	2.5	2.5		0	0.188 W/mK

Building parts Passive house - Walls

Name	Building part type	Orientation	Amount Area m² Length m	Lowest lewel m	Highest lewel m	Adjacent temperature °C	Share of total heat power %	U- Psi- Chi-value With ground and D-U
	Ext. wall	South	23.3m²	0.0	2.5		0	0.120 W/m²K
	Ext. wall	North	20.3m²	0.0	2.5		0	0.120 W/m²K
	Ext. wall	East	16.2m²	0.0	2.5		0	0.120 W/m²K
	Ext. wall	West	15.4m²	0.0	2.5		0	0.120 W/m²K
	Floor	PPM 0-1 m	20.4m²	0.0	0.0		0	0.102 W/m²K
	Floor	PPM 1-6 m	38.9m²	0.0	0.0		0	0.091 W/m²K
	Floor	PPM >6 m	72.2m²	0.0	0.0		0	0.087 W/m²K
	Roof	Roof	127.8m²	2.5	2.5		0	0.114 W/m²K
	Int. wall	Inner	240.0m²				0	
	Window flanning	South	15.4m	0.0	2.5		0	0.069 W/mK
	Window flanning	North	30.4m	0.0	2.5		0	0.069 W/mK
	Window flanning	West	6.2m	0.0	2.5		0	0.069 W/mK
	Window flanning	East	5.0m	0.0	2.5		0	0.069 W/mK
	Outer corner	South	2.5m	0.0	2.5		0	0.107 W/mK
	Outer corner	West	2.5m	0.0	2.5		0	0.107 W/mK
	Outer corner	North	2.5m	0.0	2.5		0	0.107 W/mK
	Outer corner	East	2.5m	0.0	2.5		0	0.107 W/mK
	Roof angle	Roof	24.6m	2.5	2.5		0	0.087 W/mK
	Roof angle	South	8.0m	2.5	2.5		0	0.087 W/mK
	Roof angle	North	8.0m	2.5	2.5		0	0.087 W/mK
	Roof angle	West	4.3m	2.5	2.5		0	0.087 W/mK
	Roof angle	East	4.3m	2.5	2.5		0	0.087 W/mK

Building parts for both houses – Windows and doors

Name	Building part	Orientation	Area m²	Amount of glass %	Solar-transm. Total %	Solar transm. Direct %	U-value W/m²K	Lowest lewel m	Highest lewel m	Infiltration q50 l/s,m²	Solar protection
	Window	South	7.3	80	56	44	0.80	0.0	2.5	0.50	
	Door glass	South	2.1	90	56	44	0.80	0.0	2.5	0.50	
	Door normal	South	2.1	0	0	0	0.80	0.0	2.5	0.50	
	Window	North	7.3	80	56	44	0.80	0.0	2.5	0.50	
	Door normal	South	2.1	0	0	0	0.80	0.0	2.5	0.50	
	Window	East	1.6	80	56	44	0.80	0.0	2.5	0.50	

Driftdata

Operatomg case name	Activity energy W/m²	Activity energy W/lgh	Activity energy to room W/m²	Building energy to room W/m²	Building energy external W/m²	Person energy W/m²	Hot Water W/m²	Hot Water W/lgh	Highest room temp °C	Lowest room temp °C
00-06	1.49	0.00	0.64	0.00	0.00	2.05	1.85	0.00	27.00	21.00
06-07	2.26	0.00	0.97	0.00	0.00	2.05	2.81	0.00	27.00	21.00
07-17	2.26	0.00	0.97	0.00	0.00	0.00	2.81	0.00	27.00	21.00
17-18	2.26	0.00	0.97	0.00	0.00	2.05	2.81	0.00	27.00	21.00
18-24	4.52	0.00	1.94	0.00	0.00	2.05	5.61	0.00	27.00	21.00

Operating hours

Operating case name	Week days	Week number	Time
18-24	Monday	1 - 53	18 - 24
00-06	Monday	1 - 53	0 - 6
06-07	Monday	1 - 53	6 - 7
07-17	Monday	1 - 53	7 - 17
17-18	Monday	1 - 53	17 - 18
	Tuesday	==	Monday
	Wednesday	==	Monday
	Thursday	==	Monday
	Friday	==	Monday
	Saturday	==	Monday
	Sunday	==	Monday

Ventilation unit

Unit name	Inlet air fan pressure Pa	Inlet air effc. %	Exhaust air fan pressure Pa	Exhaust air effc. %	Regulation case
Airing	0.00	0.00	0.00	0.00	Airing
Ventilation	500.00	60.00	600.00	60.00	Ventilation

Regulation case

Regulation case	Control type	Outside temp L	Control value L	Outside temp H	Control value H
Airing	Recovery	0.00 °C	0.00 %	0.00 °C	0.00 %
Ventilation	Recovery	-10.00 °C	85.00 %	25.00 °C	85.00 %

Ventilation unit – Operating hour and flow

Unit name	Week days	Supply air l/s,m²	Exhaust air l/s,m²	Week number	Starttime-endtime
Airing					
	Monday	0.025	0.025	1 - 53	0 - 24
	Tisdagar	==	Monday		
	Onsdagar	==	Monday		
	Torsdagar	==	Monday		
	Fredagar	==	Monday		
	Lördagar	==	Monday		
	Söndagar	==	Monday		
Ventilation					
	Monday	0.350	0.350	1 - 53	0 - 24
	Tuesday	==	Monday		
	Wednesday	==	Monday		
	Thursday	==	Monday		
	Friday	==	Monday		
	Saturday	==	Monday		
	Sunday	==	Monday		

Heating and cooling

Heat pump: NIBE F1145/1245-8 kW	Share of total water flow	100.0	%
Accumulator tank	0.3	Parallel linked	
NIBE F1145/1245-8 kW			
Refrigerant	R407C		
Type of heat pump	Ground heat pump		
Lowest temperature cold side	-8.0	°C	
Highest temperature warm side	61.0	°C	
Heat to drain water			
Heat to heating system			
Heating output	8010.0	W	
Heat factor	4.6		
Temperature warm side	35.0	°C	
Temperature cold side	0.0	°C	
Testing standard	EN 14511		
Power to cold carrier pump	1.0	%	
Power to circulation fan	0.3	%	
Power to heat carrier pump	0.25	%	

Heat exchanger from sewer to hot-water

Efficency	50.00	[%]

Heating system	Op. point 1	Op. point 2
Outside temperature	-20.0	20.0
Supply pipe temperature	55.0	20.0
Drain pipe temperature	45.0	20.0
HOT WATER SYSTEM		
Cold water temperature	8.0	[°C]
Hot water temperature	55.0	[°C]

Other

El pump heating 0.00% of ennergy ti room and air

Lowest dimensioning outside temperature for heating -20.0 °C

Highest dimensioning outside temperature for heating 27.0 °C

Passive cooling

10. Appendix B

Appedix B concist of a description of the calculated values for the models Time schedule and operating case

Through the following DropBox-link the excel document for the calculation can be found: https://www.dropbox.com/s/s9rwkdgeltjcyxn/Energianvisningar-Sveby-Version-1.0-2012-11-06.xls

Table Appendix B1: The inputs on the SVEBY calculations

Number of rooms	5 rk
A_{temp}	137.6
Bathtub	yes
Shower flow	12 liter/min, armature
Sink flow	6
Fridge / freezer	1, A++ class
Dishwasher	1, A klass
Cooker with induction hob	1
Microwave	1
Washing machine	1 A class
Drying cabinet	1, 800 W
Installed lighting	default value, 160 kWh/house,year
TV	2, 140 W, time 1095 h/year
Vacuum cleaner	1, 1000 W, time 52 h/year
Coffee maker	1, 800 W, time 365 h/year

The calculation result:

- Addidional activity energy: to room air: 4,52 W/m^2 and External 1,94 W/m^2
- Personal energy: 2,05 W/m^2
- Tap water: 5,61 W/m^2

How to input the values in VIP-energy:

- Electricity, personal heating and hot water use is based on an attendance of 14h/dygn. In the VIP model the calculated personal energy, in W/m2, is distributed between 17:00 to 7:00 a.m.
- Lighting, appliances, hot water and external users of electricity, in W/m2, distributed to 33% between 00:00 to 06:00, 06:00 to 18:00 50% and 100% between 18:00-24:00

11. Appendix C

An illustration of the hempcrete building process:

Figure Appendix C.1: Illustration of the hempcrete building process and its various components.

12. Figure credits

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