CHALMERS

Hemp Built

Master thesis at Chalmers School of Architecture

20:th of May, 2016

MARIANN GRUNDVALL

Master Programme Design for Sustainable Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

Hemp Built

MARIANN GRUNDVALL

Hemp Built

MARIANN GRUNDVALL

Examiner: Krystyna Pietrzyk
Supervisor: John Helmfridsson

Master programme Design for Sustainable Development
Department of Architecture
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Telephone + 46 (0)31-772 1000
Göteborg, Sweden 2016

Acknowledgements

This thesis work has been developed during a long period of time since it has not only incorporated an extensive study but also a house design for a client, which in the end was decided to only be used as a reference house for my case study of thermal envelopes instead of being a part of the main investigation. It has been a very interesting time and I have learned a lot about both materials, ecological building, crops, building physics, as well as rules and regulations around building planning and ways of interacting and collaborating with a client and other stakeholders.

I would like to thank my supervisor John Helmfridsson for all his valuable advice and my examiner Krystyna Pietrzyk for her continuous positive encouragement and feedback. Through Chalmers I have apart from that received guidance and information from carpenters and professors at building technology, construction and geology.

I would also like to to thank all the stakeholders and experts within the field that have helped me with information, input and material samples; Tom Woolley, Thomas Jacobsson, Roger Olofsson, Chadi Maalouf, Paulien Strandberg, Daniel Nymberg, Mari Elfving and Ulf Henningsson, to name a few.

Last, but not least, I would like to acknowledge my client that introduced me to this subject and has been a key figure throughout. Thank you.

Abstract

Industrial hemp is a fast growing crop that has been re-discovered in later decades for many important uses; one of them being in building insulation applications such as hemp fiber wool, battens and hemp-lime. The hemp crop is said to hold many environmental benefits, including being soil purifying, largely carbon dioxide sequestering and resistant to weed, pests and fungus. It can thus be grown and used without chemical treatments. The fiber of the hemp stalk is well known for its strength, durability and vapour tolerance. There are already industries developed around different types of hemp-based insulation- and lighter structural building products in other European countries but the production and development in Sweden is in its infancy.

Based on a few different evaluation criteria I am in this thesis work exploring the main hemp insulation applications used and if they still can be considered environmentally friendly when they are combined with other additives in industrial processing. I am also comparing them to conventionally used insulation products with similar properties.

My investigation generates a case study of three suggestions for thermal envelopes incorporating different types of hemp insulation. The reference object used in this study is a house design that I have developed together with a client, located in a Swedish cold-tempered inland climate. My question formulations are the following: how do different hemp-based thermal insulation products and their construction techniques work? How sustainable and sound are they and would they be suitable in a cold tempered climate? Apart from the learning experience the aim of my work is to try to give a contribution to a further development around these promising building products.

Keywords
Hemp, hemp-lime, hempcrete, hemp fiber, natural insulation, bio-based, renewable, biodegradable, building material, sustainability, design, architecture

Table of contents

Nomenclature

	Unit	*Symbol/Equation*	
Life cycle assessment (LCA)			Well-recognized scientific studies over products' or processes' environmental impacts throughout their life cycle (Mermer 2012)
Cradle to gate			Life cycle assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (Jensen et al. 1998)
Cradle to grave			Full life cycle assessment from resource extraction ('cradle') to use and disposal phase ('grave') (Mermer 2012)
Carbon footprint			Summation of a product's, process's, individual's or organisation's greenhouse gas emissions and effect on climate change (Mermer 2012)
Embodied energy			The sum of all the energy required to produce any goods or services (© 2016 Circular Ecology Ltd 2016)
Thermal conductivity/lambda	W/mK	λ	A measure of how quickly heat transfers through conduction (internal vibrations of molecules) in a material; a lower value meaning a slower heat flow rate and better insulative performance (Hens 2007)
Thermal convection			The transfer of heat through fluid motion (Hens 2007)
Thermal radiation			Radiant heat transfer caused by electromagnetic waves, emitted from surfaces warmer than 0 K and whose absorbtion by other surfaces causes matter to charge (Hens 2007, p.59)
Thermal transmittance/U-value	W/m^2K	U	A figure of heat loss through an element that considers all three ways of heat transfer (thermal conductivity, convection and radiation), the depth of the structure per square meter and temperature difference (Hens 2007)
Heat capacity/specific heat capacity	(k)J/kgK	c	A measure of the amount of energy needed to rise the temperature of unit mass by one degree (Hagentoft 2001, Ståhl 2009)
Volumetric heat capacity	$(k)J/m^3K$	$c\ \rho$	Heat capacity multiplied with density (Hagentoft 2001, Ståhl 2009)

	Unit	*Symbol/Equation*	
Periodic penetration depth	m		The depth at which a temperature shift at the surface of a material has been reduced to 37 percent of its original amplitude, a dampening factor that is depended upon a material's thermal diffusivity (Ståhl 2009, p.17-18)
Thermal effusivity	$J/m^2Ks^{1/2}$	$\sqrt{(\lambda \cdot c\rho)}$	A measure of the rate at which a material can absorb and release heat from its surroundings; how easily heat can be exchanged at the surface of the material when air temperature increases (Ståhl 2009)
Thermal diffusivity	m^2/s	$\frac{\lambda}{(\rho \cdot c)}$	A measure of how well a material is able to dampen surrounding temperature variations (Ståhl 2009)
Time shift/lag	h		E.g. the amount of time it takes for a certain temperature on one side of a wall to travel through and be reflected on the other side (Maalouf et al. 2011a)
Airtightness	*e.g* $m^3(m^2h)$@50PA		The resistance to air leakage through unintentional leakage points or areas in the building envelope (Hagentoft 2001)
Thermal bridge			Areas or spots on objects/thermal envelopes with a significantly higher heat transfer than the surrounding elements, i.e. reduced thermal insulation and inside surface temperature (Hens 2007)
Relative humidity	%		The relationship between the actual vapour concentration and the saturation concentration at a given temperature (Hens 2007)
Hygroscopicity			Ability to attract and retain moisture (Berge 2009)
Vapour resistance factor		μ	Indicates how many times the vapour permeability of a material is smaller than that of stagnant air, at the same temperature and total pressure conditions, with values from 1 to infinity (Hens 2007, p.164))
Moisture buffer value (MBV)	*e.g* $g/(m^2\%RH)$		A measure of how much water vapour uptake and release a certain material is capable of, per open surface area during daily cyclic variations of relative humidity in a defined period of time (Berge 2009)

Introduction

BACKGROUND

The building sector accounts for approximately 40 percent of the total global energy consumption and about one third of the world's carbon dioxide emissions (UNEP, n.p.). Around 85 percent of buildings' total energy use is evaluated to come from their operational phase and 15 percent from the building materials' production energy use (Adalberth 2000, p.6). The same percental estimation can also be seen for buildings' total environmental impacts, including global warming potential, acidification, eutrophication, photochemical ozone creation potentials, and human toxicity (Adalberth 2000, p.7, Berge 2009, p.33). The development towards efficient renewable energy- and passive house systems is going quite fast though, why the materials we use and how we use them are starting to have a higher relevance (Ståhl 2009). In a well-insulated building the materials used can account for as much as 50 percent of its total global warming effect (Berge 2009, p.33). Another incentive for focusing more on materials' impact during manufacture is that it might be much more urgent to deal with the energy we use and carbon dioxide we release now to be able to fend off a climate change "tipping point" (Berge 2009). Postponing the environmental benefits 20 years could actually mean that reductions need to be 3-7 times bigger to achieve the same effect (Berge 2009, p.33-34).

Saving our environment is not just about lessening energy usage and carbon dioxide emissions though; the construction field accounts for astonishing 77 percent of Sweden's total material supply, a large part of which is non-recyclable and/or containing hazardous substances (Wallner 2004, p.24). Around 80 000 chemicals are in use in the building industry, and the number of health-damaging chemicals has quadrupled since 1971 (Berge 2009, p.31). 75 percent of the construction waste is estimated to be later dumped directly into landfill in lack of better options, contaminating our ground waters (Wallner 2004, p.24).

The term ”sustainable” is today frequently used and many times misused. Some suppliers claim that their products are sustainable solely through providing an insulation product with a good U-value that will potentially lower buildings' energy demand. A truly sustainable approach involves many aspects. Energy use, carbon dioxide and other emissions during production are important issues, as well as durability and chemical profile to be able to provide a good indoor quality for inhabitants as well as a safe disposal, reuse or recycling at the end of life.

OBJECTIVES

The idea and feeling of being captured and sheltered by nature itself, a thermal envelope without toxic chemicals and synthetic materials, is intriguing to me. One can ponder about how large effect the toxins around us actually have on our health and wellbeing. Why I want to examine bio-based insulation products in-depth is also because I am concerned about our global environment and feel that there does not seem be as much done to introduce hands-on sustainable products on the market, as there are general discussions around sustainability today. A lot of high goals and standards are set, and measures are taken to raise awareness in the issue, but companies working with actual product developments in this field will often need to work hard to be able to compete with well-established industries. To change this I believe that knowledge and guidance around environmentally friendly building products is key for attracting new investors as well as a larger interest from professionals and consumers. This will be my little contribution to this development.

WHY HEMP?

Having read a bit about different bio-based insulation materials' pros and cons before, hemp has especially caught my interest. It is sometimes advertised as a wonder plant that could save the world. This partly because it can be used as an environmentally friendly alternative to many otherwise petro chemically derived products, one of them being insulation material in buildings. A claimed benefit to other natural fibres is its resilience, both in agriculture, to vapour, rot, decay, vermin and more, which makes it possible to cultivate the plant without pesticides, fungicides and herbicides as well as use the product in its natural state without impregnating agents. It is also said to have the ability to grow fast and well in Northern colder conditions and lock up very large amounts of carbon dioxide. This sounds very exiting to me and is an incentive behind choosing to investigate this material further.

QUESTION FORMULATIONS

”How do different hemp-based thermal insulation products and their construction techniques work? How sustainable and sound are they and would they be suitable in a cold tempered climate?”

STRUCTURE

My work is mainly a research project consisting of a material in-depth investigation used for a case study of thermal envelopes incorporating different forms of hemp insulants. A house project that I have developed together with a client will be used as a reference object in a typical Swedish cold-tempered inland climate in my case study. The house design is however not a part of my main investigation why a short graphical presentation of it will only be enclosed in a separate appendix. The thesis work will in two main parts present the following:

PART I Building with hemp: material investigation

- **Properties of the hemp plant**
- **Hemp insulation building applications**
  - declaration
  - environmental profile
  - thermal performance
  - moisture performance
  - construction technique
  - durability and end of life
- **Comparison tables over different hemp insulation applications and conventionally used insulation materials**
  - specifics
  - carbon footprint and energy use
- **Renders and plasters**
- **Industrial market around hemp-based building products**

PART II Case study: designing thermal envelopes

- **A case study of three variants for a thermal envelope involving hemp-based insulation**

Conclusions and discussion

DELIMITATIONS

Hemp is a crop with numerous varieties as well as usage areas. This thesis work will only investigate the sorts that fall under the category industrial hemp that can be used as insulation material in buildings. Whenever the term "hemp" is used, this will thus refer to industrial hemp. I have focused on investigating hemp fiber wool, hemp fiber battens and hemp-lime since they are all able to provide the main thermal insulation layer in building structures located in cold tempered climates. Complementary building elements not investigated in detail in this thesis include different kinds of hemp boards, made from hemp alone or in form of composite boards mixed with other types of natural and/or synthetic fibres. In warmer climates where there is lower need for insulation, hemp is sometimes also mixed with earth and lime and made into blocks.

I will compare a few properties of these three hemp insulation products with other conventional insulation alternatives that are used in similar ways. Mainly, I will take a look at things that affect the environment, both the outer and our living environment, but I will also include the materials' approximate price since economical sustainability is an important factor as well. I will not go into any deeper investigation of the comparative materials and not weigh in all different characteristics between products.

This thesis work is in first hand an evaluation of hemp insulation materials and suiting construction methods. There are however a lot of factors besides that, which will have profound effects on buildings' environmental footprints as well as indoor environment. Transport distances, other material choices, ventilation, drainage and choice of heating source are a few examples. These factors are not part of this investigation, nor is design aspects of sustainability even though they have been considered when developing the reference house. Design graphics of the house will therefore be presented in a separate appendix.

It is possible to draw examples of all kinds of thermal envelope structures that could incorporate different variants of hemp insulants. It would be very interesting to see full scale proper performance testing of such examples being done at some point in the future. Here I have presented three possible structures that thermal performance wise would be workable in a cooler climate. In all of them a certain principal for a layer build-up is used throughout the whole thermal envelope. Other alternatives that are not included in my research scope could be to use altering material layers in roof versus floor etc.

METHODS

The overall work has involved:

Research:

My literature studies have naturally mainly evolved around hemp-based insulation applications but other bio-based as well as man-made insulation and complementary materials have been examined as well, mostly in comparative purposes. The following subjects have been studied:

- Building techniques; ecological as well as conventional
- Material science/chemistry/hazardous substances
- Building physics
- Environmental data/statistics
- Sustainable development
- Agricultural science
- Price indexes and specifics from suppliers

Contacts/stakeholders:

I have been in contact with hemp farmers, researchers and other expert knowledge within the field, professors, builders, architects, entrepreneurs, industry/suppliers, authors etc.

Evaluation and presentation method:

The material investigations and evaluations have been done for the hemp crop, hemp fiber insulation and hemp-lime separately. The examined hemp insulation applications have been analysed and presented through a set of environmental evaluation criterias. They have also been compared to other insulation materials with similar properties, through tables and small summaries after each chapter.

The case study of thermal envelopes in a Northern cool climate presents three different section drawings showing material layers, benefits and drawbacks, price examples and time constant calculations. These examples have been developed from collected knowledge around construction and material physics, adapted somewhat to the house structure in question.

The final conclusion and answer to my question formulations will be presented after the case study.

THEORY

Literature references:

My literature references are mainly collected from books and studies but sometimes also directly from suppliers. It has been easy to find an extensive amount of different studies around hemp-lime but the research on hemp fibres in insulation applications is unfortunately very limited.

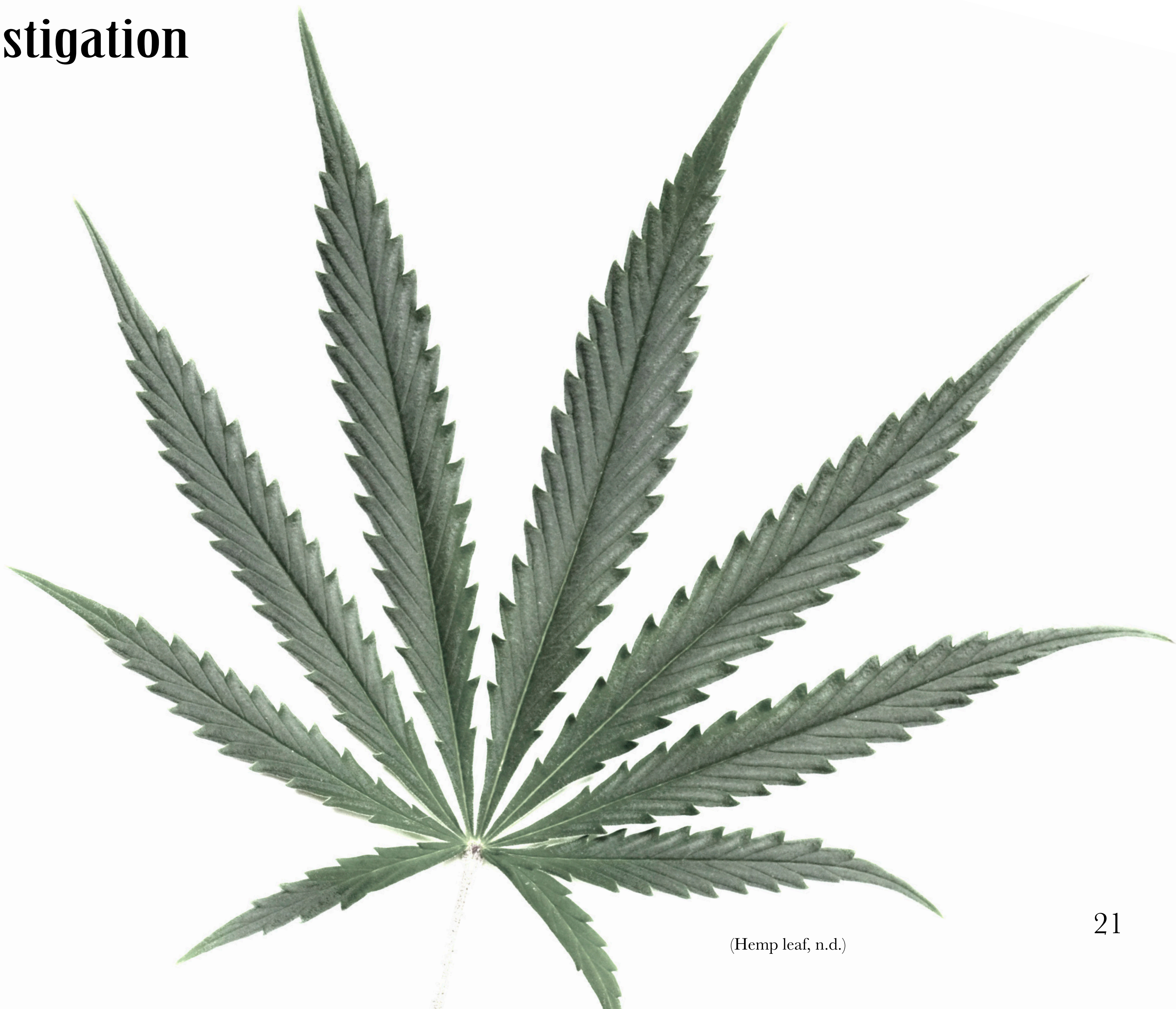
Key references:

- Tom Woolley (PhD. BArch. Edin): UK-based architect and former professor of architecture at Queens University, Belfast, specialized in renovation of old buildings and building with ecological materials. Author of *Low Impact Building*, *Hemp Lime Construction* and numerous other publications. Website: http://www.bevanarchitects.com
- William Stanwix & Alex Sparrow: hempcrete builders and directors of Hemp-Lime Construct, a UK-based company specialising in the use of hempcrete and other natural building materials. Authors of *the Hempcrete book*. Website: https://www.ukhempcrete.com
- Steve Allin: teacher and pioneer in the use of hemp in construction and director of the International Hemp Building Association. Author of *Building with Hemp*. Website: http://www.hempbuilding.com
- Numerous researchers on hemp-lime: Chadi Maalouf, Anh Dung Tran Le, Sylvie Pretot, Florence Collet, Arnaud Evrard, André De Herde, Samuel Dubois, Mourad Rahim, Mike Lawrence, Pete Walker, Edward AJ Hirst, Kevin A Paine etc.
- Iván Bócsa & Michael Karus: Iván a professor, experienced hemp breeder and agricultural botanist and Michael a physics scientist and co-founder and managing director of *Nova Institute*, Germany, that works with political and ecological innovation. Authors of *The Cultivation of Hemp* and numerous other publications.
- Roger Olofsson & Sinikka Johansson: hemp farmers involved in hemp cultivation consulting work through the non-profit association *Energinätverket Green4u*. Authors of several referenced publications.
- Bengt Svennerstedt: research manager at Swedish University of Agricultural Sciences. Author of numerous publications about the hemp plant and other plant fibres.
- Bjørn Berge: Norwegian architect and author of *the Ecology of Building Materials*. Website: http://www.gaiaarkitekter.no
- Varis Bokalders & Maria Block: Architects and authors of *Byggekologi: kunskaper för ett hållbart byggande*. Website: http://blockark.se

Part I

Building with Hemp

material investigation



(Hemp leaf, n.d.)

Evaluation criteria

I will base my evaluation of hemp-based insulation products on the following criteria:

- Environmental profile
- Thermal performance
- Moisture performance
- Construction technique
- Durability and end of life

All of these aspects will affect how large a material's environmental footprint will be. Some do also have profound effects on buildings' indoor environments, with examples of a few possible unfavourable outcomes shown below.

Environmental profile → **Chemical emissions and allergens from hazardous substances in materials**

Thermal performance → **Uneven and dissatisfying temperatures**

Moisture performance → **Poor humidity levels, moisture damage, mould, fungus and rot**

Different effects do intertwine with one another as well. The indoor temperature and relative humidity do, for instance, have profound effects on the emission level from materials (Berge 2009). The speed of a chemical reaction doubles with every 10-degree Celsius increase in temperature and chemical emissions in form of formaldehyde from chipboards containing urea-based glues are doubled with every 7-degree Celsius temperature increase or 30-70 percent increase in humidity (Berge 2009, p.12). Radioactivity, electricity, light and solar radiation can also stimulate chemical reactions in materials and closely assembled materials can speed up chemical reactions if the constituents are reactive to one another (Berge 2009).

Environmental profile

CHEMICAL PROFILE

There are many building products on the market that use highly toxic additives and components that can be both toxic to workers who manufacture and apply the products, be very toxic in case of fires, and also have effects on the indoor air through emissions (Woolley 2013, Berge 2009). There are studies done showing large amounts of toxic chemicals in human beings, many of which are associated with plastics for instance (Woolley 2013). How large the effects on the occupants can be through emissions from building materials is however still not very well understood (Woolley 2013). Lobbying within the building industry has unfortunately had a stranglehold against stricter regulations for products containing hazardous materials (Woolley 2013).

"Natural" or "bio-based" are terms often applied to products in order to market them as being very environmentally friendly. Plant-based insulation materials do usually have a very sound chemical profile, which of course can have favourable influences on the indoor environment and air quality (Woolley 2013, Lawrence et al. 2013). The pollution risk during manufacture and at the end of life is also generally much lower (Woolley 2013, Lawrence et al. 2013). Materials derived from nature are however not automatically environmentally friendly as a whole since they can be processed in an unnatural manner where chemicals, preservatives, fire retardandts, synthetic glues and/or support fibres are added, high amounts of fossil fuels are sometimes also used during production, as in the case of mineral wool (Woolley 2013). Common additives (usually in glue) used in mineral wool are formaldehyde, phenol and urea, and those can also be added to wood chipboards (Berge 2009). Borax and boric acid, which are considered moderately poisonous, are commonly used as flame-retardants and fungicides in cellulose insulation or as timber impregnation (Berge 2009). Even without additives, natural materials can contain substances that are unhealthy for man to come in contact with, asbestos being a classical example of this (Berge 2009). Dust from the natural material quartz sand, used in cement and mineral wool, is not good to come in contact with neither in a working climate, nor acidifying sulphur dioxide that is released during lime production (Berge 2009). These are however not considered to hold a health risk when enclosed in a material (Berge 2009).

CARBON FOOTPRINT AND ENERGY USE

I am in this thesis investigation considering all the energy used from a product's resource extraction (cradle) to the factory gate, a "cradle to gate" perspective. I am also looking at the products' "carbon footprint", which is a summation of its greenhouse gas emissions and effect on climate change (Mermer 2012). Here, with carbon dioxide sequestration included I am using a "cradle to grave" perspective. These factors are often studied in life cycle assessments, which are well-recognized scientific studies over products' or processes' environmental impact (Mermer 2012). Other common environmental impacts that can be evaluated through this method are for example exhaustion of recourses, acidification, eutrophication, air- and water pollution, human toxicity etc. (Adalberth 2000).

There is currently no standardized method or agreement set for how to calculate or integrate carbon dioxide sequestration in life cycle assessments (Daly, Ronchetti, & Woolley 2013, Haufe & Carus 2011). It is often shown separately since it is usually unknown what happens to that carbon dioxide at the end of life for a product. Even if it at some point will be released back into the atmosphere, the sequestration could be seen as a great storage potential over a critical time period when we are at great risk of reaching a climate change tipping point (Berge 2009).

When viewing life cycle assessments one needs to have a critical approach both regarding figures' origin and conclusions drawn; data can derive directly from suppliers and conclusions can often be more based on assumptions than actual scientific data and/or be commercially driven (Woolley 2013). The scope of different life cycle assessments can be very different and are thus extremely hard to compare with one another and the figures and calculation methods used can sometimes be misleading. Some also state that many databases frequently show higher levels of energy use and carbon dioxide emissions for natural products and much lower levels for more commercially driven products (Woolley 2013). If the source feels trustworthy, looking at them one by one can give an idea about the products' differences though why I have chosen to include a few examples of life cycle comparisons and other studies made in my evaluation.

A huge benefit for many plant-based materials is that they commonly have low embodied energy and can sequester carbon dioxide, something synthetic products normally cannot (Woolley 2013, Lawrence et al. 2013). With naturally derived materials it is possible to accomplish extremely low impact building methods, for example by using locally collected earth, straw or wood (Woolley 2013). It might however be unusual to have the oppurtunity to gather all materials nearby. Even if naturally derived materials can be very beneficial in this regard, they should still predominantly acquire some sort of processing and transport; crop based materials need farm machinery to sow and reap, for instance (Woolley 2013, Lawrence et al. 2013). In some cases, with additives and processing, their manufacturing energy use and carbon footprint might not be as beneficial as one might think.

Thermal performance

The main parameters affecting our indoor environment are usually temperature and humidity (Bokalders & Block 2014). Temperature has proven to be the most contributing factor to our cognitive ability, in a working environment for instance, according to Arbetshälsoinstitutet in Åbo (Bokalders & Block 2014). The overall energy performance of a house is naturally key to the regulation of temperature. Thermally efficient insulation materials are very important, but other factors such as solar radiation through windows, ventilation strategies, airtightness and thermal bridges all play important roles in determining a building's transmission losses (Hagentoft 2001, Bokalders & Block 2014). Approximately 30 percent of buildings' heat is lost through ventilation, 20 through the drains and 50 percent through the thermal envelope (Bokalders & Block 2014, p.468).

Differences in temperature, moisture conditions and air pressure on two sides of a thermal envelope will have a direct effect on the heat and mass (air and moisture) transfer through it (Hagentoft 2001). Therefore it is beneficial to do performance testing in a dynamic environment where all aspects affecting the thermal envelope's transmission rate are taken into account (Bevan, Woolley & Pritchett 2008, Lawrence et al. 2013, Woolley 2013).

Properties evaluated:

THERMAL TRANSMITTANCE

Heat transfers in the direction of the falling temperature and thus the transmission of energy will be moved from one place to another as a result of this temperature difference (Hagentoft 2001, Dahlin 2014). There are three ways of heat transfer; conduction, radiation and convection (Hagentoft 2001, Dahlin 2014). Thermal conductivity is the most relevant mechanism, measured in terms of lambda ($\boldsymbol{\lambda}$ = W/mK) (Hagentoft 2001). The figure reveals how quickly heat transfers through conduction (internal vibrations of molecules) in a material; a lower value meaning a slower heat flow rate and better insulative performance (Hagentoft 2001, Hens 2007). The thermal conductivity is normally measured in a "steady state" where no dynamic moisture conditions are taken into consideration (Lawrence et al. 2013, Woolley 2013).

The thermal transmittance/U-value ($\boldsymbol{U}$ = W/m^{2}K) is commonly given to describe an element's insulative performance. It considers the thermal conductivity and the depth of the structure (lambda divided with depth) per square meter and can include several layers with varying lambda values (Hagentoft 2001). It also takes temperature difference as well as thermal convection and radiation into account (Hagentoft 2001, Hens 2007).

HEAT STORAGE

Heat capacity or specific heat capacity is a measure of the amount of energy needed to change the temperature of a certain substance by one degree, measured in ***c*** = (k)J/kgK (Hagentoft 2001, Ståhl 2009, Dahlin 2014). Multiplied with density (kg/m^3) the value becomes the volumetric heat capacity, measured in ***cρ*** = (k)J/m^{3}K (Hagentoft 2001, Ståhl 2009). The potential of heat storage is directly governed by the amount of material used if all other variables are constant (Ståhl 2009). Thermal mass is a more general expression around how large the heat storage is at a whole building level.

Heat buffering materials can store and release heat to even out temperatures, which can also influence their moisture buffering ability in a beneficial way, both factors having a large effect on the indoor environment (Ståhl 2009, Woolley 2013, Bokalders & Block 2014). The energy use can be affected in a positive way as well, through lowered ventilation- and cooling demands (when there is a surplus in internal heat gains) and lowered heating demands when stored heat can be distributed during colder times a day (Olalekan et al. 2006, Ståhl 2009, Tran Le et al. 2010). Heavy materials generally have good heat storage capacities and poorer thermal conductivity, concrete and earth being classical examples of this, and light materials such as mineral wool or other porous fiber insulation materials containing a lot of air pockets, vice versa (Bokalders & Block 2014). High density materials can also dampen heat radiation and sound transmissions (Hagentoft 2001, Bokalders & Block 2014).

Heat and moisture are usually stored in the outer few centimetres in commonly used wall materials during shorter fluctuations in heat and humidity but can reach around 10-15 centimetres during a 24-hours cycle (Hagentoft 2001, p.38, Maalouf et al. 2011a, Bokalders & Block 2014, p.107,221). How far the heat can reach in a material does however differ and is a function of a material's periodic penetration depth (Hagentoft 2001, Ståhl 2009). In rock the 24-hour periodic penetration depth would reach as far as 4,2 metres (Hagentoft 2001, p.38). Long term heat buffering is done by a larger mass of the material (Berge 2009, Ståhl 2009, Bokalders & Block 2014).

Periodic penetration depth (m)

The depth at which a temperature shift at the surface of a material has been reduced to 37 percent of its original amplitude, a dampening factor that is depended upon a material's thermal diffusivity (Ståhl 2009, p.17-18).

THERMAL EFFUSIVITY

A material's thermal effusivity is a measure of the rate at which it can absorb and release heat from its surroundings; how easily heat can be exchanged at the surface of the material when air temperature increases (Ståhl 2009). It is measured in J/m^{2}Ks$^{1/2}$, which can be technically described as the square root of the product of a material's thermal conductivity times its volumetric heat capacity (Ståhl 2009). The heat capacity has been shown to affect the rating to a slightly smaller extent than the thermal conductivity but a certain effusivity value will have the same effect on the heating demand independently of the different combinations of values affecting it (Ståhl 2009, Maalouf et al. 2011a,c,). The effusivity rating is said to be the most indicative value for how much energy a material can store; a high value meaning a large heat storage capacity (Hagentoft

Thermal effusivity (J/m^2 K s$^{1/2}$) =

$$\sqrt{(\lambda \cdot c\rho)}$$

Thermal diffusivity (m^2/s) =

$$\frac{\lambda}{(\rho \cdot c)}$$

Time shift/lag (h)

E.g. the amount of time it takes for a certain temperature on one side of a wall to travel through and be reflected on the other side (Maalouf et al. 2011a).

2001, Ståhl 2009). High thermal conductivity coupled with a high volumetric heat capacity figure will generally mean high effusivity (Hagentoft 2001). Materials with low effusivity will however have the benefit of a higher surface temperature, giving a subconscious feling of thermal comfort that can be achieved at lower indoor temperatures than what is usually needed to feel warm (Bevan, Woolley & Pritchett 2008, Bokalders & Block 2014).

THERMAL DIFFUSIVITY

Thermal diffusivity is a measure of how well a material is able to dampen surrounding temperature variations (Ståhl 2009). It is defined as the thermal conductivity divided by density times heat capacity, measured in $meter^2$/second (Hagentoft 2001, Ståhl 2009). When the diffusivity of a wall material increases, heat energy diffuses more rapidly within it, time lag is lower and mean internal surface temperature gets closer to the outdoor temperature (Maalouf et al. 2011a). Some claim that low diffusivity materials used in thermal envelopes have important effects on the heat loss power through them (Maalouf et al. 2011a). Others however say that this effect is miniscule in a well insulated wall compared to other factors such as U-value and heat capacity* and could in principle be ignored (Ståhl 2009). On the interior side a greater time lag means that the penetration depth will be narrower during daily fluctuations in heat but heat will also be preserved during longer periods and can be distributed very slowly (Hagentoft 2001, Ståhl 2009). A lower time lag is thus more beneficial when dealing with fast fluctuations.

AIRTIGHTNESS & THERMAL BRIDGES

Airtightness and thermal bridges are very important factors to take into account when it comes to energy performance of buildings (Hagentoft 2001, Bokalders & Block 2014).

Airtightness performance of buildings can be specified in terms of an air exchange rate measured through pressurization tests (Hagentoft 2001). Air can leak through a building envelope intentionally through ventilation or unintentionally where sealants/air barriers are not airtight enough and will thus transfer heat and moisture (Hagentoft 2001, Bokalders & Block 2014). Airtight substrates are commonly used as inside layers in thermal envelopes and can be both vapour diffusion open and closed depending on which construction technique is used (Berge 2009, Bokalders & Block 2014). Airtight substrates are especially important in lightweight structures without internal heat storing materials since it in these cases is only the hot air trapped inside the building that is holding the heat (Stanwix & Sparrow 2014).

Thermal or cold bridges often occur where different building elements meet or where components with higher thermal conductivity bridges through a section of a building element that is otherwise well insulated (Hagentoft 2001, Hens 2007). The consequences of a thermal bridge are an increased heat flow rate and a drop in the internal surface temperature (Hagentoft 2001, Hens 2007).

* Hagentoft, Carl-Eric; Professor at Civil and Environmental Engineering, Building Technology, Chalmers University of Technology, Sweden. 2016. Interview August 24:th.

Moisture performance

RELATIVE HUMIDITY

The humidity level in a building has significant effects on the indoor air quality and user comfort (Woloszyn et al. 2009, Tran Le et al. 2010, Bokalders & Block 2014). Relative humidity shows the relationship between the actual vapour concentration and the saturation concentration at the same temperature (Hens 2007). The indoor relative humidity should optimally be around 40-60 percent (Morton & Bennetts 2008, p.8, Bokalders & Block 2014, p.116). In cold regions the air inside a building usually gets very dry during wintertime why this value might be hard to achieve (Bokalders & Block 2014). To high humidity levels can give way for bacteria, dust mites allergens and virus growth as well as mould, fungus and rot (Hens 2007, Bevan, Woolley & Pritchett 2008, Morton & Bennetts 2008). It can also lead to chemical interactions from hazardous substances in building materials (Hens 2007, Berge 2009, Bokalders & Block 2014). Low or high humidity levels can induce asthma, respiratory infections and other health issues such as "sick building syndrome" (Morton & Bennetts 2008, Bokalders & Block 2014).

MOISTURE ACCUMULATION

Moisture is commonly accumulated in a building at some point during its lifetime; mainly through lack of drainage, leakage, rising damp and moisture accumulated during the building phase (Hagentoft 2001, Hens 2007, Berge 2009). It either penetrates the climatic shield from the outside or appear as an effect of increased moisture build-up inside the building because of, for example, poor ventilation in combination with a very airtight structure, heavy use of showers etc. (Hagentoft 2001, Bokalders & Block 2014). Four out of ten Swedish buildings have had some sort of moisture or mould damage, why it is a major factor affecting the durability of materials, the indoor environment as well as the overall energy performance of the houses (Hagentoft 2001, Evrard & De Herde 2005, Tran Le et al. 2010, Maalouf et al. 2011a,b,c, Bokalders & Block 2014, p.36, Collet & Pretot 2014b).

HYGROSCOPICITY

Hygroscopicity means able to attract and retain moisture (Berge 2009, Tran Le et al. 2010). Materials showing considerable sorption at low relative humidity are refered to as hygroscopic (Hens, 2007). The vapour resistance factor (µ) is sometimes given for insulation products but that measurement does not reveal how well the material is able to retain and buffer the moisture. Depending on if

"…there will always be some uncontrolled moisture leakage, either from outside or inside, during a building's life, both due to defects, ageing and movement of materials that may be caused by differential settlement, wind or even earthquakes. In addition, these will often be invisible."

(Berge 2009, p. 249)

a wall construction is meant to being permeable or impermeable and where in a wall the material is placed, a high resistance could be either good or bad.

Natural renewable insulation materials are often hygroscopic but there is of course an upper limit to the moisture accumulation capabilities; if excessive amounts of moisture for some reason would build up, many bio-based insulation materials could be susceptical to decay as well as settling if they become to heavy (Svennerstedt 2003, Berge 2009, Bokalders & Block 2014).

MOISTURE BUFFERING AND WATER CONTENT

A moisture buffer value (MBV), measured in $g/(m^2\%RH)$, shows how much water vapour uptake and release a certain material is capable of, per open surface area during daily cyclic variations of relative humidity in a defined period of time (Berge 2009). It characterizes how well a material can moderate humidity fluctuations in the surrounding air (Berge 2009, Collet, Pretot & Lanos 2013). It is closely related to the vapor permeability but not necessarily to the amount of water a material can hold; concrete can for instance hold high amounts of water but is not the most responsive when it comes to absorbing and releasing it during daily variations (Evrard & De Herde 2005, Bevan, Woolley & Pritchett 2008, Berge 2009, Collet, Pretot & Lanos 2013).

Unfired earth is considered to be the best in this aspect (Morton & Bennetts 2008, Bokalders & Block 2014). Wood-based materials do also have a relatively good ability to buffer moisture (Berge 2009, Collet, Pretot & Lanos 2013, Bokalders & Block 2014). Woodwool cement is often used for this function in bathrooms for instance (Bokalders & Block 2014).

VENTILATION

Ventilation is used to regulate humidity levels and surplus heat and to transport out odours and emissions (Bokalders & Block 2014). Using a lot of ventilation however increases a building's heating and thus energy demand (Tran Le et al. 2010).

By using control strategies for the ventilation together with hygroscopic wall materials, studies have indicated that the energy demand can be lessened (Olalekan et al. 2006, Woloszyn et al. 2009, Tran Le et al. 2010). The ventilation rate is said to be able to be lowered at least 15 percent during occupied periods with a good hygroscopic material while still providing satisfying indoor humidity conditions (Olalekan et al. 2006, p.1279, Tran Le et al. 2010, p.1804-1805). In dryer indoor climates it is very important to cut down on the ventilation rate since heavy ventilation can make it even more dry (Bokalders & Block 2014).

Hygroscopic and thermally buffering materials are also said to work very well with natural ventilation and windows can be opened without depleting the house of its heat fast since a great portion of it is stored in the materials (Ståhl 2009, Stanwix & Sparrow 2014).

Construction technique

WALL CONSTRUCTION TYPES

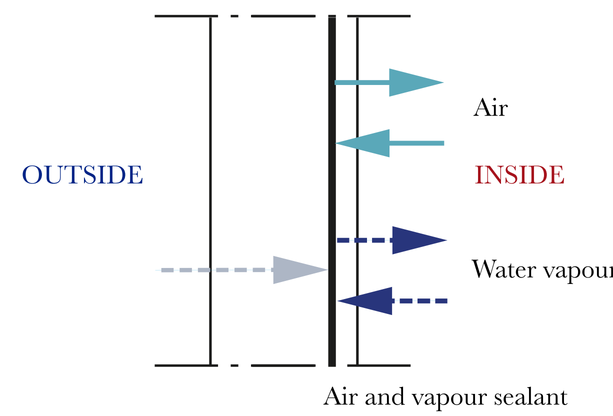
The most common used wall construction method in Sweden today is a vapour impermeable type where moisture is sealed away from entering the wall from the inside, usually through a plastic sealant behind an installation layer (Bokalders & Block 2014). Here moisture sensitive insulation such as mineral wool or synthetic materials are commonly used (Bokalders & Block 2014). Experience has however showed that this construction type can be risky since it can be enough with small rips or holes in the vapour barrier for vapour to become trapped in the wall and possibly cause problems with mould, rot, fungus etc. (Berge 2009, Bokalders & Block 2014). It is also not known how long these vapour barriers will last (Berge 2009).

Vapour permeable/open walls is another technique that is increasingly used (Bokalders & Block 2014). Vapour open means that they allow for a certain degree of vapour to pass through, why the materials used need to be hygroscopic. The term ”breathable” is sometimes used but that can easily be misinterpreted as being a less airtight structure. The airtight substrate can in a vapour permeable wall type for example be in form of cardboard or particleboards (Bokalders & Block 2014). A common technique to make vapour travel through the wall and not be trapped inside it is to use more permeable materials in the outer layers than inner since vapour naturally travels from hot to cold (Hagentoft 2001, Berge 2009, Bokalders & Block 2014). Hygroscopic materials are beneficial in very well insulated walls since thicker insulation can lead to humidity damage when less heat from inside the building leaks out into the walls to dry out any humidity that may have been gathered there (Berge 2009). In holiday houses it might also be preferable with vapour open walls since it could actually become colder inside the house than outside when heating is put off. Then there is a risk that vapour would travel in the opposite direction and become trapped and condensate inside the wall structure in a thermal envelope that is sealed to the inside.

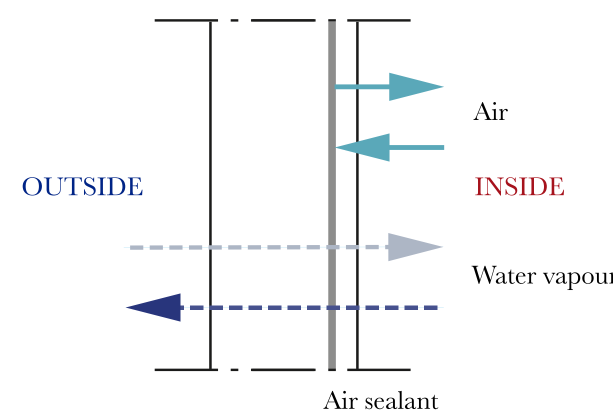
LIGHT AND HEAVY WALLS

When building with the use of heavy materials and structures this can cause a larger energy demand during construction-, demolition and transport but can through their heat storage give an advantageous in-use energy performance (Bevan, Woolley & Pritchett 2008, Ståhl 2009, Haufe & Carus 2011, Bokalders & Block 2014). A lighter building structure can apart from easing the energy burden during construction and transport use lighter foundations and fewer supports (De Bruijn 2012, Bokalders & Block 2014, Limetec).

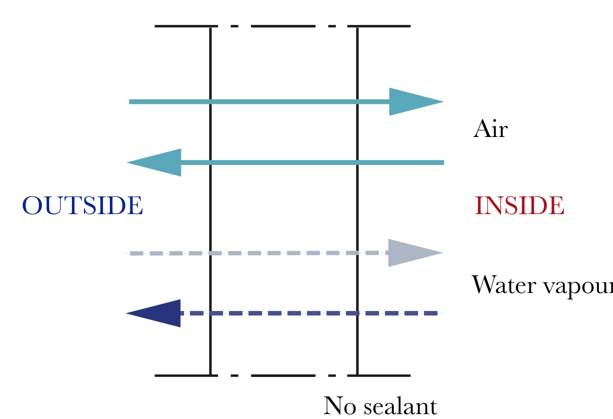
Airtight and vapour diffusion closed wall



Airtight and vapour diffusion open wall



Air and vapour diffusion open wall



(Grundvall 2016)

Durability and end of life

The end of life for a product is a very important matter that might sometimes be neglected. Many product manufacturers claim that their products are reusable and recyclable which sounds very good in theory. In practice, manufacturers usually do not take any responsibility for the products actually being so. Many insulation products, such as mineral wool for instance, often become dirty and damp during building demolitions, which make them hard to manage and reuse (Woolley 2013). Therefore they commonly end up in landfill where they can cause worrying environmental issues (Woolley 2013, Bevan, Woolley & Pritchett 2008).

A product that is claimed to be 97 percent recyclable, which could be the case in composite materials for instance, also sounds quite good in theory. It might however not be possible nor feasible to extract those 3 percent of non-recyclable substances from the product at the end of life. However, given the fact that many very hazardous materials are put directly into landfill today, a material that in most parts is bio-degradable could still mean a huge improvement.

The hemp crop

The Cannabis plant comes in three species; Cannabis Sativa, Indica and Ruderalis (van Bakel et al. 2011, Stanwix & Sparrow 2014). It is commonly known for its pharmacological and psychoactive properties that derive from the presence of over one hundred different cannabinoids (van Bakel et al. 2011, p.2). Tetrahydrocannabinol (THC) is the main psychoactive substance (van Bakel et al. 2011). Other non-psychoactive cannabinoids are for example cannabidiol (CBD), cannabichromene (CBC) and tetrahydrocannabivarin (THCV), which all have different medical effects (van Bakel et al. 2011).

Hemp is the English name that usually refers to ”industrial hemp” (Svennerstedt 2003, Stanwix & Sparrow 2014). Industrial hemp means higher growing refined breeds containing explicitly low amounts of THC; under 0,2 percent to be grown legally within the EU (Bócsa & Karus 1998, Svennerstedt & Svensson 2004, n.p., Holstmark 2006, p.2, Norberg 2009, p.28, Stanwix & Sparrow 2014, p.18, Jordbruksverket 2015). Cannabis Sativa is the species that is capable of growing very tall and producing high yields (Bócsa & Karus 1998, Holstmark 2006). There are nevertheless countless varieties of all Cannabis species (Jordbruksverket 2015). The drug producing plant commonly known as Marijuana refers to lower growing variants with very high amounts of THC (around 10-15 percent) (Svennerstedt & Svensson 2004, n.p., Bevan, Woolley & Pritchett 2008, p.28, van Bakel et al. 2011, p.2, Stanwix & Sparrow 2014, p.18).

Cannabis Sativa is characterized by narrow leaflets with branches relatively far apart (Allin 2012).

(Jasper-m through ©CC0 Public Domain, n.d.)

(Hemp paper, n.d.)

(Hemp sails, nets and ropes, n.d.)

THE HISTORY OF HEMP

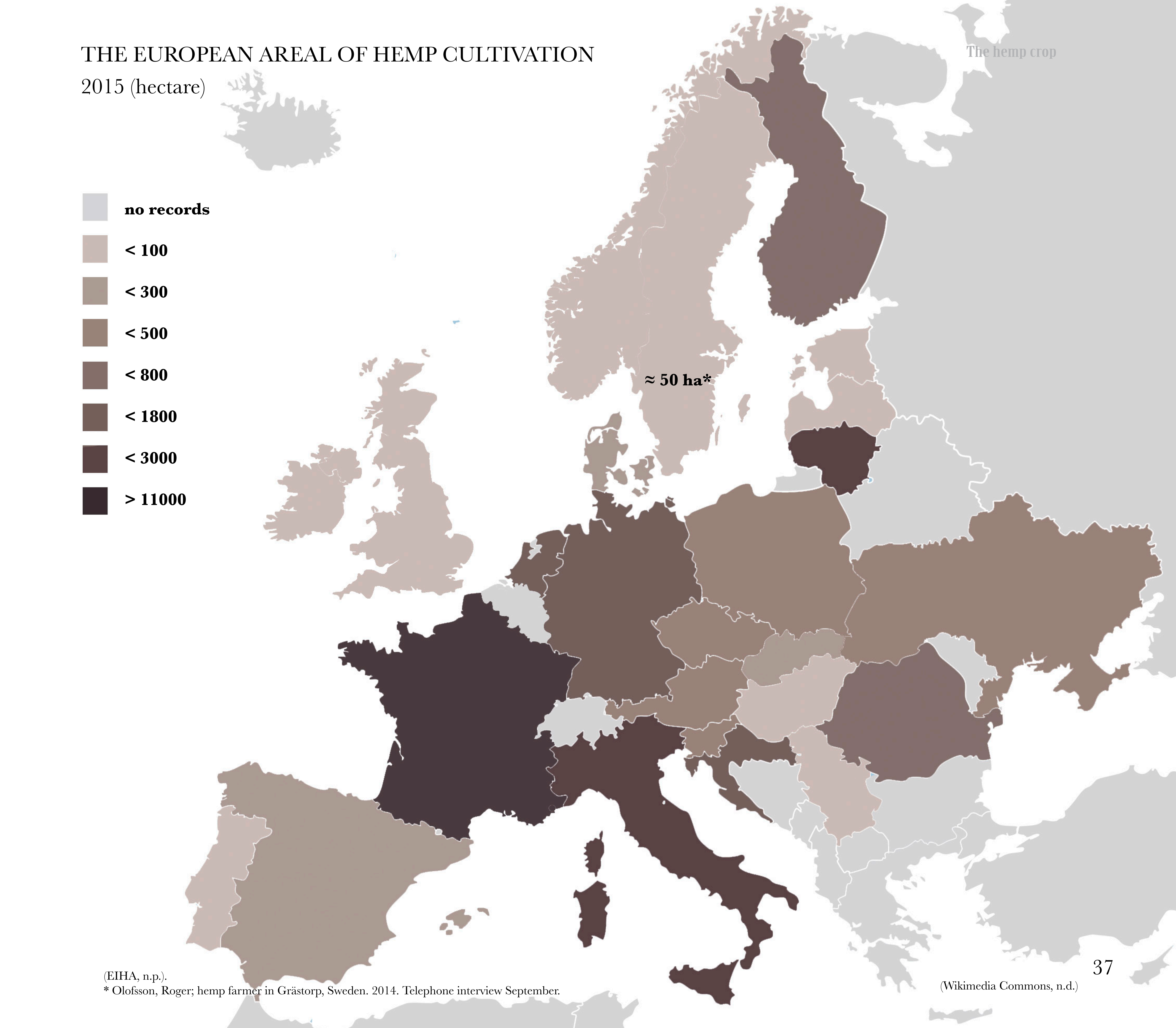
Hemp is thought to originate from China/central Asia (Ranalli & Venturi 2004, Bevan, Woolley & Pritchett 2008, van Bakel et al. 2011, Haufe & Carus 2011). It is one of the oldest crops known to man, said to have been used as early as 6000 years BP (before present) with remains of its usage found from around 2000 BP (Bócsa & Karus 1998, p.3, Ranalli & Venturi 2004, p.1, Svennerstedt & Svensson 2004, n.p., Eriksson 2008, n.p., van Bakel et al. 2011, p.1). Some say it was once the most extensively grown crop in the world (Bevan, Woolley & Pritchett 2008). The strong, durable and weather tolerant fiber has been widely used through times for ropes, nets, sails, paper and textiles, for instance, with its largest period of greatness during the seventeenth-century; the golden age of sailing ships (Bócsa & Karus 1998, p.4-5, Franck 2005, Bevan, Woolley & Pritchett 2008, Eriksson 2008, n.p.). In Sweden it has been cultivated since the middle ages, mostly in Västergötland, Jämtland and on Gotland (Svennerstedt & Svensson 2004, n.p., Skoglund 2009, n.p.). The usage of hemp started to decline during the eighteenth-century when cotton spinning machines were mechanized and in the second half of the nineteenth-century it was largely replaced with exotic fibres such as cotton, jute, sisal and ramie, that were easier and cheaper to manufacture and could be imported overseas (Bócsa & Karus 1998, p. 5, Svennerstedt 2003, Stanwix & Sparrow 2014). They were not as durable though, especially not in wet conditions (Bócsa & Karus 1998). During the World Wars hemp had a revival and was widely used in the US, Germany and Russia, for instance, partly due to importation cut offs of other fibres (Bócsa & Karus 1998). In Sweden the cultivation of hemp was around 2000 hectare during this period (Svennerstedt & Svensson 2004, n.p., Olofsson 2014, n.p.). We even had state subventions and two larger processing plants in Visby and Katrineholm (Svennerstedt & Svensson 2004, Skoglund 2009, Olofsson 2014).

All forms of hemp were made illegal in the US and UK between the years 1930-1950 due to the association with Marijuana (Bócsa & Karus 1998, p.9, Bevan, Woolley & Pritchett 2008, p.6, 28, Stanwix & Sparrow 2014, p.17). Many other Western European countries followed but Eastern Europe and France withheld their cultivation (Bócsa & Karus 1998, Svennerstedt & Svensson 2004, Stanwix & Sparrow 2014). In Sweden it was not banned until the mid 60's (Svennerstedt & Svensson 2004, n.p., Holstmark 2006, p.2, Eriksson 2008, n.p.).

The rediscovery of industrial hemp in Western Europe began in the 1990's (Bócsa & Karus 1998, p.12, Svennerstedt & Svensson 2004, n.p., Franck 2005, p.204). Here the cultivation increased around tenfold from this point onto its peak around 1998 (Bócsa & Karus 1998, p.12, Ranalli & Venturi 2004, p.4). The areal of cultivation periodically went down around the millennium shift because of reduced subventions and stricter rules but the world production is nowadays steadily going upwards with China and France in the top (Bócsa & Karus 1998, Ranalli & Venturi 2004, Franck 2005, p.202-203, Norberg 2009, p.29, EIHA, n.p.). In Sweden hemp was not legalised again until 2003 (Svennerstedt & Svensson 2004, n.p., Holstmark 2006, p.2, Eriksson 2008, n.p.).

THE EUROPEAN AREAL OF HEMP CULTIVATION

2015 (hectare)



(EIHA, n.p.).

* Olofsson, Roger; hemp farmer in Grästorp, Sweden. 2014. Telephone interview September.

(Wikimedia Commons, n.d.)

Hemp stalk (Allin 2012, p.28) (Fibre peeled from shiv, n.d.)

Seeding in spring (Jacobsson 2013)

Yield during flowering peak in early autumn (Jacobsson 2015)

PLANT SPECIFICS

Hemp is a herb and a bast fiber plant that belongs to the nettle (Urticales) order and the Cannabaceae family (Bócsa & Karus 1998, Svennerstedt 2003, Svennerstedt & Svensson 2004, Holstmark 2006). The plant is quite similar to flax, kenaf and jute and can be grown for its fiber, seeds or with dual purposes (Svennerstedt 2003). The hemp stalk has a hollow centre that is surrounded by a woody core called shiv or hurd and a stronger bast fiber (Bócsa & Karus 1998, Svennerstedt 2003). The plant has a nut that is usually referred to as a seed (Bócsa & Karus 1998). Around 30 percent of the seed's weight can be utilized as oil (Bócsa & Karus 1998, p.121, Ranalli & Venturi 2004, p.2, Holstmark 2006, p.3). The hemp plant's main constituent is cellulose and the shiv is chemically very close to wood (Bócsa & Karus 1998, Franck 2005, Sedan et al. 2008). Properties of industrial hemp vary a bit depending on factors such as origin, age, soil type and amount of nutrients and fertilizers used (Bócsa & Karus 1998, Franck 2005, Sedan et al. 2008). The stalk is commonly claimed to be between 1,5-4 meters tall and the thickness is usually around 0,5-2,5 centimetres, even though it can grow up to 6 centimetres in diameter (Bócsa & Karus 1998, p.25-26, Svennerstedt & Svensson 2004, n.p., Franck 2005, p.179, Holstmark 2006, p.2).

CULTIVATION

Hemp can be grown in most climates but different varieties of the plant can however be better suited for certain conditions; hemp for seed production does for instance generally demand a warmer climate than fiber hemp and is sometimes grown separately (Bócsa & Karus 1998, Bevan, Woolley & Pritchett 2008, Haufe & Carus 2011, Lawrence et al. 2012). It is a highly renewable, resilient and fast growing annual plant with an average yield of 6-7 tons/ha (Bócsa & Karus 1998, Norberg 2009, p.28, Haufe & Carus 2011, p.5). Yields of between 8-14 tons/ha have been reported in the southern parts of Sweden and up to 20 tons/ha* have actually been harvested in the north of Sweden where there are a lot of sun hours during summer when hemp is grown, as well as high humidity, which is very beneficial for the plant* (Svennerstedt & Svensson 2004, n.p., Holstmark 2006, p.3, Norberg 2009, Haufe & Carus 2011).

The hemp plant is seeded during spring and has its growing peak after 3-4 months, in the early autumn (Bócsa & Karus 1998, Svennerstedt & Svensson 2004, n.p., Franck 2005, p.179, Holstmark 2006, p.3, Norberg 2009, p.29). Hemp needs to be harvested during dry weather conditions after it has been retted on the ground, which is most often easier to do in the spring in Swedish conditions (Nilsson 2003, Franck 2005, Holstmark 2006, Norberg 2009, Skoglund 2009). It is in this case freeze-dried/winter retted on the field during the cold winter months, since it can survive down to -10 C (Holstmark 2006, p.3, Skoglund 2009). Advantages of freeze-retting include reductions of the risk of mould growth and improvment of the insulating and processing properties; the fiber becomes coarser, drier and more easily separated (Bócsa & Karus 1998, Nilsson 2003, Svennerstedt 2003, Svennerstedt & Svensson 2004, Holstmark 2006,

* Jacobsson, Thomas; hemp farmer in Österlen, Sweden. 2015. Mail correspondence June 23:rd.

Norberg 2009). If harvested in the beginning of autumn, the yield will however be bigger, have less spillage and the fiber would also be stronger and have a finer quality (Bócsa & Karus 1998, Nilsson 2003, Norberg 2009). Finer quality hemp fiber is commonly used for textiles, ropes, yarns and in the automobile industry (Bócsa & Karus 1998, Johansson & Olofsson 2009)

Hemp is an agronomically attractive plant that can be beneficially used as a break crop between cereals, vegetables or potato crops, for instance, meaning it will not compete for arable land with food crops (Bócsa & Karus 1998, Franck 2005, Prade, Svensson & Mattsson 2012). It can through its exceptionally long roots extract nutrients left in the ground by previously grown crops and reach deep sources of water (Bócsa & Karus 1998, Ranalli & Venturi 2004, Haufe & Carus 2011). It will also return a large quantity of nutrients to the soil, have a favourable influence on the soil structure and clean contaminated soils from heavy metals such as copper, lead and cadmium (Bócsa & Karus 1998, Nilsson 2003, Ranalli & Venturi 2004, Franck 2005, Haufe & Carus 2011, La Rosa et al. 2014).

It effectively suppresses weeds, fungus and some major soil-borne diseases, and vermin are generally not attracted to the crop (Bócsa & Karus 1998, Svennerstedt & Svensson 2004, van der Werf 2004, Franck 2005, Holstmark 2006, Eriksson 2008, Haufe & Carus 2011, Prade, Svensson & Mattsson 2012). The effective weed control carries on to the next crop if cultivated in rotation where, for instance, 10-20 percent higher wheat yields after the cultivation of hemp can be expected (Bócsa & Karus 1998, p.134, Ranalli & Venturi 2004, p.3, Holstmark 2006, Prade, Svensson & Mattsson 2012). Mould, pests and diseases do exist, but to a very low extent (Bócsa & Karus 1998). They mostly occur when hemp is grown in monoculture, but it rarely causes any economic losses (Bócsa & Karus 1998). The occurrences of rotting and pest infestations are minimal compared to other renewable crops such as canola or flax, for instance (Bócsa & Karus 1998, Franck 2005, Lawrence et al. 2012). The hemp seeds can however be attractive to birds (Bócsa & Karus 1998, Holstmark 2006).

PROCESSING

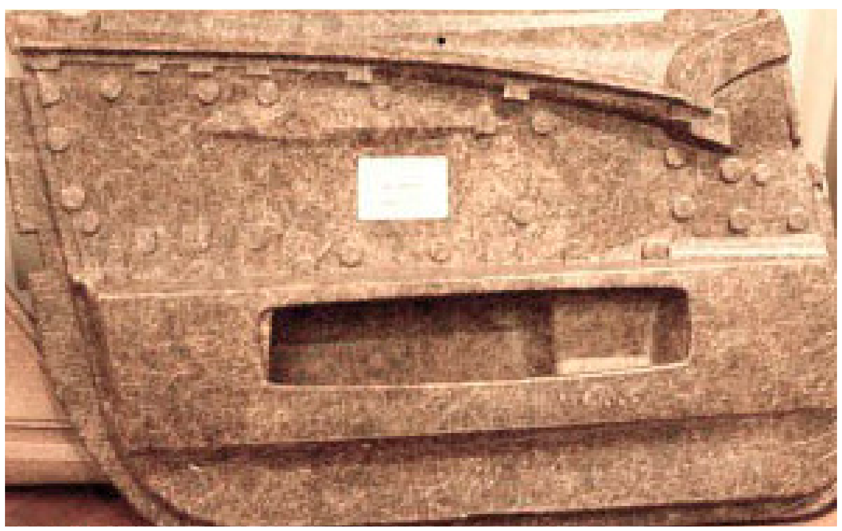
The field-retted and dried hemp straw needs to be separated into fiber and shiv in a process called decortication, which can be done with farm machinery or in a processing plant (Franck 2005, Norberg 2009, Haufe & Carus 2011). Basically the whole hemp stalk can be used; shiv will constitute around 60-75 percent and the fiber around 20-25 percent, the rest of the stalk becomes powder that can be pressed into bricks and be used as fuel (Franck 2005, p.184, Bevan, Woolley & Pritchett 2008, p.28, Norberg 2009, p.28, Prade, Svensson & Mattsson 2012, Zampori, Dotelli & Vernelli 2013, p.7415). If not used in other purposes, the leaves of the plant can be left on the ground where they can function as natural nitrogen to replenish the soil (Ranalli & Venturi 2004, Franck 2005, Norberg 2009).

Swathing of winter retted hemp straw (Jacobsson 2016)

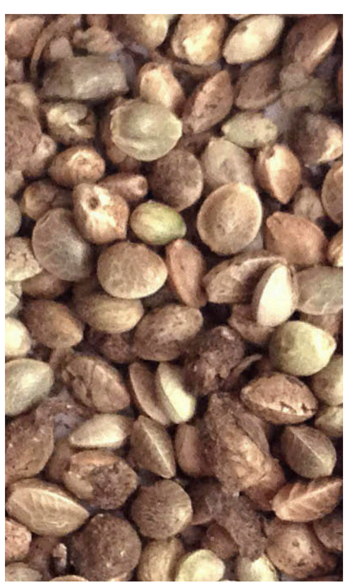
Collecting yield (Jacobsson 2007)

Baling (Jacobsson 2016)

Hemp fiber textiles (Hemp fiber textiles, n.d.)

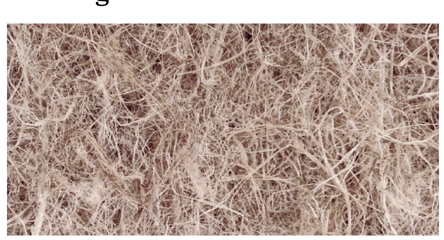


BMW series hemp door panel (Redspiderfish/Flickr, n.d.)



Hemp seeds (Grundvall 2016)

Shiv animal bedding (Jacobsson 2013)



Hemp fiber batten (Grundvall 2016)

AREA OF USE

All parts of the hemp plant can be used (Lawrence et al. 2012). The seed and its oil can be used in food production, cosmetic products and medical treatments and the seed oil also in primers and as biofuel (Bócsa & Karus 1998, Ranalli & Venturi 2004, Svennerstedt & Svensson 2004, Eriksson 2008, van Bakel et al. 2011, Stanwix & Sparrow 2014). The seed is sought for due to its high nutritional value but is considered a bit exclusive since its harvest is relatively small (Bócsa & Karus 1998, Svennerstedt & Svensson 2004, Holstmark 2006). The leaves and flowers contain the health promoting cannabinoid CBD why they can be used for oil extraction as well. Hemp fibres can be used for textiles, paper, ropes and a wide range of bio-plastic composites, the later accounting for about 40 percent of its use (Svennerstedt 2003, Svennerstedt & Svensson 2004, Ranalli & Venturi 2004, Franck 2005, Holstmark 2006, Haufe & Carus 2011, p.5, Stanwix & Sparrow 2014). One example of a nowadays commonly used hemp fiber bio-plastic product is as a composite material in car interiors, which is very beneficial because of the product's low weight (enabling less use of gas) (Nilsson 2003, Svennerstedt 2003, Svennerstedt & Svensson 2004, Franck 2005, Eriksson 2008). Hemp fibres have a growing market as hemp wool in building insulation products as well, accounting for about 40 percent of its use (Nilsson 2003, Svennerstedt 2003, Svennerstedt & Svensson 2004, Holstmark 2006, Eriksson 2008, Haufe & Carus 2011, p.5).

Hemp shiv, which is seen as a by-product to the more valuable fibres, can be used in energy production but is primarily used as animal bedding, suitable because it is dustless and has a high capability of absorbing moisture (Nilsson 2003, Svennerstedt & Svensson 2004, Franck 2005, Eriksson 2008, Johansson 2010, Haufe & Carus 2011, Prade, Svensson & Mattsson 2012). Shiv has been used a lot together with lime in composite building elements in France under the name "Chaux Chanvre" since the beginning of the 1990s; initially used in renovation projects of old half-timbered buildings due to the discovery of the material's flexibility and low cracking/shrinkage ratio (Bevan, Woolley & Pritchett 2008, Haufe & Carus 2011, Daly, Ronchetti, & Woolley 2013, p.14, Walker, Pavia & Mitchell 2014, p.340). The hemp-lime composite is referred to in English as "hemp-lime" or "hemp-lime concrete/hempcrete" since it often involves added cement (Lawrence et al. 2012).

Hemp bio-plastic shoe (Hemp bio-plastic shoe, n.d.)

Environmental profile

CHEMICAL PROFILE

If grown under normal conditions, hemp requires no chemicals, pesticides, herbicides nor fungicides (Bocsa & Karus 1998, Ranalli & Venturi 2004, Svennerstedt & Svensson 2004, van der Werf 2004, Franck 2005, Haufe & Carus 2011). Since hemp is grown very rapidly and gives a high yield return it consequently has a relatively high nutritional requirement (Bocsa & Karus 1998, Franck 2005, Holstmark 2006, Skoglund 2009). Reducing the use of nitrogen and other fertilizers is an important environmental matter even if the production of hemp in general is considered very environmentally friendly (Bocsa & Karus 1998, Franck 2005). Hemp's long roots can minimize nitrogen leaching and cultivation in rotation with other nutritious plants can also lessen the need of fertilizers (Bocsa & Karus 1998). Hemp is claimed to be well suited for organic cultivation with the use of liquid manure and dung from stables as fertilizer, but that would require an abundant supply and is not always able to produce as large of a yield as with conventional cultivation methods (Bocsa & Karus 1998, Svennerstedt & Svensson 2004, Franck 2005, Holstmark 2006, Prade, Svensson & Mattsson 2012).

Hemp plant with its long root

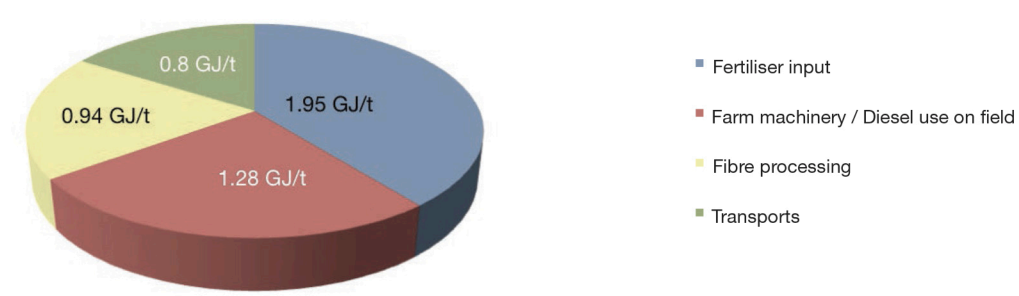
(Hemp plant and root, n.d.)

CARBON FOOTPRINT AND ENERGY USE

Zampori, Dotelli & Vernelli (2013, p.7417) estimates the total amount of carbon dioxide emissions released during the production of hemp to be around 0,11 kg CO^2/kg and the sequestration to be about -1,84 kg CO^2/kg. According to the same study, the Ministere de lÁgriculture et de la Peche (France) performed a life cycle assessment of hemp cultivation and concluded that depending on the allocation method, the amount of stored carbon dioxide could vary between -1 to -2,9 kg CO^2/kg (Zampori, Dotelli & Vernelli 2013, p.7414). Amziane & Arnaud (2013, p.302) give the figure -1,7 kg CO^2/kg and Bos & Deimling (2005, n.p.) -1,89 kg CO^2/kg. In Ip & Miller's (2012, p.3) life cycle assessment of a whole hemp-lime unit they state that defibred shiv uses 0,19 kg CO^2/kg and absorbs -1,53 kg CO^2/kg. Clearly these figures varies, which Zampori, Dotelli & Vernelli (2013) believes is due to different methodological approaches and cultivation circumstances. The plant is however without any doubt largely carbon negative.

A life cycle assessment of hemp-lime construction funded by the French government, has concluded that the nitrogenous fertilizers used in the non-ecological cultivation of hemp were responsible for the most environmentally inflicting part of the hemp production when looking at emissions of greenhouse gases, consumption of non-renewable energy resources and water pollution by nitrates (Bevan, Woolley & Pritchett 2008). This study also noted transport as being the second largest inflicting part when a transportation distance of 100 kilometres was estimated; a variable that could improve a lot if hemp were cultivated more widely in the future (Bevan, Woolley & Pritchett 2008). Other studies have shown similar results (Ip & Miller 2012, Zampori, Dotelli & Vernelli 2013).

In Haufe & Carus' (2011) review over different life cycle assessments on hemp they presented a study done by one of the authors, Carus et al. (2008), that looked at the primary energy use during hemp production separately. The agricultural input of fertilizers was shown to be the largest contributor here as well but farm machinery/diesel use on field however had a larger impact than transport, the later being a variable that naturally can be estimated differently (Haufe & Carus 2011). The total primary production energy for hemp straw was here appreciated to be 5 GJ/tone, but claims of around 2,5-3,8 MJ/kg have been made in other references (Haufe & Carus 2011, p.6, Woolley 2013, p.138, Zampori, Dotelli & Vernelli 2013, p.7418). It is stated in literature that the primary production energy used in the processing of hemp is much higher than it would need to be due to out-dated technology and mechanization processes (Bocsa & Karus 1998).



Primary energy use in the different stages of hemp fibre production

(Haufe & Carus 2011, p.6)

Hemp fiber insulation

Hemp fibres constitute the outer part of the stalk (Bócsa & Karus 1998, Svennerstedt 2003, Franck 2005). They are considered to be more valuable than the shiv, which is often regarded as a by-product (Franck 2005, Bevan, Woolley & Pritchett 2008). Hemp fibres are light and have high tensile strength (Svennerstedt & Svensson 2004, Sedan et al. 2008). Insulation made out of hemp fibres can be used in several ways. Hemp fiber wool can be used in its natural form as main insulation material, as a sealant around windows or as reinforcement in renders, plasters and cement (Svennerstedt 2003, Eriksson 2008, Haufe & Carus 2011, Stanwix & Sparrow 2014). Other European countries produce finished hemp fiber battens/quilts and boards (Svennerstedt 2003, Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Hemp fiber battens do commonly have a lighter density than fiber wool and will thus need to be enforced with other fibres for form stability and binding force, both biodegradable and synthetic alternatives are available on the market (Svennerstedt 2003, Haufe & Carus 2011, Stanwix & Sparrow 2014, Thermo Natur 2015). Hemp fibres and shiv can also be used in particleboards and MDF's (Svennerstedt 2003, Svennerstedt & Svensson 2004, Franck 2005, Bevan, Woolley & Pritchett 2008, Eriksson 2008, Haufe & Carus 2011). Using hemp fibres instead of wood fibres in boards is a bit more expensive but quite advantageous since they are lighter and stronger and can be re-grown annually (Svennerstedt 2003, Eriksson 2008).

(Grundvall 2016)

Declaration:

(Grundvall 2016)

Hemp fiber wool

- Hemp fiber wool (100 %)

100 % biodegradable

(Svennerstedt & Svensson 2004, n.p.)

(Grundvall 2016)

Hemp fiber batten 1

- Hemp fiber wool (85-90 %)
- Cornstarch fibres (8-10 %)
- Soda (2-5 %)

100 % biodegradable

(Thermo Natur 2015, n.p.)

Hemp fiber batten 2

- Hemp fiber wool (85-90 %)
- Polyolefines/polyester fibres (8-10 %)
- Soda (2-5 %)

90 % biodegradable

(Thermo Natur 2015, n.p.)

Environmental profile

Hemp fiber batten (Grundvall 2016)

CHEMICAL PROFILE

Hemp fibres are 100 percent biodegradable and can be used as fiber wool without additives (Svennerstedt 2003, Lawrence et al. 2013). They do not contain any proteins and are also naturally resistant to bacteria, vermin, mould and fungus why there is no need for impregnation treatments (Hugues, Steiger & Weber 2004, Bokalders & Block 2014, Thermo Natur 2015). Dust from hemp does not contain any dangerous nano particles but can still be an irritant for the airways why face protection during construction is recommended (Franck 2005, Norberg 2009, Thermo Natur 2015). It is said to be tolerable for our skin though, and not cause any itching (Svennerstedt 2003, Lawrence et al. 2013, Thermo Natur 2015).

Boron substances, which are regarded as moderately poisonous, are sometimes used as fire retardants in hemp fiber battens (Bevan, Woolley & Pritchett 2008, Berge 2009, Woolley 2013, Zampori, Dotelli & Vernelli 2013). Safe and harmless agents such as soda or ammonium phosphate can also be used (Svennerstedt 2003, Hugues, Steiger & Weber 2004, Berge 2009, Thermo Natur 2015). Support fibres can constitute up to 15 percent of hemp battens weight (Svennerstedt 2003, p.34, Haufe & Carus 2011, p.10, Woolley 2013, p.13). A biodegradable alternative used is cornstarch fibres (Thermo Natur 2015). Synthetic support fibres are commonly made out of polyolefines/polyester fibres (Svennerstedt 2003, Berge 2009, Woolley 2013). These are not toxic substances but they do make the product less natural and more difficult to decompose (Svennerstedt 2003, Berge 2009, Stanwix & Sparrow 2014).

CARBON FOOTPRINT AND ENERGY USE

Hemp fiber wool *

	kg CO^2/kg	*kg CO^2/m³*	*ref.*
CO^2 emissions during manufacture:	**0,11**	**7**	1
CO^2 sequestration:	**-1,84****	**-110**	1
CO^2 emissions during incineration:	**-**		
	MJ/kg	*MJ/m³*	*ref.*
Energy use during manufacture:	**2,5-3,8**	**150-228**	4,1
Combustion value:	**-17**	**-1020**	2

* based on the density 60 kg/m³

** the estimated figure can vary between 1-2,9 kg CO^2/kg, see page 41

Hemp fiber batten 1 *

	kg CO^2/kg	*kg CO^2/m³*	*ref.*
CO^2 emissions during manufacture:	**2,18**	**83**	3
CO^2 sequestration:	**-1,89**	**-72**	3
CO^2 emissions during incineration:	**-**		
	MJ/kg	*MJ/m³*	*ref.*
Energy use during manufacture:	**29,8**	**1132**	3
Combustion value:	**-17**	**-646**	2

* based on the density 38 kg/m³

Hemp fiber batten 2 *

	kg CO^2/kg	*kg CO^2/m³*	*ref.*
CO^2 emissions during manufacture:	**1,86**	**71**	3
or	**1,4**	**53**	2
CO^2 sequestration:	**-1,39**	**-53**	3
or	**-0,78**	**-30**	2
CO^2 emissions during incineration:	**0,3**	**11**	2
	MJ/kg	*MJ/m³*	*ref.*
Energy use during manufacture:	**35**	**1330**	3
or	**40**	**1520**	2
Combustion value:	(**-17**)	(**-646**)	2

* based on the density 38 kg/m³

CO^2 emissions during manufacture

How much carbon dioxide emissions a material's production accounts for, ”from cradle to gate”.

CO^2 sequestration

How much carbon dioxide a material is able to store during its production and user phase, ”from cradle to grave”.

CO^2 emissions during incineration

How much carbon dioxide emissions a material's combustion at the end of life accounts for.

Energy use during manufacture

How much energy a material uses during its production phase, ”from cradle to gate”.

Combustion value

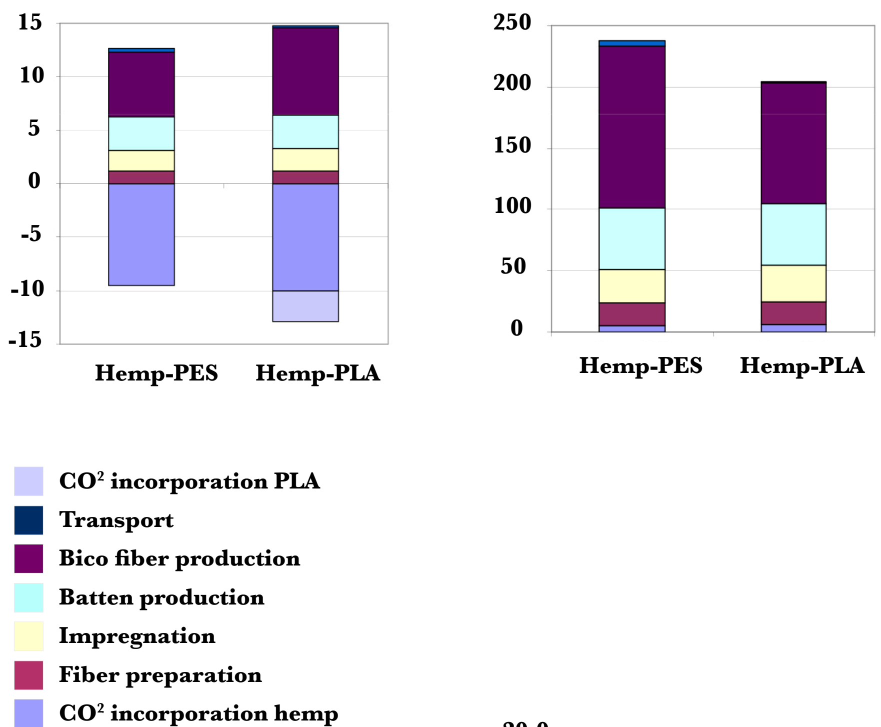
How much energy that could be recovered at the end of life if the product is incinerated. Brackets indicate that the combustion value is less available due to additives demanding purification.

References

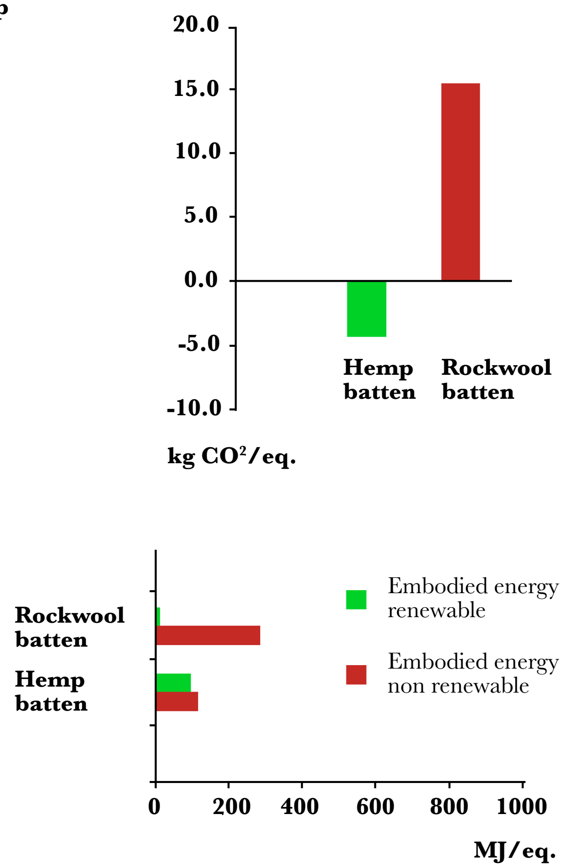
1. Zampori, Dotelli & Vernelli 2013, p.7417-7418
2. Berge 2009, p.26,46
3. Bos & Deimling 2005, n.p.
4. Woolley 2013, p.138

Global warming potential (kg CO2/eq. insulating batten)

Non-renewable energy demand (MJ/eq. insulating batten)



(Bos & Deimling 2005, n.p.)



(Zampori, Dotelli & Vernelli 2013, p.7418-7419)

Hemp fiber wool's energy use and carbon dioxide emissions from production are evidently much lower than hemp battens in general, since no processing is involved nor support fibres added. As much as three fourths of the emitted carbon dioxide as well as more than half of the embodied energy from production can in some cases be due to the addition of support fibres (Bos & Deimling 2005, n.p., Haufe & Carus 2011, p.10, Zampori, Dotelli & Vernelli 2013, p.7418-19).

The figures for hemp battens on the previous page are taken from a life cycle assessment where these two types of insulation battens were compared to one another; the biodegradable batten with cornstarch (polylactic acid/PLA) and the one with polyester support fibres (PES), shown in the graphs to the left (Bos & Deimling 2005). In both these specific products around half of the embodied energy and a substantial part of the greenhouse gas emissions from production were due to the bi-component fibres added (Bos & Deimling 2005, n.p). The PLA batten actually used up the highest amount of carbon dioxide, but when including sequestration, it achieved better values, since corn absorbs carbon dioxide as well (Bos & Deimling 2005). Even though the PLA batten uses somewhat lower amounts of energy compared to the PES batten, both of their energy use and carbon dioxide emissions during production is substantial (Bos & Deimling 2005). They are manufactured by the same company, which however claim to only use eco-electricity and the PLA batten has received many environmental awards such as Nature plus, Stiftelsen varutest, Miljömedicin och Bygghälsa and R-symbolen (Thermo Natur 2015).

Another study, shown to the left, compared a one square meter hemp fiber batten with synthetic support fibres with a rockwool batten, both corresponding to a similar U-value (Zampori, Dotelli & Vernelli 2013). Two thirds of the greenhouse gases emitted by the hemp batten was calculated to be due to the polyester fibres even though this was fully compensated by the hemp sequestration in this study (Zampori, Dotelli & Vernelli 2013, p.7418). The sum (use and sequestration) were as follows (the exact value for the rockwool batten was not given):

Hemp batten: **-4,28** kg CO^2/functional unit = **-21,4** kg CO^2/m^3 or **-0,71** kg CO^2/kg

As for the production energy use, the differences were not as striking even though the hemp batten allowed for a reduction of 28,8 percent in comparison to the rockwool batten (Zampori, Dotelli & Vernelli 2013, p.7419). Around half of the energy use for the hemp batten was appreciated to be energy from a renewable source however, which would mean a reduction of 67 percent if only accounting for the non-renewable energy (Zampori, Dotelli & Vernelli 2013, p.7419). The figures for the total energy use were as follows:

Hemp batten: **215,5** MJ/functional unit = **1077,5** MJ/m^3 or **36** MJ/kg
Rockwool batten: **302,2** MJ/functional unit = **1888,8** MJ/m^3 or **47** MJ/kg

Thermal performance

THERMAL TRANSMITTANCE

The thermal conductivity/lambda value of hemp fiber wool can as with all natural materials vary a bit depending on, for example, species type or cultivation- and harvesting circumstances (Norberg 2009). Different processing methods can have an influence on the fiber quality as well; freeze-dried/winter retted hemp can actually produce a fiber with a lower thermal conductivity than a fiber harvested during the autumn's flowering peak (Johansson & Olofsson 2009, Norberg 2009). Finer chopped fibres will usually give a more advantageous insulation value and density also play a significant role (Johansson & Olofsson 2009, Norberg 2009). Thermal conductivity tests have been performed by the SP Technical Research Institute of Sweden (Johansson & Olofsson 2009). The results do commonly vary between 0,043-0,054 W/mK, where the lowest figure refers to Swedish winter retted finer chopped hemp fibres with the density 50 kg/m^3 (Johansson & Olofsson 2009, p.11, Norberg 2009, p.31). The value 0,0457 W/mK has been noted in tests samples with the density 60 kg/m^3 that is recommended for walls. Densities of 22 and 28 kg/m^3 have also been tested for thermal conductivity performance but they actually showed higher lambda-values; 0,0667 and 0,0601 W/mK respectively (Johansson & Olofsson 2009, p.11, Norberg 2009, p.31). This is unusual since lower densities usually come with a better insulative performance.

Compared to hemp fiber wool, hemp fiber battens do generally have a lower lambda value around 0,04 W/mK even though they are lighter with a common density around 38 kg/m^3 (Bos & Deimling 2005, n.p., Norberg 2009, p.31, Thermo Natur 2015, n.p.). This might be due to the unprocessed fibres being thicker and less rinsed (Norberg 2009).

HEAT STORAGE

Hemp fiber wool and battens are regarded as lightweight insulation materials. This means that they can never have any substantial heat storage. Hemp fiber wool is however most thermally efficient around a higher density than many other commonly used lightweight insulation products (Johansson & Olofsson 2009). Both wool and battens do also present exceptionally high specific heat capacity figures, compared to other lightweight- as well as heavyweight materials (Hanffaser Uckermark, Thermo Natur 2015). These factors together do increase the heat storage potential and might thus have a somewhat favourable influence on the overall thermal performance. The figures are listed to the right.

Hemp fiber wool

Thermal conductivity:

λ 0,043-0,054 W/mK*

(Johansson & Olofsson 2009, p.11, Norberg 2009, p.31)

Heat capacity:

c 2,2 kJ/kgK**

$c\rho$ 132 kJ/m^{3}K**

(Hanffaser Uckermark, n.p.)

* based on the density 50-60 kg/m^3

** based on the density 60 kg/m^3

Hemp fiber batten

Thermal conductivity:

λ 0,04 W/mK*

(Bos & Deimling 2005, n.p., Norberg 2009, p.31, Thermo Natur 2015, n.p.)

Heat capacity:

c 2,3 kJ/kgK*

$c\rho$ 87 kJ/m^{3}K*

(Thermo Natur 2015, n.p.)

* based on the density 38 kg/m^3

Hemp fiber wool in floor (Hemp fiber wool in floor, n.d.)

THERMAL EFFUSIVITY

The thermal effusivity of lightweight insulation materials with low lambda values are generally very low since they are meant to hinder heat from being exchanged. The warm surface experience is not relevant in these cases since the materials are used within structures. Based on the references used in my comparison tables on page 54-55, the figures for hemp fiber wool and battens are 78 and 59 $J/m^2Ks^{1/2}$, respectively, which can be compared to around 170 for hemp-lime and 393 for lightweight loam that have much higher densities.

THERMAL DIFFUSIVITY

Based on the same references the thermal diffusivity figures for hemp fiber wool and battens are 3,5 and 4,6 E-07 m^2/s, respectively. Since they have very similar thermal conductivity and capacity values it seems to be the higher packed density of hemp fiber wool that slows down the diffusion rate through the material.

AIRTIGHTNESS & THERMAL BRIDGES

Since airtightness of a climatic envelope is very dependent upon the level of detailing during construction, especially in a cavity wall structure that will need specific air-blocking measures, it is difficult to give a general figure. I have not come across any measures done in buildings with hemp fiber insulation.

Moisture performance

As with most organic materials, hemp fiber insulation is vapour permeable and very absorbent (Svennerstedt 2003, Nguyen et al. 2009, Lawrence et al. 2013). It has hygroscopic properties, meaning that it is able to retain vapour; between 10-20 percent of its mass volume according to different sources (Svennerstedt 2003, Hugues, Steiger & Weber 2004, p.62, Franck 2005, Woolley 2013, p.170, Zampori, Dotelli & Vernelli 2013, Stanwix & Sparrow 2014, p.39). The insulation layer is usually not meant to be used as an indoor humidity regulator but this property is still very beneficial if vapour mistakenly ends up within a wall, as it often does at some point during its lifetime (Berge 2009, Bokalders & Block 2014). Excessive amounts of moisture is always bad since it can compromise materials' stability, insulative performance and also give way for decay and mould (Svennerstedt 2003, Berge 2009, Bokalders & Block 2014). Hemp fibres are however capable of self-drying and recovering quite quickly and are claimed to be more resistant to decay and mould than other plant fibres (Franck 2005, Zampori, Dotelli & Vernelli 2013). They have a vapour diffusion resistance factor of 0,5-1 µ and hemp fiber battens around 1-2 µ (Hugues, Steiger & Weber 2004, p.62, Hanffaser Uckermark, n.p., Thermo Natur 2015, n.p.). Flax fibres, sheep's wool, cellulose and mineral wool have 1-2 µ (Hugues, Steiger & Weber 2004, p.60-62,64).

Construction technique

Hemp fiber wool and battens can be used as direct substitutes for mineral wool in both vapour sealed and vapour open wall structures* (Svennerstedt 2003, Woolley 2013). Hemp fiber wool is most beneficially used as roof or floor insulation with a density of around 50 kg/m^3, but can also be used in walls if sufficiently packed to a somewhat higher density of 60 kg/m^3 (which is about as tightly as is possible to pack the hemp fiber) (Hanffaser Uckermark, n.p.). Higher densities for light insulation wool materials can be both beneficial and disadvantageous. A downside is larger material needs and thus higher transport loads and costs. Benefits are a higher heat storage potential and that the risk of settlements in walls, as well as air movements through them are minimized (Bokalders & Block 2014). For insulation battens, the form stability might be more influenced by the strength and quality of the fibres used than the density itself (Norberg 2009, Johansson & Olofsson 2009).

In roofs it can be practical to blow in fiber insulation in a finished structure to be able to construct a weather shield as well as support under the insulation cavity first (Berge 2009). This has in Sweden been tried out for hemp fiber wool with the same type of equipment used for mineral wool fibres (Johansson & Olofsson 2009). Longer fibres had in this test a tendency to cluster but short fibres worked fine (Johansson & Olofsson 2009). A German hemp fiber supplier uses specially adapted equipment for this (Norberg 2009).

As is common for natural fibres, hemp fibres have good sound and electrical insulating properties (Franck 2005, Hugues, Steiger & Weber 2004, Zampori, Dotelli & Vernelli 2013, Bokalders & Block 2014). A German hemp batten supplier gives a length related flow resistance value of 3.0 kPa•s/m^2 (Thermo Natur 2015, n.p.).

Hemp shiv can according to some be used as loose infill insulation as well but others claim that they need to be protected with a binder or at least some pure lime powder (Bevan, Woolley & Pritchett 2008, Norberg 2009). They do however have a higher thermal conductivity and density than hemp fiber; 0,064-0,072 W/mK and around 100-140 kg/m^3, respectively (Norberg 2009, p.31).

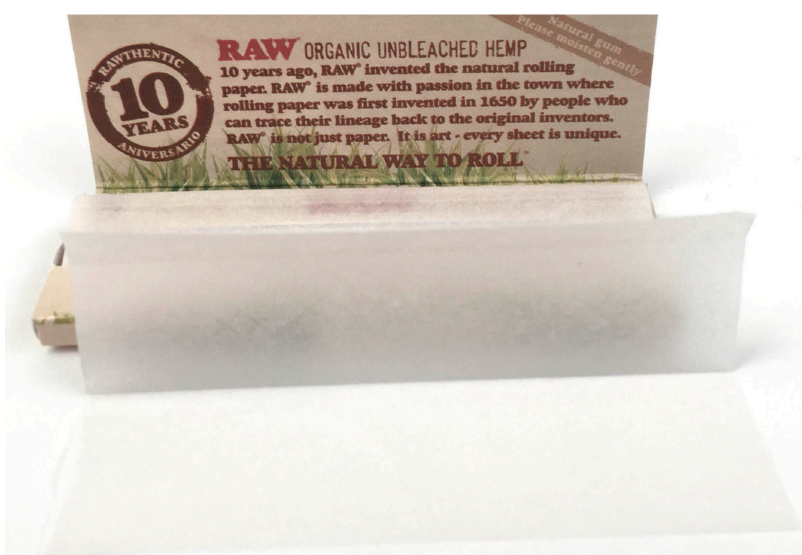
*Hemp fiber insulation can be used in both vapour permeable and impermeable construction types, but is preferably combined with a humidity variable vapour retarder or barrier.**

Hanf-Faser-Fabrik in Uckermark, Germany, uses their own specialized equipment for blowing in hemp fiber wool.

(Norberg, 2009, p.29)

* Hönle, Carina; Thermo Natur GmbH & Co.KG, Germany. 2016. Mail correspondence September 13:th.

Durability and end of life



Hemp fibres are due to their fire resistance sometimes used to make cigarett papers (Bevan, Woolley & Pritchett 2008).

(Hemp cigarette paper, n.d.)

Natural fiber insulation is claimed to be durable and long lasting as well as remain effective over a longer period of time than synthetic equivalents (Lawrence et al. 2013, Woolley 2013). Excess moisture build-ups can of course compromise the workability of all types of fiber insulation (Woolley 2013). Hemp fiber battens without synthetic support fibres are a bit weaker in their structure stability but synthetic fibres are at the same time claimed to have poorer dimensional stability when subjected to moisture (Stanwix & Sparrow 2014). Hemp fiber wool and ecologically marketed hemp battens can be fully biodegradable and retrievable (Zampori, Dotelli & Vernelli 2013, Thermo Natur 2015). If the hemp fibres are left to biodegrade the captured carbon dioxide would naturally be released back into the air though. Hemp fiber battens with added synthetic polyester fibres are not biodegradable as a whole but could be reused or recycled (Thermo Natur 2015). It is also possible to have them incinerated with purification at the end of life (Berge 2009). The combustion value for hemp fiber battens is estimated to be 17 MJ/kg, which means that almost half of the embodied energy from production for those could be able to be compensated at the end of life through energy recovery as waste (Berge 2009, p.26). It is however stated that this might not be a totally accurate figure if the material contains flame-retardants and/or other substances of toxic character (Berge 2009). I would thus assume that pure hemp fibres that have a relatively low embodied energy to begin with could be seen as a good energy resource.

FIRE RESISTANCE

Hemp fiber wool without fire retardants has the fire classification ”Euroclass E”, when tested at a density of 60 kg/m^3 and can thus be used in its natural state, at least in buildings with lower requirements for fire protection (Norberg 2009, Johansson 2010, p.8). When combined with wood based panels or calcium silicate boards the fire classification C has been reached (Hanffaser Uckermark, n.p.). Hemp fibres are actually known for their fire resistancy and would generally need to be exposed to a continuous flame to catch fire why they are sometimes used to make cigarette papers (Svennerstedt 2003, Holstmark 2006, Bevan, Woolley & Pritchett 2008, Norberg 2009). Hemp shiv burns more easily and should not be used in loose form without a fire retardant treatment (Bevan, Woolley & Pritchett 2008, Johansson 2010). Battens and boards with added polyester fibres are also a bit less fire resistant than hemp fibre wool why they are usually impregnated to attain the same fire classification level (Norberg 2009, Thermo Natur 2015).

Comparison tables

I have gathered a little bit of information about a few commonly used insulation materials with similar properties as hemp fiber wool and hemp fiber battens respectively, and compared them to each other. For other materials than hemp the information is, when available, in first hand derived from Berge (2009), except for pricing that comes directly from suppliers. The cost figures can only be seen as indicative since they always vary a lot with different traders and offers. With hemp being such a newly introduced building material on the market, information about hemp fiber wool and battens was not possible to retain from the same main source as the other materials. This information can thus only be seen as a rough estimation and cannot be fully reliable since the data is derived from both different life cycle assessments as well as directly from suppliers, which is far from optimal. If the figures from two separate sources vary considerably, I will show both values to give a more comprehensive picture.

The added volumetric figures are important since different materials have varying densities for the same volume. Two materials could look as though they have the same embodied energy, for instance, when only viewing MJ/kg but one of them might acquire the tenth amount of weight for the same volume. Additionally, it is important to note that the thickness needed for different materials to achieve a certain U-value varies a lot.

The compared materials have been shortly presented after the tables where I have also summarized the findings relative to hemp fiber insulation.

CO^2 emissions during manufacture

How much carbon dioxide emissions a material's production accounts for, "from cradle to gate".

CO^2 sequestration

How much carbon dioxide a material is able to store during its production and user phase, "from cradle to grave".

CO^2 emissions during incineration

How much carbon dioxide emissions a material's combustion at the end of life accounts for.

Energy use during manufacture

How much energy a material uses during its production phase, "from cradle to gate".

Combustion value

How much energy that could be recovered at the end of life if the product is incinerated. Brackets indicate that the combustion value is less available due to additives demanding purification.

Specifics

Lightweight insulation wool	**Hemp fiber wool**	Ref.	**Strawbales**	Ref.	**Cellulose fiber wool**	Ref.	**Rock fiber wool**	Ref.	**Glass fiber wool**	Ref.
Declaration	Hemp fiber wool	2	Straw (Waterglass 5 %)	1	Recycled cellulose 90 % Aluminium hydroxide, Ammonium sulphate & Polyphosphate 10	10	Mineral wool 95 % Bakelite < 4 % Mineral oil < 1 %	8	Glass wool > 90 % Bakelite < 10 % Paraffin oil < 1 %	8
Biodegradability	**100 %**	2	**100 %**	1	**100 %**	10				
Hazardous substances	-	2	-	1	-	10	Man made min. fibres, phenol, formaldehyde, hydrogen cyanide	1	Man made min. fibres, phenol, formaldehyde, borax, quartz	1
Price example SEK/m^3 (ex works, VAT incl.)	**720**	9	**338**	4	**550-750**	5	**592**	6	**300**	7
Density ρ = kg/m^3	**60**	2,3	**90**	1	**45**	1	**45**	6	**18**	1
Thermal conductivity λ = W/mK	**0,0457**	2	**0,052**	1	**0,042**	1	**0,038**	1	**0,038**	1
Heat capacity c = kJ/kgK / $c\rho$ = kJ/m^3K	**2,2 / 132**	3	**1,8 / 162**	1	**1,8 / 81**	1	**1,0 / 45**	1	**1,0 / 18**	1
Thermal effusivity $\sqrt{(\lambda \cdot c\rho)}$ = J/m^2 K $s^{1/2}$	**78,0**		**91,8**		**58,3**		**41,4**		**26,2**	
Thermal diffusivity $\frac{\lambda}{(\rho \cdot c)}$ = E-07 m^2/s	**3,5**		**3,2**		**5,2**		**8,4**		**21,1**	

1. Berge 2009, p.23-26,34,37-39,44-47,85, 284,293-294,297
2. Johansson 2010, p.8
3. Hanffaser Uckermark, n.p
4. Kuusiniemi Gödning, n.p
5. Ericsson, Lars; Ekofiber. 2015. Mail correspondence April 4:th.
6. XL Bygg, n.p
7. Bauhaus, n.p
8. Sunda hus, n.p.
9. Österlen Hampa, n.p.
10. Sjöberg, Peter; Icell Insulation Technology. 2016. Telephone correspondence May 23:rd.

Specifics

Lightweight insulation battens	Hemp fiber batten 1	Ref.	Hemp fiber batten 2	Ref.	Cellulose fiber batten	Ref.	Rock fiber batten	Ref.	Glass fiber batten	Ref.
Declaration	Hemp fibre wool 85-90 % Cornstarch fibres 8-10 % Soda 2-5 %	2	Hemp fiber wool 85-90 % Polyolefines/ polyester fibres 8-10 % Soda 2-5 %	2	Recycled cellulose 80-85 % Polyolefines 5-10 % Aluminium hydroxide, Ammonium sulphate & Polyphosphate 10 %	4	Mineral wool 95 % Bakelite < 4 % Mineral oil < 1 %	6	Glass wool > 90 % Bakelite < 10 % Paraffin oil < 1 %	6
Biodegradability	**100 %**	2	**85-95 %**	2	**90-95 %**	4				
Hazardous substances	-	2	-	2	-	4	Man made min. fibres, phenol, formaldehyde, hydrogen cyanide	1	Man made min. fibres, phenol, formaldehyde, borax, quartz	1
Price example SEK/m^3 (ex works, VAT incl.)	**1797**	2	**1411**	2	**1250**	5	**650**	7	**300**	8
Density ρ = kg/m^3	**38**	3	**38**	3	**45**	1	**30**	1	**18**	1
Thermal conductivity λ = W/mK	**0,04**	3	**0,04**	3	**0,04**	1	**0,038**	1	**0,038**	1
Heat capacity c = kJ/kgK / $c\rho$ = kJ/m^{3}K	**2,3 / 87**	2	**2,3 / 87**	2	**1,9 / 86**	1	**1,0 / 30**	1	**1,0 / 18**	1
Thermal effusivity $\sqrt{(\lambda \cdot c\rho)}$ = J/m^2 K s$^{1/2}$	**59,1**		**59,1**		**58,5**		**33,8**		**26,2**	
Thermal diffusivity $\frac{\lambda}{(\rho \cdot c)}$ = E-07 m^2/s	**4,6**		**4,6**		**4,7**		**12,7**		**21,1**	

1. Berge 2009, p.23-26,34,37-39,44-47,85, 284,293-294,297
2. Thermo Natur 2015, n.p.
3. Bos & Deimling 2005, n.p.
4. Sjöberg, Peter; Icell Insulation Technology. 2016. Telephone correspondence May 23:rd.
5. Isoleringsbutiken, n.p.
6. Sunda hus, n.p.
7. XL Bygg, n.p.
8. Bauhaus, n.p.

Carbon footprint and energy use

Lightweight insulation wool	**Hemp fiber wool**	Ref.	**Strawbales**	Ref.	**Cellulose fiber wool**	Ref.	**Rock fiber wool**	Ref.	**Glass fiber wool**	Ref.
CO^2 emissions - manufacture CO^2/kg	**0,11**	2	**0,005**	1	**0,23**	1	**1,74**	1	**1,7**	1
kg CO^2/m^3	7		0,45		10,35		78,3		30,6	
CO^2 sequestration kg CO^2/kg	**-1,84***	2	**-0,8**	1	**-0,8**	1	**-**	1	**-**	1
kg CO^2/m^3	-110		-72		-36		-		-	
CO^2 emissions - incineration kg CO^2/kg	**-**	1	**-**	1	**-**	1	**0,05**	1	**0,1**	1
kg CO^2/m^3	-		-		-		2,25		1,8	
Energy use - manufacture MJ/kg	**2,5-3,8**	3, 2	**14,5**	1	**19**	1	**20**	1	**35**	1
MJ/m^3	150-228		1305		855		900		630	
Combustion value MJ/kg	**-17**	1	**-14**	1	**(-15)**	1	**(-1)**	1	**(-2)**	1
MJ/m^3	-1020		-1260		(-675)		(-45)		(-36)	

*the estimated figure can vary between 1-2,9 kg CO^2/kg, see page 41.

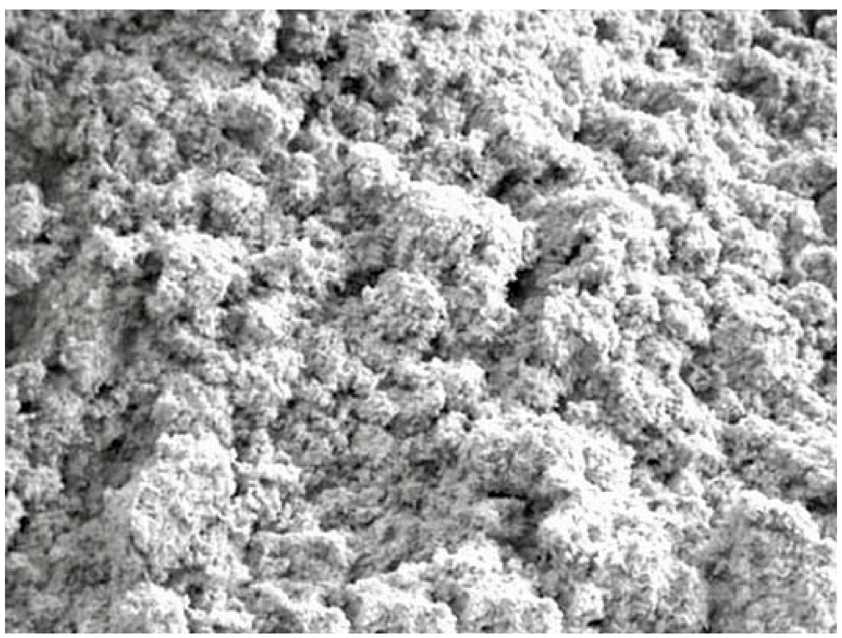
1. Berge 2009, p.23-26,34,37-39,44-47,85, 284,293-294,297
2. Zampori, Dotelli & Vernelli 2013, p.7417-7418
3. Woolley 2013, p.138

Carbon footprint and energy use

Lightweight insulation battens	Hemp fiber batten 1	Ref.	Hemp fiber batten 2	Ref.	Cellulose fiber batten	Ref.	Rock fiber batten	Ref.	Glass fiber batten	Ref.
CO^2 emissions - manufacture kg CO^2/kg	**2,18**	2	**1,86** or **1,4**	2, 1	**1,6**	1	**1,74**	1	**1,7**	1
kg CO^2/m^3	83		71 or 53		72		52		30,6	
CO^2 sequestration kg CO^2/kg	**-1,89**	2	**-1,39** or **-0,78**	2, 1	**-0,775**	1	**-**	1	**-**	1
kg CO^2/m^3	-72		-53 or -30		-35		-		-	
CO^2 emissions - incineration kg CO^2/kg	**-**	1	**0,3**	1	**0,3**	1	**0,05**	1	**0,1**	1
kg CO^2/m^3	-		11,4		14		1,5		1,8	
Energy use - manufacture MJ/kg	**29,8**	2	**35** or **40**	2, 1	**35**	1	**20**	1	**35**	1
MJ/m^3	1132		1330 or 1520		1575		600		630	
Combustion value MJ/kg	**-17**	1	**(-17)**	1	**(-18)**	1	**(-1)**	1	**(-2)**	1
MJ/m^3	-646		(-646)		(-810)		(-30)		(-36)	

1. Berge 2009, p.23-26,34,37-39,44-47,85, 284,293-294,297
2. Bos & Deimling 2005, n.p.

Straw (Pixel2013 through © CC0 Public Domain, 2016)



Cellulose fiber wool (Cellulose, n.d.)

Flax straw (Putmanbuilt through © 2016 Photobucket, 2012)

STRAW

Straw bale building is a well known ecological building technique in Sweden. The material is cheap and very accessible, being an agricultural by-product to cereal crops (Munch-Andersen & Møller Andersen 2004). It also comes in practical pre-fabricated building blocks/bales (Munch-Andersen & Møller Andersen 2004, Bevan, Woolley & Pritchett 2008, Berge 2009). Straw fibres are a bit susceptible to biological decay and fungus but they can be dipped in a solution with waterglass, thin runny clay or lime gruel for additional rot and fire resistance (Berge 2009, Lawrence et al. 2012, Bokalders & Block 2014). Straw bale walls can in small houses be load-bearing since they are packed to a very high density (Berge 2009). A higher packed density will mean a better heat storage, but at the expense of a poorer thermal conductivity value. Thick walls are often needed to achieve an acceptable U-value in colder climates but the insulative ability is also very different depending on which direction the fibres are placed in (Berge 2009, Bokalders & Block 2014).

CELLULOSE

Cellulose fibres for thermal insulation are mainly made from timber and can be in form of virgin fibres or recycled fibres from newspapers (Berge 2009). Cellulose and many other plant fibers such as hemp basically have the same chemical composition (Bócsa & Karus 1998, Franck 2005, Norberg 2009). Cellulose fibres need protection in form of fire retardants and fungicides in relatively large amounts (Berge 2009). Borates have been used a lot in the past as fungicides but nowadays healthier alternatives like ammonium phosphate and tannin have entered the market (Berge 2009). Water repellents in form of, for example, wood resin can be used and polyester or polyolefines are commonly added as reinforcement in battens (Berge 2009). The paper industry involves high pollution levels as well as large water consumption (Berge 2009). The manufacturing process will leave a substantial amount of lye as a by-product, some of which will be released into nature, and the fibres will contain traces of silica, sulphur and calcium from fillers in the initial paper waste (Berge 2009). Recycled fibres from paper waste are thus preferable over virgin fibres (Berge 2009).

OTHER CROP FIBRES

Many fibres such as, for example, jute, sisal, kenaf, coir and ramie are mainly produced in developing countries and are best suited to be grown in exotic climates (Svennerstedt 2003, Franck 2005, Bokalders & Block 2014). Fibres from developing countries can sometimes be imported for a cheap price but it might however be harder to safeguard the quality and ecological handling for those and long transportation distances are always an issue (Franck 2005).

Flax has a large part of its production in Europe and is probably the best comparative crop grown in our Northern climate since it has very similar properties to hemp and can be used in similar ways (Nilsson 2003, Svennerstedt

2003, Franck 2005). It is, just as hemp, a renewable, high quality, strong bast fiber with low embodied energy (Nilsson 2003, Svennerstedt 2003, Franck 2005, Bokalders & Block 2014). It is also very hygroscopic with the ability of cleaning soils from heavy metals (Nilsson 2003, Svennerstedt 2003, Franck 2005). Flax is somewhat weed and pest resistant, but it will still require a small amount of weed and pest controlling chemicals during its cultivation (Nilsson 2003, Franck 2005). It does not produce as high yield per hectare as hemp but in return, the amount of fertilizers can be lessened (Nilsson 2003, Franck 2005). The cultivation of flax is somewhat skill required and the plant is a bit weather sensitive (Nilsson 2003, Franck 2005). Flax fibres used in building applications are often sprayed with boron salts to increase fire resistance (Nilsson 2003).

MINERAL WOOL

Rockwool and glasswool are produced through a melting process in an oil burner (Berge 2009). Rockwool's main constituents are coke, diabase and limestone (Berge 2009). Glasswool is made from quartz sand, soda, dolomite, lime and up to 65 percent recycled glass (Berge 2009, p. 261). Up to 9 percent borax, and about 5,5 percent phenol-formaldehyde glue is commonly added in glasswool whereas rockwool use a, relative to that, lower amount of around 2 percent of phenol-formaldehyde (Berge 2009, p.261). The production process generates large amounts of waste and smaller amounts of emissions from phenol, ammonia, hydrogen cyanide, formaldehyde and dust (Berge 2009). Mineral wool is vapour permeable but non hygroscopic, why it cannot buffer nor handle moisture without loosing its insulating properties (Bokalders & Block 2014). If subjected to moisture it can be susceptible to mould growth and emissions of toxic, irritant and suspected carcinogenic substances (Berge 2009, Bokalders & Block 2014). Moisture can also pour down at the surface of the material and accumulate in the wooden framework instead (Bokalders & Block 2014). Mineral wool is therefore preferably used in vapour sealed walls (Berge 2009).

Mineral fiber wool (Øyvind Holmstad CC-1.0 Universal Public Domain Dedication, n.d.)

Summary

The properties of cellulose-based plant fibre wool used as insulation can be quite comparable on paper in regards to for example thermal behaviour as well as many times density used (Svennerstedt 2003, Franck 2005). The main claimed benefits of hemp fibre wool are its resiliency in wet conditions, its resistance to decay, mould and infestations and that it is not in need of fire retardants nor chemical treatments (Svennerstedt 2003, Franck 2005, Zampori, Dotelli & Vernelli 2013). It is also a very agronomically attractive crop and a highly effective carbon storer (Bócsa & Karus 1998, Zampori, Dotelli & Vernelli 2013).

Plant-based fibres used for insulation usually accomplish lambda values around 0,04-0,045 W/mK. Straw has a somewhat poorer value though as well as a comparatively higher density used. Mineral wool has a slightly better thermal conductivity value than plant-based materials in general. This figure alone will however not give a full picture of the materials' thermal performance.

Hemp is currently a bit more expensive than other commonly used lightweight insulation alternatives. The price is based on a higher density though, which in the case of hemp fiber wool could give other benefits. In roofs or floors, the somewhat lighter density of 50 kg/m^3 is recommended, which would actually mean a similar price as rock wool and cellulose, with the price figures that I got hold of.

The environmental footprints of many natural fibres are very low compared to mineral wool, especially since they are able to sequester greenhouse gases and possibly be used for energy recovery at the end of life. When made into battens this image changes for cellulose in the same manner as with hemp fibers, both regarding energy use and carbon emissions as well as in some cases biodegradability and possibility for energy recovery. A cellulose batten can have the double price compared to a rock wool fiber batten and a hemp fiber batten almost the triple. With glass wool the difference is even larger.

Hemp-lime

Hemp-lime is a building element mixture made out of hemp shiv, lime binder and water (Bevan, Woolley & Pritchett 2008, Tran Le et al. 2010, Lawrence et al. 2012, Walker, Pavia & Mitchell 2014, Hirst et al. 2015). Sometimes the binder incorporates pozzolanic and/or cementious stabilizers and minor amounts of other additives (Bevan, Woolley & Pritchett 2008, De Bruijn 2012, Lawrence et al. 2012, Walker, Pavia & Mitchell 2014). It is a porous middleweight material that provides both insulation and heat storage (Bevan, Woolley & Pritchett 2008, Tran Le et al. 2010, De Bruijn 2012, Lawrence et al. 2012). It has relatively low levels of failure stress, compressive strength and elastic modulus and can therefore not be load-bearing, as it would settle (Nguyen et al. 2009, De Bruijn 2012, Walker, Pavia & Mitchell 2014, Hirst et al. 2015). This composite material can be cast between or sprayed against permanent or temporary shuttering forming a monolithic, one layered wall element or be prefabricated as building blocks or panels (Bevan, Woolley & Pritchett 2008, Lawrence et al. 2012, Stanwix & Sparrow 2014, Hirst et al. 2015). Trough adjusting densities and mixes, it has also been used successfully in floors and roofs, although this is, by some, still considered somewhat experimental (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014).

(Hemp-lime, n.d.)

Lime powder (Lime powder, n.d.)

Hemp shiv (Grundvall 2016)

LIME BINDER

Lime is a widely used building material with the largest consumer today being the cement industry (Berge 2009). Lime has been used in building applications since around 10 000 BC and has been the main way of preserving timber in housing for centuries due to its natural biocidal properties (Bevan, Woolley & Pritchett 2008, Walker, Pavia & Mitchell 2014). Historically, lime renders used on stone, clay and earth walls have demonstrated good moisture resistance and durability; there are many examples of 2-3000 year-old pure lime mortars on buildings that are still intact (Berge 2009, p.92,200, Daly, Ronchetti, & Woolley 2013).

Lime is produced by heating calcium carbonate coming from limestone, chalk, shells, coral etc. in limekilns to a temperature of about 900-1000 degrees Celsius where it forms calcium oxide, known as quick lime (Bevan, Woolley & Pritchett 2008, p.51, Berge 2009, p.85, Daly, Ronchetti, & Woolley 2013, p.18, Pretot, Collet & Garnier 2014, p.227, Limetec, n.p.). Very pure calcium carbonate sources are used to produce air limes/hydrated limes, which set in the presence of air (Bevan, Woolley & Pritchett 2008, Berge 2009, Limetec). Hydraulic lime is heated quicklime that has reacted with water to form a dry powder (Bevan, Woolley & Pritchett 2008, Berge 2009, Limetec). If excess water is added, the process is called slaking, which will form a lime putty (calcium hydroxide) often used for renders, mortars and concrete (Bevan, Woolley & Pritchett 2008, Berge 2009, Limetec).

In a hemp-lime wall, lime functions as a binder giving the wall some structural strength and stiffness (Stanwix & Sparrow 2014, Walker, Pavia & Mitchell 2014). Lime is a hygroscopic material that is able to buffer moisture (Stanwix & Sparrow 2014). Its alkaline and water-retrieving properties will also protect the shiv and built-in timber structures from biological decay, mould, insect and bacteria attacks (Yates 2002, Evrard & De Herde 2005, Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014, Walker, Pavia & Mitchell 2014).

The type of lime used can strongly influence the quality of the binder (Bevan, Woolley & Pritchett 2008, Walker & Pavia 2014). It is recommended to use lime binders that are specially formulated to be used with hemp shiv; the two main products on the market being *Tradical HB* and *Batichanvre* (Yates 2002, Bevan, Woolley & Pritchett 2008, Limetec). Mixing cheap hydrated lime can, for instance, lead to walls having trouble drying out (Bevan, Woolley & Pritchett 2008, Limetec). There can also be a competition of water between the lime binder and hemp shiv when inappropriate lime binders are used, resulting in damp hemp and dry powder; hemp shiv is very absorbent and lime needs water to be able to set (Bevan, Woolley & Pritchett 2008, Nguyen et al. 2009, Stanwix & Sparrow 2014, Limetec).

SHIV

Shiv, the inner woody core of the hemp stem has a porous cellular structure with air pockets that contributes to favourable insulating as well as hygroscopic properties in hemp-lime (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014, Rahim et al. 2015). It performs substantially better in this particular application than other natural fibres, which can have a greater tendency to rot (Bevan, Woolley & Pritchett 2008, Lawrence et al. 2012). Due to it being a hard cellulosic material, similar to wood, it can tolerate repeated moisture absorption and desorption over an almost indefinite period of time as long as it is not soaked as well as protected by a binder (Stanwix & Sparrow 2014).

The shiv should preferably be dry and well rinsed from dust and fines (small pieces of bast fiber) since some claim that they can, due to their higher pectin content, soak up too much water and delay setting time (Dalmay et al. 2010). Others however state that the kinetics of absorption is quite similar for pure shiv and fibered shiv and that there are successfully built walls with some fiber added why it might not be that critical (Nguyen et al. 2009, Stanwix & Sparrow 2014).

Shiv can besides the hemp-lime wall mixture also be used in hemp-lime renders and mortars (Tran Le et al. 2010).

STABILIZERS

Portions of cement or fibrous, hydraulic and/or pozzolanic materials such as fly- or volcanic ash are sometimes added to the lime binder as stabilizers (Bevan, Woolley & Pritchett 2008, Nguyen et al. 2009, De Bruijn 2012). Cement and pozzolan can also be added as water repellers to quicken the setting and drying time and pozzolan can give a better workability to the mix (De Bruijn 2012, Walker & Pavia 2014). Suppliers that add these strengtheners have not confirmed the exact amount used but it is assumed to be between 15-30 percent for cement and around 10 percent for pozzolan (Bevan, Woolley & Pritchett 2008, p.50, Nguyen et al. 2009, p.1043, De Bruijn 2012, p.43, Pretot, Collet & Garnier 2014, p.226, Rahim et al. 2015, p.2). Adding too much cement and other additives can compromise other important benefits of hemp-lime as well as impact the claimed environmental soundness of the material (Bevan, Woolley & Pritchett 2008, Berge 2009, De Bruijn 2012). There are currently also more environmentally friendly stabilizers in form of clay-based pozzolan and kaolin-clays to obtain metakaolin under development*. The ancient building agent "Roman cement" used in Roman buildings and aqueducts had sand and pozzolan added to the lime making it resistant against both fresh and salt water and is thus a building method proven durable over time (Berge 2009, De Bruijn 2012).

Cement has been tried out as main binder but it is not as compatible with shiv as lime is; lime's slower carbonation process interacts better with the fast water uptake of the shiv and is more flexible in construction (Evrard & De Herde 2005, Bevan, Woolley & Pritchett 2008). Lime is also more porous and permeable and the density and thermal conductivity is lower than that of cement (Evrard & De Herde 2005, De Bruijn 2012).

There is at least one supplier that offers a lime binder without the use of pozzolan and cement with claimed good results and no problems with drying time if climate conditions are respected, but it has yet to date only been used in France, Holland and Belgium, according to Beghin**, administrator for the company.

* Woolley, Tom; Author, Rachel Bevan Architects. 2016. Mail correspondence April 5:th.
** Beghin, Olivier; IsoHemp Natural Building. 2015. Mail correspondence September 6:th.

Declaration:

Hemp-lime 275 kg/m^3

- Hemp shiv (21 %)
- Lime binder (sometimes including cementious/ pozzolanic strengtheners) (36 %)
- Water (43 %)

biodegradable/non biodegradable depending on the additives used

Proportions of the two main constituents vary depending on what characteristics are required but other common used wall mixes can look like this:

220 kg/m^3:

- Hemp shiv - 24 %
- Lime binder - 27 %
- Water - 48 %

330 kg/m^3:

- Hemp shiv - 16 %
- Lime binder - 36 %
- Water - 48 %

(Hirst et al. 2015, n.p., Bevan, Woolley & Pritchett 2008, p.81, Limetec, n.p)

Cement (Gzvezdov through © CC0 Public Domain 2016)

Fly ash (Coal fly ash, n.d.)

Environmental profile

Lime quarry (Susbany through © CC0 Public Domain 2013)

CHEMICAL PROFILE

Hemp-lime is said to be a non-toxic natural material without hazardous emissions (Bevan, Woolley & Pritchett 2008, Woolley 2013, Stanwix & Sparrow 2014, Limetec). This might however be a truth with modification in the cases when fly ash is added as stabilizer, since it can emit poisonous beryllium and soluble sulphates can leach out from its waste disposals into ground waters (Berge 2009, De Bruijn 2012). If that would have any effect on the indoor environment when encapsuled in a building element is a bit unclear though. There are also sometimes unspecified inorganic materials added to lime binders (Limetec). Dust can be an irritant during processing and construction since lime is a very strong alkaline substance that can cause damage to the skin (Berge 2009, Stanwix & Sparrow 2014, Limetec).

Hemp-lime does not require any preservatives nor treatments against vermin (pests) and infestation (herds of parasites for instance) and no problems with that have been noted in built examples (Yates 2002, Bevan, Woolley & Pritchett 2008, Limetec).

Lime is regarded as a non-renewable but we have quite large global reserves of limestone (Berge 2009). The quarrying of limestone can have substantial impacts on the landscape and natural habitat for wildlife, but when extracted from the sea the impact is a bit less (Berge 2009, Daly, Ronchetti, & Woolley 2013).

CARBON FOOTPRINT AND ENERGY USE

	kg CO^2/kg	*kg CO^2/m³*	*ref.*
CO^2 emissions during manufacture:	**0,49**	**135**	1,2
CO^2 sequestration:	**-0,85**	**-234**	1,2,3
CO^2 emissions during incineration:	**-**		2
	MJ/kg	*MJ/m³*	*ref.*
Energy use during manufacture:	**4**	**1099**	4,2
Combustion value:	**-**		2

Figures based on the dry density of 275 kg/m³ with 100 kg shiv (21 %) & 165 kg lime binder (36 %) and the following figures for each component:

Carbon dioxide

- Hemp shiv emissions: 0,11 kg CO^2/kg [1]
- Hemp shiv sequestration: -1,84 kg CO^2/kg [1,3]
- Lime emissions: 0,75 kg CO^2/kg [2]
- Lime sequestration: - 0,30 kg CO^2/kg [2]

Energy

- Hemp shiv use: 2,5-3,8 MJ/kg [4,1]
- Lime use: 4,5-5 MJ/kg [2]

References

1. Zampori, Dotelli & Vernelli 2013, p.7417-7418
2. Berge 2009, p.23,34,44,47,85
3. Bevan, Woolley & Pritchett 2008, p.81
4. Woolley 2013, p.138

Lime is the most environmentally inflicting part of hemp-lime (Bevan, Woolley & Pritchett 2008, Pretot, Collet & Garnier 2014). It can use up to as much energy and emit as much carbon dioxide when produced as cement, which also contains lime (Bevan, Woolley & Pritchett 2008, Berge 2009, Woolley 2013). Calcium-based building products will however absorb carbon dioxide in a carbonation process, where they slowly recarbonate into their original state as calcium carbonate; a process that will also add extra strength and density to them (Bevan, Woolley & Pritchett 2008, Berge 2009, Woolley 2013, Hirst et al. 2015). Some say that lime can be considered more or less carbon neutral due to this but the rate and quantity of this sequestration is in reality not well established and the data is inconclusive why some life cycle assessments do not include this factor at all (Bevan, Woolley & Pritchett 2008, Berge 2009, Ip & Miller 2012, Daly, Ronchetti, & Woolley 2013).

The figures that I have presented are based on a sequestering of around 40 percent of the carbon dioxide emissions released during production. This is a bit conservative since Berge (2009, p.34,47) appreciates the rate to be around 25-50 percent for all calcium-based products, including cements and concretes, which contain other additives as well. Another reference gives a sequestration rate of 58 percent for pure lime (Ip & Miller 2012, p.7). Lime renders are thought to be able to sequester up to 80 percent of their initial carbon dioxide emissions since a very high percentage of the material will be in direct contact with the outside air during the user phase (Berge 2009, p.47). This is naturally different to a 40-centimetre thick hemp-lime wall structure where most of the material will be enclosed within the structure (Berge 2009).

Hemp-lime as a whole is referred to as carbon negative since hemp is said to sequester more carbon dioxide than both hemp and lime release during their lifetime (Bevan, Woolley & Pritchett 2008). For the dry density of 275 kg/m^3, Lime technology (Limetec, n.p.) estimates that cast hemp-lime will sequester 110-165 kg CO^2/m^3 (including carbon dioxide emissions). Ip & Miller (2012, p.7) present a figure around 119 kg CO^2/m^3 for the same density. My estimation of 99 kg CO^2/m^3, seen on the previous page, is based on a lower appreciated carbon storage potential of lime. The exact figure for hemp-lime is hard to appreciate since it depends on a lot of different variables for both main constituents; apart from the evaluated sequestration rates for lime, it also depends on the cultivation circumstances and thus properties of the type of hemp shiv used as well as the compaction rate of the blend (Zampori, Dotelli & Vernelli 2013, Limetec, n.p.).

Using fly ash as stabilizer instead of cement is, even though not being a sound material in itself, more environmentally friendly in terms of energy demand since it is a widely available by-product from coal-fired power stations (Berge 2009, De Bruijn 2012). A reduction of lime's primary energy use in production might also be possible through the use of biomass kilns (Berge 2009).

CO^2 emissions during manufacture

How much carbon dioxide emissions a material's production accounts for, ”from cradle to gate”.

CO^2 sequestration

How much carbon dioxide a material is able to store during its production and user phase, ”from cradle to grave”.

CO^2 emissions during incineration

How much carbon dioxide emissions a material's combustion at the end of life accounts for.

Energy use during manufacture

How much energy a material uses during its production phase, ”from cradle to gate”.

Combustion value

How much energy that could be recovered at the end of life if the product is incinerated. Brackets indicate that the combustion value is less available due to additives demanding purification.

Thermal performance

THERMAL TRANSMITTANCE

A typical thermal conductivity value for hemp-lime is about 0,06-0,09 W/mK, but can vary between 0,05-0,14 W/mK depending on what type of binder is used and the composition and compaction rate of the blend (Bevan, Woolley & Pritchett 2008, p.59, Daly, Ronchetti, & Woolley 2013, p.26, Collet & Pretot 2014b, Stanwix & Sparrow 2014, Walker & Pavia 2014, p.275, Limetec, n.p.). The more lime used, the greater the density, heat storage, stiffness and strength will be, but at the expense of a poorer insulative performance (Bevan, Woolley & Pritchett 2008, Nguyen et al. 2009, De Bruijn 2012, Walker & Pavia 2014, Hirst et al. 2015). Since hemp-lime walls are non load-bearing a lighter mix with less lime is often preferred, at least in colder climates (Bevan, Woolley & Pritchett 2008, De Bruijn 2012).

Thermal behaviour in-situ

Houses built with hemp-lime walls do seem to perform better than their estimated U-values indicate (Yates 2002, Lawrence et al. 2012). In the report over the houses at Haverhill, the Building Research Establishment (BRE) in the UK conducted a comparison between a conventionally built brick house with rockwool cavity infill and a hemp-lime house of the same model next to each other (Yates 2002). The U-value calculations prior to building indicated that the hemp-lime house would use significantly more energy than the brick house (Yates 2002). Their investigation however showed equivalent energy consumption rates for the different construction types, and with the same amount of heat input, the hemp-lime house gave a 1-2 degrees Celsius higher indoor temperature as well as less condensation (Yates 2002, p.40). Hemp lime's warm walls did also contribute to a higher perceived temperature in rooms for occupants and could thus hold down the use of heat (Yates 2002).

Limetec's hemp-lime wall mix

Thermal conductivity:

λ 0,06 W/mK*

(Limetec, n.p.)

* based on the density 275 kg/m^3

(Allin 2012, by permission of BRE, p.58)

Houses at Haverhill, Suffolk, UK
Brick house, front elevation

Houses at Haverhill, Suffolk, UK
Hemp-lime house, front elevation

HEAT STORAGE

Hemp-lime is in some ways comparable with cellular concrete that is also a middleweight material that incorporate both insulation and good heat storage in relation to its weight (Maalouf et al. 2011a). In the study below where cellular concrete has a higher density, it is however shown to store around 30 percent more energy per surface area than hemp-lime, but at the expense of a poorer thermal conductivity value (Maalouf et al. 2011a, n.p.). The heat capacity for hemp-lime vary a lot depending on the specific blend used. According to the supplier Limetec (n.p.), their hemp-lime mix with the density 275 kg/m^3 has a storage potential of 1500 J/kgK (1,5 kJ/kgK) and Evrard & De Herde (2005, n.p.) give the figure 1550 J/kgK (1,55 kJ/kgK) for a mix with the density 480 kg/m^3. This is quite different compared to 1000 J/kgK (1,0 kJ/kgK) shown in the study below (Maalouf et al. 2011a, n.p.).

The study below also reveal that the amount of stored energy in hemp-lime and cellular concrete increases more with wall thickness than the other presented materials (Maalouf et al. 2011a). Earth block, solid brick and concrete are all heavy materials with substantial heat storage, meaning high capabilities of storing energy already at a thickness of 2,5 centimetres (Maalouf et al. 2011a, n.p.). The utilization of the heat capacity is very high for hemp-lime, cellular concrete and earth blocks, especially at 2,5 centimetres (Maalouf et al. 2011a, n.p.). A high heat capacity figure is thus not totally linear with actual performance since different materials are differently responsive and have varying surface resistances (Ståhl 2009, Maalouf et al. 2011a, Woolley 2013). The periodic heat storage capacity of a material is generally at a peak level at its specific periodic penetration depth why that can be an important factor to consider when deciding upon which thickness to use for thermal buffering (Ståhl 2009). The periodic penetration depths for cellular versus regular concrete during a 24 hour period are for example 9 and 15 centimetres respectively (Hagentoft 2001, p.38).

Periodic penetration depth (m)

The depth at which a temperature shift at the surface of a material has been reduced to 37 percent of its original amplitude, a dampening factor that is depended upon a material's thermal diffusivity (Ståhl 2009, p.17-18).

Limetec's hemp-lime wall mix

Heat capacity:

c 1,5 kJ/kgK*

cρ 440 kJ/m^{3}K*

(Limetec, n.p.)

* based on the density 275 kg/m^3

L = 0.025m	Thermal heat capacity per surface area Wh/m² °C	Stored energy (Qcalc) per surface area for sinusoidal variation of (±1C) Wh/m² °C	Effective heat capacity %
Hemp concrete	3.1	6.09	98
Cellular concrete	4.5	8.7	97
Solid brick	12.8	21.04	82
Earth block	11.5	21.74	95
Concrete	15.3	23.7	77
L=0.1 m			
Hemp concrete	12.50	12.6	50
Cellular concrete	17.33	17.7	51
Solid brick	51.39	31.2	30
Earth block	46.04	30.7	33
Concrete	63.89	33.6	26

Calculation of the surface heat capacities and the fraction of heat capacities effectively used for thicknesses of 2,5 and 10 centimetres in different materials

(Maalouf et al. 2011a, n.p.)

Material	Density Kg/m^3 ***ρ***	Thermal conductivity W/m K ***λ***	Specific heat J/(Kg K) ***c***
Hemp concrete	450	0.11	1000
Cellular concrete	650	0.2	1000
Brick	1850	1	1000
Earth block	1950	0.87	850
Concrete	2300	1.75	960

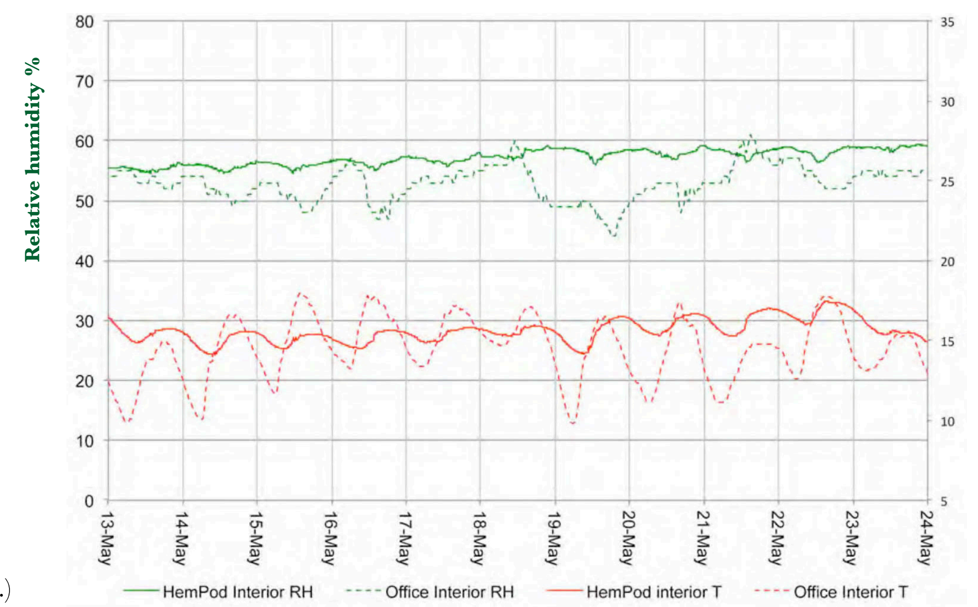
Physical properties of materials

(Maalouf et al. 2011a, n.p.)

The Hempod test house (Hempod test house 1, n.d.)

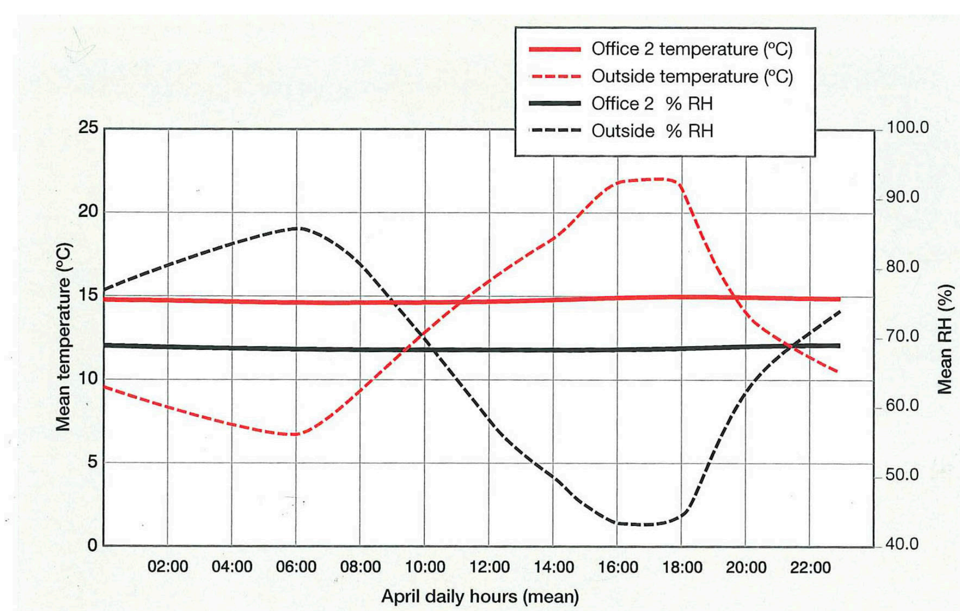
Lime Technology Ltd head office, Oxfordshire, UK (Pritchett, n.d.)

A comparison was made over the temperature and humidity stabilizing ability of two small houses, "the HemPod" with 20 centimetres thick hemp-lime walls (solid lines) and a small office house with 15 centimetres thick mineral wool walls (dotted lines) (Lawrence et al. 2012). There it was clearly shown that the house with the hemp-lime walls gave a much more stable indoor climate as well as a higher mean temperature even though the two different walls corresponded to a similar U-value (Lawrence et al. 2012). Hemp-lime is however only able to give a stable temperature in locations where there are no heavy and fast occuring surpluses in internal heat gains (Bevan, Woolley & Pritchett 2008, Maalouf et al. 2011a).



Monitoring of the Hempod and a similar sized small office with mineral wool walls

(Lawrence et al. 2012, n.p.)

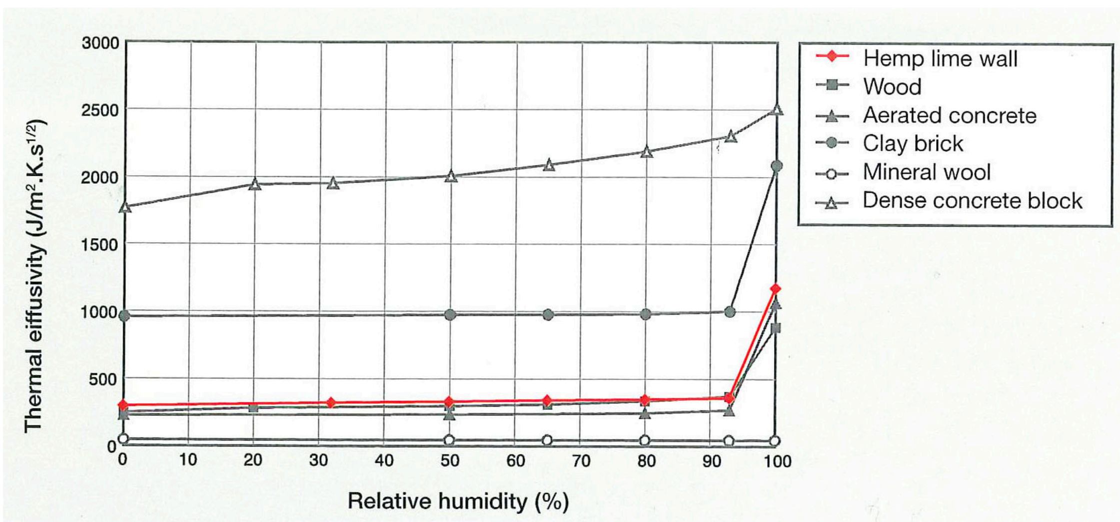


In-situ monitoring during April 2007 of the Lime Technology Ltd head office, UK, where 50 centimetres thick hemp-lime walls have been used.

(Bevan, Woolley & Pritchett 2008, p.69)

THERMAL EFFUSIVITY

The thermal effusivity rating for hemp-lime is quite low and in the graph below, where it had the density 480 kg/m^3, it was comparable to the values for wood, cellular concrete and woodwool cement (the later only shown in my comparison table, page 82) (Bevan, Woolley & Pritchett 2008, p.68, Träullit, n.p.). A lighter density mix of hemp-lime, 275 kg/m^3, would receive a figure around 170 J/m^2.K.s$^{1/2}$, based on the values from the sources in my comparison table, page 82. In these materials the energy storage is thus mediocre but the lower effusivity will on the other hand give a pleasant warm surface that can be experienced in direct contact with the material.



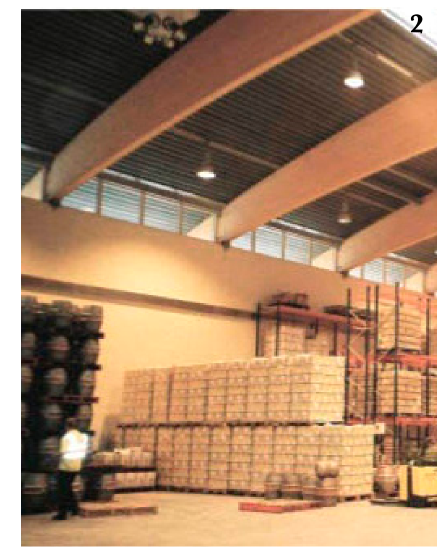
Thermal effusivity of various materials

(Bevan Woolley & Pritchett 2008, p.68)

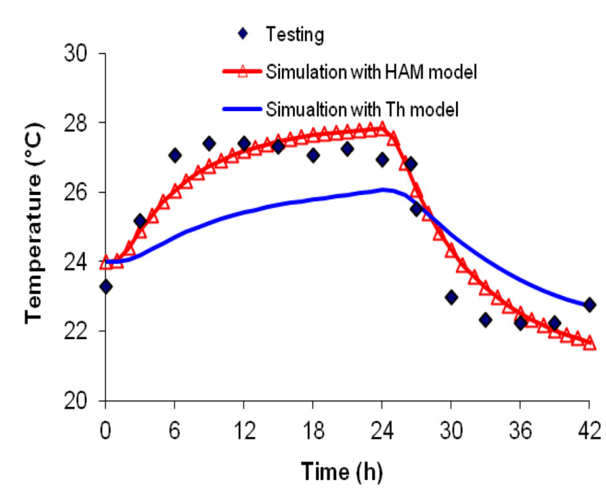
Adnams Brewery, Suffolk, UK

This building with hemp-lime walls has the ability to obtain an, for this particular business, optimal internal temperature between 12-14 degrees Celsius without the need for mechanical cooling or heating systems (Bevan Woolley & Pritchett 2008, p.20, Daly, Ronchetti, & Woolley 2013).

(Limetec through © 2016 Linkedin Corporation Slide share, 2011)

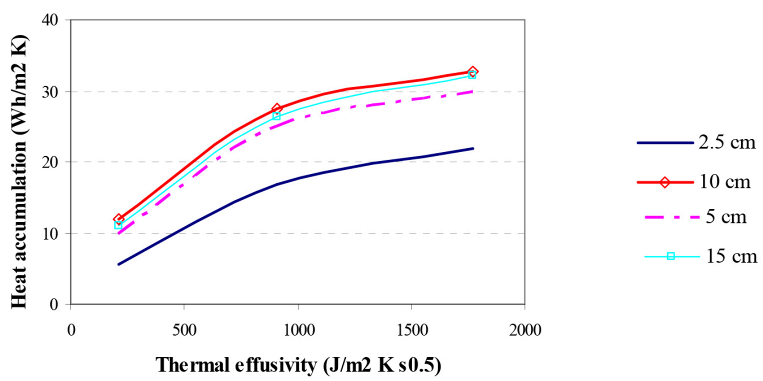


The graph to the right shows the heat flux for two hemp-lime wall samples, one that takes moisture transfer into account (HAM-model) and one that does not (TH-model) (Tran Le et al. 2014). The temperature within the wall will increase when moisture absorption occurs and decrease during desorption periods (Tran Le et al. 2014). The same is true for the surface temperature (Maalouf et al. 2011a). The building's energy consumption is lower during absorption and higher during desorption (Olalekan et al. 2006).

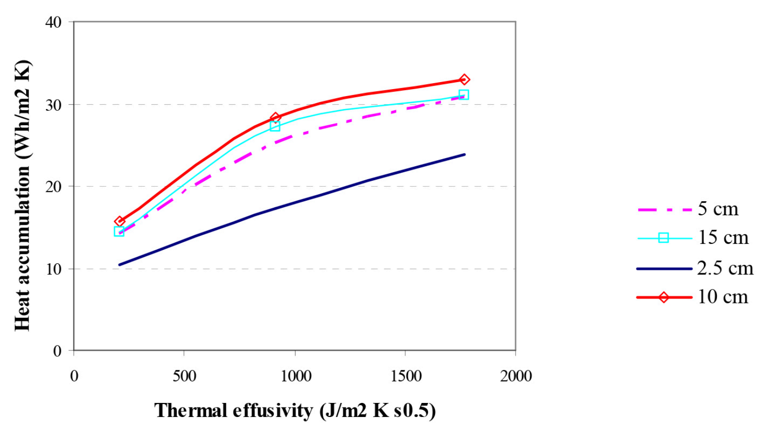


Effect of HAM and TH models on the temperatures profiles in the middle of the wall

(Tran Le et al. 2014, p.524)



TH model: variation of the sensible stored energy within the wall as a function of material effusivity



HAM model: variation of the sensible stored energy within the wall as a function of material effusivity

(Maalouf et al. 2011b, p.1130-1131)

The graphs to the left visualises how much the stored energy changes with wall thickness for hemp-lime and also that it is a function of the material's effusivity (Maalouf et al. 2011b). At 15 centimetres the accumulated energy will actually decline somewhat, implying that the material's periodic penetration depth is reached after 10 centimetres (Maalouf et al. 2011b, p.1130-1131). These tests were done on two different models; one that did not take moisture transfer into account (TH-model) and one that did (HAM-model) (Maalouf et al. 2011b). The sample that took moisture transfer into account stored 40 percent more energy than the one that did not at 2,5 centimetres thickness (Maalouf et al. 2011b, p.1130-1131). At 10 centimetres thickness the difference was 30 percent (Maalouf et al. 2011b, p.1130-1131). Water in a material will thus give it greater density, heat storage and effusivity rating but at the expense of a higher thermal conductivity value (Maalouf et al. 2011b, De Bruijn 2012, Collet & Pretot 2014b). Water uptake can also increase time lag slightly in a hemp-lime wall, but that is not true for all materials (Maalouf et al. 2011b,c).

How does moisture buffering in the thermal envelope affect the energy consumption of a building?

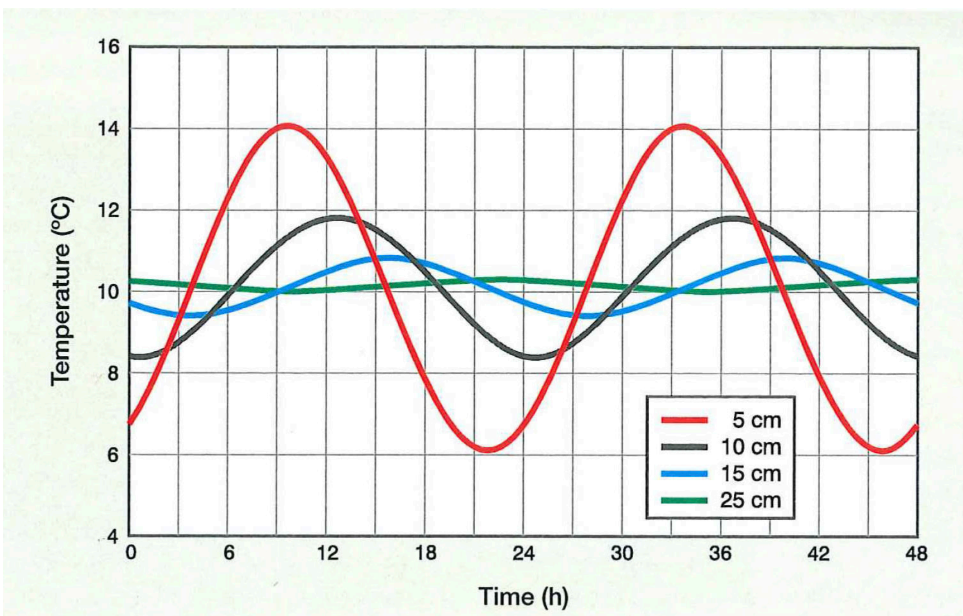
Maalouf et al. (2011c,d) have shown in several studies that the increase in heat capacity have been higher in relation to the increase in thermal conductivity when a hemp-lime wall has been subjected to moisture. One of them revealed that an increase of 6,8 percent in thermal conductivity during a three months' long sorption period equalled an increase of 11,2 percent in heat capacity for a 20 centimetres thick hemp-lime wall (Maalouf et al. 2011c, p.42). A study by another author gave more or less corresponding percentual differences for both parametres (Evrard & De Herde 2005).

The energy consumption of the building is however what is most relevant. Tran Le et al. (2010) showed that the moisture transfer in a hemp-lime wall did not have a significant effect on the heating energy; slightly more energy used when taking moisture buffering into account in this study. Olalekan et al. (2006) presented that the energy consumption during occupation decreased 10 percent when using hygroscopic materials in the walls, compared to non-hygroscopic walls, but at the same time concluded that energy would also be needed to dry out the walls during unoccupied periods, why the net use was nearly equal for both cases. According to Maalouf* the heat consumption will be higher for a house with moisture buffering wall materials if the desorption period in relation to absorption period is longer.

* Maalouf, Chadi; co-author of Tran Le et al. (2010). Université de Reims Champagne-Ardenne. 2015. Mail correspondence December 1:st.

THERMAL DIFFUSIVITY

The thermal diffusivity for hemp-lime is very low, meaning it will take longer for the material to change temperature (Evrard & De Herde 2005, Maalouf et al. 2011a). Hemp-lime with a higher density of 480 kg/m^3 did in the study below show a similar diffusivity value as wood, around 1,40 E-07 m^2/s (Evrard & De Herde 2005, n.p.). This of course varies with different hemp-lime mixes as well as type of timber used. A mix with the density 275 kg/m^3 will have a slightly higher figure around 1,70 E-07 m^2/s, based on the references in my comparison table, page 82. Low thermal diffusivity seems to be a characteristic of many middleweight materials where neither thermal conductivity, heat capacity nor density are spiking in any direction.



(Bevan Woolley & Pritchett 2008, p.67)

Dampening of temperature variation at different wall depths in *Tradical Hemcrete*

Other materials examined in this test showed the following results at 25 centimetres depth:

	Dampening factor (%)	Time shift (hours)
Wood	98,8	16
Hemp-Lime	98,5	15
Cellular concrete	95	10,5
Mineral wool	77,5	6
Concrete	89,5	7

(Evrard & De Herde 2005, n.p.)

Time shift/lag (h)

E.g. the amount of time it takes for a certain temperature on one side of a wall to travel through and be reflected on the other side (Maalouf et al. 2011a).

The Hempod test house (Hempod test house 2, n.d.)

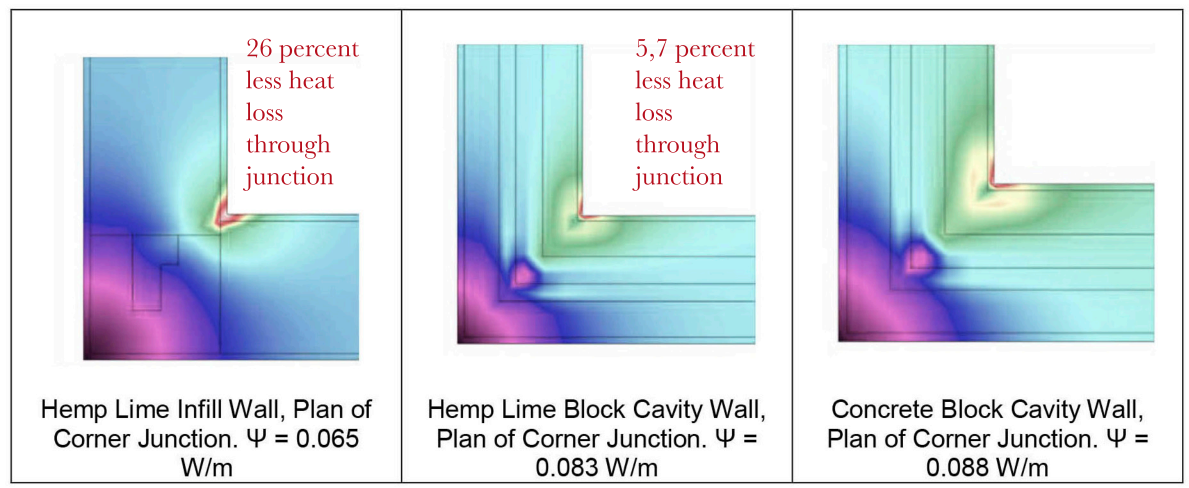
In-situ tests of airtightness in hemp-lime buildings have in some cases shown exceptionally good results (Stanwix & Sparrow 2014). The study of the "HemPod" done by Bath University in the UK, gave the values of 0,55 m^3hr-1m^{-3}, exceeding the PassivHaus standard of < 0,6 m^3hr-1m^{-3}, even with relatively thin walls and a lot of wall surface in relation to floor size, being a very small house (Lawrence et al. 2012, n.p.).

Limetec (n.p.) states that a well constructed house made with their binder Tradical Hemcrete will normally achieve a rating below 2.5 $m^3(m^2h)$@50PA. There have been houses constructed with reported figures between 1-1.5 $m^3(m^2h)$@50PA (Daly, Ronchetti, & Woolley 2013, p.57, Stanwix & Sparrow 2014, p.312).

AIRTIGHTNESS & THERMAL BRIDGES

A solid wall of hemp-lime in one monolithic element will not be at risk of having air leakages through the material, which often occurs in conventional walls with several layers where one needs to put a lot of effort in making sure that they are carefully sealed (Bevan, Woolley & Pritchett 2008). It will also remain airtight over time (Limetec). Airtightness will further improve significantly with plastered/ rendered surfaces (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014).

A wooden frame structure embedded inside a hemp-lime wall will not become a thermal bridge since the thermal conductivity is not that different to hemp-lime (Bevan, Woolley & Pritchett 2008, Collet & Pretot 2014a, Pretot, Collet & Garnier 2014). Images taken with thermographic cameras in a number of hemp-lime houses reveal that there are almost no thermal bridges through the walls (Bevan, Woolley & Pritchett 2008, Allin 2012).



Linear thermal transmittance modelling using Therm 5.2 showing reduced thermal bridges at junctions

(Daly, Ronchetti, & Woolley 2013, p.57)

Houses at Haverhill, Suffolk, UK:
In-situ comparison of two identical house designs with different wall build-up's through thermographic images

Brick house with rockwool cavity infill

Hemp-lime house with a higher U-value

(Allin 2012, by permission of BRE, p.58)

Moisture performance

Hemp-lime is a vapour diffusion open and hygroscopic material (Tran Le et al. 2010, Dubois, Evrard & Lebeau 2012, Collet & Pretot 2014a, Rahim et al. 2015). Hemp's cellulose and hemp-lime's unique porosity structure enables it to handle a certain amount of moisture without significant risk of decay, provided that it can dry out again (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014).

MOISTURE BUFFER VALUE (MBV)

Hemp-lime is capable of rapid liquid transfer and has an excellent moisture buffering performance that helps regulate fast indoor humidity fluctuations (> 2 g/(m^2 %RH)) (Tran Le et al. 2010, Dubois, Evrard & Lebeau 2012, n.p., Collet, Pretot & Lanos 2013, n.p., Collet & Pretot 2014a, n.p., Rahim et al. 2015, p.5). Water absorption is actually part of lime's curing process where it over time stiffens and gains strength through carbonation (Bevan, Woolley & Pritchett 2008).

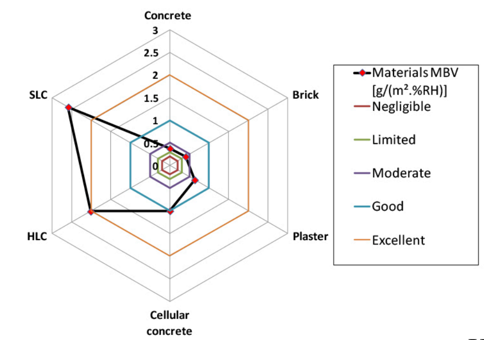
Walls are usually covered with plasters why the moisture buffer value for the chosen plaster needs to be taken into account as well since they in some cases can reduce it (Yates 2002, Tran Le et al. 2010). More information about renders and plasters is presented in the chapter "Renders and plasters" since they are used in combination with both hemp insulation types examined.

VAPOUR RESISTANCE FACTOR

With this high absorbency comes a low vapour resistance factor, $\mu \approx 5$, which could be compared to cellular concrete (7,7), solid brick (9,5), gypsum board (8,3), lime plaster (7,3), cement-lime plaster (19) and concrete (110) (Evrard & De Herde 2005, n.p., Evrard 2006, n.p., WUFI Pro, 2D, Plus 2009, n.p., Walker & Pavia 2014, p.274). The Building Research Establishment (BRE) in the UK has done a water spray test on hemp-lime wall samples (Yates 2002). In this test the water absorption reached about 5-7 centimetres behind the rendered face of the four test walls after 96 hours of massive water spraying, equal to a minimum of one year's wind driven rain on a severly exposed location (Yates 2002, p.23-24).

De Bruijn's (2012) rain exposure test of hemp-lime walls showed a moisture content that increased rapidly. Hemp-lime wall mixes with higher amounts of shiv dried out faster and absorbed moisture more slowly in this study, which indicated that lighter walls might be more preferable in cold and wet climates (De Bruijn 2012).

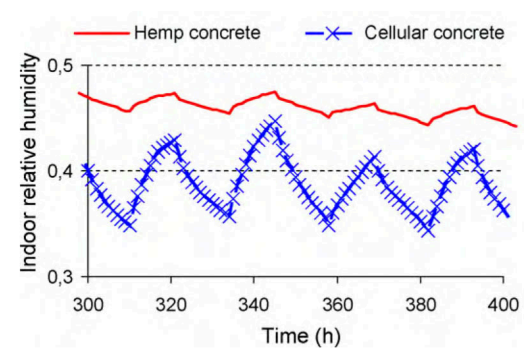
In a heavy prolonged rain exposure test lasting for two weeks, which was done by De Bruijn (2012) as well, the moisture content inside the wooden studs used as load-bearing structure was hardly affected, which kept the risks of rot, decay and microbial growth at a low level.



HLC = Hemp-lime concrete
SLC = Rape straw concrete

Practical MBV of different materials according to the Nordtest project classification

(Rahim et al. 2015, p.5)



Hemp-lime and cellular concrete are both porous materials that will soak up moisture but hemp-lime is much more moisture buffering than cellular concrete (Evrard & De Herde 2005, Tran Le, A. D. et al. 2010).

Variation of relative humidity in hemp-lime and cellular concrete rooms

(Tran Le et al. 2010, p.1804)

Building Research Establishment's 96 hour water spray test on a hemp-lime wall sample

(Yates 2002, by permission of BRE)

The first hemp-lime dwelling in a Swedish climate, Gotland.

(Melkersson 2016, p.2)

Even though having a somewhat lower moisture resistance, test walls of hemp-lime have actually been left out in the rain without renders for several years without deteriorating (Stanwix & sparrow 2014). If they are soaked their thermal performance might however become affected in an unfavourable way why renders are advised (De Bruijn 2012, Stanwix & sparrow 2014). When renders are made with certified materials they should be able to give reasonable moisture resistance, looking at the experience in use (Daly, Ronchetti, & Woolley 2013, Stanwix & Sparrow 2014).

Construction technique

Casting technique (Stanwix & Sparrow 2014, p.28)

Spraying technique (Allin 2012, p.84)

Pre-fabricated wall panels (Lime Technology, n.d.)

CASTING AND SPRAYING TECHNIQUE

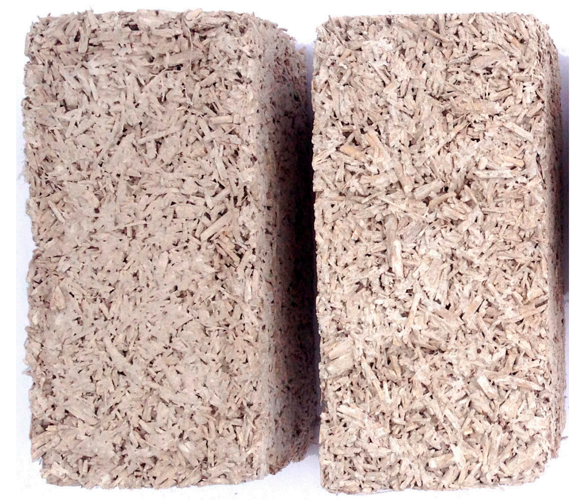
Hemp-lime is most commonly cast in or sprayed onto permanent or temporary shuttering around a structural frame (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). These building techniques create very airtight monolithic wall elements (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Casting in formwork is a simple approach that demands minimal mechanization and spray-application is suitable in larger projects where fast-track construction is required (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Spray-application also ensures another level of consistency concerning density since tamped walls might sometimes become over-tamped and consequently too dense (Bevan, Woolley & Pritchett 2008).

WALL PANELS

There are suppliers that provide pre-fabricated hemp-lime wall panels with a thin layer of hemp fiber quilt added (Stanwix & Sparrow 2014). There are variants with or without a load-bearing structural framework integrated in the panel (Stanwix & Sparrow 2014). This method is mostly used in more rational larger scaled constructions (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). A great benefit is that it ensures sufficient drying in factory anytime of the year (Bevan, Woolley & Pritchett 2008, Lawrence et al. 2013, Stanwix & Sparrow 2014). More mechanization and care during transport is needed though, why they might not be able to claim the same level of environmental credentials as cast-in-situ hemp-lime (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). To achieve good airtightness, greater care sealing joints between elements onsite needs to be taken as well, where junctions between two timber elements are particularly vulnerable since timber shrinks and cracks (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014).

MASONRY BLOCKS

Hemp-lime can also be cast into masonry blocks, which have either a structural or thermal function (Bevan, Woolley & Pritchett 2008, Daly, Ronchetti, & Woolley 2013, Stanwix & Sparrow 2014, Limetec). If used in a structural purpose higher densities are required, typically around 600-1200 kg/m^3 (Daly, Ronchetti, & Woolley 2013, p.51, Stanwix & Sparrow 2014). If used as a thermal layer, densities between 300-500 kg/m^3 are commonly used (Daly, Ronchetti, & Woolley 2013, p.51). Added sand will give the blocks a higher density, stiffness and strength, but at the expense of insulating performance (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Unfortunately this addition will not be enough for them to be able to be used as a load-bearing structure, the way concrete blocks work (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Block construction is more expensive than cast or sprayed hemp-lime walls and the walls will be more difficult to airtighten (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014).



Building blocks (Grundvall 2016)

FLOORS

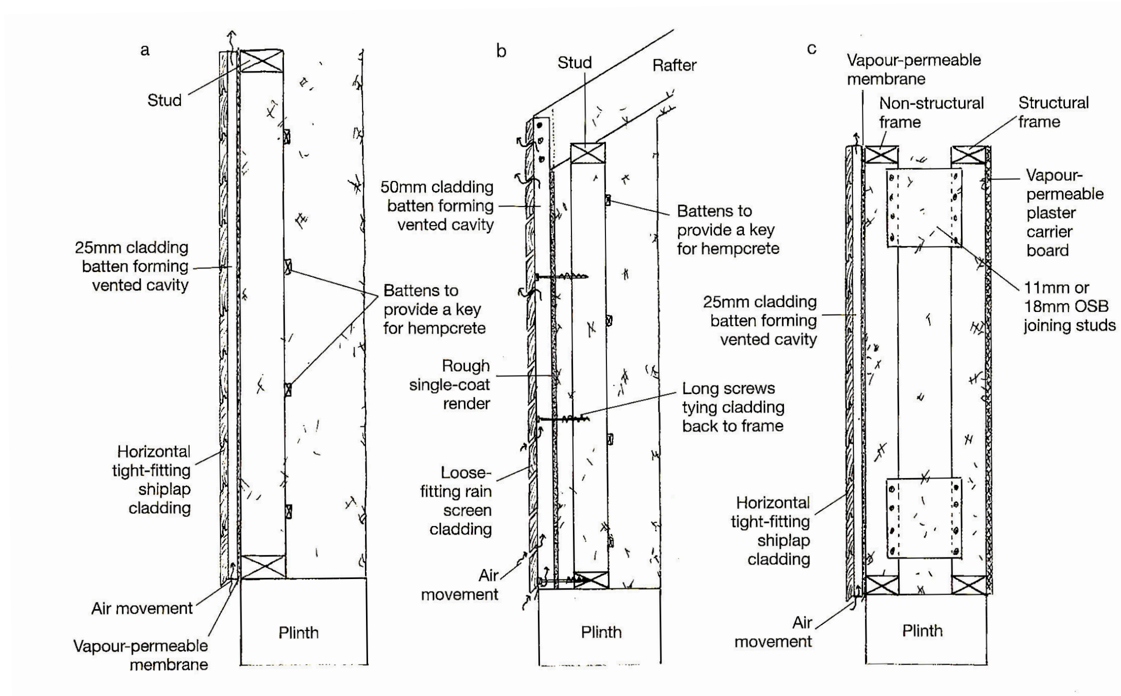
Hemp-lime can be used in intermediate- or in ground floor slabs but might in the later case need appropriate damp proofing measures underneath and higher additions of cement, lime or sand to reach the strength requirements (Bevan, Woolley & Pritchett 2008, Daly, Ronchetti, & Woolley 2013, Stanwix & Sparrow 2014). The British architect Ralph Carpenter however claims to have successfully constructed totally vapour open floor slabs (Bevan, Woolley & Pritchett 2008, Daly, Ronchetti, & Woolley 2013). Hydraulic lime can be waterproof and cope well with wet grounds why limecrete can be used in foundations and footings (Bevan, Woolley & Pritchett 2008). Limecrete resembles concrete but uses hydraulic lime instead of cement (Bevan, Woolley & Pritchett 2008). More or less any type of foundation or footing can be used with a hemp-lime wall though (Bevan, Woolley & Pritchett 2008).

Mechanized pouring technique (Voase 2009)

ROOFS

In France, lightweight hemp-lime is commonly sprayed or poured onto permanent sloping ceiling boards functioning as roofing slabs (Bevan, Woolley & Pritchett 2008). Roof insulation should preferably be as lightweight and highly insulating as possible since a lot of heat transmissions upward. Using hemp-lime in roofs is uncommon in the colder UK and more testing of appropriate mix proportions are needed (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). It can however be used as a thinner, denser packed roof layer functioning as a ceiling board, with additional lightweight thermal insulation on top to gain the benefits of both; airtightness, heat storage, fire proofing and support combined with high insulating ability (Stanwix & Sparrow 2014). Hemp-lime walls can also be combined with other types of roof insulation materials (Stanwix & Sparrow 2014).

Hemp-lime at the eaves (Stanwix & Sparrow 2014, p.302)

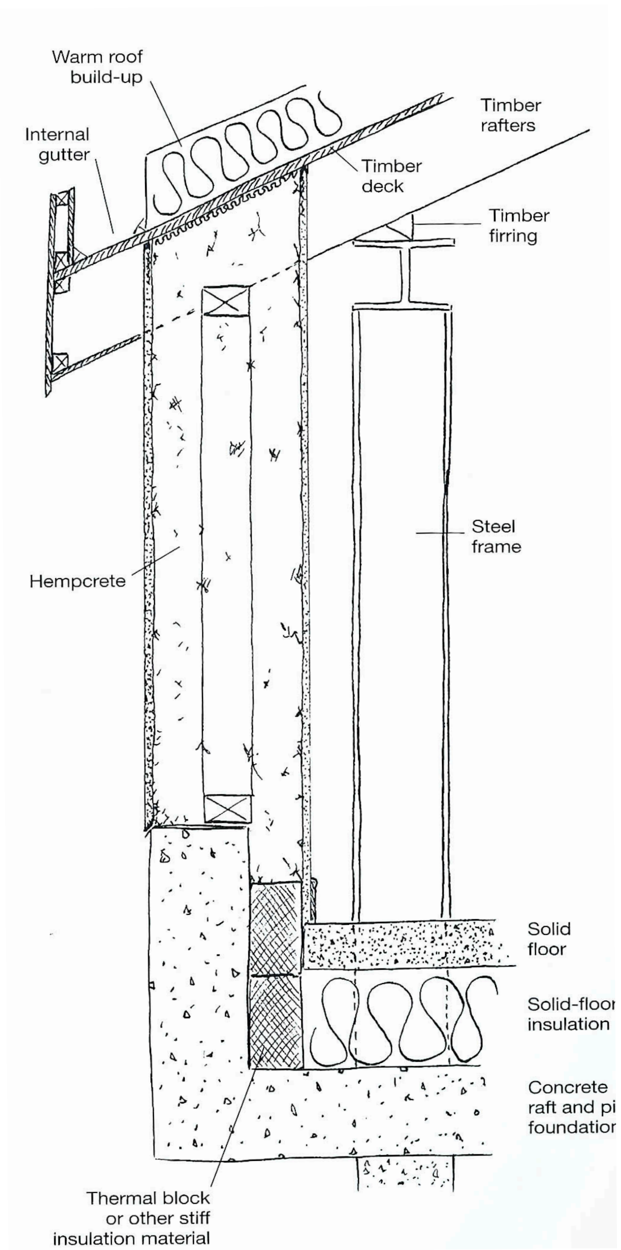


Different alternatives for stud placement within a hemp-lime wall (Stanwix & Sparrow 2014, p.332)

a) Simple timber cladding detail. The structural frame is placed flush against the external face of the wall. Airtightness and protection from moisture ingress are provided by a taped vapour-permeable membrane fixed across the frame.

b) Natural cladding detail comprising a timber rain screen fixed to vertical cladding battens, which sit within the 50 millimeter vented cavity and are fixed to the rafters that bear on the plinth. The structural frame is placed 50 millimetres inside the wall and a rough basecoat of lime render is applied to the face of the hemcrete.

c) Double-frame cladding detail, in which timber cladding is attached to a softwood cladding frame placed flush with the surface of the wall under a vapour-permeable membrane. The structural frame is on the internal face of the wall and therefore not vulnerable to moisture ingress.



Placement of steel structures by hemp-lime walls (Stanwix & Sparrow 2014, p.301)

WALL STRUCTURE

The load-bearing framework can be made from wood, concrete or steel (Bevan, Woolley & Pritchett 2008, Pretot, Collet & Garnier 2014). Studs can be placed far out, in the middle or to the inside of a wall and all types of frame constructions can be used (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Hemp-lime's mechanical flexibility allows for some movement in the structure without it cracking, why it is very suitable to use with timber (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014).

Insulation is generally most beneficial to use far out in a wall (Woolley 2013). In refurbishment projects, where building exteriors are important to preserve, hemp-lime can work well as an inside layer as well, since it incorporates both insulating properties and heat storage (Bevan, Woolley & Pritchett 2008, Allin 2012).

Hemp-lime adheres to most materials, such as steel, brick, concrete, stone, earth, wood and renders but may not stick to plastic materials that well (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Steel structures are however not recommended to use inside a hemp-lime wall since the alkalinity of lime can make the steel corrode (Stanwix & Sparrow 2014). Smaller steel fixings are okay to use if they are made of stainless steel or painted with an anti-corrosion coating but stainless steel for an entire structural frame would probably not be feasible cost wise (Stanwix & Sparrow 2014). Hemp-lime is not suitable to be cast by impermeable membranes or in-between two material layers that are not sufficiently vapour permeable; concrete block walls or other cement-based products for instance (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Permanent shuttering used in direct connection with hemp-lime needs to be both vapour diffusion open and water repellent on the outside surface (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014).

CONSTRUCTION TECHNIQUE

The report over the Haverhill housing project documents that the skills required in building the hemp-lime houses were not radically different to some other more well established craft skills used in concrete work and carpentry in the UK (Yates 2002). Hemp-lime walls that are cast on site can be seen as a somewhat labour intensive construction technique, but it might save energy since less mechanization is needed in factory (Yates 2002, Berge 2009, Stanwix & sparrow 2014). With fewer material layers and less detailing it might also be a suitable construction type to learn for inexperienced self-builders (Stanwix & sparrow 2014).

Hemp-lime is non load-bearing and therefore easy to remove and replace using common hand or low power tools (Bevan, Woolley & Pritchett 2008, Lawrence et al. 2013, Limetec).

COMPRESSIVE STRENGTH

Hemp-lime does have relatively low compressive strength but the material will be stronger after just 3-6 months as lime carbonates (Bevan, Woolley & Pritchett 2008, Nguyen et al. 2009, p.1046, Walker, Pavia & Mitchell 2014, p.344-355, Hirst et al. 2015). A number of studies have shown a high deformation capacity of hemp-lime, meaning it is able to cope with significant amounts of straining before failure (above 50 percent without collapse), especially when having a higher compaction rate (Nguyen et al. 2009, p.1047, Daly, Ronchetti, & Woolley 2013, Stanwix & Sparrow 2014, Walker, Pavia & Mitchell 2014). Even though the material is non load-bearing it can thus provide a substantial racking strength for the frame, which will not need additional bracing (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014, Walker, Pavia & Mitchell 2014). It is also said to be suitable to use in high seismic zones but that is something that needs to be tested and evaluated further though, especially with lighter mixtures that are less stiff but more preferable insulation wise (Bevan, Woolley & Pritchett 2008, Nguyen et al. 2009, Stanwix & sparrow 2014).

DRYING

Hemp-lime is a wet material by its nature and is slow to dry out (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014, Walker, Pavia & Mitchell 2014). Around 6 percent of accumulated moisture is considered normal (Hirst et al. 2015, n.p.). Building is advised during warm weather conditions, at least over 5 degrees Celsius (Yates 2002, Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014, p.123). Drying time for a 20-centimetres thick wall during warm and ventilated weather conditions is at least 1-2 months even if walls do stand firm after 24 hours (Yates 2002, p.35, Bevan, Woolley & Pritchett 2008, p.10,41, Stanwix & Sparrow 2014, p.217). Very thick walls in colder regions can in extreme cases take several years to dry out fully and might need assistance from fans and/or be wraped up to keep warm and dry* (Lawrence et al. 2013, Stanwix & Sparrow 2014). A hemp-lime builder in Canada* however attested to that research have shown that there are no benefits of using such thick walls, why

* Hermann, Anndrea; President, Hemp-Technologies (Canada). 2017. Mail correspondence February 7:th.

Casting technique in reusable plastic shuttering (Plastic shuttering, n.d.)

Cast hemp-lime in renovation project (Bevan Woolley & Pritchett 2008, p.15)

Hemp-lime house with other materials integrated in facade (Allin 2012, p.117)

Hemp-lime house by Hemporium, Cape Town, South Africa (Allin 2012, p.8)

they there commonly use between 30-40 centimetres' thickness*.

Hemp-lime has a very small shrinkage ratio after drying, which is very beneficial for the airtightness of the wall (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). Small gaps will however still occur where cast walls meet other materials, which will need to be sealed off (Stanwix & Sparrow 2014).

WEATHER PROTECTION

Hemp-lime needs to be weather protected, for example in forms of breathable renders or timber cladding (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). A good roof overhang is beneficial in wet climates but a lot of houses have been erected with smaller variants as well without any damage made to the walls (Bevan, Woolley & Pritchett 2008).

Hemp-lime can be somewhat sensitive to freeze-thaw cycles, depending on what type of binder is used (Walker, Pavia & Mitchell 2014). In a study, nine-months samples of lime binders with and without additives such as cement and pozzolan were subjected to ten freeze-thaw cycles ranging from -15 to 20 degrees Celsius (Walker, Pavia & Mitchell 2014, p.342). A commercial binder without additives was proven to be the most resistant and none of the six different test samples investigated had any cracks or changes in the microstructure (Walker, Pavia & Mitchell 2014).

The same study also examined impacts after salt exposure during one month (Walker, Pavia & Mitchell 2014). No cracks were found and the salt crystallization damage was low for all the binder variants but some of them showed a higher salt content and weight gain (Walker, Pavia & Mitchell 2014). A wall in extreme conditions where it never would have the ability to dry out was however not tested (Walker, Pavia & Mitchell 2014).

ACOUSTICS

The acoustic performance of hemp-lime is good according to research done at ENTPE in France; the innate porosity creates a bigger surface to absorb sound (Bevan, Woolley & Pritchett 2008). Sound insulation tests done by BRE showed results above common requirements (Yates 2002). A denser mix will give a better acoustic performance but other variables such as particle size distribution and porosity also play important roles (Stanwix & Sparrow 2014). Added cement gives poorer sound absorption (Stanwix & Sparrow 2014).

DESIGN

Design wise, construction with this material holds very few limitations; it could be made in all kinds of imaginative shapes, straight as well as curved or sprayed onto organic shapes, provided that the structural frame is responsible for the whole building load (Bevan, Woolley & Pritchett 2008). Style wise there have been both very modern as well as more traditional house examples built (Bevan, Woolley & Pritchett 2008).

Durability and end of life

The life span of hemp-lime buildings is predicted to be extensive and maybe last over centuries because of lime's preservative qualities (Bevan, Woolley & Pritchett 2008, Ip & Miller 2012, Stanwix & Sparrow 2014, Limetec). There have been no serious reported weathering or durability failures on houses built in France to this day (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014, Walker, Pavia & Mitchell 2014). Canada, which has a colder tempered climate, does also have experience from over a decade using this material.

Hemp-lime is regarded as a low maintenance material; estimates have been made of needed coating renewal every 50 years for the indoor side and every 33 years for the outdoor side (Yates 2002, Bevan, Woolley & Pritchett 2008, Pretot, Collet & Garnier 2014, p.225). These figures probably vary a lot though depending on the weather conditions of the site, type of coating used etc.

Pure lime can in principle be recycled through re-burning (Berge 2009). The end of life for hemp-lime is not well known why recycling methods are not yet developed (Ip & Miller 2012, Pretot, Collet & Garnier 2014). Landfill is the most common used practice (Pretot, Collet & Garnier 2014). Apart from disposal to landfill it is possible to crush the material and use as lightweight aggregates for building blocks, backfill or spread on fields to increase the PH of the soil (Yates 2002, Ip & Miller 2012, Daly, Ronchetti, & Woolley 2013, Limetec). If crushed up and spread on a field, the shiv is assumed to biodegrade and release the stored carbon dioxide though, which is otherwise not the case since hemp-lime does not decompose easily (Pretot, Collet & Garnier 2014, Limetec).

FIRE RESISTANCE

No fire retardants are needed when using hemp with lime (Bevan, Woolley & Pritchett 2008). Testing carried out by the Building Research Establishment (BRE) in the UK on an unrendered test wall panel achieved 73 minutes of fire resistance withholding integrity, insulation and load-bearing capacity (Daly, Ronchetti, & Woolley 2013, p.44, Stanwix & Sparrow 2014). Tests done by the centre Scientifique et Technique du Batiment, for the French manufacturer Isochanvre classifies hemp-lime as "M2", which according to the French classification system means "low flammability" (Daly, Ronchetti, & Woolley 2013, p.44-45). Tests from the same research centre have also revealed that a wall of 25 centimetres hemp-lime blocks remained intact for 1 hour and 40 minutes during a fire test, emitting no toxic substances (Bevan, Woolley & Pritchett 2008, p.75). Hemp-lime cast as monolithic walls assures reduced risks of fire since there are no cavities and air passages in the material where fire might spread and if the walls are rendered that is appreciated to add extra protection as well (Bevan, Woolley & Pritchett 2008, Daly, Ronchetti, & Woolley 2013).

Hemp-lime house with gypsum plaster, Pierrefleur Terrain d' Adventure by Pascale Favre, Lausanne, Switzerland (Allin 2012, p.6)

A study of biodeterioration after seven months of repeatedly added microorganisms made on hemp-lime showed that the microorganisms dried and died off within two months after every new inoculation.

(Walker, Pavia & Mitchell 2014)

Comparison tables

I have gathered a little bit of information about a few commonly used insulation materials with similar properties as hemp-lime, and compared them to each other. For other materials than hemp-lime the information is, when available, in first hand derived from Berge (2009), except for pricing that comes directly from suppliers. The cost figures can only be seen as indicative since they always vary a lot with different traders and offers. With hemp-lime being a relatively newly introduced building material on the market, information about it was not possible to retain from the same main source as the other materials. This information can thus only be seen as a rough estimation and cannot be fully reliable since the data is derived from both different life cycle assessments as well as directly from suppliers, which is far from optimal. If the figures from two separate sources vary considerably, I will show both values to give a more comprehensive picture.

The added volumetric figures are important since different materials have varying densities for the same volume. Two materials could look as though they have the same embodied energy, for instance, when only viewing MJ/kg, but one of them might acquire the tenth amount of weight for the same volume. Additionally, it is important to note that the thickness needed for different materials to achieve a certain U-value varies a lot.

The compared materials have been shortly presented after the tables where I have also summarized the findings relative to hemp-lime.

CO^2 emissions during manufacture

How much carbon dioxide emissions a material's production accounts for, ”from cradle to gate”.

CO^2 sequestration

How much carbon dioxide a material is able to store during its production and user phase, ”from cradle to grave”.

CO^2 emissions during incineration

How much carbon dioxide emissions a material's combustion at the end of life accounts for.

Energy use during manufacture

How much energy a material uses during its production phase, ”from cradle to gate”.

Combustion value

How much energy that could be recovered at the end of life if the product is incinerated. Brackets indicate that the combustion value is less available due to additives demanding purification.

Specifics

Medium dense insulation materials	Hemp-lime	Ref.	Cellular concrete	Ref.	Timber	Ref.	Woodwool cement	Ref.	Lightweight loam/earth	Ref.
Declaration	Hemp shiv 21 % Lime binder 36 % Water 43 % (pozzolan, cement)	6	Sand 60-70 % Cement 15-30 % Lime 10-20 % Water (gypsum, aluminium, leca)	2, 11	Timber 100 %	10	Portland cement 48 % Woodwool 35 % Lime 17 %	8	Loam ≈ 90 % Straw ≈10 %	9
Biodegradability	**(100 %)**	4			**100 %**	1			**100 %**	1, 9
Hazardous substances	-	4	-	2	-	1	-	8	-	
Price example SEK/m³ (ex works, VAT incl.)	**2773** or **1512 ***	4, 3, 5	**2363**	7	**4433**	10	**2320**	8	**Miniscule**	
Density ρ = kg/m³	**275**	4	**500**	1	**550**	1	**400**	8	**700**	9
Thermal conductivity λ = W/mK	**0,07**	4	**0,08**	1	**0,12**	1	**0,085**	8	**0,21**	9
Heat capacity c = kJ/kgK / $c\rho$ = kJ/m³K	**1,5 / 413**	4	**1,0 / 500**	1	**2,1 / 1155**	1	**1,6 / 640**	8	**1,05 / 735**	1
Thermal effusivity $\sqrt{(\lambda \cdot c\rho)}$ = J/m² K s$^{1/2}$	**170,0**		**200,0**		**372,3**		**233,2**		**392,9**	
Thermal diffusivity $\frac{\lambda}{(\rho \cdot c)}$ = E-07 m²/s	**1,7**		**1,6**		**1,0**		**1,3**		**2,9**	

* the two different prices are from Limetech's approved formula and a mix with shiv from Österlen Hampa and imported lime binder from St Astier (not tried out together)

1. Berge 2009, p.23-26,34,37-39,44-47,85, 284,293-294,297
2. Sunda hus, n.p.
3. Österlen Hampa, n.p.
4. Limetec, n.p.
5. Nymberg, Daniel; Målarkalk. 2015. Mail correspondence September 24:th.
6. Hirst et al. 2015, n.p.
7. Johansson, Fredrik; Ytong. 2015. Mail correspondence October 12:th.
8. Träullit AB, n.p.
9. Minke 2013, p.49
10. Burträsk Bygg & Trä AB. 2015. Telephone correspondence October 12:th.
11. Byggipedia, n.p.

Carbon footprint and energy use

Medium dense insulation materials	Hemp-lime	Ref.	Cellular concrete	Ref.	Timber	Ref.	Woodwool cement	Ref.	Lightweight loam/earth	Ref.
CO^2 emissions - manufacture CO^2/kg	**0,49***	3, 1	**0,27**	1	**0,3**	1	**1,6**	1	**0,02**	1
CO^2/m^3	135		135		165		640		14	
CO^2 sequestration kg CO^2/kg	**-0,85***	3, 1	**-0,02**	1	**-0,85**	1	**-0,4**	1	**-0,08**	1
kg CO^2/m^3	-234		-10		-468		-160		-56	
CO^2 emissions - incineration kg CO^2/kg	**-**	1	**-**	1	**-**	1	**-**	1	**-**	1
kg CO^2/m^3	-		-		-		-		-	
Energy use - manufacture MJ/kg	**4,0***	2, 1	**4,0**	1	**16,5**	1	**28,0**	1	**1,9**	1
MJ/m^3	1099		2000		9075		11200		1330	
Combustion value MJ/kg	**(-6,2)***	1	**-**	1	**-16**	1	**(-8)**	1	**(-1,4)**	1
MJ/m^3	(-1700)		-		-8800		(-3200)		(-980)	

* Based on the dry density of 275 kg/m^3 with 100 kg shiv (21 %) & 165 kg lime binder (36 %) and the following figures for each component:

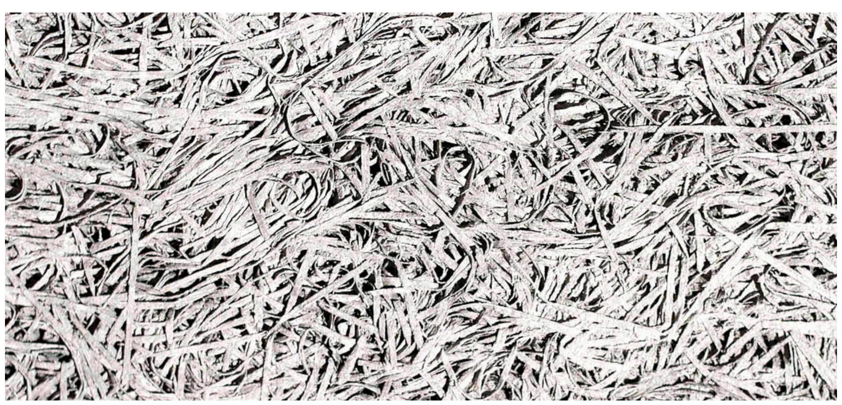
Carbon dioxide
- Hemp shiv emissions: 0,11 kg CO^2/kg (3
- Hemp shiv sequestration: -1,84 kg CO^2/kg (3,4
- Lime emissions: 0,75 kg CO^2/kg (1
- Lime sequestration: - 0,30 kg CO^2/kg (1

Energy
- Hemp shiv use: 2,5-3,8 MJ/kg (2,3
- Hemp fiber combustion value -17 MJ/kg (1 (no figures available for shiv)
- Lime use: 4,5-5 MJ/kg (1

1. Berge 2009, p.23-26,34,37-39,44-47,85, 284,293-294,297
2. Woolley 2013, p.138
3. Zampori, Dotelli & Vernelli 2013, p.7417-7418
4. Bevan, Woolley & Pritchett 2008, p.81

Cellular concrete (Cellular concrete, n.d.)

Timber (PublicDomainPictures through © CC0 Public Domain 2012)



Woodwool cement (Woodwool cement, n.d.)

Rammed earth (Rammed earth, n.d.)

CELLULAR CONCRETE

Cellular concrete is used in blocks, beams, wall, roof and slab elements and can be reinforced and load-bearing (Byggipedia). It constitutes air pores, which makes it lighter and weaker but more insulative than regular concrete (Byggipedia). Light expanded clay aggregates (LECA) are also sometimes added (Byggipedia).

TIMBER

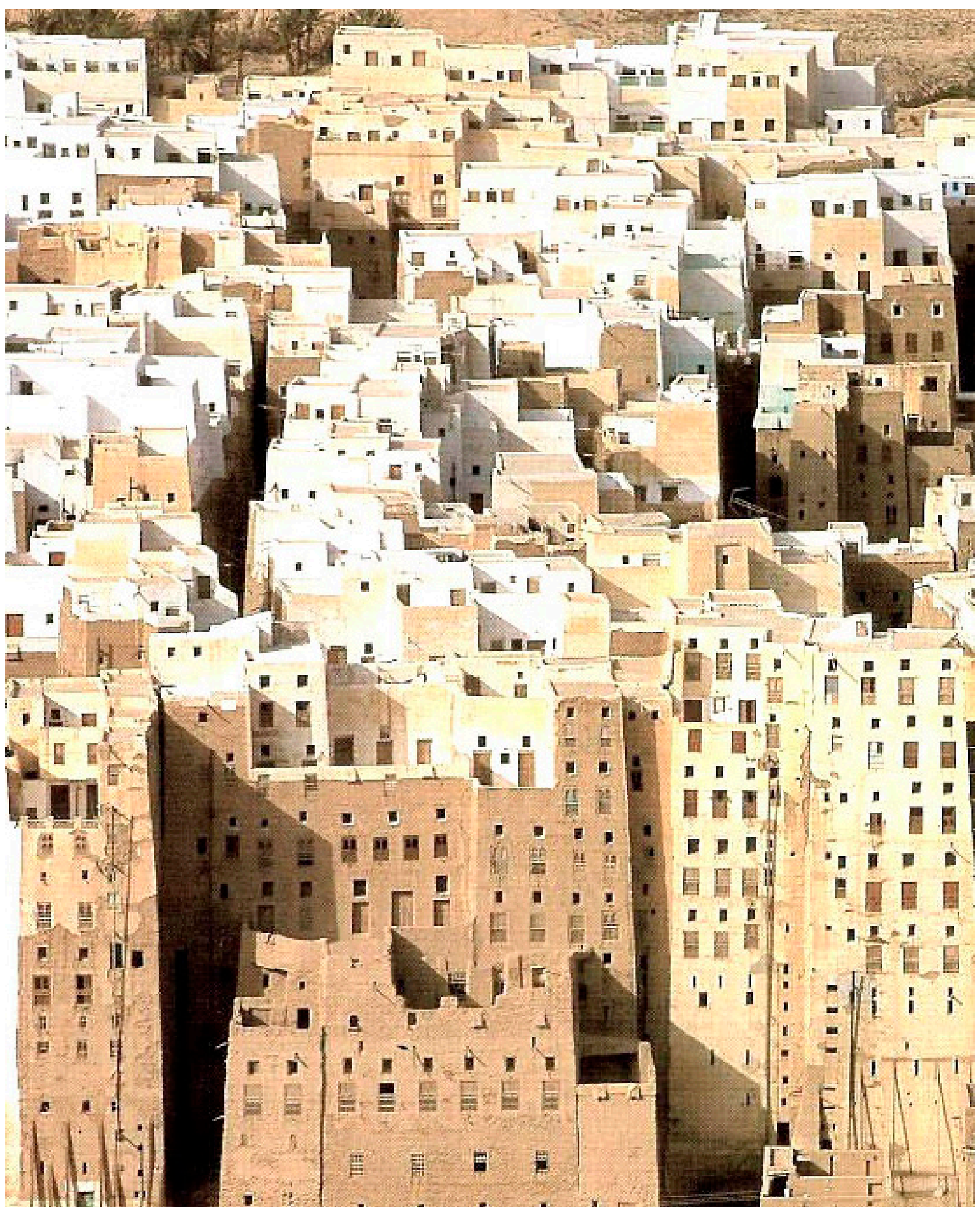
Timber is a middle to heavier weight material with a few thermal properties similar to higher density mixes of hemp-lime (Bevan, Woolley & Pritchett 2008, Berge 2009). It is very well suited to use as a load-bearing structure both with hemp-lime and hemp fiber wool, as well as for cladding and other details (Berge 2009, Bokalders & Block 2014, Stanwix & Sparrow 2014). Log walls might not totally fulfill present insulation standards but massive wood elements, wood shavings and boards gives a better performance (Berge 2009). Timber is often referred to as highly sustainable but using more wood than necessary may not be incentivized since it cannot be regrown annually and forests are vital to the maintenance of the ecological balance (Bevan, Woolley & Pritchett 2008). Responsible forestry is not always the case and real quality heartwood is hard to come across since trees are seldom allowed to grow for that long.

WOODWOOL CEMENT

Woodwool cement can be in form of boards, structural blocks or complete wall elements, the later being a relatively new technique where armatures are embedded in the material for it to become load-bearing (Berge 2009). Woodwool cement is resistant to rot and mould and has a slightly alkaline chemistry (Berge 2009). Woodwool cement boards can be used as insulation by foundations since they can both handle moisture vapour and regulate humidity levels (Berge 2009). They are also very commonly used in acoustical and fire proofing purposes (Berge 2009). Woodwool cement products cannot be recycled but re-used as whole elements (Berge 2009).

LOAM

Loam/earth is the second most widespread building material in the world, after bamboo, available in most places (Berge 2009). It is a highly sustainable, natural and sound material (Morton & Bennetts 2008). It is often used with straw to form lightweight loam, but can also be combined with hemp fibres, hemp shiv and lime and for example be made into blocks (Munch-Andersen & Møller Andersen 2004, Berge 2009, Cannabric 2009, Bokalders & Block 2014). The thermal conductivity of loam is high even when fibres are added why it may not be applicable as main insulation material in colder climates where there are high energy requirements (Berge 2009, Bokalders & Block 2014). It is not preferable to be used unprotected on an outside surface in cold, wet and windy climates neither since it is susceptical to rising damp, freeze and thaw cycles and can erode (Morton & Bennetts 2008, Bokalders & Block 2014). Since the heat storage capacity and moisture buffering ability is splendid, it is nevertheless very useful in warmer climates and as an inside wall layer in colder climates (Morton & Bennetts 2008, Berge 2009, Bokalders & Block 2014). This could be in form of a few centimetres of earth plaster, unburned earth brick (adobes) or a layer of rammed earth (Morton & Bennetts 2008, Berge 2009). Loam also has the ability to extract excess moisture from other materials, absorb toxins and pollutants, insulate against electromagnetic radiation and demonstrates very good acoustic performance (Morton & Bennetts 2008, Bokalders & Block 2014, Stanwix & Sparrow 2014).



Earth buildings in Shibam, Yemen (Shibam, n.d.)

Summary

Hemp-lime and other middleweight materials such as cellular concrete and woodwool cement do have quite similar lambda-values. They would also have similar volumetric heat capacities, effusivity and diffusivity figures if a hemp-lime mix with a slightly higher proportion of lime than I have used as an example in my comparison were to be used. A lighter mix of 275 kg/m^3 is however preferable since insulation is what is most important in this non load-bearing application. Lightweight loam and timber are, in comparison, heavier materials with better heat storage and poorer insulating abilities.

The prices for most of the middleweight materials that I have taken a look at are substantial compared to lightweight wool but comparable to hemp and cellulose fiber battens (seen in previous chapter). Lightweight loam is almost free. As mentioned earlier, prices should however preferably be compared with regards to function and how much material is needed to reach a certain thermal performance/U-value.

The overall environmental impact of lightweight loam is miniscule. After that, cellular concrete and timber uses the lowest amounts of carbon dioxide during production. In the case of cellular concrete it is due to its relatively small addition of cement and lime. Cellular concrete will however not have the ability to store any amount of carbon dioxide worth mentioning. With sequestration included in the calculation, wood and hemp-lime are the clear winners, with wood in the top when considering weight per volume. The energy used in production is substantial for woodwool cement and more moderate for hemp-lime and cellular concrete. Lighter mixtures of hemp-lime do however only account for half the energy usage by volume compared to cellular concrete.

At the end of life, plant-based composite materials could need purification to be able to be incinerated and used for energy recovery, which is not neccesarily a feasible action. Landfill is the most common practice.

Renders and plasters

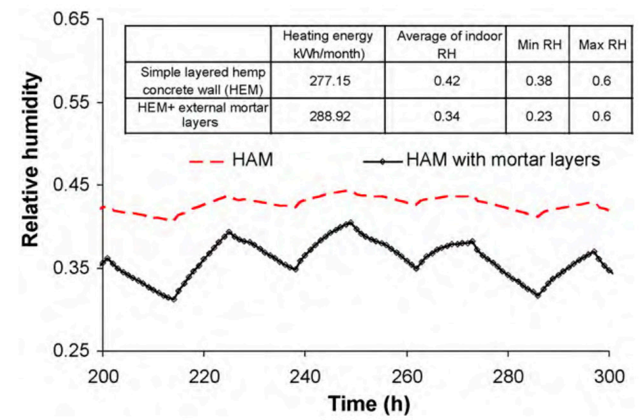
It is usually recommended to combine vapour open wall constructions with permeable renders and plasters so that moisture will not risk getting trapped within the structure (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014). The same type of render or plaster can in many cases be used on both sides of a wall since the permeability of renders and plasters has been shown to increase with moisture content, which would naturally make them more diffusion open to the outside (Munch-Andersen & Møller Andersen 2004, Berge 2009).

RENDERS

Examples of vapour permeable renders are lime-, lime-sand, lime-hemp and earth based mixes (Munch-Andersen & Møller Andersen 2004, Morton & Bennetts 2008, Stanwix & Sparrow 2014). Lime-hemp renders and plasters can use both shiv and fibres as reinforcement (Stanwix & Sparrow 2014). Lime can be somewhat sensitive to frost but has the advantage that it will gradually harden as it re-carbonates at the same time as it will maintain its important permeability (Berge 2009, Stanwix & Sparrow 2014). Earth based renders are not that common to use on outside surfaces since they are sensitive to the weathers but can be used on a well-sheltered wall (Morton & Bennetts 2008, Stanwix & Sparrow 2014). Cement based renders are resistant to moisture but not very permeable why there can be a risk of moisture getting trapped behind them in a vapour diffusion open wall (Munch-Andersen & Møller Andersen 2004, Bokalders & Block 2014). They are however also claimed to be able to extract moisture from underlying layers (De Bruijn 2012). Cement based renders on vapour diffusion open walls are not common practice and they will not perform in the same flexible way as lime renders since they are stiff and cracks easily (Berge 2009, Bokalders & Block 2014, Stanwix & Sparrow 2014).

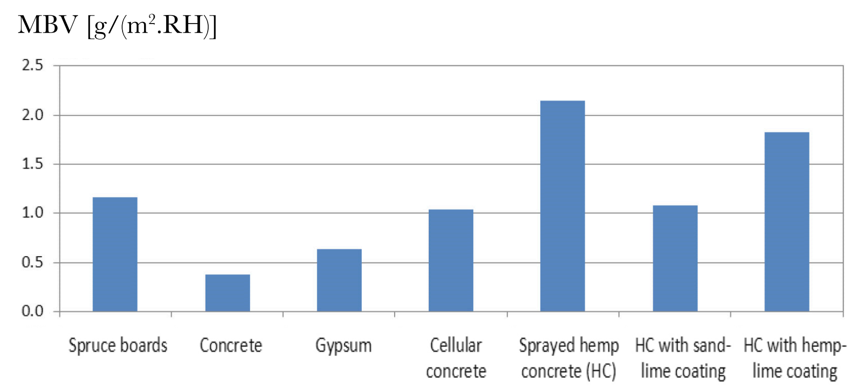
PLASTERS

Some type of plasters on the inside of a moisture- and heat buffering wall might make them less absorbent (Tran Le et al. 2010, Collet, Pretot & Lanos 2013). The more closed the coating is, the lower the moisture buffer value will be (Collet, Pretot & Lanos 2013). Earth plasters are superior when it comes to buffering moisture, but hemp- and lime based coatings show a good performance as well (Collet, Pretot & Lanos 2013, Bokalders & Block 2014, Stanwix & Sparrow 2014). Airtightness and fire protection can be well improved when adding a plaster; hemp-lime plasters have, for instance, been shown to successfully increase airtightness and lessen energy consumption (Bevan, Woolley & Pritchett 2008, Stanwix & Sparrow 2014).



Difference in indoor relative humidity when using an unplastered hemp-lime wall versus one plastered with a cement mortar

(Tran Le et al. 2010, p.1803)



Comparison of moisture buffer values for different building materials

One centimetre thick hemp-lime plaster on a hemp-lime wall shows almost an excellent MBV according to the Nordtest project classification (Collet, Pretot & Lanos 2013). The sand-lime coating does only have half the moisture buffering ability in comparison, even though still rating good (Collet, Pretot & Lanos 2013).

(Collet, Pretot & Lanos 2013, n.p.)

Industrial market

The growing, processing and manufacturing of hemp for industry is already large global business (Bevan, Woolley & Pritchett 2008, Woolley 2013). Many countries in Europe such as France, Germany, Great Britain, Belgium and Poland are long far ahead in the research and industrial development around hemp (Nilsson 2003). France actually serves for almost half of the total hemp cultivation within the whole EU (Norberg 2009, EIHA). Germany has both certified hemp battens, very well developed technologies in their production and processing of hemp fibres as well as good government support and many research institutes involved (Nilsson 2003). Denmark and Finland do also conduct biofiber research but have not reached as far (Nilsson 2003).

The industry around hemp-lime in building elements is well established in many European countries such as France, Belgium, the UK and Germany, globally also in the US, Canada, Australia and many other countries (Woolley 2013, Stanwix & Sparrow 2014). France has come a long way in their development and has codes of standards for hemp shiv used in this particular application, as well as LABC-approvals (Local Authority Building Control) for different binders (Daly, Ronchetti, & Woolley 2013, Woolley 2013, Stanwix & Sparrow 2014). UK has yet no codes of standards but their leading hemp-lime supplier has received a BBA-certificate (British Board of Agrément) as well as LABC-approvals for their wall mixes, which means that they are in compliance with the UK building regulations (Daly, Ronchetti, & Woolley 2013, Woolley 2013). Hemp-lime blocks have been produced commercially in Europe for several years as well (Stanwix & Sparrow 2014).

In Sweden we do not have any larger industrial development or product refinement around hemp insulation products (Olofsson 2014). There are a small number of cultivators that supply hemp fiber and shiv by bulk but no current local production of insulation battens, boards nor lime binders especially formulated to fit the purpose of application in a hemp-lime wall. We do however have resellers that import the products and a new-founded company that offers hemp-lime prefabricated panels with the aim of also supplying a lime binder in the future that will be cheaper than *Tradical HB* and *Batichanvre**. The areal of cultivation needs to expand why larger investments in better decortication machinery are needed locally to make hemp more competitive on the market (Norberg 2009, Olofsson 2014). There has been a new type of smaller scale processing equipment tried out that could have the possibility to both dry and decorticate the plant at the same time (Norberg 2009). The separation technique is said to be more efficient, which could create a finer fiber that would give a better insulation performance in relation to its weight (Norberg 2009). The technique could make it possible for hemp to be harvested already in the autumn, which would mean a larger utilization rate (Norberg 2009). It would also mean less transportation distances of large material loads since the plant harvest would not

* Jacobsson, Henrik; Hampahus AB, Sweden. 2016. Meeting October 7:th.

need to take an extra route through a larger processing plant.

Some say that hemp might be hard to profit from in other areas than high value uses without subsidies, due to its higher production costs in relation to some other crops (Olofsson 2014). A few potential investors that cultivators have been in contact with have also been hesitant about the demand for the product; the profitability for a larger scale production with better machinery (Olofsson 2014). Both farmers and suppliers of building materials and furniture have shown interest in the crop but hesitant farmers want an assurance of a sustainable market development and the suppliers a guarantee regarding price, quality and the raw material supply (Svennerstedt 2003, Eriksson 2008, Johansson & Olofsson 2009, Johansson 2010, Olofsson 2014). Swedish farmers do make profits and are not able to meet the growing demand for the crop but for more farmers to become interested a good incentive might be to give subsidizes for the hemp processing as well, besides the common farmers support (Skoglund 2009). Another way to make the product more profitable might be to use the hemp shiv, which is currently seen as a by-product to the more valuable fiber, in higher value usage fields, such as the building industry. For that to become a reality in Sweden, more information propagation is necessary to increase the demand. It is also important to have a local production of a lime binder specifically formulated to fit this application. Most of the Swedish people are probably not aware of this product and how it can be used in building applications. The interest for hemp is growing though and academia is involved in research here as well, even though there yet to date has been a limited amount of work published on the subject (Skoglund 2009, Olofsson 2014).

Part II

Case study

designing thermal envelopes

In my case study I have investigated three alternatives for a thermal envelope involving one or two kinds of hemp-based insulation applications. I will use the house that I have designed for my client as a reference, why I will first shortly present its climatic conditions, structure design and measurements. After that I will present the three envelopes, one by one. I have based their build-ups on available knowledge of how to use these materials in construction and adapted it to the structure of the house example in question. They are not all neccesarily possible to build exactly this way but are developed with thicknesses that correspond to an equivalent U-value for each element in comparative purposes.

I will list benefits and drawbacks for each structure build-up, and based on the house's measurements, calculate approximate price examples for the different insulation materials and present their time constant; a figure of the amount of time it takes for a building's indoor temperature to react to sudden temperature changes outside, or disruptions in the heating supply. It can also be called a building's thermal inertia, which is very dependent upon how large the material masses with heat storing capacities are towards the inside.

The House

Location

- Gränna, Jönköping, Småland.

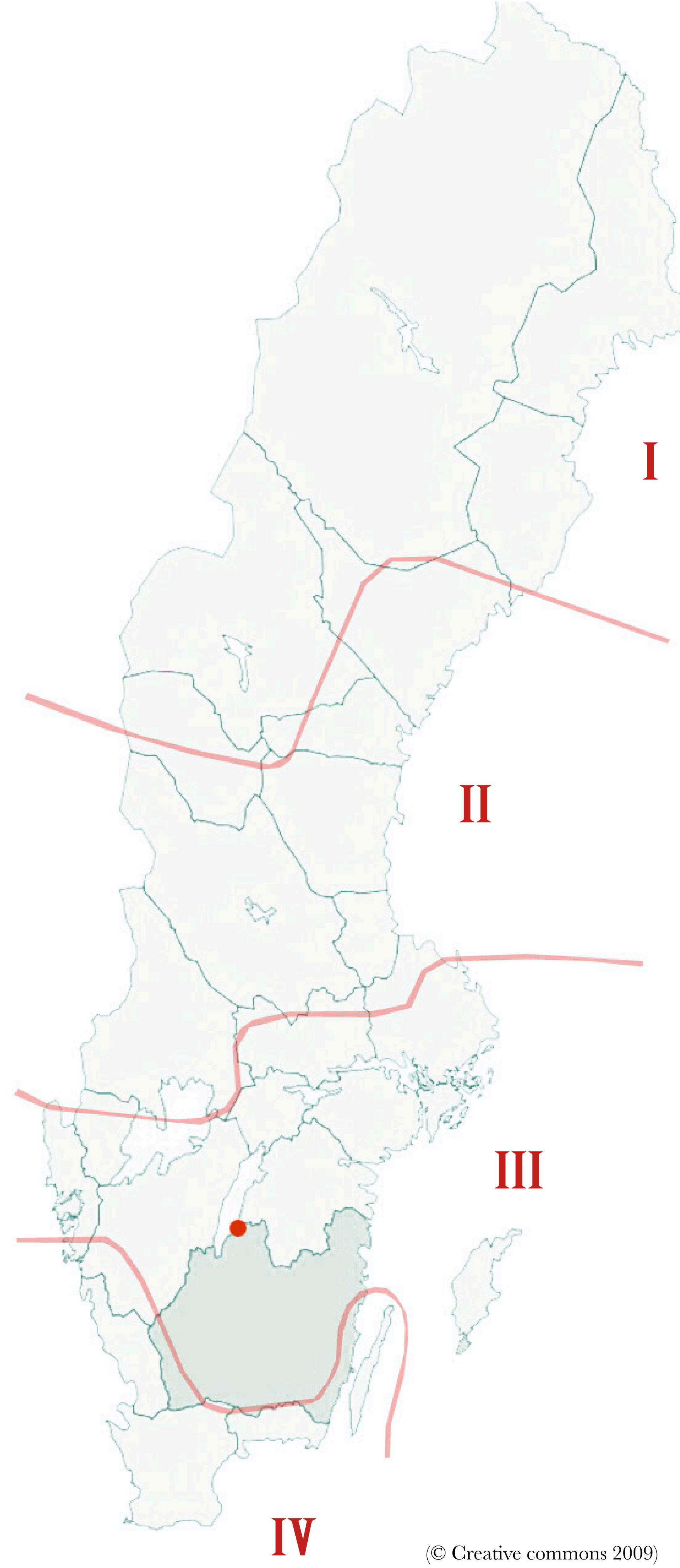
Climate considerations

- Temperature: Below subarctic climate zone, fluctuating cold and hot air-streams. Average seasonal temperatures between minus 2 and plus 17 degrees Celsius.
- Snow: Around 80-100 days per year with more than 5 mm of snow on the ground
- Precipitation: Yearly mean precipitation level around 700 mm
- Altitude: > 200 metres
- Climate zone: III = maximum allowed energy use of small houses below 55 and 90 kwh/m^2/year, respectively, depending on if the house will be heated through electricity or other sources (rules not applicable to holiday houses) (Boverket).

House specifics

- Context: Hilly terrain with surrounding dense vegetation and woodlands
- Geology: Incoherent thin layer of earth on rock, no known high radon levels
- House type: Holiday house
- Structure: Timber framework, 2 roof ridges
- Materials: Timber cladding, roof tiles
- Foundation: Crawling space
- Area/measurements: 136 m^2 divided in two floors

(Grundvall 2016)



(© Creative commons 2009)

Thermal envelope 1

hemp fiber wool, internal clay plaster, wooden roof and floor finishes

Benefits:

- Light construction = lower transport burdens and lighter foundations
- Thinner thermal envelope (better lambda)
- Lower material cost for insulation
- Local material availability
- Locally tried out construction technique
- Hemp fibres are resilient and durable in humid conditions
- Hemp fibres can be used in both vapour permeable and impermeable structures
- Clay plaster enables highly effective heat storage to the inside why a thinner layer is adequate for daily heat fluctuations
- Low environmental impact for all materials
- Hemp fibres can be used for energy recovery at the end of life

Drawbacks:

- Lesser amount of heat storage for long-term heat buffering
- Cold wall surfaces
- More detailing involved in airtightening of the building envelope
- Higher risk of vapour condensation in-between layers than in monolithic elements
- Harder to avoid thermal bridges
- The durability for fibres and sealants might not be as extensive as for hemp-lime
- Higher shrinkage and cracking ratio for clay plaster compared to hemp-lime

Price - insulation

Hemp fiber wool

31 m^3 with the density 60 kg/m^3 x 720 SEK = 22 320 SEK

57 m^3 with the density 50 kg/m^3 x 600 SEK = 34 200 SEK

TOTAL: 56 520 SEK*

(need of outside cladding)

* Österlen Hampa hemp fiber

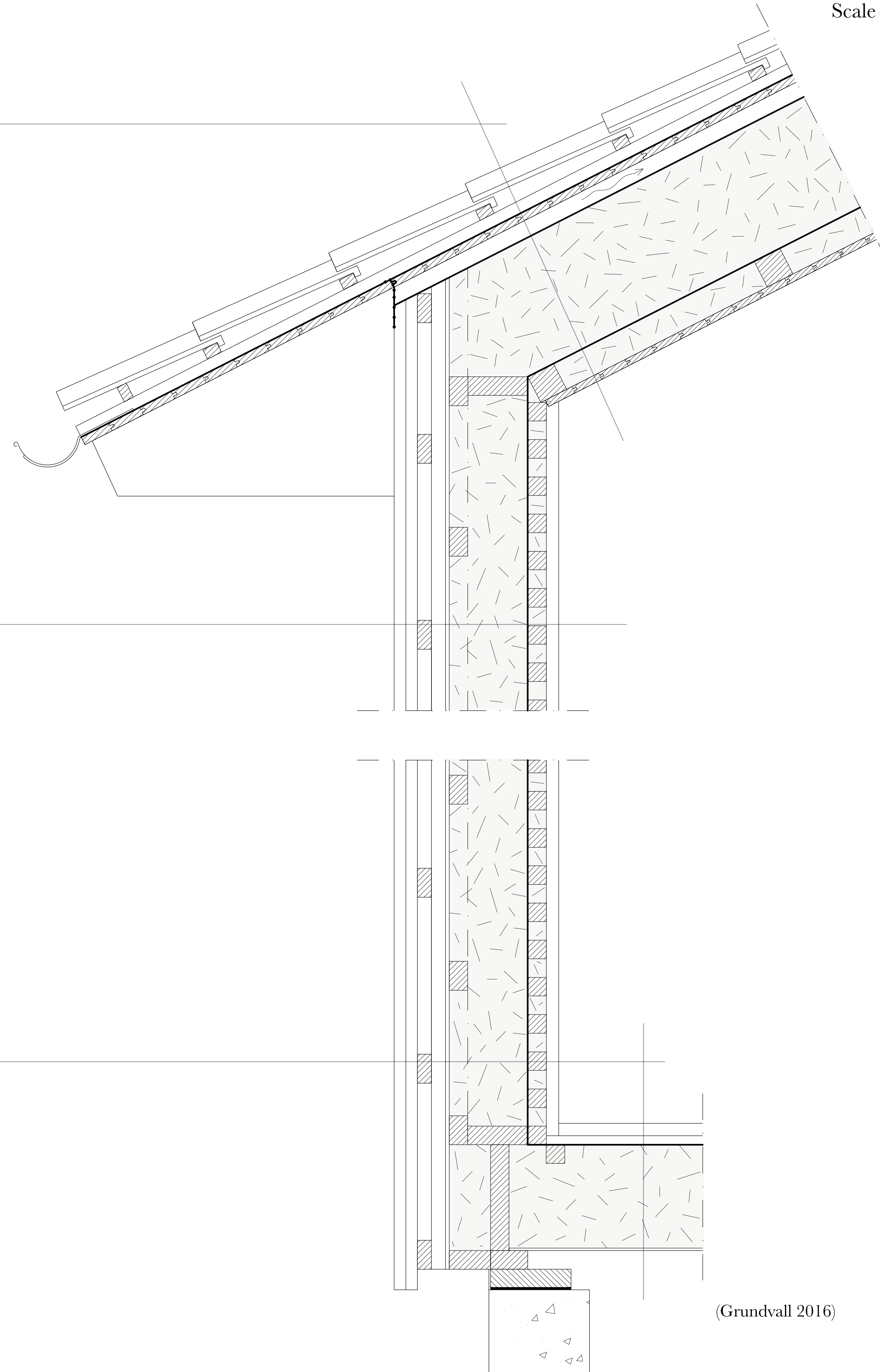
Scale 1:12

Roof 574 mm

U-value ≈ 0,120 W/m²K

71	Roof tiles
25	Battens
25	Battens
1	Roofing felt
23	Tongue & groove
40	Battens & vented air cavity
1	Wind barrier
300	Lightweight beams & hemp fiber wool
1	Air barrier
70	Battens, hemp fiber wool & installations
17	Tongue & groove

(mm)



Wall 399 mm

U-value ≈ 0,210 W/m²K

2 x 28	Timber cladding
2 x 34	Battens & vented air cavity
9	Vapour permeable & water resistant board
45	Battens & hemp fiber wool
145	Studs & hemp fiber wool
1	Air barrier
45	Battens, hemp fiber wool & installations
30	Clay plaster

(mm)

Floor 309 mm

U-value ≈ 0,175 W/m²K

6	Carrier board
250	Lightweight beams & hemp fiber wool
1	Air barrier
22	Floor carrier board
30	Wooden flooring

(mm)

(Grundvall 2016)

Thermal envelope 2

hemp-lime, limecrete floors, wooden roof finish

Benefits:

- Airtight & very fire resistant element to the inside around the whole thermal envelope
- Thermal bridges avoided in hemp-lime cast (and sprayed) walls and floor screeds
- Reduction in project management and construction time possible through less detailing with several layers and sealants and a limited amount of material suppliers
- Supportive racking strength in hemp-lime could possibly lessen need for bracing and narrow down structure dimensions
- A simple render can be a sufficient weathershield that can be applied directly to the cast elements
- Monolithic elements effectively deal with moisture transport without risk of vapour condensation in-between layers
- Heat storage through the whole wall thickness for possible long term heat buffering, however mostly utilized between two tempered spaces
- Energy use proven to be lower than expected from viewing hemp-lime U-values
- Hemp-lime is carbon neutral with a long durability and carbon storage period
- Makes use of a rest material (shiv)
- Low thermal effusivity material towards living area = warm surfaces

Drawbacks:

- Long drying time
- New construction method locally
- Relatively heavy insulation material for roofs
- Currently no local production of lime binders made for hemp-lime walls
- Available lime binders are a bit expensive (but still comparable to other middle weight building materials)
- Relatively thick walls needed in a Swedish climate
- High embodied energy in lime
- Low thermal effusivity material towards living area = less effective heat storage

Price - insulation

Hemp-lime

139 m^3 x 1 512 SEK = 210 168 SEK

TOTAL: 210 168 SEK*

(without need of outside cladding)

* Österlen Hampa hemp shiv & St Astier lime binder

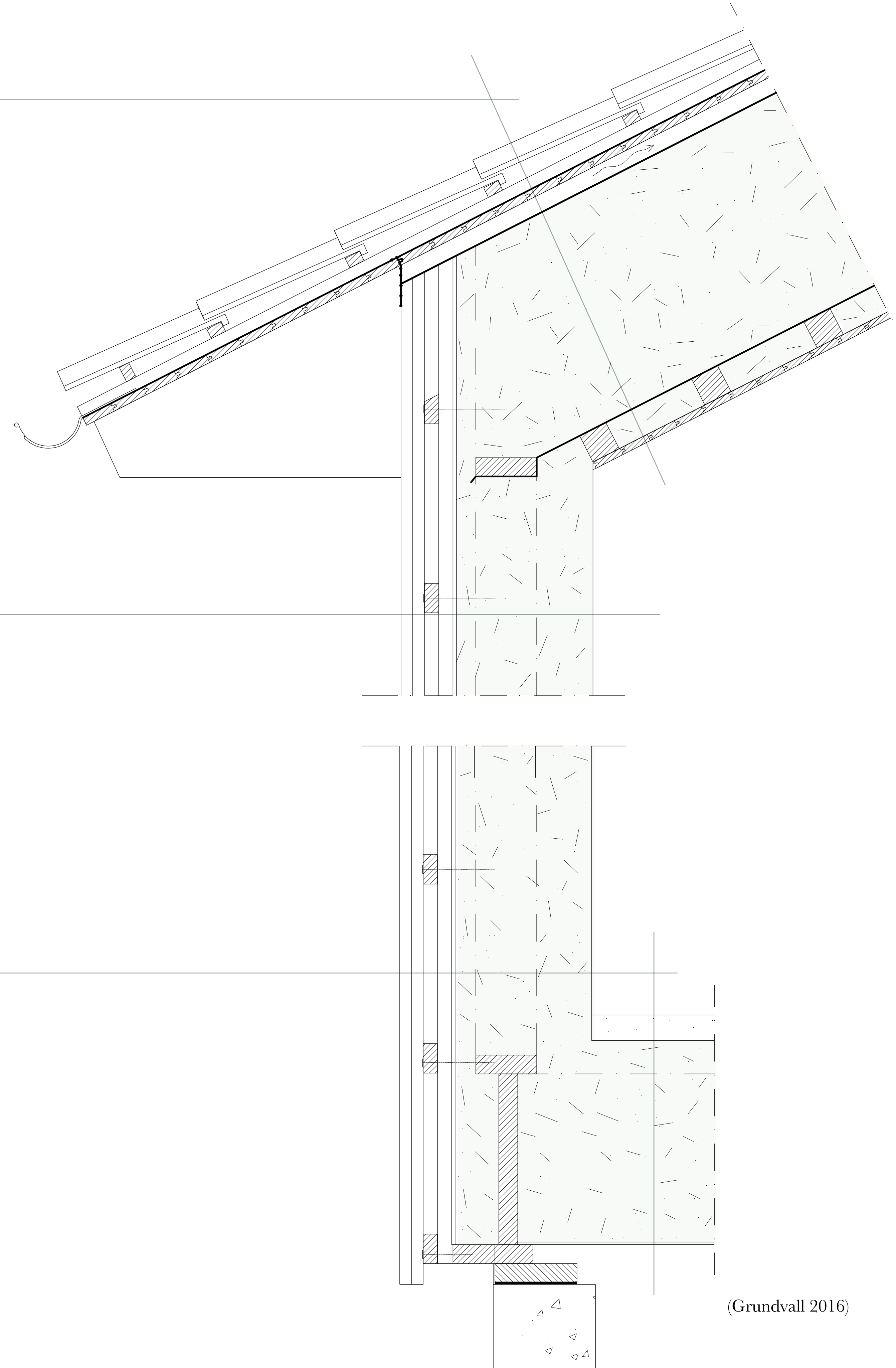
Scale 1:12

Roof 789 mm

U-value ≈ 0,120 W/m²K

71	Roof tiles
25	Battens
25	Battens
1	Roofing felt
23	Tongue & groove
40	Battens & vented air cavity
1	Wind barrier
515	Beams & cast hemp-lime
1	Air barrier
70	Battens, cast hemp-lime & installations
17	Tongue & groove

(mm)



Wall 457 mm

U-value ≈ 0,210 W/m²K

2 x 28	Timber cladding
2 x 34	Battens & vented air cavity
8	Limecrete render
325	Studs & cast hemp-lime

(mm)

Floor 546 mm

U-value ≈ 0,175 W/m²K

6	Carrier board
400	Beams & cast hemp-lime
80	Cast hemp-lime screed
60	Limecrete plaster

(mm)

(Grundvall 2016)

Thermal envelope 3

hemp-lime and hemp fiber wool, limecrete floors, wooden roof finish

Benefits:

- Takes advantage of both materials' key characteristics where they are most needed
- Airtight & very fire resistant element to the inside around the whole thermal envelope
- Thermal bridges avoided in hemp-lime cast (and sprayed) walls and floor screeds
- Less detailing with sealants
- Hemp-lime reaches its peak in heat storage at around 10 centimetres, which is normally enough depth to deal with daily temperature and humidity fluctuations
- Reduced drying time and weight of hemp-lime through a thinner layer
- Energy use proven to be lower than expected from viewing hemp-lime U-values
- Supportive racking strength to the structure
- Hemp-lime is carbon neutral with a long durability and carbon storage period, very low environmental impact for hemp fiber wool
- Makes use of a rest material (shiv)
- Low thermal effusivity material towards living area = warm surfaces

Drawbacks:

- New construction method locally
- More materials
- Higher risk of vapour condensation in-between layers than in monolithic elements
- Currently no local production of lime binders made for hemp-lime walls
- Available lime binders are a bit expensive (but still comparable to other middle weight building materials)
- High embodied energy in lime
- Low thermal effusivity material towards living area = less effective heat storage

Price - insulation

Hemp fiber wool

21 m^3 with the density 60 kg/m^3 x 720 SEK = 15 120 SEK

48 m^3 with the density 50 kg/m^3 x 600 SEK = 28 800 SEK

Hemp-lime

30 m^3 x 1512 SEK = 45 360 SEK

TOTAL: 89 280 SEK*

(need of outside cladding)

* Österlen Hampa hemp fiber wool and shiv & St Astier lime binder

Scale 1:12

Roof 639 mm

U-value ≈ 0,120 W/m²K

71	Roof tiles
25	Battens
25	Battens
1	Roofing felt
23	Tongue & groove
40	Battens & vented air cavity
1	Wind barrier
340	Lightweight beams & hemp fiber wool
1	Air barrier
95	Battens, cast hemp-lime & installations
17	Tongue & groove

(mm)

Wall 383 mm

U-value ≈ 0,210 W/m²K

2 x 28	Timber cladding
2 x 34	Battens & vented air cavity
9	Vapour permeable & water resistant board
150	Studs & hemp fiber wool
40	Studs & hemp-lime
60	Cast hemp-lime

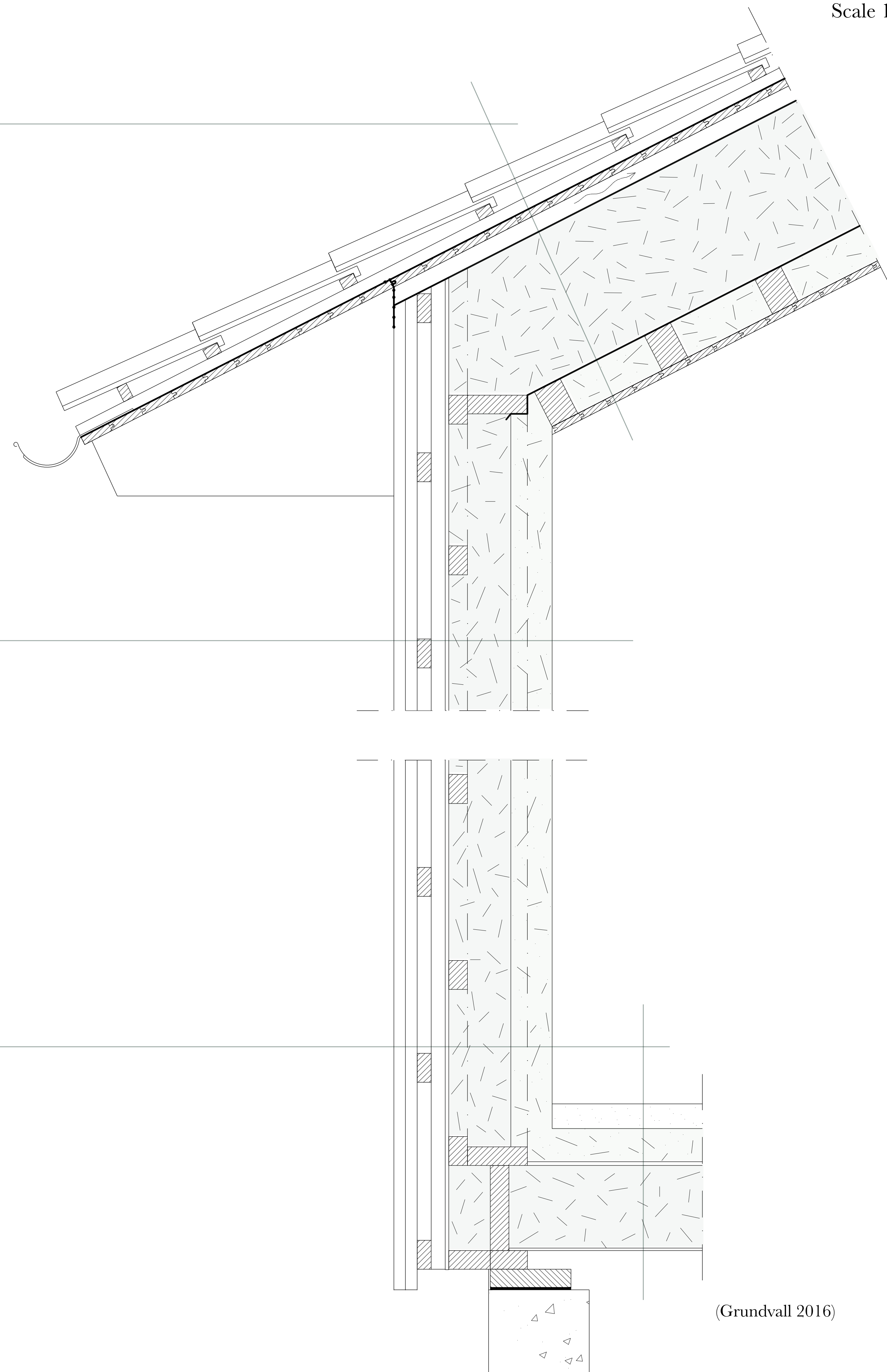
(mm)

Floor 355 mm

U-value ≈ 0,175 W/m²K

6	Carrier board
200	Lightweight beams & hemp fiber wool
9	Carrier board
80	Cast hemp-lime screed
60	Limecrete plaster

(mm)



(Grundvall 2016)

Calculation sum up

Heat capacity*

material masses in 100 mm inside layer (m^3) ·
volumetric heat capacities (J/m^3K) /
3600 (sek/h)

Thermal envelope 1: **6 686** Wh/K

Thermal envelope 2: **6 062** Wh/K

Thermal envelope 3: **5 858** Wh/K

Transmission losses*

For the floor area (BOA) of 136 m^2 and the thermal envelope surface area of 374,8 m^2:

Ventilation losses without ftx: **26,93** W/K
Ventilation losses with ftx: **5,65** W/K

Air leakage: **9,35** W/K

Thermal bridges envelope (15 %): **13,05** W/K

Thermal envelope transmission losses: **87** W/K

TOTAL with ftx: **115** W/K

TOTAL without ftx: **136** W/K

* full calculation can be viewed in appendix 1

Time constant

heat capacity / transmission losses (h = wh/K / w/K)

A measure of the amount of time it takes for the building's indoor temperature to react to sudden temperature changes outside, or disruptions in the heating supply. A building's time constant/thermal inertia is higher if it has a large heat capacity to the inside in combination with small power losses through the thermal envelope.

Time constant thermal envelope 1

With ftx: **58,14** h = **2,42** days
Without ftx: **49,16** h = **2,05** days

Time constant thermal envelope 2

With ftx: **52,71** h = **2,20** days
Without ftx: **44,57** h = **1,86** days

Time constant thermal envelope 3

With ftx: **50,94** h = **2,12** days
Without ftx: **43,07** h = **1,79** days

A calculation of the time constant is usually done by only considering the first 100 millimetres of the wall since that is where the main heat storage is claimed to occur. The time constant for both wall types are quite similar with slightly more beneficial figures for wall number one with hemp fibres and earth plaster. This is due to earth's substantial heat storage. The whole material mass of hemp-lime is in theory heat buffering but since a previous shown study indicated that the heat storage from the inside declined beyond 100 millimetres I have not taken that into consideration in this calculation. I am however reserving myself to the possibilty that it might give the wall a slightly more beneficial value, depending on the length of the storage period.

Conclusions

”How do different hemp-based thermal insulation products and their construction techniques work? How sustainable and sound are they and would they be suitable in a cold tempered climate?”

In this thesis work I have investigated hemp fiber wool, hemp fiber battens and hemp-lime since they are all able to provide the main thermal insulation layer in building structures.

Hemp fibre wool and battens can be used in both vapour impermeable and permeable thermal envelopes. They have a good insulative ability that through experience has been shown to perform better than their thermal conductivity value indicate. Hemp fibres hold an advantage in wet climates since they can tolerate vapour to some degree and are said to not be as susceptible to biological decay, mould, fungus nor arsonists attacks as many other natural and synthetic fibres. Hemp fibers do also have a very high heat capacity figure and used in wool form they are most thermally efficient at a relatively (for lightweight insulation) high density, which adds on to the heat storage capability and minimizes the risk of settlements in walls, as well as air movements through them.

Hemp-lime has a, relative to lightweight hemp fiber, poorer thermal conductivity value and a larger capacity for heat storage. It does however also seem to perform much better than the U-value indicates but would need somewhat thicker walls or to be combined with a more thermally effective lightweight insulation material in colder regions. Fans to help the material dry out and/or wrap-arounds to keep it warm can in extremer cases be needed if very thick walls were to be cast on site and depending on the local weather conditions, renders might need to be maintained and renewed more frequently. The thermal and moisture buffering properties of hemp-lime will most probably not be completely utilized through the whole wall thickness in an ordinary single housing, but be more useful for walls between apartments or outer walls directly connected to a green house. Another very suitable area of use for hemp-lime in-fill is in refurbishment projects where exteriors are important to preserve. It adapts well to wooden structures in old log houses, for instance, through its vapour open pore structure, durability, preservative and fire proofing qualities as well as small shrinkage ratio. The main differences in properties between hemp fiber insulation and hemp-lime are that hemp-lime is a middle weight material that provides both insulation, heat storage, structure support, airtightness and fire protection in one single layer, which is very different from hemp fiber wool and hemp fiber battens that are solely used as lightweight insulation. It is debated whether this is more beneficial than dividing up different qualities in several layers where each layer function is maximized for its specific purpose.

My case study shows that a multi-layered thermal envelope with a combination of lightweight hemp fiber insulation and a highly thermal and moisture buffering loam plaster to the inside could in theory be made much thinner than a hemp-lime wall with an equivalent U-value. The thickness of the hemp-lime roof in thermal envelope two might not even be feasible in practice. I have however only based my calculations on estimated lambda figures. The actual U-value needs to be tested in a test facility where all three ways of heat transfer are taken into account and the dynamic thermal performance at a whole building level where other factors such as thermal bridges, airtightness, hygroscopic behaviour etc. are included in the evaluation. A monolithic hemp-lime element is, in fact, said to be very airtight, minimize thermal bridges and be able to handle moisture that travells through the wall very effectively. Other benefits of single layered structures are that they could simplify the construction management and complexity and thus be easier to quality proof for an inexperienced builder. Fewer materials can lessen the amount of suppliers used and the transport burden, if the material in the future becomes more widely available.

Insulation is generally what is most important in cold climates and heat storage is more important and has greater effects on buildings' energy use in warmer climates or in places that hold a risk of becoming overheated, such as in offices or other public facilities that at times can be heaviliy populated. Thermal and moisture buffering towards the inside is still sought for though, since it can balance out heat and moisture fluctuations enabling a stable and comfortable indoor environment with good air quality and lower the risk for moisture damage in the construction (and possible health damaging effects of that). It will also lower the need for ventilation. As can be noted in my time constant calculations, hemp-lime does not have as high heat storing capability as heavier materials such as loam or concrete why a thicker layer would be needed to gain the same effect. The low effusivity of hemp-lime is also indicative of this but that will at the same time enable warm surfaces, possibly giving comfort and higher perceived temperatures for inhabitants when used in floors, for instance.

The low diffusivity of hemp-lime will slow down the heat absorbtion rate, but will on the other hand enable the material to store the heat during a longer period before it is released again, if there are cases where the heat flow varies very slowly or there are longer periods of disruptions in the heating supply. Some say that this characteristic is beneficial in outer walls, giving them a time lag of heat transfer, but that might only give a measurable effect in poorer insulated structures.

All of my examined hemp insulation applications have very sustainable credentials. The common strong points are hemp's resilience, sound chemical profile, large carbon dioxide sequestration and potential of being an energy resource at the end of life. The later is however only true when the hemp product can be incinerated and the soundness of the total chemical profile of course depends on what other additives the material is combined with. Processing will in all examined materials add to the energy use and carbon footprint. Practical products and the easy and fast-track handling of those is however often regarded as imperative in larger scaled constructions why it is important to make the processing more environmentally friendly, one example of that being the usage of renewable energy in the production of battens. As for the carbon dioxide emissions of processed hemp insulation applications, hemp-lime will still be a carbon negative product if taking sequestration into account and hemp battens' emissions are also largely compensated by the plants' high ability to lock up green house gases.

It is important to regard the longer perspective in all kinds of environmental assessments. Pure hemp fibres are naturally carbon negative. If the fibres would be left to biodegrade or burn, they would however release their captured carbon dioxide again (but be able to be used as an energy source). Hemp-Lime, being a very robust and durable material, might be more prone to be re-used or put in landfill at the end of life. Without a full deterioration of the material, the captured carbon dioxide would remain enclosed within the building block, possibly for centuries, which I think should be regarded as a benefit. It all depends on the context and how long the building in question is meant to last. Even though lime has a lower environmental impact than cement, the amounts of energy used and carbon dioxide emitted during its production might still be a somewhat critical factor right now in regards to the importance of us trying to fend off a climate change tipping point.

The sustainable credentials of the examined materials are the same in a cooler climate, except for the possible need of using energy for fans to help hemp-lime dry out and larger amounts of insulation material in general, the later not a product specific phenomena. The current scarce availability in Sweden will however add to the transport burden.

Discussion

Price

Whenever new products are being established on a market it is common that price is initially higher, which can be a deal breaker for many consumers. The cultivation and production technologies for hemp and its building applications are still at a very early stage in Sweden and a lot of mechanization improvements are needed. Some bio-based building materials are free or at least very cheap, such as earth or straw, the later being an agricultural by-product to cereal crops, readily available. Even though hemp shiv is also seen as a by-product to the more valuable fiber, hemp might never be as cheap despite this since separation of the plant's parts (decortication) is needed. Being a plant with many extraordinary qualities and capabilities, it might be worth paying at least a price comparable to other conventionally used insulation products though. Processing hemp fibres into battens can unfortunately however more than double it. The prices for hemp-lime can vary substantially depending on if you are using a certified formula for both main constituents or not; a certified formula can almost double the cost here as well. A future local production of a customized lime binder might be able to lower the cost for both the product and its transport.

A cost aspect that is not taken into account in my comparison over thermal envelopes is that the use of timber cladding on the outside is not needed on hemp-lime walls and the timber structure might also be able to be slimmed down due to the supporting qualities of the material; factors that of course could lower the construction cost substantially. The fact that the construction complexity in hemp-lime monolithic building elements is lowered and the number of materials and suppliers are narrowed down could also mean substantial cost reductions, looking at the bigger picture, the labor and construction management are usually far bigger expences than the building materials.

Market development potentials

With an increasing awareness of environmental issues and holistic thinking on a societal level the interest for good quality sustainable and sound building products does seem to grow accordingly. This gives good basic conditions for a positive market development for hemp-based insulation products.

Standardization of natural materials holds many great benefits since at least larger scaled building projects demand quality assurance. This can sometimes come at the expense of the environmental soundness of the product though since substances added to secure, for instance, fire or rot resistance, are in some cases questionable in that sense. Considering hemp, where the fibres are so naturally resilient it is however evidently perfectly possible to develop hazardous free building components. Crop-based materials can be harder to standardize due to their natural diversity, but looking at the forerunner France that has set standards on the quality of shiv used for building purposes, it clearly is not an impossible task.

Standardization and product refinement usually comes with a higher price tag, which, for example, can be due to higher production costs, quality assurances and special formulas. It is however good to have alternatives for both the smaller scale self-builder with a tight budget and the larger construction contractor where time management and efficacy is of uttermost importance.

Another significant matter worth mentioning is that well-established suppliers of conventionally used insulation products often do strong promotion and lobbying for their products where large parts of the building research can actually be funded by industry (Woolley 2013). This is of course very hard for small developing businesses to compete against. If renewable and sound building materials, as well as more unbiased research, were to be subsidized by government and manufacturers of hazardous petrochemical materials would be obliged to take more responsibility for the substances in their products, through taxes, indoor air monitoring schemes and waste handling measures, for instance, smaller local hemp productions might be able to become more viable. The leading experts on indoor air quality at the Building Research Establishment (BRE) in the UK have actually demanded indoor air quality management plans for new developers, likewise could be done in Sweden (Bevan, Woolley & Pritchett 2008). An expensive investment for a small hemp farmer to overcome can be a qualitative and cost-effective processing equipment, why larger investors and/or subventions are needed (Johansson & Olofsson 2009). With more processing plants or other smaller scaled effective decortication methods established, hemp might in the future become more available/locally sourced and cheap.

Since being relatively new building materials on the market, hemp fiber insulation applications and hemp-lime are also in need of further performance testing, optimization and evaluation. Areas of further development could for instance be:

- Building technique optimization in colder climates
- Limitations of the use of cement and environmentally inflicting components
- Comparative performance testing of several wall build-ups using different combinations of hemp-based insulation
- In-situ performance testing and measurable data on mechanical properties,

thermal and moisture behaviour, air permeability etc., as well as durability in cold and wet climates

- More tests on fire behaviour and solutions for further improvements in fire resistance
- Tests on acoustic performance and optimization of sound reducing qualities

Sustainability perspectives

One can have many different perspectives on sustainability. According to the Brundtland report, which is the most widely stated formulation around the concept, it involves three important factors working together; environment, economics and society. Ecological sustainability can in many terms be seen as hard to create at the same time as economic sustainability when our whole financial system is built upon consuming more and more. Self-sustained solutions often work against the capital driving forces that teaches us to consume and throw away at a faster and faster rate to enable a flourishing economy. Large corporations do currently often have much more influential power than what I think many people realize and within the EU it can be hard to put pressure on legislations around environmentally inflicting products if it is seen as a threat against free trading; a way to protect larger industries' financial interests.

Since peoples' attitudes around their expenditures are continuously changing, this will hopefully in the end be the stronger force. There is, for instance, a growing body around the concept of "circular economy", which is built upon the idea that the profitability lies in the service needed when re-using a product, as opposed to only being profitable through a never ending desire amongst people for completely new wares. As in the case of biodegradable materials that do not need to be reused, it will not be the product and its maintenance that holds the great economic value, people will instead pay for the manufacturing and labour costs around the product, which could enable new job opportunities.

Different ways of looking at sustainability also include perspectives, short-term effects weighed against long-term benefits; which is most important? One example of this could be that there is a large focus on using locally supplied materials since transport is a significant part of materials' embodied energy and carbon dioxide emissions. Looking at the case of hemp and hemp-lime, where the availability in Sweden as for right now is very limited, products or at least product components might in an initial phase have to be imported to be able to give them local publicity. This way better incentives can be created for larger production investments in the future, i.e. possibilities for long-term positive effects on our environment. Another aspect is that short-term effects are very important right now since we are currently approaching a climate change tipping point in a very fast rate.

Whatever view on which approach that might be the more sustainable, that one might have, I think the most important thing is that we keep working towards a common goal and avoid the largest contaminants. A wider usage of crop-based insulation products without hazardous components in buildings is, in my opinion, a great step in the right direction. Hazardous chemical compounds in building materials (and in merchandise and food at large) is a huge threat to our eco-systems and our health that is often completely overlooked in the thrive towards energy (and cost) efficiency. Energy use and carbon dioxide emissions are very important matters, but we are also seeing the field of renewable and clean energy developing in a very fast rate at the same time as fossil fuels are being gradually phased out. I think it is about time that we also carefully look into what substances we are leaving behind in nature, if we want to be able to keep feeding off of it in the future. A holistic view where all impacts on nature are considered is of course important to keep, as long as it is not hindering us in taking small steps forward (as opposed to a lot of discussion with no steps at all).

List of illustrations

23: [*Hemp leaf*] n.d. [image online] Available from: https://medworksmedia.com/associations-cannabis-use-physical-health-problems-early-midlife/. [Accessed: 11th April 2016].

33: Grundvall, M. (2016) *Wall construction types.* [drawing] (author's own collection).

37: Jasper-m through © CC0 Public Domain (2010) *Hemp plant.* [image online] Available from: https://pixabay.com/sv/marijuana-växt-ört-hampa-ogräs-1545759/. [Accessed: 11th October 2016].

38: [*Hemp paper*] n.d. [image online] Available from: http://www.herbmuseum.ca/content/brief-history-paper. [Accessed: 2nd September 2015].

[*Hemp sails, nets and ropes*] n.d. [image online] Available from: http://newearthhemp.com/2016/02/27/hemp-101-101-facts-about-hemp/. [Accessed: 2nd September 2015].

39: Wikimedia Commons (n.d.) *Map over Europe*. [image online] Available from: https://commons.wikimedia.org/wiki/Atlas_of_Europe?uselang=sv#Maps_of_Regions. [Accessed: 8th February 2015].

40: Allin, S. (n.d.) *Image: cross section hemp stalk*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

[*Fibre peeled from shiv*] n.d. [image online] Available from: http://www.hemparchitecture.com/hemp-plant/. [Accessed: 11th April 2016].

Jacobsson, T. (2013) *Seeding*. [image online] Available from: https://www.facebook.com/329602997142096/photos/a.337386339697095.1073741828.329602997142096/337386799697049/?type=3&theater. [Accessed: 15th April 2016].

Jacobsson, T. (2015) *Yield*. [image online] Available from: https://www.facebook.com/329602997142096/photos/a.337386339697095.1073741828.329602997142096/623510967751296/?type=3&theater. [Accessed: 15th April 2016].

41: Jacobsson, T. (2016) *Swathing*. [image online] Available from: https://www.facebook.com/329602997142096/photos/a.337386339697095.1073741828.329602997142096/686841818084877/?type=3&theater. [Accessed: 15th April 2016].

Jacobsson, T. (2007) *Collecting yield*. [image online] Available from: http://www.osterlenhampa.se/%D6sterlenhampa/Tidigare.htm. [Accessed: 15th April 2016].

Jacobsson, T. (2016) *Baling*. [image online] Available from: https://www.facebook.com/329602997142096/photos/a.337386339697095.1073741828.329602997142096/708434062592319/?type=3&theater. [Accessed: 15th April 2016].

42: [*Hemp fiber textiles*] n.d. [image online] Available from: http://organic.lovetoknow.com/Organic_Hemp_Clothing. [Accessed: 11th April 2016].

Redspiderfish/Flickr (n.d.) *A BMW 5 series door panel made out of hemp.* [image online] Available from: http://hemphealthytoday.blogspot.se/2013_11_01_archive.html. [Accessed: 11th April 2016].

Grundvall, M. (2016) *Hemp seeds.* [image] (author's own collection).

Jacobsson, T. (2013) *Shiv animal bedding*. [image online] Available from: http://www.osterlenhampa.se/%D6sterlenhampa/hampodling.htm. [Accessed: 15th April 2016].

Grundvall, M. (2016) *Hemp fiber batten.* [image] (author's own collection).

[*Hemp bio-plastic shoe*] n.d. [image online] Available from: http://www.maison-objet.com/en/paris/exhibitors/september-2015/plasticana-14073?offset=2465. [Accessed: 11th April 2016].

43: [*Hemp plant and root*] n.d. [image online] Available from: http://www.cbdweb.org/medical-cannabis-guide/hemp-oil-arthritis-pain-relief. [Accessed: 16th April 2016].

44: Carus, M. (2008) *Diagram: hemp cultivation energy use*. Reproducted in: Haufe, J. & Carus, M. (2011) *Hemp Fibres for Green Products – An Assessment of Life Cycle Studies on Hemp Fibre Applications*. [online] Germany: nova-Institute GmbH. Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCMQFjAAahUKEwjX-iZ-f1_fHAhUKvXIKHbawDlQ&url=http%3A%2F%2Feiha.org%2Fmedia%2F2014%2F10%2FHemp-Fibres-for-Green-Products-----An-assessment-of-life-cycle-studies-on-hemp-fibre-applications-2011.pdf&usg=AFQjCNHDoCWga5YOR7kD1yV-fYDj-6-V_Yw. [Accessed: 8th September 2015].

47: Grundvall, M. (2016) *Hemp fiber wool.* [image] (author's own collection).

48: Grundvall, M. (2016) *Hemp fiber wool.* [image] (author's own collection).

Grundvall, M. (2016) *Hemp fiber batten.* [image] (author's own collection).

Grundvall, M. (2016) *Hemp fiber batten.* [image] (author's own collection).

50: Bos, U. & Deimling, S. (2005) *Diagrams: LCA hemp battens*. Reproduced in: Bos, U. & Deimling, S. (2005) Development of a Complete Biogenous Insulating Material – LCA Results. [online] Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB4QFjAAahUKEwjl6uDVs9n-HAhWKBiwKHUrYCjc&url=http%3A%2F%2Fwww.agroscope.ch%2Faktuell%2F02720%2F02722%2F03985%2F04043%2Findex.html%3Flang%3Dde%26download%3DN-HzLpZeg7t%2Clnp6I0NTU042l2Z6ln1acy4Zn4Z2qZpnO2Y-uq2Z6gpJCEdIN9gmym162epYbg2c_JjKbNoKSn6A--&usg=AFQjCNGI4vSG0rt05fA8QSj_stMpL_D5UA. [Accessed: 2nd September 2015].

Zampori, L., Dotelli, G. & Vernelli, V. (2013) *Diagrams: LCA hemp and Rockwool battens*. Reproduced in: Zampori, L., Dotelli, G. & Vernelli, V. (2013) Life Cycle Assessment of Hemp Cultivation and Use of Hemp-Based Thermal Insulator Materials in Buildings. *Environmental Science & Technology*. [online] ACS Publications. 47 (13/June). p.7413-7420. Available from: http://pubs.acs.org/doi/full/10.1021/es401326a. [Accessed: 8th September 2015].

52: [*Hemp fiber wool in floor*] n.d. [image online] Available from: https://se.pinterest.com/pin/444237950723807261/. [Accessed: 7th April 2016].

53: [*Image: hanffaser hemp fiber equipment*] n.d. Reproduced in: Norberg, P. (2009) Lösullsisolering med hampa. *Bygg & teknik*. [online] 5 (August). p. 28-32 Available from: https://issuu.com/byggteknikforlaget/docs/5-09. [Accessed: 7th April 2016].

54: [*Hemp cigarette paper*] n.d. [image online] Available from: https://www.ruffhousestudios.com/product/raw-organic-1-25-rolling-paper-pack-50-leaves/. [Accessed: 2nd September 2015].

60: Pixel2013 through © CC0 Public Domain (2016) *Straw.* [image online] Available from: https://pixabay.com/sv/halm-skörd-jordbruk-fältet-stubb-1529063/. [Accessed: 20th July 2016].

[*Cellulose*] n.d. [image online] Available from: http://www.soluzionidecocreative.it. [Accessed: 15th April 2016].

Putmanbuilt through © 2016 Photobucket (2012) *Flax*. [image online] Available from: http://s1142.photobucket.com/user/putmanbuilt/media/2012/002-20.jpg.html?sort=3&o=95. [Accessed: 15th April 2016].

Øyvind Holmstad CC-1.0 Universal Public Domain Dedication (n.d.) *Mineral wool*. [image online] Available from: http://pennypincherjournal.blogspot.se/2014/02/home-insulation-save-money-on-utility.html. [Accessed: 15th April 2016].

63: [*Hemp-lime*] n.d. [image online] Available from: http://www.naturallimeplaster.ca/content/hempcrete. [Accessed: 11th April 2016].

64: [*Lime powder*] n.d. [image online] Available from: http://www.pulpandpaper-technology.com/company/finishing-converting/ankur-minerals. [Accessed: 11th October 2016].

Grundvall, M. (2016) *Hemp shiv.* [image] (author's own collection).

65: Gzvezdov through © CC0 Public Domain (2016) *Cement.* [image online] Available from: https://pixabay.com/sv/gips-konsistens-bakgrund-betong-1564520/. [Accessed: 11th October 2016].

[*Coal fly ash*] n.d. [image online] Available from: http://cornerstonemag.net/commercial-recovery-of-metals-from-coal-fly-ash/. [Accessed: 8th April 2016].

66: Susbany through © CC0 Public Domain (2013) *Lime quarry.* [image online] Available from: https://pixabay.com/sv/stenbrott-sten-grop-sten-stenbrott-77462/. [Accessed: 11th October 2016].

68: Yates, T. (n.d.) *Image: Houses of Haverhill 1*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

Yates, T. (n.d.) *Image: Houses of Haverhill 2*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

69: Maalouf, C. et al. (2011a) *Table: heat capacities in different materials*. Reproduced in: Maalouf, C. et al. (2011a) A Study of the Use of Thermal Inertia in Simple Layer Walls and its Application to the use of a Vegetal Fibre Material in Buildings. *International Journal of Energy, Environment and Economics*. [online] ResearchGate. 19 (5/Januari). p. 467-489. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Maalouf, C. et al. (2011a) *Table: physical properties of different materials*. Reproduced in: Maalouf, C. et al. (2011a) A Study of the Use of Thermal Inertia in Simple Layer Walls and its Application to the use of a Vegetal Fibre Material in Buildings. *International Journal of Energy, Environment and Economics*. [online] ResearchGate. 19 (5/Januari). p. 467-489. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

70: [*Hempod test house 1*] n.d. [image online] Available from: http://www.worldarchitecturenews.com/wanmobile/mobile/article/14757. [Accessed: 7th April 2016].

Pritchett, I. (n.d.) *Lime Technology Ltd head office.* [image] (Ian Pritchett's own collection).

Lawrence, M. et al. (2012) *Diagram: monitoring of the Hempod and small office test houses*. Reproduced in: Lawrence, M. et al. (2012) Hygrothermal Performance of an Experimental Hemp-lime Building. *Construction and Building Materials*. [online] ScienceDirect. 36 (November). p. 270–275. Available from: http://www.sciencedirect.com/science/article/pii/S0950061812003273. http://opus.bath.ac.uk/30377/1/Lawrence_Key%2DEng%2DMat_2012_517.pdf. [Accessed: 2nd September 2015].

Bevan, R., Woolley, T. & Pritchett, I. (2008) *Diagram: in-situ monitoring of Lime technology Ltd head office*. Reproduced in: Bevan, R., Woolley, T. & Pritchett, I. (2008) *Hemp lime construction: a guide to building with hemp lime composites*. Bracknell: IHS BRE Press.

71: Bevan, R., Woolley, T. & Pritchett, I. (2008) *Diagram: thermal diffusivity of various materials*. Reproduced in: Bevan, R., Woolley, T. & Pritchett, I. (2008) *Hemp lime construction: a guide to building with hemp lime composites*. Bracknell: IHS BRE Press.

Limetec through © 2016 Linkedin Corporation Slide share (2011) *Adnam's brewery 1.* [image online] Available from: http://www.slideshare.net/limetech/thermal-performance-of-hemcrete-with-photos. [Accessed: 11th October 2016].

Limetec through © 2016 Linkedin Corporation Slide share (2011) *Adnam's brewery 2.* [image online] Available from: http://www.slideshare.net/limetech/thermal-performance-of-hemcrete-with-photos. [Accessed: 11th October 2016].

Tran Le, A. D.et al. (2014) *Diagram: temperature profiles in wall*. Reproduced in: Tran Le, A. D.et al. (2014) Effect of Simulation Parameters on the Hygrothermal Behaviour of a Wall and a Room made of Hemp-lime Concrete. *International Journal of Mathematical Models and Methods in Applied Sciences*. [online] 8. Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB0QFjAAahUKEwjqqtb-fwP_IAhUovXIKHT7ZDsM&url=http%3A%2F%2Fwww.naun.org%2Fmain%2FNAUN%2Fijmmas%2F2014%2Fa522001-052.pdf&usg=AFQjCNESaZVE269Oyme3yugOZEFYYu3JeA. [Accessed: 2nd October 2015].

72: Maalouf, C. et al. (2011b) *Diagram: TH model - stored energy and effusivity*. Reproduced in: Maalouf, C. et al. (2011b) Effect of Moisture Transfer on Heat Energy Storage in Simple Layer Walls: Case of a Vegetal Fibre Material. *International Journal of Mathematical Models and Methods in Applied Sciences*. [online] ResearchGate. 5 (6/Januari). p. 1127-1134. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Maalouf, C. et al. (2011b) *Diagram: HAM model - stored energy and effusivity*. Reproduced in: Maalouf, C. et al. (2011b) Effect of Moisture Transfer on Heat Energy Storage in Simple Layer Walls: Case of a Vegetal Fibre Material. *International Journal of Mathematical Models and Methods in Applied Sciences*. [online] ResearchGate. 5 (6/Januari). p. 1127-1134. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

73: Evrard, A. & De Herde, A. (2005) *Diagram: dampening of temperature variations at different wall depths*. Reproduced in: Bevan, R., Woolley, T. & Pritchett, I. (2008) *Hemp lime construction: a guide to building with hemp lime composites*. Bracknell: IHS BRE Press.

74: [*Hempod test house 2*] n.d. [image online] Available from: http://www.worldarchitecturenews.com/wanmobile/mobile/article/14757. [Accessed: 7th April 2016].

BESRaC (2010) *Simulation: linear thermal transmittance at junctions*. Reproduced in: Daly, P., Ronchetti, P. & Woolley, T. (2013) *Hemp Lime Bio-composite as a Building Material in Irish Construction*. [online] Ireland: Environmental Protection Agency. Available from: http://erc.epa.ie/safer/resource?id=608582c3-80f5-102e-a0a4-f81fb11d7d1c. [Accessed: 8th September 2015].

Yates, T. (n.d.) *Image: Houses of Haverhill 3*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

Yates, T. (n.d.) *Image: Houses of Haverhill 4*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

75: Rahim, M. et al. (2015) *Diagram: practical MBV of different materials*. Reproduced in: Rahim, M. et al. (2015) *Moisture Properties of Rape Straw Concrete and Hemp Concrete*. Paper presented at the First International Conference on Bio-based Building Materials, Clermont-Ferrand, France, June 2015. [online] ResearchGate. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Tran Le, A. D. et al. (2010) *Diagram: relative humidity variations - hemp and cellular concrete*. Reproduced in: Tran Le, A. D. et al. (2010) Transient Hygrothermal Behaviour of a Hemp Concrete Building Envelope. *Energy and Buildings*. [online] ResearchGate. 42 (10/May). p. 1797-1806. Available from: http://www.researchgate.net/publication/222533736_Transient_hygrothermal_behaviour_of_a_hemp_concrete_building_envelope._Energy_Build. [Accessed: 2nd September 2015].

Yates, T. (2002) *96 hour water spray test on hemp-lime wall sample.* [image] (Tim Yates's own collection).

76: [*Image: kretsloppsgård i Burs*] n.d. Reproduced in: Melkersson, D. (27th April 2016) *Kretsloppsgård i Burs* [Leaflet obtained through e-mail from author], 1st June 2016.

Stanwix, W. & Sparrow, A. (n.d.) *Image: Cast-in-situ hand placed hempcrete*. Reproduced in: Stanwix, W. & Sparrow, A. (2014). *The hempcrete book: designing and building with hemp-lime*. Cambridge: Green Books. **www.greenbooks.co.uk**

Allin, S. (n.d.) *Image: Spraying technique*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

Lime Technology (n.d.) *Hemclad* ©. [image online] Available from: http://www.archiexpo.com/prod/lime-technology/product-70036-580598.html. [Accessed: 11th October 2016].

77: Grundvall, M. (2016) *Building blocks.* [image] (author's own collection).

Voase, N. (2009) *Mechanized pouring technique.* [image] (Nick Voase's own collection).

Stanwix, W. & Sparrow, A. (n.d.) *Image: Hempcrete at the eaves*. Reproduced in: Stanwix, W. & Sparrow, A. (2014). *The hempcrete book: designing and building with hemp-lime*. Cambridge: Green Books. **www.greenbooks.co.uk**

78: Stanwix, W. & Sparrow, A. (n.d.) *Drawing: Steel frame set away from the wall internally*. Reproduced in: Stanwix, W. & Sparrow, A. (2014). *The hempcrete book: designing and building with hemp-lime*. Cambridge: Green Books. **www.greenbooks.co.uk**

Stanwix, W. & Sparrow, A. (n.d.) *Drawing: Non-masonry cladding details*. Reproduced in: Stanwix, W. & Sparrow, A. (2014). *The hempcrete book: designing and building with hemp-lime*. Cambridge: Green Books. **www.greenbooks.co.uk**

79: [*Plastic shuttering*] n.d. [image online] Available from: https://www.periodliving.co.uk/advice/insulating-with-hemcrete/. [Accessed: 18th July 2016].

Bevan, R., Woolley, T. & Pritchett, I. (2008) *Image: Cast hemp-lime in renovation project*. Reproduced in: Bevan, R., Woolley, T. & Pritchett, I. (2008) *Hemp lime construction: a guide to building with hemp lime composites*. Bracknell: IHS BRE Press.

80: Allin, S. (n.d.) *Image: Hemp-lime house with other materials integrated in facade*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

Budden, T. (n.d.) *Image: Hemp-lime house by Hemporium*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

81: Leu, L. (n.d.) *Image: Pierrefleur Terrain*. Reproduced in: Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

86: [*Cellular concrete*] n.d. [image online] Available from: http://www.lincopia.se/wp-content/uploads/2012/05/SSF_pressbild3.jpg. [Accessed: 15th April 2016].

PublicDomainPictures through © CC0 Public Domain (2012) *Timber.* [image online] Available from: https://pixabay.com/sv/bakgrund-brown-cirkel-klippa-84678/. [Accessed: 15th April 2016].

[*Woodwool cement*] n.d. [image online] Available from: https://www.pinterest.se/pin/442478732111793054/. [Accessed: 15th April 2016].

[*Rammed earth*] n.d. [image online] Available from: http://www.

rammedearthworks.com/pre-cast-rammed-earth/4. [Accessed: 18th July 2016].

87: [*Shibam*] n.d. [image online] Available from: http://archinect.com/forum/thread/100798261/does-anybody-recognize-this-architecture. [Accessed: 18th July 2016].

89: Tran Le, A. D. et al. (2010) *Diagram: relative humidity variations with and without cement plaster*. Reproduced in: Tran Le, A. D. et al. (2010) Transient Hygrothermal Behaviour of a Hemp Concrete Building Envelope. *Energy and Buildings*. [online] ResearchGate. 42 (10/May). p. 1797-1806. Available from: http://www.researchgate.net/publication/222533736_Transient_hygrothermal_behaviour_of_a_hemp_concrete_building_envelope._Energy_Build. [Accessed: 2nd September 2015].

Rode, C. (2005) *Diagram: comparison of MBV for different materials*. Reproduced in: Collet, F., Pretot, S. & Lanos, C. (2013) Effect of Coating on Moisture Buffering of Hemp Concrete. [online] ResearchGate. (September). Available from: www.researchgate.net/. [Accessed: 18th November 2015].

96: Grundvall, M. (2016) *The house.* [image] (author's own collection).

97: © Creative commons (2009) *The historical provinces of Sweden.* [image online] Available from: https://commons.wikimedia.org/wiki/File:Sverigekarta-Landskap.svg. [Accessed: 8th April 2016].

99: Grundvall, M. (2016) *Thermal envelope 1.* [drawing] (author's own collection).

101: Grundvall, M. (2016) *Thermal envelope 2.* [drawing] (author's own collection).

103: Grundvall, M. (2016) *Thermal envelope 3.* [drawing] (author's own collection).

APPENDIX II

142: Grundvall, M. (2016) *The house.* [image] (author's own collection).

143: Grundvall, M. (2016) *Plot overview.* [image] (author's own collection).

Grundvall, M. (2016) *Lake view.* [image] (author's own collection).

Grundvall, M. (2016) *Sunrise over lake.* [image] (author's own collection).

144: Grundvall, M. (2016) *Site plan.* [drawing] (author's own collection).

146: Grundvall, M. (2016) *East facade.* [drawing] (author's own collection).

147: Grundvall, M. (2016) *South facade.* [drawing] (author's own collection).

148: Grundvall, M. (2016) *North facade.* [drawing] (author's own collection).

149: Grundvall, M. (2016) *West facade.* [drawing] (author's own collection).

150: Grundvall, M. (2016) *Floor 1.* [drawing] (author's own collection).

Grundvall, M. (2016) *Floor 2.* [drawing] (author's own collection).

151: Grundvall, M. (2016) *Section A-A.* [drawing] (author's own collection).

Grundvall, M. (2016) *Section B-B.* [drawing] (author's own collection).

Bibliography

Adalberth, K. (2000) *Energy use and environmental impact of new residential buildings*. Diss. (summary), Lund University. Available from: http://lup.lub.lu.se/record/40295. [Accessed: 11th April 2016].

Allin, S. (2012) *Building with hemp*. 2. ed. Kenmare, Co. Kerry: Seed Press.

Amziane, S. & Arnaud, L. (red.) (2013) *Bio-aggregate-based building materials: applications to hemp concretes*. London: ISTE

Bauhaus. *Bauhaus*. [online] Available from: http://www.bauhaus.se/?gclid=CKXi5KjtusgCFSQHwwodvp8GQQ. [Accessed: 2nd September 2015].

Berge, B. (2009) *The ecology of building materials*. 2. ed. Amsterdam: Elsevier/Architectural Press.

Bevan, R., Woolley, T. & Pritchett, I. (2008) *Hemp lime construction: a guide to building with hemp lime composites*. Bracknell: IHS BRE Press.

Bocsa, I. & Karus, M. (1998) *The cultivation of hemp: botany, varieties, cultivation and harvesting*. Sebastapol, Calif.: Hemptech.

Bokalders, V. & Block, M. (2014) *Byggekologi: kunskaper för ett hållbart byggande : [sunda hus, hushållning, kretslopp, platsen]*. 3. ed. Stockholm: Svensk Byggtjänst.

Bos, U. & Deimling, S. (2005) Development of a Complete Biogenous Insulating Material – LCA Results. [online] Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB4QFjAAahUKEwjl6uDVs9nHAhWKBiwKHUrYCjc&url=http%3A%2F%2Fwww.agroscope.ch%2Faktuell%2F02720%2F02722%2F03985%2F04043%2Findex.html%3Flang%3Dde%26download%3DNHzLpZeg7t%2Cln-p6I0NTU042l2Z6ln1acy4Zn4Z2qZpnO2Yuq2Z6gpJCEdIN9gmy-m162epYbg2c_JjKbNoKSn6A--&usg=AFQjCNGI4vSG0rt05fA-8QSj_stMpL_D5UA. [Accessed: 2nd September 2015].

Boverket. *Boverket*. [online] Available from: http://www.boverket.se/sv/lag--ratt/forfattningssamling/gallande/bbr---bfs-20116/. [Accessed: 16th April 2016].

Byggipedia. *Byggipedia*. [online] Available from: http://byggipedia.se/category/byggmaterial/lattbetong/. [Accessed: 2nd May 2016].

Cannabric. (2009) *Cannabric*. [online] Available from: http://www.cannabric.com. [Accessed: 2nd September 2015].

© 2016 Circular Ecology Ltd. (2016) *Circular Ecology*. [online] Available from: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.Wa50g8az6V4. [Accessed: 16th April 2016].

Collet, F., Pretot, S. & Lanos, C. (2013) Effect of Coating on Moisture Buffering of Hemp Concrete. [online] ResearchGate. (September). Available from: www.researchgate.net/. [Accessed: 18th November 2015].

Collet, F & Pretot, S. (2014a) Experimental Highlight of Hygrothermal Phenomena in Hemp Concrete Wall. *Building and Environment*. [online] ResearchGate. (December). Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Collet, F. & Pretot, S. (2014b) Thermal Conductivity of Hemp Concretes: Variation with Formulation, Density and Water Content. *Construction and Building Materials*. [online] ResearchGate. 65 (June). Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Dahlin, J-E. (2014) *Hållbar utveckling: en introduktion för ingenjörer.* Lund:

Studentlitteratur.

Dalmay, P et al. (2010) Properties of Cellulosic Fibre Reinforced Plaster: Influence of Hemp or Flax Fibres on the Properties of Set Gypsum. *Journal of Materials Science*. [online] SpringerLink. 45 (3/ February). p. 793-803. Available from: http://link.springer.com/article/10.1007/s10853-009-4002-x. [Accessed: 8th September 2015].

Daly, P., Ronchetti, P. & Woolley, T. (2013) *Hemp Lime Bio-composite as a Building Material in Irish Construction*. [online] Ireland: Environmental Protection Agency. Available from: http://erc.epa.ie/safer/resource?id=608582c3-80f5-102e-a0a4-f81fb11d7d1c. [Accessed: 8th September 2015].

De Bruijn, P. (2012) *Material properties and full-scale rain exposure of lime-hemp concrete walls: measurements and simulations* [online]. Diss. (summary), Swedish University of Agricultural Sciences. Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:slu:epsilon-e-596. [Accessed: 8th September 2015].

Dubois, S., Evrard, A. & Lebeau, F. (2012) *Hygrothermal Modelling of Lime-Hemp Concrete used as Building Material and Indoor Climate Buffering Characterization*. Paper presented at the International Conference of Agricultural engineering (CIGR-Ageng), Valencia, Spain, July 2012. [online] ResearchGate. Available from: www.researchgate.net/. [Accessed: 2nd September 2015].

Dubois, S., Evrard, A. & Lebeau, F. (2014) Modeling the Dynamic Hygrothermal Behavior of Biobased Construction Materials. *Journal of Building Physics*. [online] Sage journals. (June) Available from: http://orbi.ulg.ac.be/bitstream/2268/150902/2/COMSOL_complete.pdf. [Accessed: 2nd September 2015].

EIHA. *European Industrial Hemp Association*. [online] Available from: http://eiha.org/media/2014/10/15-08-24-Industrial-Hemp-Cultivation-Area-2015-EIHA1.pdf. [Accessed: 8th April 2016].

Eriksson, D. (2008) *Industrihampa – Marknad och Odlingsareal*. [online] Sweden: Swedish University of Agricultural Sciences. Available from: http://194.47.52.113/janlars/partnerskapAlnarp/ekonf/20080313/20080313_hampa.pdf. [Accessed: 8th September 2015].

Evrard, A. (2006) *Sorption Behaviour of Lime-Hemp Concrete and its Relation to Indoor Comfort and Energy Demand*. Paper presented at PLEA2006 – 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, September 2006. [online] Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCAQFjAAahUKEwihsfbhkoTJAhUBi3IKHcIYCfE&url=http%3A%2F%2Fplea-arch.org%2FARCHIVE%2F2006%2FVol1%2FPLEA2006_PAPER603.pdf&usg=AFQjCNFpTEdV2NEe05OmgMjlfZJtQKvmxw. [Accessed: 2nd October 2015].

Evrard, A. & De Herde, A. (2005) Bioclimatic Envelopes made of Lime and Hemp Concrete. [online] Available from: https://scholar.google.be/citations?view_op=view_citation&hl=en&user=RS6t-7pwAAAAJ&citation_for_view=RS6t7pwAAAAJ:qjMakFHDy7sC. [Accessed: 2nd September 2015].

Evrard, A. & De Herde, A. (2006) Dynamical Interactions between Heat and Mass Flows in Lime-Hemp Concrete. *Research in Building Physics and Building Engeneering*. [online] Dial Digital access to the libraries. p. 69-76. Available from: http://dial.uclouvain.be/handle/boreal:73819?site_name=UCL. [Accessed: 2nd September 2015].

Franck, R. R. (2005) *Bast and other plant fibres* [Electronic resource]. Ed. Cambridge: Woodhead.

Hagentoft, C. (2001) *Introduction to building physics*. Lund: Studentlitteratur.

Hanffaser Uckermark. *Hanffaser Uckermark*. [online] Available from: http://www.hanffaser.de/uckermark/. [Accessed: 8th October 2015].

Haufe, J. & Carus, M. (2011) *Hemp Fibres for Green Products – An Assessment of Life Cycle Studies on Hemp Fibre Applications*. [online] Germany: nova-Institute GmbH. Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCMQFjAAahUKEwjX-iZ-f1_fHAhUKvXIKHbawDlQ&url=http%3A%2F%2Feiha.org%2Fmedia%2F2014%2F10%2FHemp-Fibres-for-Green-Products-----An-assessment-of-life-cycle-studies-on-hemp-fibre-applications-2011.pdf&usg=AFQjCNHDoCWga5YOR7kD1yV-fYDj-6-V_Yw. [Accessed: 8th September 2015].

Hens, H. S.L.C. (2007) *Building physics - heat, air and moisture: fundamentals and engineering methods with examples and exercises*. Berlin: Ernst & Sohn.

Hirst, E. AJ. et al. (2015) Characterisation of Low Density Hemp-Lime Composite Building Materials under Compression Loading. [online] ResearchGate. Available from: http://www.researchgate.net/publication/268415710_Characterisation_of_Low_Density_Hemp-Lime_Composite_Building_Materials_under_Compression_Loading. [Accessed: 2nd September 2015].

Holstmark, K. (2006) *Hampa i Ekologisk Odling*. [online]. Sweden: Jordbruksverket. Available from: http://www.hemp.no/pdf/ekologisk_hampa.pdf. [Accessed: 8th September 2015].

Hugues, T., Steiger, L. & Weber, J. (2004). *Timber construction: details, products, case studies*. Basel: Birkhäuser.

Isoleringsbutiken. *Isoleringsbutiken*. [online] Available from: http://www.isoleringsbutiken.se. [Accessed: 11th April 2016].

Ip, K. & Miller, A. (2012) Life Cycle Greenhouse Gas Emissions of Hemp-lime Wall Constructions in the UK. *Resources, Conservation and Recycling*. [online] ScienceDirect. 69 (December). p. 1-9. Available from: http://www.sciencedirect.com/science/article/pii/S0921344912001620. [Accessed: 8th September 2015].

Jensen, A.A. et al. (1998) *Life cycle assessment (LCA); a guide to approaches, experiences and information sources*. [online]. Denmark: European Environment Agency. Available from: https://www.eea.europa.eu/publications/GH-07-97-595-EN-C. [Accessed: 11th April 2016].

Johansson, S & Olofsson, R. (2009) *Utveckling av Hampa som Energigröda i Mellansverige genom Separering av Ved och Fiber*. [online] Sweden: Energinätverket Green4u. (2007-34443). Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB4QFjAAahUKEwiDgdm-4unHAhUoAHMKHSzDBJ8&url=http%3A%2F%2Fwww.energigarden.se%2Fdotnet%2FGetAttachment.aspx%3Fid%3D1577%26siteid%3D88&usg=AFQjCNEaCRQ6lOPnsFOHGBIb_U89it1-CQ. [Accessed: 8th September 2015].

Johansson, S. (2010) *Hampaprodukter*. [online]. Sweden: Energinätverket Green4u. Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&ved=0CDcQFjADahUKEwiKx4DK6enHAhXm6HIKHWDiCW0&url=http%3A%2F%2Fwww.leaderskaraborg.se%2Fvastra%2FUserFiles%2FFile%2FHampaprodukter%2520slutrapport_klar.pdf&usg=AFQjCNEG59foY4lP5h9cPcTQsELkS_72ww. [Accessed: 8th September 2015].

Jordbruksverket. *Jordbruksverket*. [online] Available from: http://www.jordbruksverket.se/amnesomraden/stod/jordbrukarstod/gardsstod/villkor/markforodlingavhampa.4.57971bc14bbfb4901e21a8b.html. [Accessed: 8th September 2015].

La Rosa, A. D. et al. (2014) Bio-based versus Traditional Polymer Composites. A Life Cycle Assessment Persective. *Journal of Cleaner Production*. [online] ScienceDirect. 74 (July). p.135-144. Available from: http://www.sciencedirect.com/science/article/pii/S0959652614002388. [Accessed: 8th September 2015].

Lawrence, M. et al. (2012) Hygrothermal Performance of an Experimental Hemp-lime Building. *Construction and Building Materials*. [online] ScienceDirect. 36 (November). p. 270–275. Available from: http://www.sciencedirect.com/science/article/pii/S0950061812003273. http://opus.bath.ac.uk/30377/1/Lawrence_Key%2DEng%2DMat_2012_517.pdf. [Accessed: 2nd September 2015].

Lawrence, M. et al. (2013) Hygrothermal Performance of Bio-based Insulation Materials. *Proceedings of the Institution of Civil Engineers: Construction Materials*. [online] Proceedings of the ICE. 166 (4/March). p. 257–263. Available from: http://www.icevirtuallibrary.com/content/article/10.1680/coma.12.00031. [Accessed: 2nd September 2015].

Limetec. *Limetec - LMR Traditional Limited* [online] Available from: http://www.limetec.co.uk. [Accessed: 8th September 2015].

Maalouf, C. et al. (2011a) A Study of the Use of Thermal Inertia in Simple Layer Walls and its Application to the use of a Vegetal Fibre Material in Buildings. *International Journal of Energy, Environment and Economics*. [online] ResearchGate. 19 (5/Januari). p. 467-489. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Maalouf, C. et al. (2011b) Effect of Moisture Transfer on Heat Energy Storage in Simple Layer Walls: Case of a Vegetal Fibre Material. *International Journal of Mathematical Models and Methods in Applied Sciences*. [online] ResearchGate. 5 (6/Januari). p. 1127-1134. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Maalouf, C. et al. (2011c) Effect of Moisture Transfer on Thermal Inertia in Simple Layer Walls, Case of a Vegetal Fibre Material. *International Journal of Mathematical Models and Methods in Applied Sciences*. [online] ResearchGate. 5 (1/Januari). p. 33-47. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Maalouf, C. et al. (2011d) *Numerical Investigation of Heat and Mass Transfer in Flax and Hemp Concrete Walls*. Paper presented at the Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, Australia, November 2011. [online] ResearchGate. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Mermer, T. through © United Nations Environment Programme (2012) Greening the Economy through Life Cycle Thinking. [online] Available from: http://www.lifecycleinitiative.org/wp-content/uploads/2013/03/2012_LCI_10_years_28.3.13.pdf. [Accessed: 2nd September 2016].

Minke, G. (2013). *Building with earth: design and technology of a sustainable architecture*. 3., rev. ed. Basel: Birkhäuser.

Morton, T. & Bennetts, R. (2008) *Earth Masonry: design and construction guidelines*. Bracknell: IHS BRE Press.

Munch-Andersen, J. & Møller Andersen, B. (2004) *Halmhuse; udformning og materialeegenskaber.* [online]. Denmark: Statens Byggeforskningsinstitut. Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCcQFjABahUKEwiio87w7rDIAhXFiywKHWrABpU&url=http%3A%2F%2Fwww.sbi.dk%2Fbyggeteknik%2Fkonstruktioner%2Fserlige-konstruktioner%2Fhalmhuse%2F2006-01-12.9974566144%2Fat_download%2Ffile&usg=AFQjCNEoV_6ZoLIFjCZE9OYBporHCKO_lQ. [Accessed: 8th September 2015].

Nguyen, T-T. et al. (2009) Influence of Compactness and Hemp Hurd Characteristics on the Mechanical Properties of Lime and Hemp Concrete. *European Journal of Environmental and Civil Engineering*. [online] Taylor & Francis Online. 13 (9). p. 1039-1050. Available from: http://www.tandfonline.com/doi/abs/10.1080/19648189.2009.9693171?journalCode=tece20. [Accessed: 8th September 2015].

Nilsson, D. (2003) *Production and use of flax and hemp fibres: a report from study tours to some European countries*. Uppsala: Swedish University of Agricultural Sciences.

Norberg, P. (2009) Lösullsisolering med hampa. *Bygg & teknik*. [online] 5 (August). p. 28-32. Available from: https://issuu.com/byggteknikforlaget/docs/5-09. [Accessed: 7th April 2016].

Olofsson, R. (2014) *Mycket Hampa! Slutrapport för projekt*. [online]. Sweden: Hampaprodukter i Sverige ek. för. (2012-2038) Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCQQFjABahUKEwiyhp3G7enHAhUEi3IKHb7WA7E&url=http%3A%2F%2Fwww.leaderskaraborg.se%2Fvastra%2F_dokument%2F105%2520LVS%2520Slutrapport%2520Mycket%2520Hampa%252014-05-08%2520R%25C3%25A4ttad.doc&usg=AFQjCNGMYoPTG3JfeLZr1IW1-U2THP3pSg&bvm=bv.102022582,d.bGQ. [Accessed: 8th September 2015].

Prade, T., Svensson, S-E. & Mattsson, J. E. (2012) Energy Balances for Biogas and Solid Biofuel Production from Industrial Hemp. *Biomass and Bioenergy*. [online] ScienceDirect. 40 (May). p. 36-52. Available from: http://www.sciencedirect.com/science/article/pii/S0961953412000657. [Accessed: 8th September 2015].

Pretot, S., Collet, F. & Garnier, C. (2014) Life Cycle Assessment of a Hemp Concrete Wall: Impact of Thickness and Coating. *Building and Environment*. [online] ScienceDirect. 72 (Februari). p. 223-231. Available from: http://www.sciencedirect.com/science/article/pii/S0360132313003247. [Accessed: 8th September 2015].

Rahim, M. et al. (2015) *Moisture Properties of Rape Straw Concrete and Hemp Concrete*. Paper presented at the First International Conference on Bio-based Building Materials, Clermont-Ferrand, France, June 2015. [online] ResearchGate. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Ranalli, P. & Venturi, G. (2004) Hemp as a Raw Material for Industrial Applications. *Euphytica*. [online] SpringerLink. 140 (1/Januari). p. 1-6. Available from: http://link.springer.com/article/10.1007%2Fs10681-004-4749-8. [Accessed: 8th September 2015].

Sankari, H. (2000) *Towards Bast Fibre Production in Finland: Stem and Fibre Yields and Mechanical Fibre Properties of Selected Fibre Hemp and Linseed Genotypes*. Diss., University of Helsinki. Available from: https://helda.helsinki.fi/bitstream/handle/10138/20759/towardsb.pdf?sequence=1. [Accessed: 11th April 2016].

Sedan, D. et al. (2008) Mechanical Properties of Hemp Fibre Reinforced Cement: Influence of the Fibre/matrix Interaction. *Journal of the European Ceramic Society*. [online] ScienceDirect. 28 (1). p.183–192. Available from: http://www.sciencedirect.com/science/article/pii/S0955221907003925. [Accessed: 2nd September 2015].

Skoglund, G. (2009) Nationell konferens om hampa. *Miljömagasinet*. [online] 17 (April) Available from: http://www.miljomagasinet.se/artiklar/090427_hampa.html. [Accessed: 11th April 2016
SMHI. SMHI. [online] Available from: http://www.smhi.se/#ws=wpt-a,proxy=wpt-a,geonameid=2673730. [Accessed: 16th April 2016].

Ståhl, F. (2009) *Influence of thermal mass on the heating and cooling demands of a building unit*. Diss. (summary) Göteborg: Chalmers tekniska högskola, 2009.

Stanwix, W. & Sparrow, A. (2014). *The hempcrete book: designing and building with hemp-lime*. Cambridge: Green Books.

Sunda hus. *Sunda hus*. [online] Available from: https://www.sundahus.se/tjanster/miljodata/. [Accessed: 2nd September 2015].
Svennerstedt, B. (2003) *Plant fibres in sustainable constructions*. Alnarp: Inst. för jordbrukets biosystem och teknologi (JBT), Swedish University of Agricultural Sciences.

Svennerstedt, B. & Svensson, G. (2004) Industrihampa – odling, skörd, beredning och marknad. *Fakta Jordbruk*. [online] Swedish University of Agricultural Sciences. (7) Available from: http://www.slu.se/Documents/externwebben/overgripande-slu-dokument/popvet-dok/faktajordbruk/pdf04/Jo04-07.pdf. [Accessed: 11th April 2016].

Thermo Natur. (2015) *Thermo Natur GmbH & Co. KG* [online] Available from: http://www.thermo-natur.de. [Accessed: 8th September 2015].

Tran Le, A. D. et al. (2010) Transient Hygrothermal Behaviour of a Hemp Concrete Building Envelope. *Energy and Buildings*. [online] ResearchGate. 42 (10/May). p. 1797-1806. Available from: http://www.researchgate.net/publication/222533736_Transient_hygrothermal_behaviour_of_a_hemp_concrete_building_envelope._Energy_Build. [Accessed: 2nd September 2015].

Tran Le, A. D.et al. (2014) Effect of Simulation Parameters on the Hygrothermal Behaviour of a Wall and a Room made of Hemp-lime Concrete. *International Journal of Mathematical Models and Methods in Applied Sciences*. [online] 8. Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB0QFjAAahUKEwjqqtbfwP_IAhUovX-IKHT7ZDsM&url=http%3A%2F%2Fwww.naun.org%2Fmain%2FNAUN%2Fijmmas%2F2014%2Fa522001-052.pdf&usg=AFQjCNESaZVE269Oyme3yugOZEFYYu3JeA. [Accessed: 2nd October 2015].

UNEP. *United nations environment programme*. [online] Available from: http://www.unep.org/sbci/AboutSBCI/Background.asp. [Accessed: 8th April 2016].

Van Bakel, H. et al. (2011) The Draft Genome and Transcriptome of Cannabis Sativa. *Genome Biology*. [online] BioMed Central. 12 (R102/October). Available from: http://www.genomebiology.com/content/12/10/r102. [Accessed: 8th September 2015].

Van der Werf, H. M. G. (2004) Life Cycle Analysis of Field Production of Fibre Hemp, the Effect of Production Practices on Environmental Impacts. *Euphytica*. [online] SpringerLink. 140 (1/January). p. 13-23. Available from: http://link.springer.com/article/10.1007%2Fs10681-004-4750-2. [Accessed: 8th September 2015].

Walker, R. & Pavia, S. (2014) Moisture Transfer and Thermal Properties of Hemp-Lime Concretes. *Construction and Building Materials*. [online] ScienceDirect. 64 (August). pp. 270-276. Available from: http://www.sciencedirect.com/science/article/pii/S0950061814003985. [Accessed: 2nd October 2015].

Walker, R., Pavia, S & Mitchell, R. (2014) Mechanical Properties and Durability of Hemp-lime Concretes. *Construction and Building Materials*. [online] ResearchGate. 61 (June). pp. 340-348. Available from: www.researchgate.net/. [Accessed: 2nd October 2015].

Wallner, S. (2004) *Stigfinnare: innovativt byggande för en hållbar utveckling*. Göteborg: Chalmers University of Technology.

Woolley, T. (2013) *Low impact building: housing using renewable materials*. Oxford: Wiley-Blackwell.

Woloszyn, M. et al. (2009) The Effect of Combining a Relative-humidity-sensitive Ventilation System with the Moisture-buffering Capacity of Materials on Indoor Climate and Energy Efficiency of Buildings. *Building and Environment*. [online] ScienceDirect. 44 (3/March). p. 515-524. Available from: http://www.sciencedirect.com/science/article/pii/S0360132308000772. [Accessed: 2nd September 2015].

WUFI Pro, 2D, Plus. (2009) *WUFI Pro, 2D, Plus*. [online] Available from: http://www.wufi-wiki.com/mediawiki/index.php5/Details:WaterVaporDiffusion. [Accessed: 13th November 2015].

Yates, T. (2002) *Final Report on the Construction of the Hemp Houses at Haverhill, Suffolk*. [online]. UK: Building Research Establishment. Available from: http://projects.bre.co.uk/hemphomes/. [Accessed: 8th September 2015].

Zampori, L., Dotelli, G. & Vernelli, V. (2013) Life Cycle Assessment of Hemp Cultivation and Use of Hemp-Based Thermal Insulator

Appendix I

time constant - full calculation

Time constant:

heat capacity / transmission losses
(h = wh/K / w/K)

A measure of the amount of time it takes for the building's indoor temperature to react to sudden temperature changes outside, or disruptions in the heating supply. A building's time constant/thermal inertia is higher if it has a large heat capacity in combination with small power losses through the thermal envelope.

Transmission losses

Ventilation losses with ftx:

BOA floor area (m^2) • ventilation flow (l/s / m^2) • (s/h) • (m^3/l) • heat capacity air (Wh/m^3K) • heat exchanger effect (%) • run time (h/day)

(136) • (0,35) • (3600) • (0,001) • (0,33) • (0,15) • (16/24) = **5,65** W/K

Ventilation losses without ftx:

BOA floor area (m^2) • ventilation flow (l/s / m^2) • (s/h) • (m^3/l) • heat capacity air (Wh/m^3K) • run time (h/day)

(136) • (0,25) • (3600) • (0,001) • (0,33) • (16/24) = **26,93** W/K

Air leakage:

surface area thermal envelope (m^2) • airtightness (l/s, 50Pa) • heat capacity air (Wh/m^3K) • location

(374,8) • (0,3) • (0,33) • (0,07) = **9,35** W/K

Thermal bridges envelope:

15 % of transmission losses

(0,15) • (87) = **13,05** W/K

Thermal envelope transmission losses:

u-values (W/m^2K) • surface area (m^2)

Roof: 0,120 • 99 = 11,88
Wall: 0,210 • 160 = 33,60
Floor: 0,175 • 93,1 = 16,29
Door: 0,8 • 1,89 = 1,51
Windows: 1,0 • 11,35 = 11,35
Window doors: 1,3 • 9,43 = 12,26

TOTAL = **87** W/K

Total transmission losses with ftx: **115** W/K

Total transmission losses without ftx: **136** W/K

Heat capacity

(material depth (m) • surface area (m^2) = (m^3)) • (volumetric heat capacity (J/m^3K))

Thermal envelope 1

Roof:
Hemp fiber wool: (0,0747 • 99 = 7,395) • (110 000) = 813 450
Wood: (0,0253 • 99 = 2,505) • (1 155 000) = 2 893 280

Wall:
Hemp fiber wool: (0,0445 • 160 = 7,12) • (132 000) = 940 100
Wood: (0,0255 • 160 = 4,08) • (1 155 000) = 4 712 400
Clay plaster: (0,03 • 160 = 4,8) • (1 700 000) = 8 160 000

Floor:
Hemp fiber wool: (0,0432 • 93,1 = 4,022) • (110 000) = 442 420
Wood: (0,0568 • 93,1 = 5,288) • (1 155 000) = 6 107 640

TOTAL = **24 069 290 Ws/K** or **6686 Wh/K**

Thermal envelope 2

Roof:
Hemp-lime: (0,0747 • 99 = 7,395) • (413 000) = 3 054 140
Wood: (0,0253 • 99 = 2,505) • (1 155 000) = 2 893 280

Wall:
Hemp-lime: (0,089 • 160 = 14,24) • (413 000) = 5 881 120
Wood: (0,011 • 160 = 1,76) • (1 155 000) = 2 032 800

Floor:
Limecrete plaster: (0,06 • 93,1 = 5,586) • (1 100 000) = 6 144 600
Hemp-lime: (0,04 • 93,1 = 3,724) • (488 000) = 1 817 310

TOTAL = **21 823 250 Ws/K** or **6062 Wh/K**

Thermal envelope 3

Roof:
Hemp-lime: (0,0747 • 99 = 7,395) • (413 000) = 3 054 140
Wood: (0,0253 • 99 = 2,505) • (1 155 000) = 2 893 280

Wall:
Hemp-lime: (0,0952 • 160 = 15,235) • (413 000) = 6 292 060
Wood: (0,0048 • 160 = 0,768) • (1 155 000) = 887 040

Floor:
Limecrete plaster: (0,06 • 93,1 = 5,586) • (1 100 000) = 6 144 600
Hemp-lime: (0,04 • 93,1 = 3,724) • (488 000) = 1 817 310

TOTAL = **21 088 430 Ws/K** or **5858 Wh/K**

Time constant

Thermal envelope 1

With ftx:
6 686 Wh/K / 115 W/K = 58,14 h
58,14 / 24 h = **2,42** days

Without ftx:
6 686 Wh/K / 136 W/K = 49,16 h
49,16 / 24 h = **2,05** days

Thermal envelope 2

With ftx:
6 062 Wh/K / 115 W/K = 52,71 h
52,71 / 24 h = **2,20** days

Without ftx:
6 062 Wh/K / 136 W/K = 44,57 h
44,57 / 24 h = **1,86** days

Thermal envelope 3

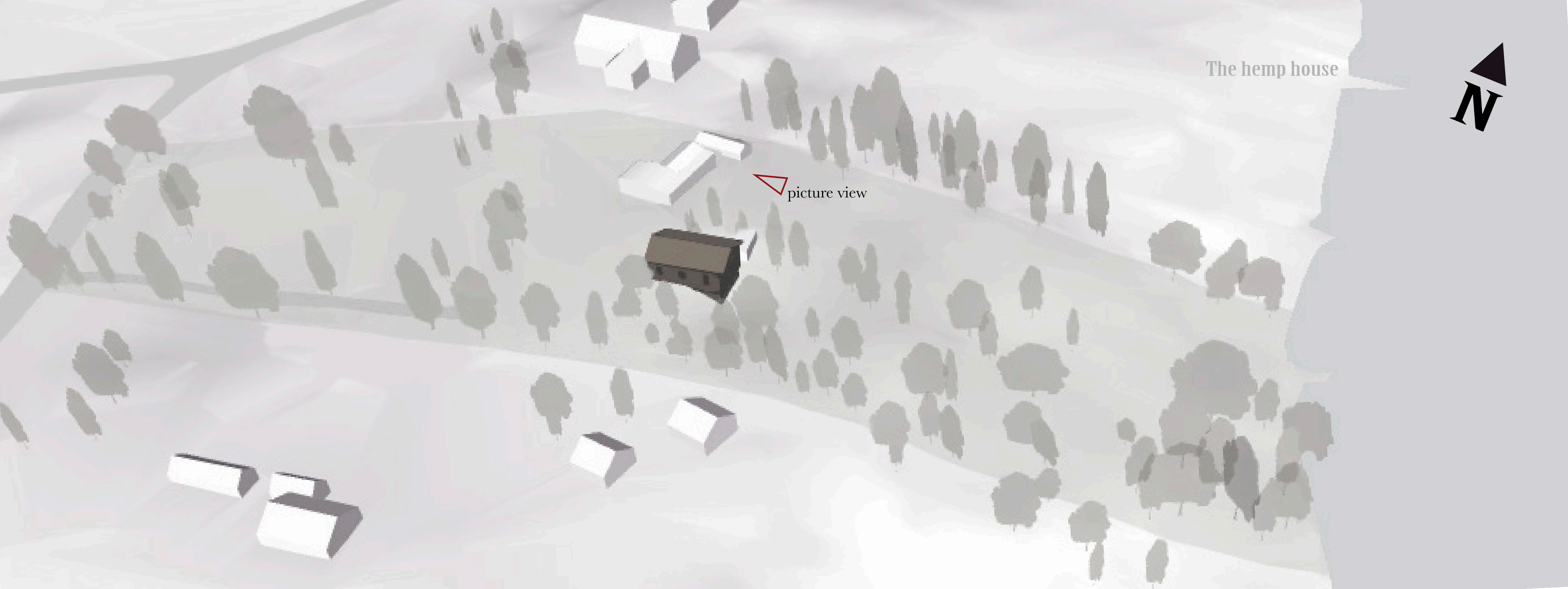
With ftx:
5 858 Wh/K / 115 W/K = 50,94 h
50,94 / 24 h = **2,12** days

Without ftx:
5 858 Wh/K / 136 W/K = 43,07 h
43,07 / 24 h = **1,79** days

Appendix II

the hemp house

(Grundvall 2016)



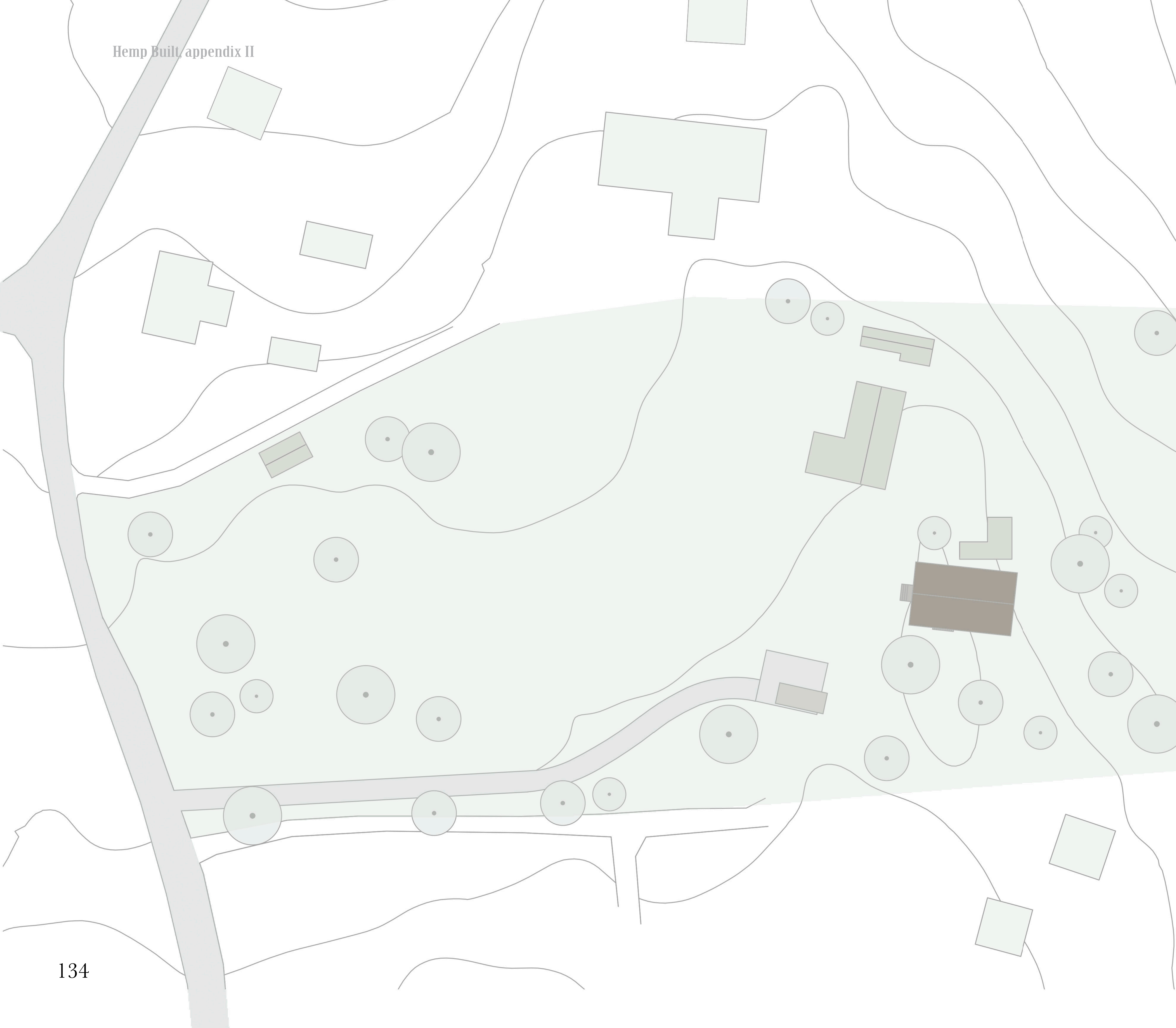
(Grundvall 2016)

(Grundvall 2016)

Sun and orientation

The plot lies on the western shore of a lake near the small town Gränna, in the mystical woodlands that inspired John Bauer's famous paintings with fairytail-like forrest motives. The lake view heads towards the sunrise in east. The evening sun therefore comes from what is experienced as from behind, since the outlook and focus will naturally go in the opposite direction. The eastern part of the lot is sheltered from winds through woodlands on the neighbouring area.

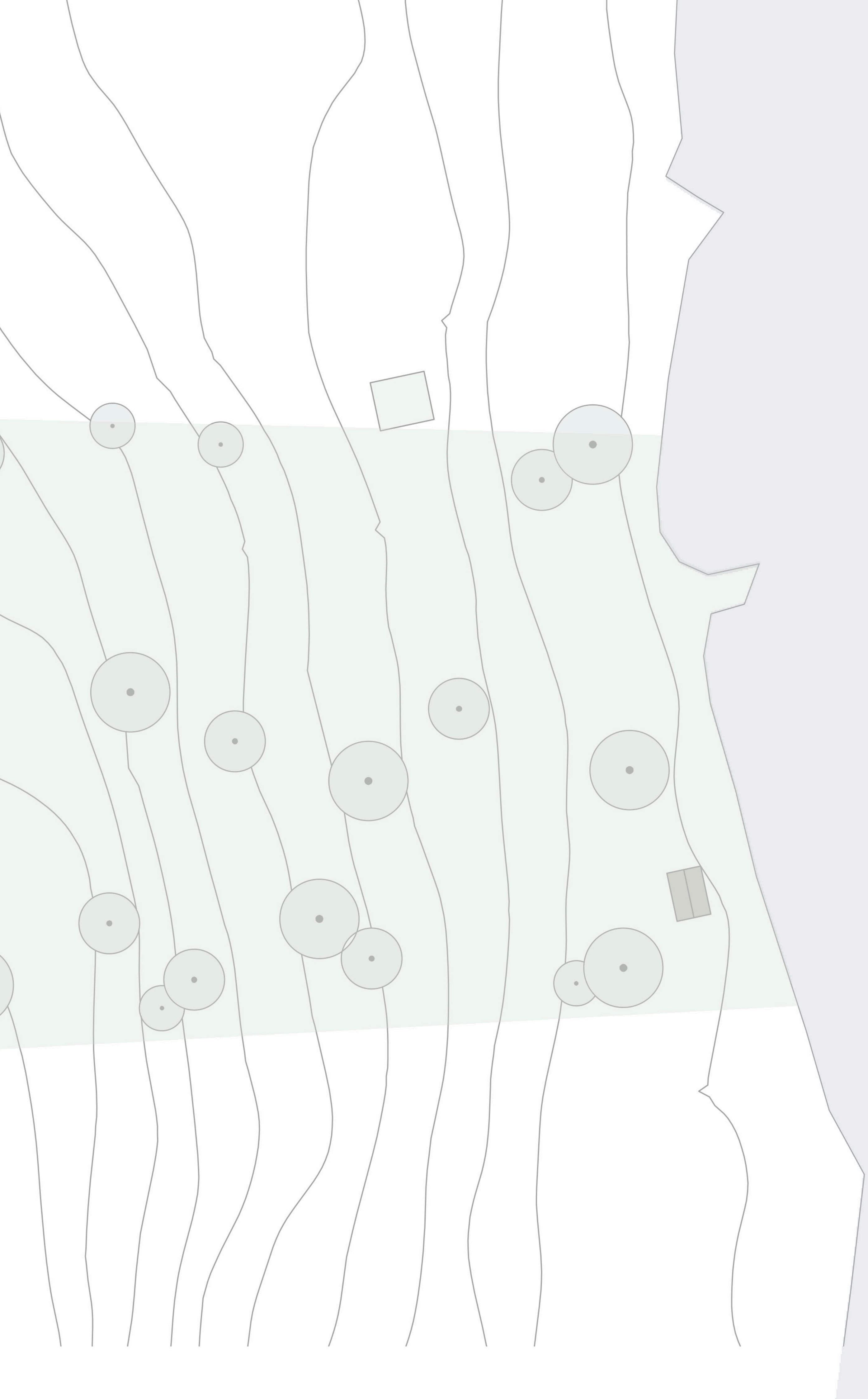
(Grundvall 2016)



House placement

After thorough investigations of the plot and considerations to the 100 meter long shore protection area where it is not permitted to build, the house placement was decided to be on the highest point of the land, as close to the lake as permitted. Through this placement one enables both a tremendous lake view as well as evening sun coming from the west. Pushing the placement as far to the east as possible is also in respect to the existing holiday house on the lot; creating space in-between.

The house is placed relatively near an existing shed/outhouse, mainly to create more space to the opposite side, preserve a beautiful old pine tree and gain southern sun without the need of taking down to much trees that make up a natural border towards the neighbouring lot. The shed will eventually be taken down.



(Grundvall 2016)

User preferences/ design criteria

- Privacy
- Security/shelter
- Light and unimpeded outlook
- Restricted exposure/view in
- Contact between rooms/spaces
- Close connection to nature
- Preservation of the natural habitat with many large, old and very beautiful pine trees
- Traditional design inspired by old log houses with rustic materials

Key points around the choice of insulation and wall structure for my client involves both ecological profile, cost, availability, logistics, time management and skills required for construction.

House design

The house design is ”traditional with a twist”, maybe unconsciously a little bit inspired by alpine chalets, almost resembling a cuckoo’s clock or a bird’s nest in its eastern façade shape. This fits well with the traditional architecture in the surrounding area as well as with the actual sense of being high up by the trees in a bird’s nest; a cuckoo’s nest!

(Grundvall 2016)

East facade


(Grundvall 2016)

0 5 m
Scale 1:100

South facade

(Grundvall 2016)

North facade

West facade

It will be a one and a half storey building, with the second floor in form of a loft space with a somewhat elevated pitched roof. The height of the building will thus be a half storey higher than the existing cottage on the plot. Due to its placement, the larger part of the house will however be hidden from the cottage in the steep slope as well as by the trees between the two houses.

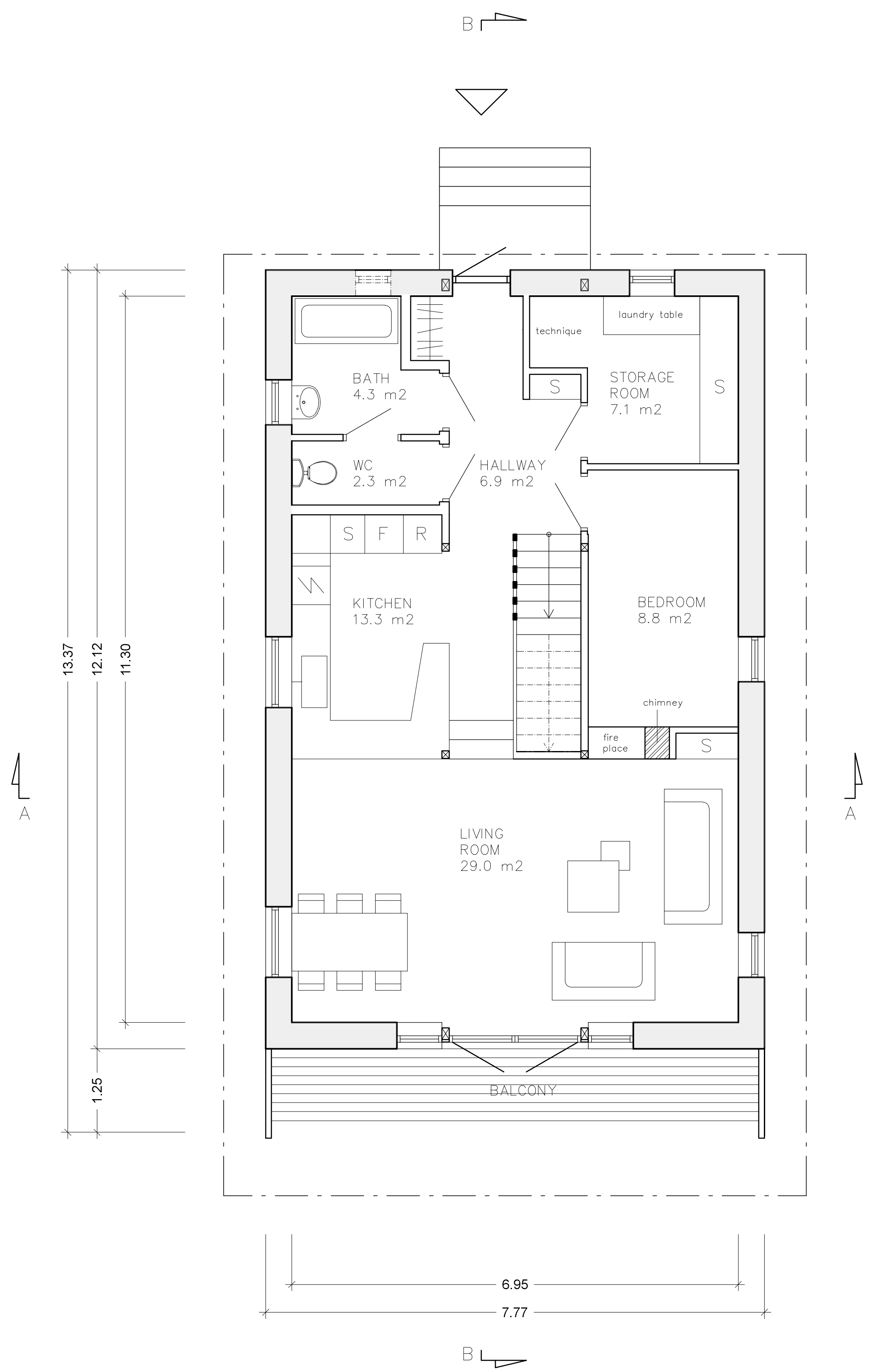
By the southwest corner of the house a space is created under a great old pine tree where it will be possible to both enjoy the lake view and gain afternoon- and evening sun.

The orientation of the house, with gables to the east and west, as well as the plan layout and house shape is worked out to enhance the direction towards the lake view.

The first floor will be substantially elevated over the surrounding land in three directions to enable storage underneath and restrict direct view in, except in the west facade where the main entrance is located and it is more important for the house to be perceived as smaller to fit in with the size and shape of the surrounding cottages and villas.

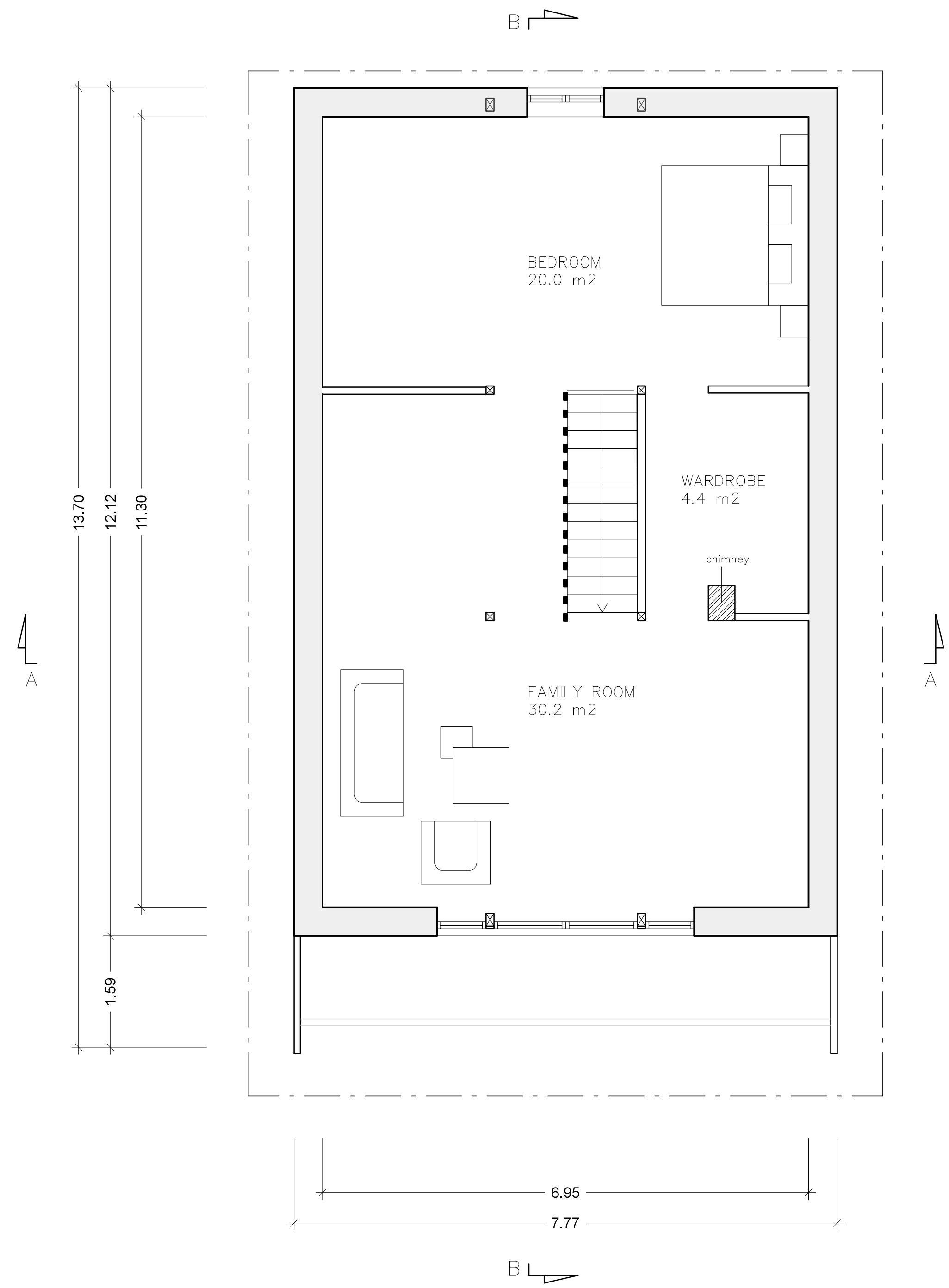
The upper floor will be high up, almost among the tree crowns by the east facade, enabling a tremendous view over the lake.

N



Floor 1

(Grundvall 2016)

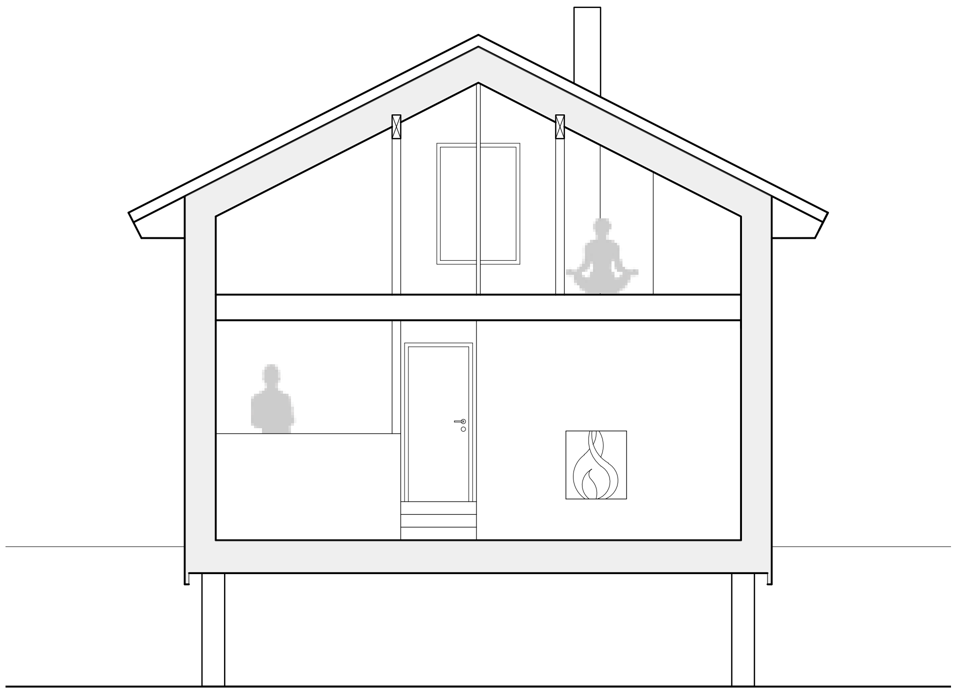


Floor 2

(Grundvall 2016)

0 5 m

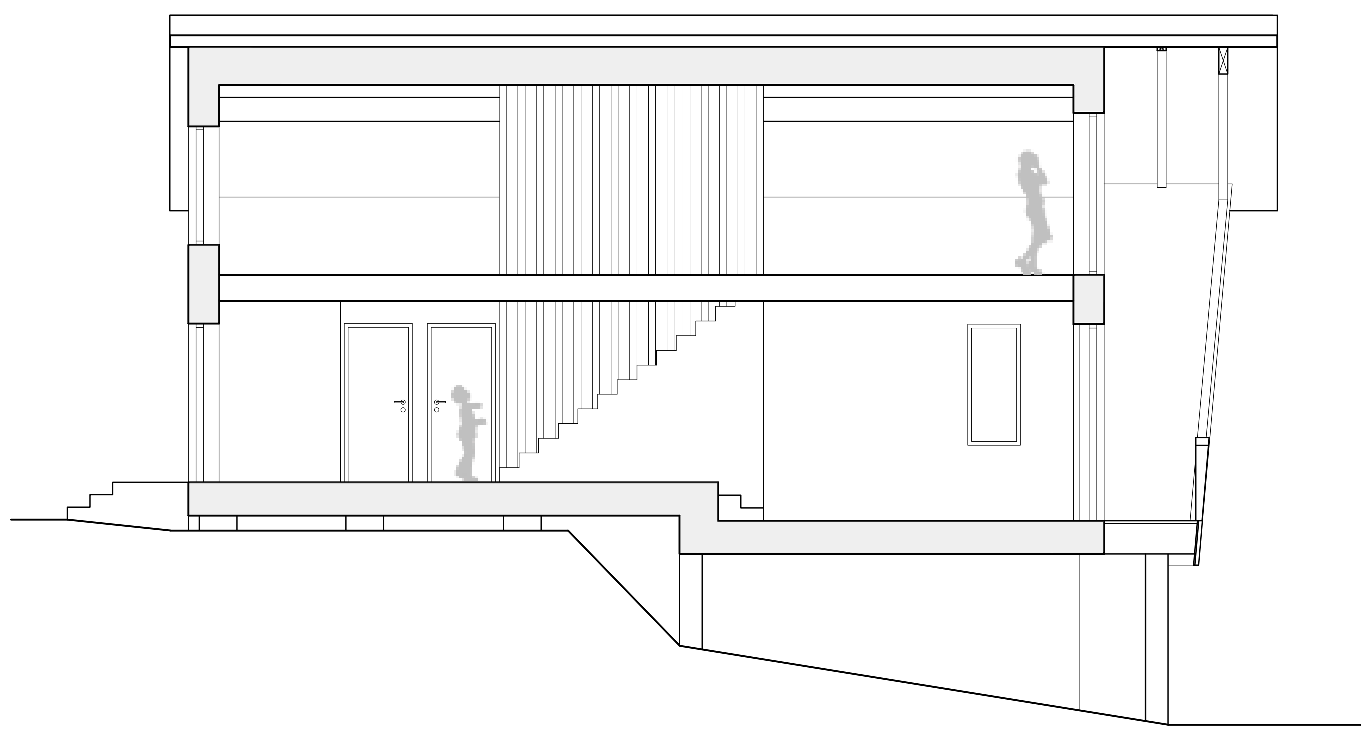
Scale 1:100



"Connection between spaces, viewpoints, axiality, sun gain and close contact with nature are key considerations in the plan layout. A view over the treetops can, for instance, be directly gained through the stair opening in the hallway..."

(Grundvall 2016)

Section A - A



Section B - B

(Grundvall 2016)

Scale 1:100