Investigating Bio-Based Insulation

Hygrothermal Performance: from Material Properties to the Building Envelope

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Investigating Bio-Based Insulation

Hygrothermal Performance: from Material Properties to the Building Envelope

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Förord – Swedish Preface

Denna avhandling är blott hälften av vad min doktorandresa innehöll. Jag har lärt mig så otroligt mycket av både det som kom med i, samt det som hamnade utanför. Bland det som inte ryms i avhandlingen finns allt från nedmontering av kärnkraftverk till stresstest av hjärtstartare, från att lära robotar att mura till att dra sönder flygplansbälten. För varje sak jag haft sönder, både planenligt men även oavsiktligen, har jag lärt mig något vilket är en fantastisk löneförmån.

Först och främst vilja rikta ett stort tack till mina handledare: Eva Frühwald Hansson och Anders Rosenkilde som har varit ett stöd under hela doktorandtiden, men även Jonas Niklewski och Paulien Strandberg-de Bruijn som drogs in under resan. För de experimentella delarna av min forskning har jag fått fantastisk och ovillkorlig hjälp av Stefan Backe och Per-Olof Rosenkvist, vilket jag är mycket tacksam för. Sen vill jag även tacka Lars Wadsö och Sven Thelandersson för gott medförfattarskap och att ni alltid bistått med diskussioner när vetenskapen närmat sig filosofi (eller kanske bara förvirring).

Jag måste såklart uppmärksamma och tacka för det stora intresse och hjälp jag fått av trähusindustrin. Stort tack till: Stefan Ferrari BoKlok, Leif Sjöskog och tidigare Rickard Zetterstedt Trivselhus, David Norrman Eksjöhus, Ida Edskär Lindbäcks, David Ulinder Götenehus, Peter Erlandsson VIDA Building, Henrik Ödeen Moelven Byggmodul, Carl-Johan Sigfridsson OBOS och Anders Carlsson Derome. Jag hoppas att ni fått ut lika mycket av vårt samarbete som mig. Jag har ett stort hopp om fortsatt gott samarbete.

Vill även passa på att tacka för den goda arbetsmiljö som finns på avdelningen och institutionen, så tack till *alla* jag har druckit kaffe med. Men ett särskilt tack till institutionsstyrelsen, och i synnerhet Patrick van Hees och Jesper Arfvidsson som mina chefer. Vill även tacka Magnus Larson och Miklós Molnár för gott sällskap i restriktionsbrytandet, när övriga världen stod still. Sen vill jag ju lite extra tacka alla andra arbetsnarkomaner för det trevliga umgänget på kvällar och helger, särskilt: Clemens Klante, Mohammad Kahangi, Behshid Khodaei och under sista tiden alla italienare med Simone Celati i spetsen. Slutligen vill jag tacka Anna Adell för hjälpen och stödet i rollen som doktorandrepresentant, funkar inte karriären inom forskning har vi en karriär som diplomater.

Till min familj och mina vänner vill jag bara säga förlåt för min totala resignation från alla sociala sammanhang de senaste åren. Jag bjuder på långburk, när som helst, var som helst. Saknat både turerna i skogen och dem på Lången.

Table of contents

Abstract

The transition towards sustainable building practices necessitates exploring innovative solutions to improve energy efficiency while reducing environmental impact. This thesis synthesises findings from four studies investigating the potential of bio-based insulation materials in building construction.

The first study developed an experimental method to explore the discrepancy between predicted and actual energy use. The method worked well and benchmarked well against other sources of measurement. The results suggest that bio-based materials exhibit better-than-expected energy performance.

A numerical study, as described in the second study, evaluates the energy performance of materials with varying hygroscopic properties using numerical simulations. Results indicate that bio-based insulation materials have a significant energy-saving potential due to their high moisture capacity, emphasising the importance of latent heat transfer in energy modelling.

The third study investigates the hygrothermal properties of three bio-based insulation materials, eelgrass, grass, and wood fibre, with traditional stone wool insulation added as a reference. Experimental analyses measure distinct sorption properties and thermal conductivity of the materials. All bio-based materials have significantly different U-values from Hot Box tests compared to those solely based on thermal conductivity measurements.

Lastly, a comparative performance test between wood fibre and stone wool insulation materials under actual climatic conditions highlights their energy performance differences. Despite wood fibre's higher thermal conductivity, its comparable energy consumption for space heating suggests that its hygroscopicity plays a crucial role, highlighting the need to consider diurnal changes in temperature and humidity in energy modelling.

These studies underscore the potential of bio-based insulation materials to improve energy efficiency and reduce environmental impact in building construction. They advocate for a holistic approach that considers both thermal and hygrothermal properties of materials, paving the way for sustainable building practices.

Sammanfattning - Swedish summary

På vägen mot en mer hållbar byggsektor är det nödvändigt att utforska nya lösningar för att förbättra energieffektiviteten samtidigt som att vi minskar den inbyggda klimatpåverkan. Denna sammanläggningsavhandling presenterar fyra studier som undersöker potentialen hos bio-baserade isoleringsmaterial för användning inom trähussektorn.

I den första studien utvecklades en experimentell metod för att undersöka den påstådda skillnaden mellan projekterad och faktisk energianvändning. Metoden visade sig vara effektiv och presterade jämförbart med andra mätmetoder för icke-hygroskopiska isolermaterialen. Dock visar resultaten på att bio-baserade isolermaterial presterar bättre än förväntat när det gäller energiförbrukning, jämfört med att bara mäta värmeledningen.

Den andra studien är en numerisk studie, vilken utvärderade energiprestandan hos material med varierande hygroskopiska egenskaper genom numeriska simuleringar. Resultaten indikerar att hygroskopiska isoleringsmaterial har en betydande potential för energibesparing, detta på grund av deras högre fuktbuffringskapacitet. Detta understryker vikten av korrekt materialdata i energimodellering, och potentialen hos latent värme.

I den tredje studien undersöktes de hygrotermiska egenskaperna hos tre bio-baserade isoleringsmaterial: ålgräs, gräs och träfiber. Dessa jämfördes mot konventionell stenullsisolering. Experimentella försök synliggör tydliga skillnader i sorptionsegenskaper och termisk ledningsförmåga hos de testade materialen. De bio-baserade materialen visade stora skillnader i uppmätta U-värden jämfört med dem beräknade från värmekonduktiviteten.

Den sista studien var en jämförande studie mellan träfiber och mineralullsisolering under verkliga förhållanden i fullskala. Trots att träfiber har högre värmekonduktivitet visade den jämförbar energiförbrukning, troligen för att dess hygroskopiska egenskaper spelat en avgörande roll. Detta understryker vikten av att inkludera de hygroskopiska egenskaperna och ett varierande dygnsklimat i energimodellering.

Tillsammans visar dessa studier på potentialen hos bio-baserade isoleringsmaterial att förbättra energieffektiviteten och genom deras implementering minska klimatpåverkan inom byggsektorn. Studierna förespråkar en helhetssyn som tar hänsyn till både termiska och hygroskopiska egenskaper hos bio-baserade material.

List of Appended Papers

Paper I

Development of a hot-box test setup with a dynamic outdoor climate

Ranefjärd, Oskar; Rosenkilde, Anders, Frühwald Hansson, Eva (2019). 14th International Conference on Thermal Performance of the Exterior Envelopes of Whole Buildings.[1]

Paper II

Investigating the Potential of Latent Heat in Hygroscopic Insulating Materials

Ranefjärd, Oskar; Rosenkilde, Anders; Niklewski, Jonas; Frühwald Hansson, Eva; Strandberg-De Bruijn, Paulien (2022). Thermal Performance of the Exterior Envelopes of Whole Buildings, pp. 85-94.[2]

Paper III

Hygrothermal properties and performance of bio-based insulation materials locally sourced in Sweden

Ranefjärd, O.; Strandberg-de Bruijn, P.B.; Wadsö, L. (2024). Materials, 17, 2021. [3]

Paper IV

Assessing the Energy Performance of Wood Fibre and Mineral Wool Insulation Through a Co-Heating Test.

Ranefjärd, Oskar; Niklewski, Jonas; de-Bruijn, Paulien; Rosenkilde, Anders; Frühwald Hansson, Eva. Under review for Construction and Building Materials.

Other publications of relevance to this thesis

Parametric Study of Mould Risk in the Climate Envelope of Timber Buildings Using Hygrothermal Simulations

Ranefjärd, Oskar; Rosenkilde, Anders; Frühwald Hansson, Eva (2019). 14th International Conference on Thermal Performance of the Exterior Envelopes of Whole Buildings.[4]

Author’s contribution to the papers

Paper I

OR developed the test setup with input from other authors. OR built the test setup, conducted the experiments, analysed the results, and wrote the first draft of the paper. Other authors helped with the analysis and commented on the paper.

Paper II

OR developed the numerical study with support from JN. OR also did the modelling and analysis and wrote the first draft of the paper. Other authors have commented on the paper.

Paper III

OR, together with PS, developed the study. OR did tests with HotBox and TPS, PS carried out tests with moisture buffer value, and LW did tests with sorption calorimetry and DVS. OR has analysed the data, with help from PS and LW, for their respective part. OR drafted the paper, and the other authors joined the writing process.

Paper IV

OR developed the experimental study with input from other authors. OR built the test setup and specimens, made the measurements, analysed the data, and drafted the paper. The other authors gave feedback on the analysis and participated in editing the paper.

Acknowledgement

This research was carried out with financial support from BioInnovation within the projects “Framtidens biobaserade byggande och boende” (Bio-based Building and Housing of the Future), “Biobased houses in industrial construction” and “Hållbara biobaserade klimatskal” (Sustainable/Durable bio-based building envelopes). BioInnovation is an innovation program financed by Vinnova, the Swedish Energy Agency and the Swedish Research Council Formas. Their financial support is gratefully acknowledged. Furthermore, I acknowledge some minor financial support from TMF — the Swedish Federation of Wood and Furniture Industry.

This project got laboratory and equipment support from the Civil Engineering Laboratory of Lund University, mainly from the Division of Structural Engineering and the Division of Building Materials, especially using the “provhus” (test house). Also, some minor use of material from the Division of Building Physics and the Division of Fire Safety. Their help is gratefully acknowledged.

Lastly, I’m thankful for the intellectual support from the reference group comprised of TMF—the Swedish Federation of Wood and Furniture Industry—and Swedish timber house manufacturers: BoKlok, Derome, Eksjöhus, Götenehus, Lindbäcks, Moelven, OBOS, Trivselhus, VIDA Building and during part of the project time Hjältevadshus and LB-hus. Their input and feedback are thankfully acknowledged.

Introduction

Thesis Background

The idea behind the project which led to this thesis came from the timber house industry. The cause of concern was the upcoming energy rules from the European Union's Energy Performance of Buildings Directive that had to be implemented on the 1st of January 2021, which in Sweden was named “NNE” (near-zero energy building). The first draft of the energy requirements showed a very harsh reduction of 30% of allowed energy use, and the industry needed objective research to guide them to make informed decisions. A research project titled “Future building envelopes” was initiated as a collaboration between academia and industry to address some challenges. This project became the starting point for the present PhD project that later resulted in additional grants and projects.

Reference group

Leading Swedish timber house industry actors initiated the project mentioned above through their technical committee “Teknikergruppen – Trähus”. Additional companies not on this committee joined the reference group at the project start; two more companies have joined the group since the beginning, and two have left for different reasons. This group has continued working together and is currently on its third research project. Throughout this PhD project, the reference group always consisted of at least nine companies, each represented by a technical manager, head of research and development or head of sustainability. These companies have allocated time and resources to these projects. Their estimated share of the Swedish housing market is around 60% of single-family houses and 10% of multifamily houses, but they also build schools and other types of buildings. The author’s role in this group has been to serve as a bridge between the timber house industry and academia and, along the way, between industry and policymakers.

Thesis Overview

The need for sustainable building practices has driven research towards innovative solutions that can be energy efficient while reducing environmental impact. This thesis focuses on the potential of bio-based insulation materials, integrating findings from a series of experimental and numerical studies.

Being a project initiated by the reference group consisting only of Swedish timber house manufacturers, that perspective has naturally been maintained throughout the thesis work. The aim of these research projects for the reference group was to improve what is being put on the market, especially regarding sustainability. With upcoming energy requirements being the initiating factor, the choice of insulation became the focal point. Due to close collaboration with the reference group, the research had to be applicable to the industry. Insulation materials to be studied had to be commercially available as batt insulation. Even though the materials, test methods, and research questions were specifically chosen in connection with the reference group, the conclusions of this thesis could be generalised for on-site construction and structural materials other than timber.

The primary objective of this research is to evaluate the performance of bio-based insulation materials in terms of energy efficiency in building construction. Specifically, the thesis aims to:

- Develop a test setup capable of testing different climates and investigating the difference between bio-based materials' theoretical and experimental thermal performance.
- Investigate the impact of hygroscopic properties on the energy performance of these materials.
- Explore the thermal and hygrothermal properties of various bio-based insulation materials.
- Compare the full-scale performance of bio-based materials against conventional insulation under varying climatic conditions.

The studies use mixed methods, combining experimental and numerical analyses to evaluate bio-based insulation materials systematically on different scales. The thesis is divided into four studies, as shown in Figure 1.

I. Experimental benchmarking: Develop an experimental methodology to measure the actual energy performance of bio-based materials and compare these results against predicted values and benchmarks from existing literature.

II. Numerical Simulations: Assess the energy performance of materials with different hygroscopic properties, highlighting the role of latent heat transfer in energy performance.

III. Hygrothermal Performance: In the laboratory, investigate the hygrothermal behaviour of three specific bio-based materials: eelgrass, grass, and wood fibre — and compare them to mineral wool. This involves detailed laboratory testing of sorption properties and thermal conductivity.

IV. Comparative Full-scale testing: The final study compares the performance of wood fibre and mineral wool insulation in a real-world setting, focusing on energy consumption for space heating and moisture dynamics.

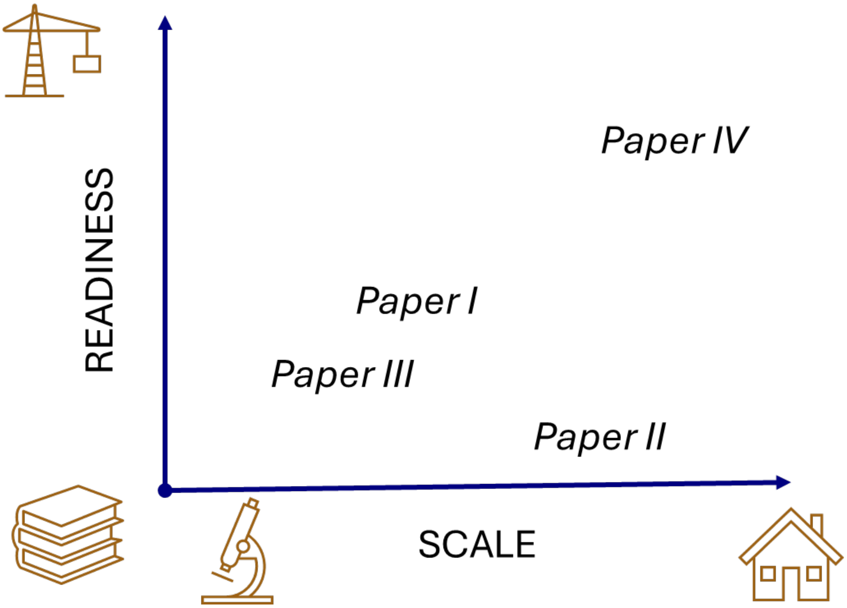

Figure 1: Schematic of included papers, how close to industry they are and on what scale.

The research provides insight into the material properties and full-scale energy performance of hygroscopic insulation materials in the building envelope. The findings can be used to develop more sustainable and energy-efficient building practices, which are especially important in the context of climate change and resource scarcity.

This thesis overview sets the stage for detailed discussion and analysis in subsequent chapters, summarising and contextualising the four papers. The holistic approach adopted in this thesis underscores the complexity and interdependence of factors affecting building insulation performance, aiming to shorten the way to more sustainable building technologies.

External Factors

To understand the thesis's background, one must first understand the underlying forces, specifically three perspectives working towards the same goal: societal, industrial, and academic. Readers familiar with the Swedish construction sector will not read much news in this chapter. However, understanding the Swedish context is critical for understanding the background of this thesis. Figure 2 shows a graphical interpretation of the External factors where societal changes should reach the industry through academic research. This way of innovation is known as the triple helix model [5–7], and the starting point of this thesis was somewhere in the middle of the three institutions.

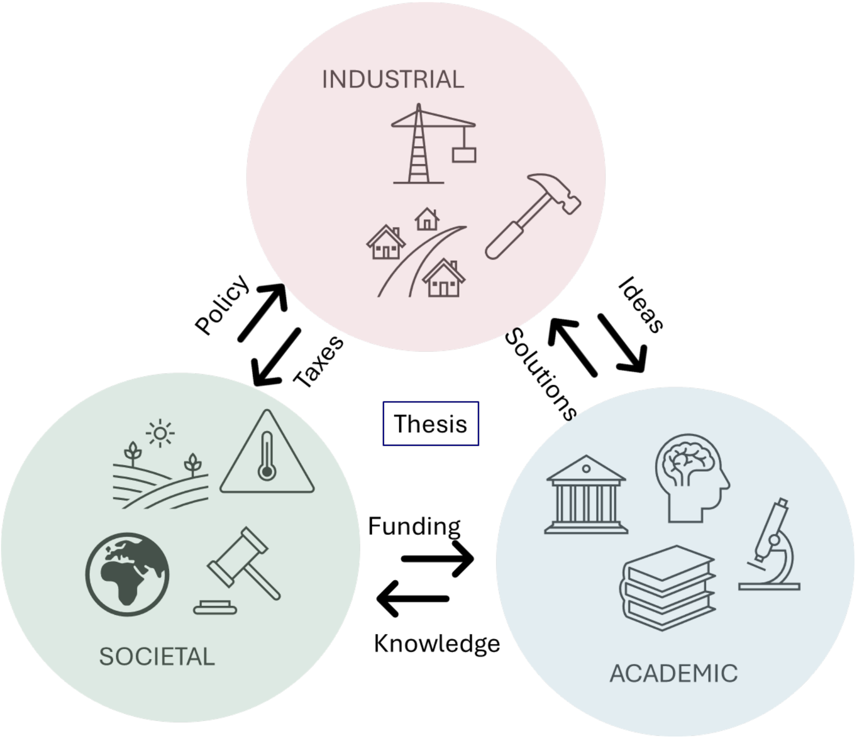

Figure 2: Graphical interpretation of the project background and how it connects to the thesis work. Societal changes require industry change, which is done by creating knowledge through academic research.

Societal background

The building sector accounts for 40% of Europe's energy demand, of which 80% stems from fossil fuels [8]. Worldwide, ongoing efforts are made to reduce energy use in buildings and construction [9]. For example, the European Union introduced requirements in 2020 for all new buildings to be "nearly zero-energy" [10]. This has led to tighter restrictions on the maximum energy use of buildings. By improving and increasing the amount of insulation in the building envelope, the energy consumption in buildings can be considerably reduced, especially in colder and moderate climates. In the European Union, 60-80% of energy use in buildings is connected to space heating [11].

For Sweden, the numbers are similar, as seen in Figure 3; in 2022, 139 TWh of the total final energy of 355 TWh was used for “residential & services”. The final energy is the energy used by customers and excludes energy used by the energy sector. Figure 4 shows the constituent subcategories of “residential & services”. In 2022, 82 TWh were used in households, 30 TWh in commercial buildings, 15 TWh in public administration, and 5 TWh in construction, totalling 132 TWh. In other terms, the building sector accounts for approximately 37% of Sweden’s total energy use.

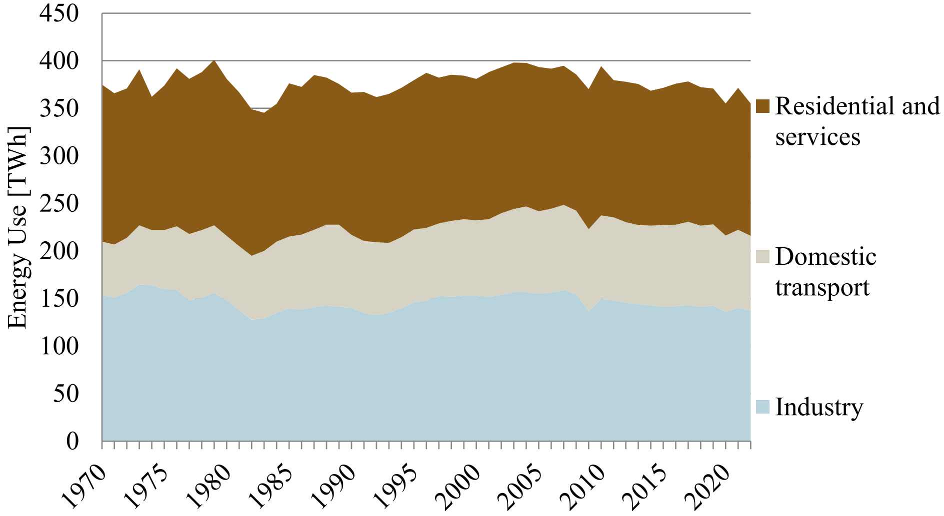

Figure 3: Sweden's total final energy use, by sector, from 1970. Source: Swedish Energy Agency [12]

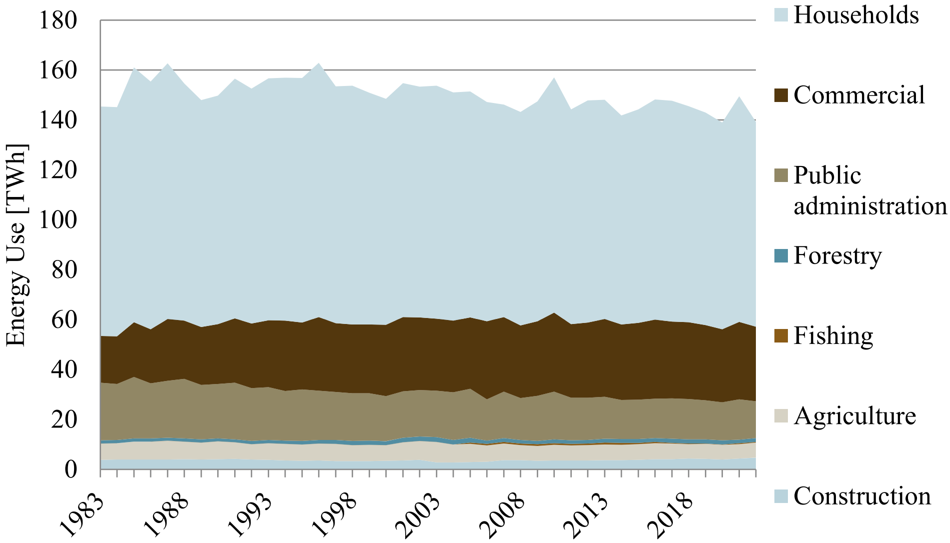

Figure 4: Energy use in the residential and services sector by subsector, from 1983. Source: Swedish Energy Agency [12]

To reduce this number, Sweden enforced its first strict limitation on energy consumption in 2006 through the Swedish National Board of Housing, Building and Planning (Boverket). Prior requirements prescribed insulation thickness or thermal transmittance. After 2006, the energy requirements successively became more stringent. As an example, the maximum annual energy per square meter for a house heated with electricity (heat pump) in Malmö, southern Sweden, is shown in Figure 5. The current limit, which has been in place since 2021, is the Swedish interpretation of the European Union requirement of “near zero energy buildings” [10]. All municipalities in Sweden have a different geographical factor, which is then multiplied by the requirement, from a low value (0.8) in the southern part to a higher value in the north (1.9). This creates an energy requirement of 40 kWh/m^2 in the south to 95 kWh/m^2 in the north. From a mathematical perspective, 40 kWh/m^2 is still far from “zero energy”. Recent fluctuations in energy prices (see Figure 6), combined with a binding EU agreement to aim for "cost-optimal levels" [10,13], make it likely that requirements will become more stringent.

Figure 5: Example of allowed maximum annual energy usage per m² for an electricity-heated (heat pump) detached single-family house in Malmö, southern Sweden, according to the Swedish building code BBR.

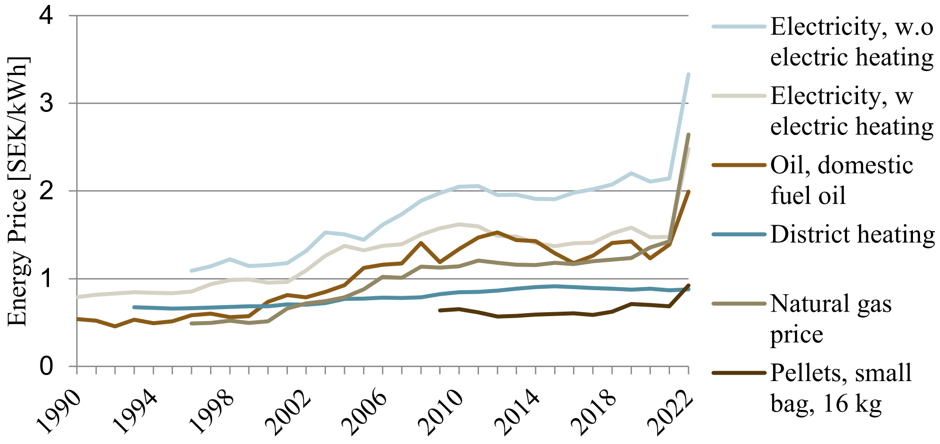

Figure 6. Energy prices for the residential and services sector, including taxes and VAT, from 1970, real (2022) prices. 1 SEK is approx. 0.1€. Source: Swedish Energy Agency [12]

Figure 7 shows the outcomes of these regulatory changes through an analysis of annual energy usage for heating and hot water in detached and semi-detached houses, as recorded in the mandatory energy declarations. This graph shows the annual energy consumption (measured in kWh/m²) according to the year of building completion, ranging from 2009 to 2022. The data presented underscores the relationship between implementing stricter energy requirements and their tangible effects on reducing energy consumption in residential buildings.

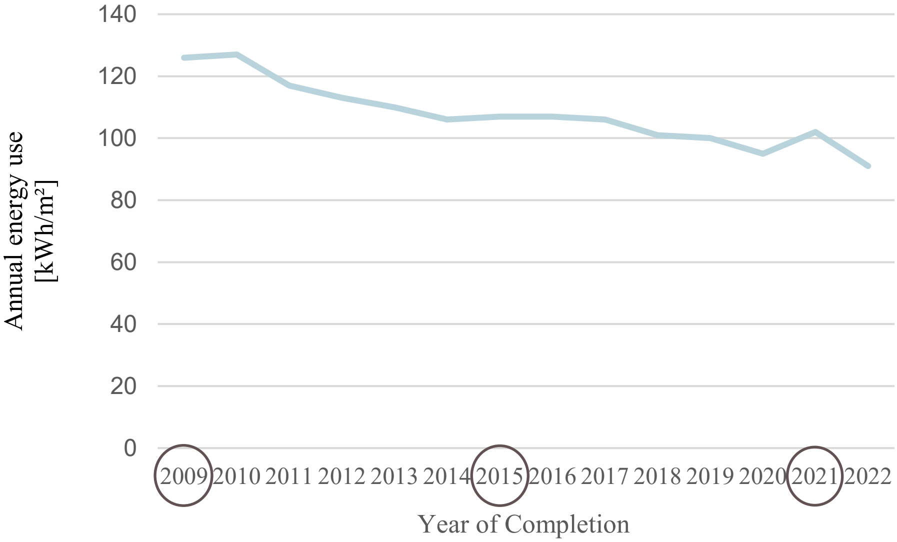

Figure 7: Annual average energy for heating and hot water in detached- and semi-detached houses from 2009 to 2022, by year of completion (in kWh/m²). Highlighted are the years when energy requirements became stricter. Source: Swedish Energy Agency [12]

Reducing the operational energy use of buildings is critical in decreasing their climate impact, but analysing total emissions from cradle to grave reveals a more complex situation [14]. Adding more insulation to buildings will increase their embodied energy; as early as 2002, it was shown that the embodied energy for well-insulated buildings accounted for 45% of the total energy needed over 50 years [15]. Recent studies suggest that 50-60% of a building's climate impact may come from the construction phase alone (including resource extraction, material manufacturing, etc.) [16]. That study used an environmental impact of 102 g CO_2/kWh for electricity and 52 g CO_2/kWh for district heating, based on the Nordic energy mix at that time. The current (2021) Nordic energy mix results in 90 g CO_2/kWh for electricity and 51g CO_2/kWh for district heating [17].

If one uses the suggested values from UN sources [18,19] instead of the national values, the electricity production on average for the last five years in Sweden was 26.4 g CO_2/kWh. This means estimating the construction phase's climate impact to 50-60% is likely a gross underestimation. A better estimate for the construction phase for an electricity-heated house in Sweden would be approximately 63-81% (assuming the same climate impact from the construction). Additionally, these numbers do not consider any improvement in the energy mix over time. As technological advances continue, the proportion of embodied energy, incorporating all energy required to produce building materials and construct buildings, increasingly influences the total environmental footprint. Figure 8 shows the greenhouse gas emissions per produced kWh electricity in the European Union, according to the European Environment Agency [20] using data from [21,22] for 32 years. This visualisation not only underscores the overall improvement in the EU's energy mix but also contextualises the unique challenges of sustainable construction within different national frameworks, particularly emphasising Sweden's distinct situation in Europe.

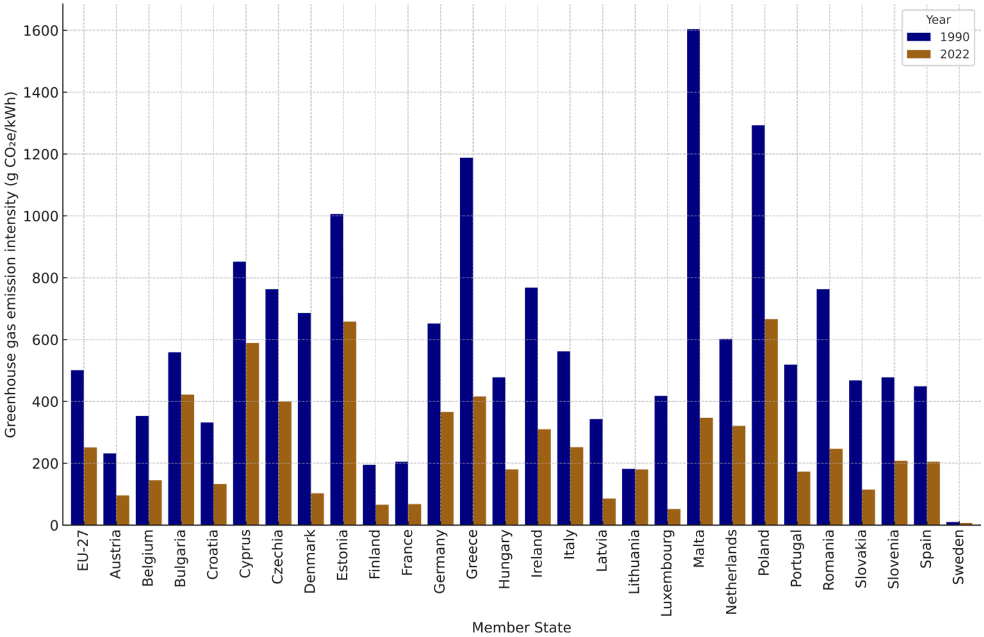

Figure 8: Greenhouse gas emission intensity, measured in grams of CO_2 equivalent per kilowatt-hour (g CO_2 e/kWh). This metric represents the ratio of CO_2 equivalent emissions from public electricity production to the gross electricity output, including combined heat and power generation emissions. The data spans EU member states between 1990 and 2022, highlighting significant changes over these 32 years.

Thus, the needle of the "break-even” point between adding more energy to heat a building or adding more thermal insulation to reduce its space heating demands is moving towards reducing the embodied energy to produce insulation materials [23]. In many European countries (e.g. Sweden [24], Norway, Denmark, Finland, the Netherlands, France and parts of the UK), regulations for the declaration of buildings environmental impact [25] have already come or are about to come into effect over the next couple of years. In the case of Sweden, developers are currently required to account for the climate impact of construction by registering a climate declaration, but there are no limit values. However, implementing limit values would be the logical next step. In the near future, restrictions on the maximum levels of climate impact per square metre will likely be introduced [26]. Sweden is bound by the European Union to commit to net-zero emissions by 2045, meaning that the Swedish government is obliged to introduce measures to limit emissions from buildings. Boverket published a suggestion on the implementation of limit values in May 2023 [27]; at the time of writing this thesis, the suggestion is currently out for referral by the Swedish government.

The proposed regulation aims to cap the carbon dioxide equivalent emissions per square meter of gross floor area (GFA), taking effect on June 1, 2025. This limit is initially set at the 75th percentile of emissions from recently constructed buildings [28] and is planned to decrease by 25% every five years thereafter [29]. The initial suggested limits are set at 180 kg CO_2e/m^2 GFA for single-family houses and 375 kg CO_2e/m^2 GFA for multifamily dwellings. However, looking at what has been declared by the industry years 2022 and 2023 suggests that these limits could potentially be set even lower, particularly for multifamily houses [30]. Figure 8 compares climate impact data from the construction phase for reference projects studied in the background report for this new legislation [28]. It is clear that there are discrepancies between the median of the reported values and the proposed regulatory limit values. The declared values for single-family houses align with the detailed life cycle analysis in the background report [28]. However, the values for multifamily houses are notably lower in comparison. Boverket is also surprised by this discrepancy but does not want to speculate whether it is due to effective solutions or inaccurate life-cycle-analysis calculations.

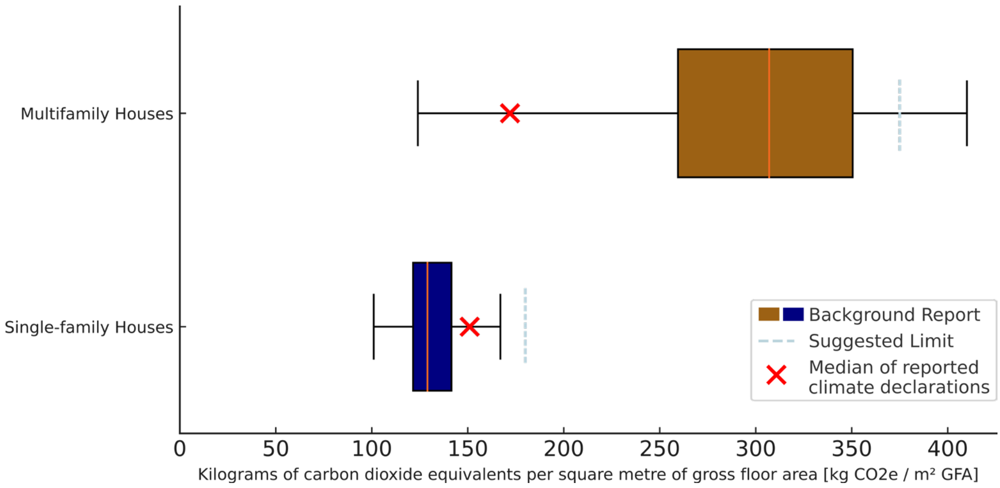

Figure 9: This plot compares the data for climate impact from the construction phase for the reference projects used in the background report [28] for single-family and multifamily houses, depicted by box plots. The red crosses indicate the median of declared CO_2e/m^2 emissions as reported by the industry for 2022-2023 [30]. The dashed lines represent the suggested limit values for CO_2e emissions, with 180 kg CO_2e/m^2 for single-family houses and 375 kg CO_2e/m^2 for multifamily houses, highlighting the gap between reported medians and suggested limit values [29].

Worth noting for an international reader is that forestry, the wood industry, and its derivatives are a big part of the Swedish economy, which means that for Sweden, there are economic benefits in addition to environmental benefits when including more biomaterials in our buildings [31]. As a nation, Sweden aims to transition into a bio-based economy by removing our dependence on fossil fuels [32,33]. Today, waste from the forestry and wood industry is used for district heating [34]. It would be much more beneficial if these materials were used for products with a longer lifespan, such as insulation, before being downcycled for energy [35].

Industrial background

The industry perspective in this thesis refers specifically to the timber house industry. In Sweden, the timber house industry, specifically light frame timber, accounts for 98% of single-family production and approximately 10% of multifamily houses [36]. The reference group is estimated to represent 60% of the single-family house production and 95% of the multifamily output of timber frame houses in Sweden. All involved companies in the reference group produce houses industrially, off-site, and in a factory with different levels of prefabrication and automation. Figure 10 shows a photograph of a factory by a manufacturer with a high degree of prefabrication and industrialisation. Construction or manufacturing in a factory means that technical decisions are not always based on performance; repeatability and producibility are just as important from a manufacturing point of view. For more reading about Swedish industrial construction, see, e.g. [37,38]. Being highly industrial and focusing on repetition, these manufacturing processes benefit from the return of experience and continuous development, increasing efficiency and quality over time. However, this also means that should a flawed design slip through, it can quickly be replicated across many units. This risk is particularly pronounced if there is a significant delay before the onset of damage is noticed, potentially leading to a substantial number of faulty houses.

Figure 10: The floor assembly line from Lindbäcks factory in Piteå, Sweden. This is one of the companies within the reference group with a high degree of prefabrication. The photograph was taken in February 2019.

Timber holds several advantages over other common building materials, but it is the only one that is primarily renewable. However, timber has one drawback compared to other commonly used materials: It is moisture-sensitive. Wood can encounter multiple moisture-induced problems (mould, rot, deformation); in practice, the margin of error regarding moisture is smaller than that of other structural materials [39].

With the global efforts in reducing energy consumption, the Swedish government, through the Swedish Board of Housing, Building and Planning (Boverket), has continuously lowered the limit of allowed energy consumption per liveable area as discussed in the previous chapter, "Societal background". In most cases, these advancements have resulted in more energy-efficient building envelopes. As a consequence, new buildings have become more sensitive to moisture. In older houses with poor insulation and airtightness, heat- and airflow helped the structure to dry out. Conversely, air and heat leakage are minimised to maximise energy efficiency in modern high-performance building envelopes. This focus on airtightness and the importance of continuity of the air-tight layer has led to almost all new buildings in Sweden being tested for air leakage, according to a trade-specific standard. Knowing that the house will be tested has increased energy performance and the general quality of craftsmanship.

Unfortunately, the lack of drying capability became very apparent during the beginning of this millennium, referred to as a 'construction scandal' in Sweden. When at the time, the commonly used structure of ETICS (External Thermal Insulation Composite System), also known as EIFS (Exterior Insulation Finishing System) in North America, was widely used. The principal layout of this system is seen in Figure 11. These façades started having major moisture problems [40]. It is estimated that between 15000-30000 houses were built with this system. In a study that picked 821 randomly selected buildings of this type, 55% were damaged [40]. Problems occurred because the design assumed the façade system was watertight, but small cracks and defects allowed rainwater to intrude into the wall [41]. With the otherwise impermeable layer, no drying after rainfall could occur, water started to accumulate, and especially houses built in timber began to have problems with mould and, in some severe cases, even rot. All the companies in the reference group were affected by this 'scandal', some more than others. From these events, one important and expensive lesson was that it does not matter how well-documented and 'proven' a solution is from a third party. Since then, the reference group stated that they cannot trust external reviewing and have taken a much more active role in research and quality control among themselves.

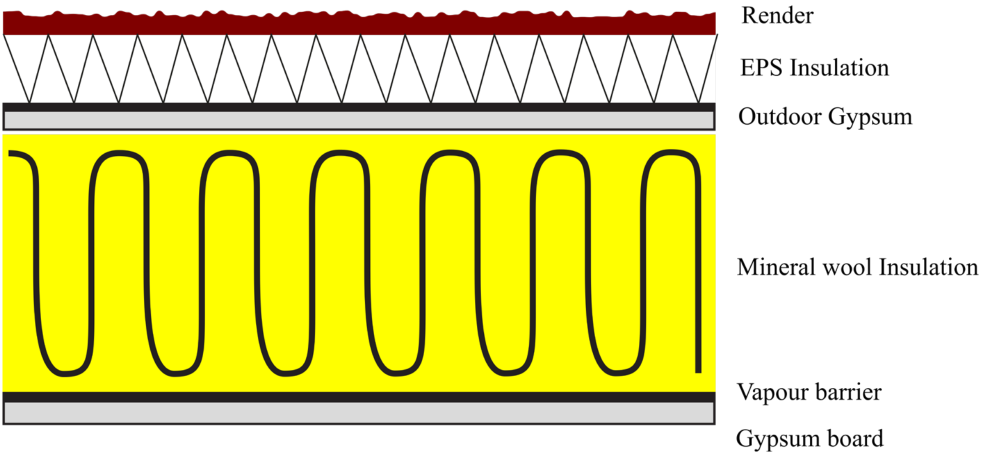

Figure 11: Schematic horizontal section of an ETICS facade. Re-adaptation of an informative figure from Boverket [42].

Addressing stringent energy requirements for the reference group has traditionally involved increasing the amount of insulation. However, this approach now presents challenges. Thicker walls reduce the liveable space, diminishing the sellable area. This is an even more significant concern for manufacturers of modular or volume-based homes; see a modular element being lifted into place in Figure 12. These manufacturers face contradicting restrictions due to accessibility and traffic laws, limiting adjustments to indoor living areas and module widths.

Figure 12: Timber module lifted into place. Photograph by Moelven Byggmodul used with permission.

In Sweden, the conventional method for insulating timber-framed buildings is mineral wool. Today, all companies in the reference group use either stone or glass wool. From a project-internal survey at the time for energy requirement of 50 kWh/m² per year (2017), wall thickness measured between 250-300mm for single-family houses. The same survey showed that the mean thermal transmissivity of the walls was 0.179 (std. 0.022) W/mK, and the mean energy consumption for a single-family house with an 'L-shape' was 40.5 kWh/m^2 and year (see a rendering of that type of house in Figure 13). Anticipating a sharp reduction to 35 kWh/m² and year by 2021, the companies expressed concerns about potential increases in wall thickness, particularly for architecturally distinctive buildings. This concern became a focal point in the project's early stages. The survey found that companies emphasise affordable solutions while maintaining or reducing the thickness of the walls. However, as noted in the previous chapter, there has been a shift in Swedish society over the course of the project. Initially, the focus was on minimising resource usage during the usage phase of products, but over time, attention has shifted toward the production phase. This change in societal priorities led the project to shift its focus from using high-performance materials to choosing sustainable materials instead.

Figure 13: A single-family house with a 'L-shape'. Architect rendering from Eksjöhus model PRIO 141, used with permission.

The recent moisture issues with the ETICS facades have prompted the industry to prioritise moisture safety, making the sector more risk-averse and hesitant about innovation. Two quotes from a project internal interview study regarding the innovativeness of the reference group highlight this mindset. These quotes are from different persons at different companies (translated from Swedish):

> “If all industries were countries, the construction industry would be a developing country. That's just how it is...”

> “That we are so damn conservative is not only bad. We've stumbled a few times, but we would have stumbled many more times if we weren't so conservative.”

This risk aversion stems from a low tolerance for uncertainties and inadequate decision-making information, with the interviews underscoring the need for objective scientific research. Initially, the reference group focused on "high-performing" materials, with bio-based insulation materials considered unlikely due to their generally higher thermal conductivity. However, societal changes and a heightened focus on climate impact shifted the perception of bio-based insulation from a peripheral idea to a central focus. From a sustainability perspective, timber is inherently eco-friendly, with timber framing being particularly efficient [16]. Historically driven by economic considerations like material optimisation and waste reduction, industrial practices for the reference group now align closely with sustainability goals. As carbon footprint regulations become more stringent, timber-frame manufacturers find themselves in an advantageous position. A third quote, from a third company and person from the interview study (again translated from Swedish), pinpoints this ‘feeling’:

> "We had a bit of a headwind with moisture from '06 to '08. Now it's the concrete industry's turn to sweat a little."

If legislation aligns with current building practices, timber-frame manufacturers may not practically face restrictions on multifamily housing until 2030 or 2035 [28]. However, for single-family homes, a 25% reduction in carbon footprint is required before these regulations take effect [28]. From that point of view, the reference group found insulation emerging as a low-hanging fruit for reducing their carbon footprint.

Academic background

With the societal changes and recent moisture problems within the industry, the trends in academia and the scientific community have been strongly correlated to this. The global topics in the field of building science at the time of project start could be generalised to include moisture safety, energy efficiency, variations in building performance, envelope performance, and renovations [43].

Since the scandal with ETICS [40–42], moisture concerning the building envelope has been studied considerably, primarily regarding serviceability or durability. This has led to many improvements in considering moisture safety in design, e.g. [50–52]. The building envelope's thermal performance has been scientifically studied both nationally and internationally. The scientific knowledge gap is primarily between theory, often numerical simulations, and reality [53–55]. This reflects the feedback from members of the reference group, who have indicated that they find the research somewhat academic and not sufficiently practical, as also identified in [56]. Similarly to the house manufacturers' desire to have repeatability in their factories, scientists want to have repeatable and known parameters in their scientific studies. This is practically impossible to have in real houses, and realistic test setups introduce many potential sources of error. This is one reason for this knowledge gap and also why this gap will never be completely covered as the building sector develops continuously.

The focus on energy efficiency was due to the upcoming transition towards zero or near-zero energy consumption for upcoming restrictions such as the European Union's 20-20-20 target [44] or the later 'near-zero-energy buildings' [10]. Sweden was no different, focusing on passive houses, e.g. [45–47]. One company in the reference group even built a passive house within a project with the goal of residents using less than one tonne of CO_2 per year, which they almost succeeded in [48,49].

The standard way to decrease the energy consumption of buildings is to increase the amount of insulation or use insulation with better insulating properties. Various types of insulation materials are available on the European market; the most commonly used are mineral wool and plastic foam insulation materials [64]. In Sweden, mineral wool is the most common and is exclusively used by the reference group. Mineral wool is made from basalt rock (stone wool), sand, or recycled glass (glass wool). These mineral wool insulation materials are mineral-based and have a high environmental impact from manufacturing [65]. Technical parameters for the performance of insulation materials are accessible in literature, see e.g. [66] for a comparative analysis of insulation materials for the building sector or for more unconventional materials, see, e.g. [67,68]. Thermal conductivity is seen to be the lowest among the more engineered insulation materials, such as polyisocyanurate (PIR), aerogel, or vacuum-insulated panels (VIP) [69]. Even though aerogel and

VIP can be produced from natural materials [70–72], their climate impact is still high [73–75].

Internationally, it is natural to optimise insulation thickness concerning cost [76]. If one instead tries to optimise towards the environmental aspect, it becomes much more complex [77]. To give a few examples; in Iran's climate, the optimal insulation thickness is 98mm for rock wool and 219mm for glass wool, regarding environmental impact [78]. Another study shows that the optimal wall thickness in Stockholm is 120mm, compared to 290mm in Berlin or 300mm in Athens, since Sweden has, in comparison, a clean energy mix [79]. A Danish study shows that even with the ever-improving energy mix, a building in Danish Building Class 2020 (close to the Swedish standard) would have been environmentally detrimental even if it was built in 1970, with the coal-fuelled power plants and otherwise environmentally harmful energy mix [23]. Other studies show no optimal insulation thickness but many optima, depending on boundary conditions and the millions of combinations of materials, window design, etc. [80]. With more recent Swedish studies [16,81], it is becoming more apparent that the point when continuing to use conventional insulation is increasing the total emissions instead of decreasing them is very close or already reached. A graphical conceptualisation of this optimisation problem is seen in Figure 14. The y-axis could be, e.g. cost, energy, or climate impact, where increasing the insulation thickness reduces the consumption in the in-use-phase whereas the embodied consumption from the construction-phase increases.

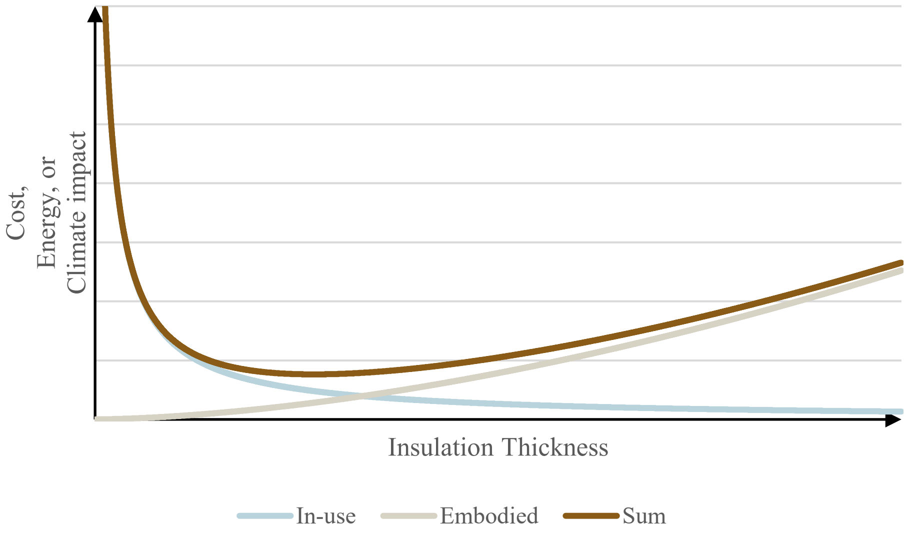

Figure 14: Conceptual figure of increasing insulation thickness. The concept is the same regardless of what is being studied. Here, it is exemplified as Energy, Climate Impact, or Cost. Note that the optimal point is, of course, different for the different values.

Bio-based insulation is covered in more detail in the next chapter, ‘Bio-based Insulation‘ but is briefly commented here. Holistically looking at the bibliometric studies, one paper studied ‘Green buildings’, defined as ‘buildings designed and constructed with ecological principles’, and identified 2980 articles between the years 2000 and 2016 [57]. Comparing this to the keyword “bio-based”, 1778 studies from the years 1900-2022 regarded bio-based materials, of which very few studies investigated the performance [58]. Moreover, note that publications have increased exponentially in the last few years. Regarding articles about high-performing, low-energy buildings, the word “sustainability” is rare compared to other keywords [59]. Furthermore, few studies have examined bio-based insulation and how it should be commercially implemented in buildings [60].

Another noteworthy background is the energy performance of buildings with large amounts of bio-based materials, which, anecdotally, have a lower energy use than predicted [61,62]. Being just anecdotal evidence, it is impossible to draw any scientific conclusions, meaning that there is a scientific knowledge gap. As mentioned in “Societal background”, during the work of this thesis, the Swedish Board of Housing, Building and Planning (Boverket) introduced stricter energy restrictions, which is commonly the deciding factor. At the same time, they also lowered the highest allowed mean thermal transmittance value for the entire envelope to 0.3 from 0.4 W/(m^{2}K). This value is meant to stop solutions where low-performing building envelopes are combined with high-performing heat pumps. However, this change effectively ‘banned’ log and massive timber houses that fulfil the energy requirements without an advanced heat pump, which was not Boverkets’ intention. So, at the time of writing this thesis, Boverket used the research presented in this thesis to investigate an exemption of their rules [63]. Similar anecdotal evidence from the reference group is found in houses built with bio-based insulation such as cellulose or wood fibre. However, if scrutinised, a house owner who pays extra for a house insulated with environmentally friendly materials will likely differ from the average consumer in terms of heat, water, and electricity.

Bio-based Insulation

Background

The European Union aims to achieve carbon neutrality by 2050 by promoting zero-emission buildings [82]. This focus on reducing the environmental impact of building materials, often called the climate footprint, has spurred innovation and increased demand for low-carbon insulation solutions, many of which are bio-based [35,83]. Using raw materials from renewable sources with low embodied energy can significantly decrease a building's climate impact [81,84]. Several European countries have already taken steps to accelerate the adoption of bio-based building materials through national regulations. For instance, the Netherlands has mandated that by 2030, at least 30% of insulation used in renovation projects must be bio-based [85]. Similarly, France has implemented legislative and regulatory measures to support using bio-based building materials [86]. In Sweden, there are restrictions on declaring negative CO_2 emissions in mandatory climate declarations due to the complexity of the issue and the need for consensus [87–89]. Regardless of the approach to achieving negative carbon emissions, insulation materials derived from renewable bio-based resources are expected to create a resource-efficient, decarbonised building stock.

Bio-based insulation materials offer several advantages for enhancing a building's energy performance while maintaining a low environmental impact [90,91]. Compared to fossil-based or mineral-based insulation materials, bio-based insulation materials have a lower environmental impact at every stage of their product lifecycle and lower embodied energy values while offering comparable thermal performance [92–96]. The carbon footprint of bio-based insulation materials can vary widely depending on their origins. Materials with faster growth rates usually have a lower CO_2 footprint [66]. These materials can be derived from various renewable sources, including wood fibre, cellulose, hemp, flax, jute, eelgrass [66,97], and even wood waste [98,99]. When considering the biogenic carbon in the life cycle analysis, the benefits of using bio-based insulation materials become even more pronounced [65,66,100]. However, it is worth noting that the additives used in bio-based insulation materials to combat decay and pests and improve fire safety contribute to their climate impact. Therefore, reducing emissions from these additives or developing bio-insulation alternatives without them could minimise environmental impact [90].

State-of-the-art

Energy performance

Today, energy performance is one of the most important factors to consider when designing a building. In Europe, regulations mandate that all buildings constructed after 2020 meet the criteria for zero-energy buildings [10]. Despite the significant time and effort invested in ensuring compliance with strict energy consumption standards, there remains a notable discrepancy between predicted and actual energy consumption, even with advanced hygrothermal models [101]. There is a substantial knowledge gap, and limited experience exists regarding the performance of bio-based insulation materials in both industry and academia [67,102]. This gap contributes to what is commonly referred to as the 'energy performance gap,' where the actual energy use in buildings deviates from predictions. While this gap has been extensively studied [103–109], it is often attributed to unpredictable user behaviour [110]. Although anecdotal, examples of buildings constructed using a significant proportion of bio-based materials demonstrate better-than-expected energy performance [62,111,112]. These instances often involve confounding factors such as towel dryers, measurement errors, or occupants' political views. Scientific evidence supporting these claims is limited and typically involves smaller-scale studies [60,113–116]. Accurate projections of operational energy are particularly crucial in cold climates [117]. Stringent requirements are already in place for obtaining building permits. Data from actual dwellings indicate a significant discrepancy between projected (lower) and actual energy usage (higher) for heating [118,119].

Experience from the reference group suggests that modern buildings constructed with timber-frame structures and insulated using bio-based materials, such as wood fibre, may have lower space heating requirements than anticipated from energy simulation models. However, these findings remain primarily anecdotal and require further validation through research. It is hypothesised that the hygroscopic properties of bio-based materials could contribute to this potential energy-saving effect, possibly due to latent heat and hygrothermal mass effects.

Latent heat

Previous research has hypothesised that buildings incorporating a significant proportion of bio-based materials may experience lower energy consumption due to latent heat [120–124]. Latent heat refers to the heat absorbed or released when a material undergoes a phase change, such as the transition of water vapour between gas and liquid phases. This energy is derived from both the heat of condensation and the latent heat of mixing, with the former being predominant and the latter accounting for only 10 to 20% of the total latent heat [125]. The latent heat of mixing decreases with higher moisture content [126], whereas the heat of condensation is constant. Some researchers have referred to this concept of latent heat in indoor timber as "sauna physics," a phenomenon familiar to anyone who has experienced a sauna. Experimental results have demonstrated a significant temperature increase on the surface when water is poured onto a heater in a sauna [123]. Similar behaviour has been observed in other settings, such as climate chambers [120]. Studies have shown that subjecting a wooden surface to moisture can lead to a surface temperature increase of 2K, potentially resulting in energy savings by reducing the operational temperature of the building [124]. The same or even higher temperature increments can be seen in bio-based insulation materials. Figure 15 shows a simple experiment where the three bio-based insulation materials studied in *Paper III* (Eelgrass, Grass and Wood Fibre), along with mineral wool, were placed in a climate chamber going from 20% relative humidity to 90% at 27°C constant temperature. After 90 minutes, the three bio-based materials are significantly warmer than the mineral wool and the surrounding room, which can be seen in the thermography image. Other studies have explored chemically modifying wood with bio-based phase change materials to enhance latent heat storage and energy performance, while also improving resistance to biological threats such as termites and wood boring beetles [127,128].

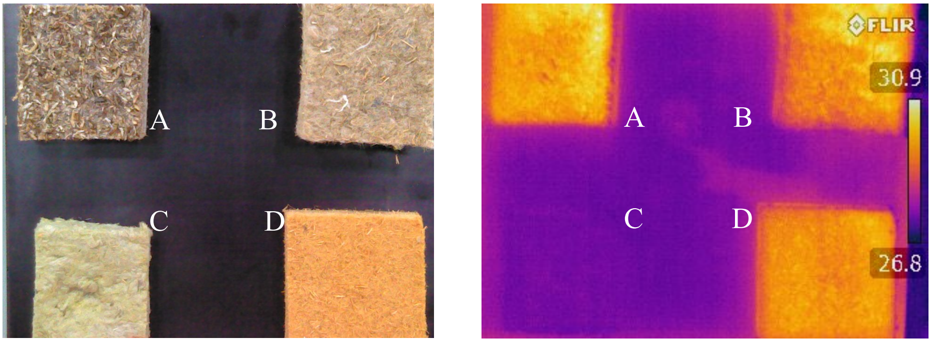

Figure 15: A simple experiment highlighting latent heat 90 minutes after increased relative humidity. On the left is a photograph, and on the right is a thermography image. Materials in the experiment are Eelgrass (A), Grass (B), Stone Wool (C), and Wood Fibre (D).

Previous research on latent heat in buildings [122] has indicated that optimising ventilation systems to utilise latent heat can reduce energy requirements for heating and cooling by 5% to 20%. Furthermore, [121] suggested that latent heat could reduce energy consumption by 4-8% with minor fluctuations in indoor humidity levels (between 40-50% relative humidity). With more significant diurnal humidity variations (between 30-60%) and improved wall insulation, this effect could increase energy savings by up to 46%. These findings are based on the assumption of visible wooden structures and reduced operational temperatures due to increased temperatures resulting from latent heat when occupants are present. In dynamic hot-box tests, log and cross-laminated timber (CLT) walls exhibited 57% and 34% lower energy consumption compared to theoretical values [129], further highlighting the potential energy-saving benefits of incorporating bio-based materials with latent heat properties into building designs.

Material parameters

Predicting the energy use of buildings often relies on thermal transmittance (U-value) calculations, which estimate heat loss through building components based on their thickness and thermal conductivity (λ-value) [130,131]. The thermal conductivity of bio-based insulation materials is notably influenced by their porosity and pore size distribution [132]. This conductivity can vary significantly between different materials [97,133] and is challenging to measure accurately [134]. Building materials' thermal properties are commonly obtained using steady-state conditions, and thermal conductivity is measured using the hot plate or heat-flow methods [130,131]. Unfortunately, in actual buildings, steady-state conditions are rarely present on the exterior side, where neither the temperature nor the humidity is steady for long periods, see Figure 16.

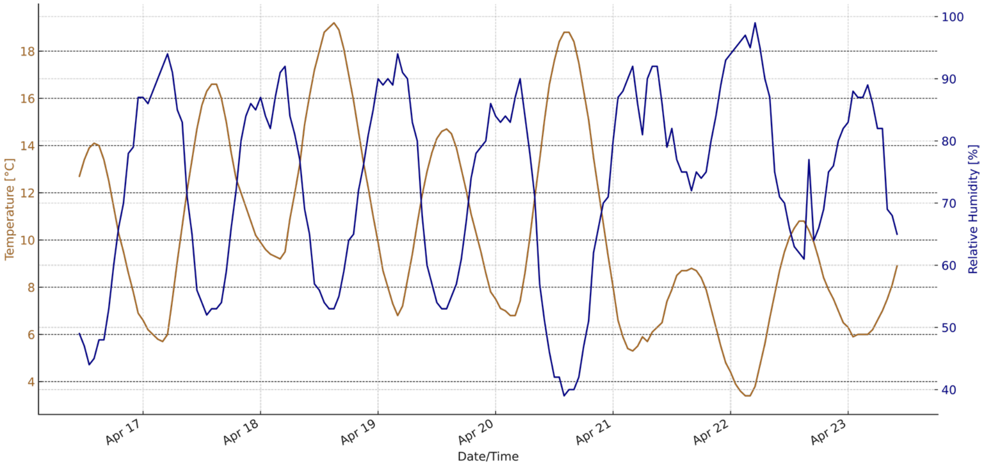

Figure 16: Meteonorm data for Lund [135], one April week, shows fluctuating conditions.

Thermal mass and thermal lag play crucial roles in determining heat flow through wall structures by accounting for the hygroscopic properties of materials [136]. Bio-based insulation materials are often hygroscopic with a high moisture capacity [131]. The moisture content changes the thermal conductivity of insulation materials [137]; however, experimentally, it has a limited impact within the hygroscopic range for materials like cellulose [138–140]. Regardless, the hygroscopic properties will influence energy performance, particularly in walls designed for moisture diffusion [141,142]. Thereby, accounting for the hygroscopic properties of materials, energy performance calculations could be improved [121–123,143]. Moisture buffering refers to a material's ability to absorb and release moisture, significantly influencing indoor environmental conditions and comfort. Despite extensive research, there needs to be globally agreed-upon methods for measuring hygroscopic materials' transient moisture transport properties. Most simulation tools rely on steady-state material properties, which may not accurately reflect dynamic real-world behaviour [144]. Implementing appropriate hygroscopic materials can reduce total energy consumption by 25-30% in cities like Paris and Madrid, regions with significant humidity fluctuations between day and night [145].

Laboratory research has demonstrated differences between expected and actual heat loss when using bio-based insulation [1,138,146], possibly due to the benefits of hygroscopic loading and unloading [2,147]. For instance, measurements of loose-fill cellulose using a heat-flow meter have shown that a dry specimen reaches a steady state within one to two days, while a moist specimen requires a week to reach a steady state [139], highlighting the influence of moisture content. Similar findings have been observed in massive timber structures, such as 'IsoTimber', subjected to temperature changes [62,148]. Notably, the hygrothermal mass varies with the direction of temperature change, likely due to moisture and latent heat effects [148].

Scientific gap

Research regarding latent heat has predominantly focused on studying interior and visible bio-based surfaces, but it is plausible that similar phenomena occur within the structure of a wall. This suggests that a wall with bio-based insulation and the correct diffusion properties could exhibit similar behaviour. To illustrate this concept in a practical building application, consider an exterior hygroscopic material that experiences condensation heat with moisture adsorption when outdoor temperatures drop at night. This moisture will evaporate in the morning when the sun rises. If the temperature increase and solar radiation can offset the energy lost through evaporation, this could result in a net energy gain for the heating system.

Studies of bio-based insulation materials have primarily been on a material scale. More studies need to target performance on component and full scale, especially with more realistic setups.

Methods

To grasp the hygrothermal performance of hygroscopic insulation materials, it is crucial to understand their moisture-handling capabilities and thermal properties. Various approaches have been employed to assess the energy efficiency of bio-based insulation, ranging from small-scale material investigations to full-scale experiments. Additionally, a model has been created to compare experimental findings with a supplementary numerical calculation method. While *Papers I, III,* and *IV* primarily focus on experimental data, *Paper II* relies on numerical simulations. Notably, the model developed in *Paper II* finds application in *Paper IV*. Despite the thesis's emphasis on in-situ performance, numerical models are indispensable for comparative analysis and broader insights. See Figure 17 for a graphical overview of the properties investigated. The following section provides a general overview of the methods used. For detailed descriptions, please refer to the appended papers.

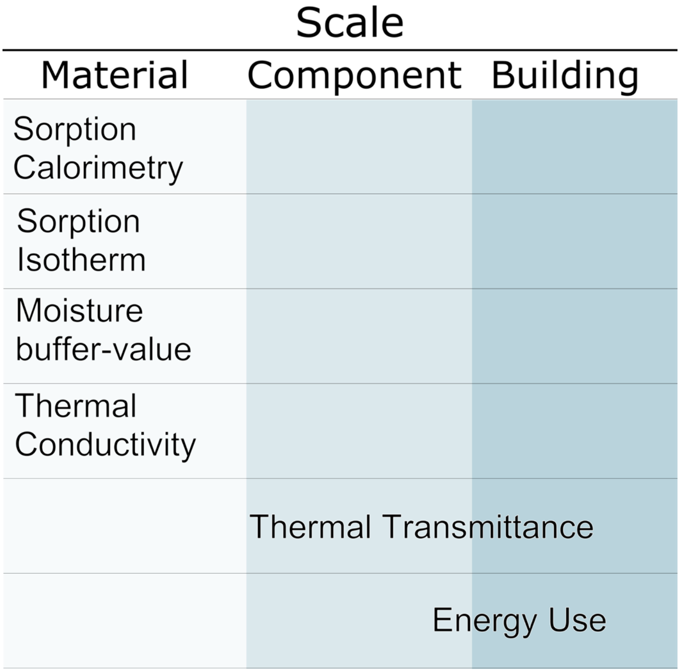

Figure 17: Overview of hygrothermal properties investigated and the scales experimentally.

Industry connection – Reference Group

The reference group played a crucial role throughout the project by helping to maintain focus on industry-identified knowledge gaps. It convened naturally in trade-specific settings like conferences or meetings. Occasionally, one company would test something new and invite the reference group to a factory or site visit. Additionally, individual meetings were arranged with companies, usually to discuss design changes or upcoming pilot projects. Formal workshops were conducted twice a year during the thesis work, where the reference group gathered to discuss current topics. These discussions typically followed the three-part system outlined in the chapter 'External Factors': societal, industrial, and academic. While members of the reference group freely shared their perspectives, additional efforts were undertaken to gather qualitative data through other means to prevent skewed or biased input. This included conducting two interview studies and one survey within the reference group aimed at triangulating their insights. It is important to highlight that the data obtained from these activities was strictly intended for internal use and will not be published due to the sensitive nature of the findings, which could potentially benefit competitors.

Experimental Methods

Experiments were conducted in *Papers I, III*, and *IV* on different scales. *Paper III* was primarily on the material scale, *Paper I* was mainly on the component scale, and *Paper IV* was with full-scale walls. *Paper I* focused on developing a test setup to test components (more straightforward wall elements) that was benchmarked against tests done on the material level. *Paper III* also used the test setup developed in *Paper I*.

Material level

Thermal properties

Assessing the thermal conductivity of insulation materials commonly involves two methods: the Hot-plate apparatus or Heat-flow meter. These techniques operate under steady-state conditions and offer consistency in insulation measurement [130,131,149]. However, for porous insulation materials, the direction of heat flow influences the results [150]. Additionally, steady-state conditions are rare in real-world building environments, particularly when factoring in moisture. In *Papers I* and *III*, thermal conductivity, diffusivity, and heat capacity were assessed using the Transient-Plane-Source (TPS) method. This approach is significantly faster than the steady-state tests, and this speed may be needed for bio-based insulation materials due to the impact of conditioning and test conditions on the results. Despite the advantages of the TPS method, it is worth noting that errors are more pronounced for low conductivity, especially concerning specific heat and thermal diffusivity [151]. The results of the TPS experiments in both *Papers I* and *III* are compared with values provided by material manufacturers and the HotBox developed in *Paper I*. Figure 18 shows a sensor and sample holder for TPS (HotDisk) experiments, where full depth samples with the approximate size of 150 × 150mm^2 were tested.

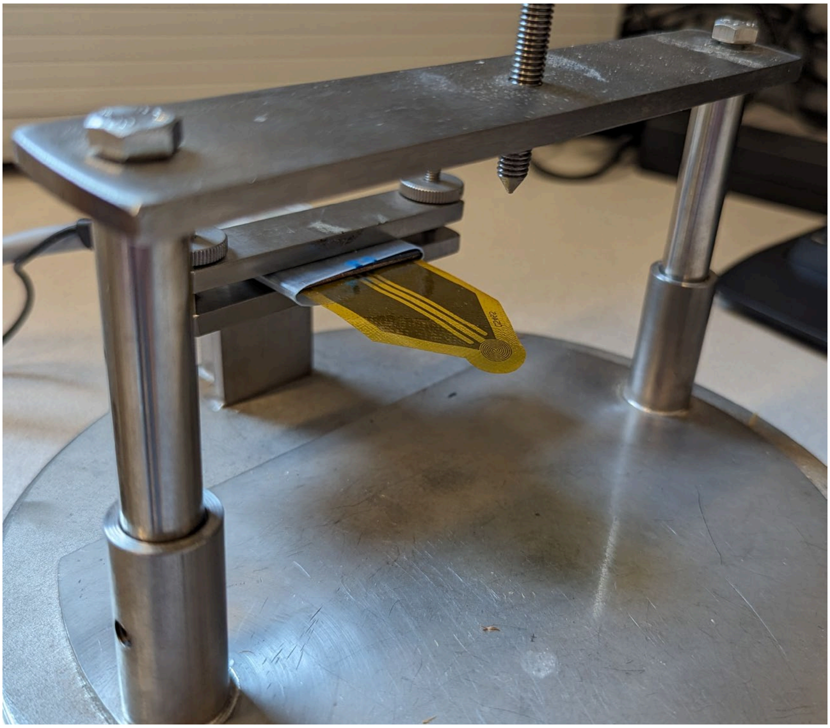

Figure 18: Holder for specimens and a sensor for TPS (HotDisk) measurements.

Moisture properties

Sorption isotherm

A sorption isotherm visualises the interaction between a substance and a solid surface (adsorbent) in relation to the concentration of that substance in the surrounding fluid or gas (adsorbate), all at a consistent temperature. It illustrates how much of a solid material can adsorb a substance under specific conditions [130]. Utilised across various scientific fields, sorption isotherms help comprehend and forecast adsorption and desorption processes. The shape of the sorption isotherm curve offers valuable insights into the nature of the adsorption process. For instance, in physical adsorption (physisorption), the isotherm typically exhibits a characteristic sigmoidal shape, initially steeply increasing and reaching a plateau as the surface becomes saturated [130]. Conversely, in chemical adsorption (chemisorption), the isotherm might lack a distinct plateau, with adsorption potentially increasing continuously with rising concentration [130]. In *Paper III*, the sorption isotherm was determined using a DVS machine. The DVS (dynamic vapour sorption) method is a widely used technique for measuring material sorption isotherms, depicting the relationship between the material's equilibrium moisture content and the relative humidity of its surrounding environment [152]. This method involves exposing a sample to controlled humidity conditions and measuring its mass change as it adsorbs or desorbs moisture [153]. The sample size tested in the DVS is small, typically around 50 mg.

Sorption Calorimetry

Sorption calorimetry is a technique used to measure the heat of sorption, which refers to the heat released or absorbed when a substance interacts with or adsorbs another substance, in this case, water vapour. Except for a study on wood [126], *Paper III* was the first use of sorption calorimetry to study the sorption energetics of construction materials; previous studies using this method have been on pharmaceutical compounds and other biomolecules [154–157]. However, studies where the heat of condensation and sorption are both included have been done in bio-based materials [158]. Sorption calorimetry provides insights into the energetics of the sorption processes (enthalpy of sorption/mixing), allowing for a better understanding of a material’s interaction with moisture and whether, e.g., excess heat from the interaction between water and material will influence the overall thermal performance of building assemblies. In the sorption calorimeter used, continuous measurements of the thermal power of vaporisation from a water source and the thermal power of sorption in a sample are made. The sample sizes for the sorption calorimetry are very small, between 20-30 mg.

MBV - Moisture Buffer Value

Moisture buffer value indicates the ability of hygroscopic materials to regulate humidity levels. In a moisture buffer test, a material sample is typically subjected to steady temperature conditions and fluctuating relative humidity to investigate the moisture buffering of building materials [130,131]. The weight change (change in mean moisture content) is then measured over time. A common and standardised test method to determine moisture buffering value is the NORDTEST method [159], which involves exposing a material sample to cyclic changes (24 hours) in temperature and humidity and measuring the moisture uptake and release rate. In *Paper III*, a slight adaptation of the NORDTEST protocol was used to determine the moisture buffering properties of the insulation materials. Three samples were tested for each material; see Figure 19 for a photograph of the test setup. The sample sizes were full depth and approximately 150 × 150 mm^2, which weighed 50-100g.

Figure 19: Three samples right before an MBV test. The samples are hanging in balances placed in plastic containers.

Component level

Measuring thermal performance on a component level is usually done using a Hot Box [130]. *Paper I* aimed to develop a Hot Box with the possibility of a dynamic outdoor climate. The general concept of a Hot Box test is to measure the heat flow from the hot side to the cold side. This is, in practice, done by measuring the energy required to keep the warm side at a specific temperature or assessing the heat flow with a heat flow meter. A schematic figure of the Hot Box setup is shown in Figure 20.

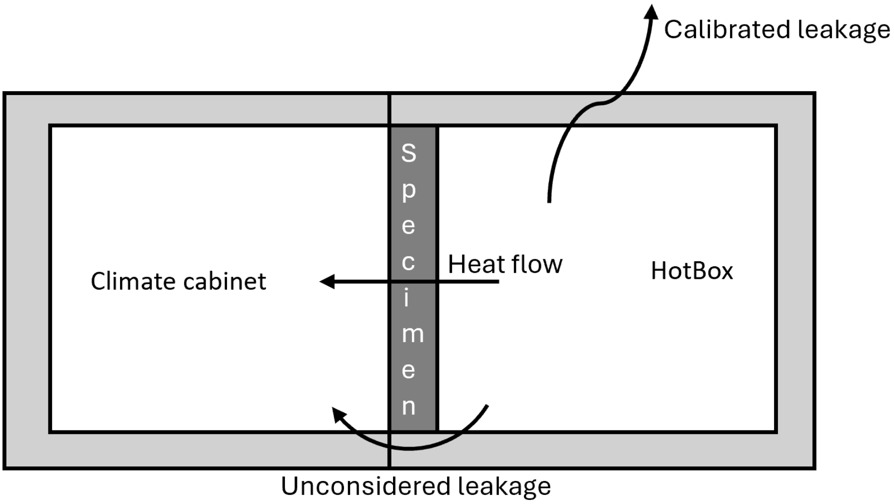

Figure 20: The principal figure of the Hot Box test setup shows test conditions and general assumptions.

Other Hot box versions have been developed for similar purposes [160]. One variant of the Hot Box is seen in [161], called the "small hot box", where the temperature of the hot side is increased with good results instead of cooling the cold side. A similar device to *Paper I* was developed simultaneously and found similar results [129]; however, the test setup developed in *Paper I* has more capacities regarding moisture variation. The same equipment was used in [162], and very little difference is shown between steady-state and dynamic tests.

The difference between a standard Hot Box and the 'Dynamic Hot Box' presented in *Paper I* is that the cold side is represented by a climate chamber in the 'Dynamic Hot Box', allowing for simulation of almost any outdoor conditions. Similar projects have shown the importance of simulating realistic conditions when testing walls, where air leakage and temperature will change the insulating properties of the wall [163]. A comparison between two different Hot Box setups [164] and [165] is seen in [149], which concluded that measuring energy used for heating to obtain heat flow is an efficient way. Another study [166] investigated a similar question and compared heat-flux meters and radiative heaters in a Hot Box setup with good results. Even more simplistic ‘Hot Box’ setups than *Paper I* still show promising results for non-hygroscopic materials [167], highlighting the Hot Box method's efficiency.

The materials in *Paper I* were chosen because they are commonly used but have very different physical properties, e.g., porosity, density, and stiffness. Mineral wool is an exterior facade insulation board and is typically the standard way to insulate a facade in northern Europe. Extruded polystyrene insulation (XPS) is a board commonly found in foundations. The tested bio-based insulation is a wood fibre insulation board that could be used between studs of a timber-framed building.

Apart from steady-state benchmark tests, tests were carried out using diurnal changes in the outdoor climate, either with dynamic temperature or humidity. The cycle time for the dynamic tests was set to ten hours to simulate a colder night. The outdoor temperature for the dynamic temperature test was varied from 0 to -10°C and back to 0°C in steps of 2K for ten hours. The outdoor temperature for the dynamic humidity test was chosen to be 0°C, and the relative humidity was programmed to vary from 95% to 50% and back within 10 hours. See Figure 21 for a photograph of the test setup.

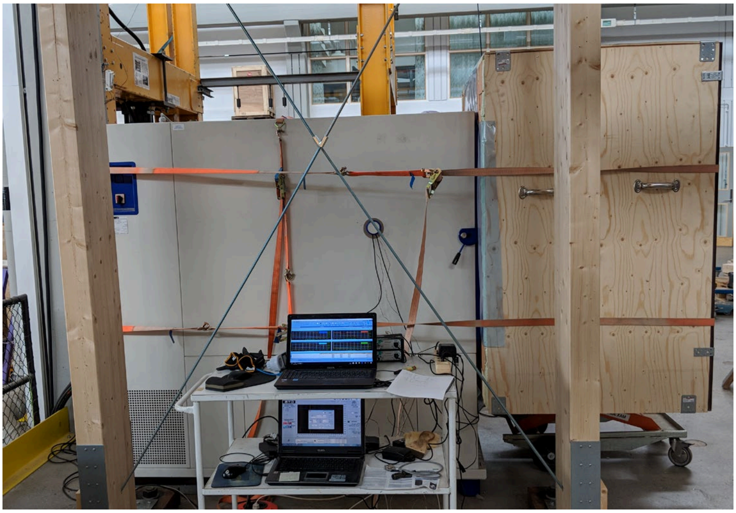

Figure 21: Photograph of the HotBox setup from *Paper I.* To the left is the climate chamber (cold side), and to the right is the Hot Box (warm side).

Full-scale level

From literature and small-scale tests (*Paper I*), it was evident that bio-based insulation performed differently than mineral wool. However, whether this effect makes a noticeable difference in energy performance in full-scale walls with a realistic wall assembly has not been studied earlier. At Lund University Campus, there are some possibilities for full-scale testing; one is the “Facade Laboratory,” seen as it was in September 2020 in Figure 22.

Figure 22: This photograph was taken of Lund University's facade laboratory in September 2020, before renovations were done within this thesis work. The building's normal use is to test the facade materials; at the time of the photograph, experiments were conducted with salt intrusion into brick walls.

Testing the energy performance of full-scale buildings presents significant challenges [168], with multiple methods available for conducting such assessments [169]. One approach is the "whole house heat loss test method", commonly known as a co-heating test. This experimental method aims to determine a building's overall heat loss coefficient resulting from conductive and ventilation heat losses [170]. The procedure involves maintaining a constant air temperature inside the building while measuring the daily heat input and the temperature difference between the interior and exterior environments [171]. The heat loss coefficient can then be calculated by plotting the mean heat input against the internal-to-external temperature difference, providing insights into the building's real-world performance.

Co-heating tests offer valuable diagnostic capabilities as part of the building performance toolkit, such as crucial information about a building's envelope and infiltration heat losses, allowing for comparisons between actual performance and design expectations [172]. However, the co-heating test has drawbacks: the test is expensive and time-consuming, and its sensitivity and accuracy are not fully understood. Concerns have been raised regarding the reliability and practicality of the co-heating test method. The extended duration of the test and uncertainties in the results pose challenges. External weather conditions, especially solar radiation, significantly impact the test's accuracy and repeatability.

To facilitate comparative testing, the test house was reconstructed with four cells, each accommodating a wall specimen (see Figure 23 for the two southern specimens). These cells allowed for the simultaneous testing of four specimens, with significant air volume ensuring one-directional heat flow within each cell [166]. The cells were constructed on an elevated and ventilated floor, enabling air circulation on all five sides for uniform temperature distribution within the test house.

Figure 23: Southern facade of the test house. This photograph was taken while walls were being mounted to the house. The two timber framed walls are the ones tested. The brick wall is used in another project, and the wall to the right is just a ‘dummy’.

A small electric radiator was installed in each thermal test cell to generate heat. This radiator was linked to an electricity meter, allowing for continuous tracking of the electricity consumed for heating purposes. By measuring electricity usage and assuming that all electricity consumed by the radiator is converted to heat, the energy used for space heating in each cell was determined.

The wall specimens were designed to represent walls typically found in single-family houses in Sweden. These specimens were insulated to meet the minimum insulation requirements stipulated by the Swedish building code [173], ensuring realistic yet significant heat loss. Please refer to Figure 24 for details on the wall assembly. While manufacturers provide material data, it is important to note that measurements conducted in a laboratory may differ from real-world conditions, especially wood fibre [1,134,174]. A vapour retarder was chosen to facilitate moisture diffusion, promoting the concept of "breathing walls” [175,176]. This feature is particularly advantageous when working with hygroscopic materials like wood fibre insulation [177]. The wall specimens were constructed off-site in a workshop and then transported to the test house, which helps minimise quality defects [178]. On-site installation involved mounting cavity insulation, a weather barrier, and facade cladding. Thermography was used during construction to identify potential leaks, ensuring the assembly's integrity.

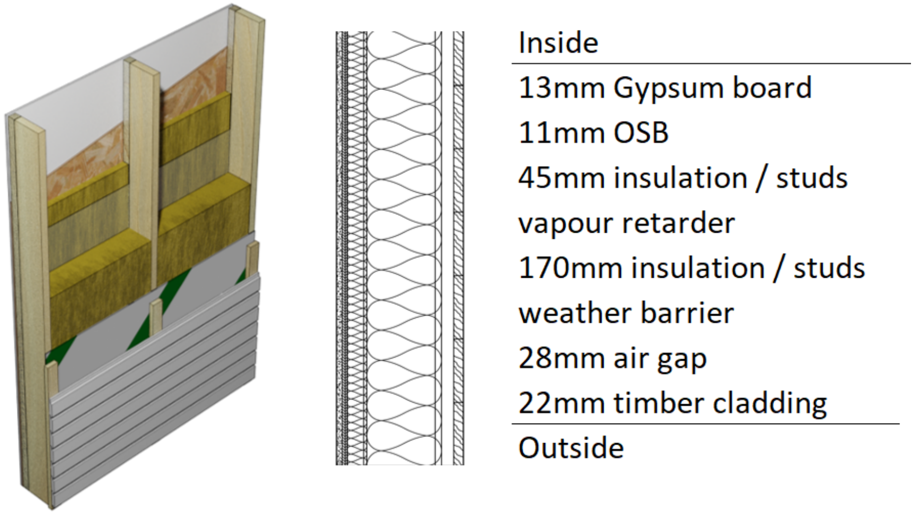

Figure 24: 3D - rendering and a vertical section of the walls tested in full-scale experiments. Figure from *Paper IV.*

Both indoor and outdoor temperatures and the temperature within the test house were monitored using thermocouples, generally considered sufficient for in-situ measurements [179]. In the analysis of *Paper IV*, a time step of 24 hours was chosen, resulting in daily mean temperature values that align with recommendations from [170]. The heating period was selected as the period when the mean outdoor temperature was below 10 degrees Celsius, and with a 21°C indoor temperature resulted in a temperature difference between inside and outside of at least 10 Kelvin. This approach, advocated by [170], underscores the importance of a substantial temperature difference for accurately determining the true U-value, as emphasised in previous research [180].

To facilitate numerical simulations, humidity sensors were strategically positioned centrally on the specimen's interior surface (one sensor) and three sensors within the air cavity behind the facade cladding. The temperature and humidity data collected from these sensors served as input for the simulations. For exterior sensor placements, see Figure 25.

Figure 25: Southern facade with humidity sensors that are installed in the air gap between the timber cladding and weather barrier.

Numerical methods

Assessing a building's hygrothermal performance typically requires the use of numerical software. While numerical models are commonly relied upon to predict building energy performance, as discussed in the ‘Bio-based Insulation’ chapter, a performance gap often exists. This is particularly true for bio-based materials due to their hygroscopic nature, which makes accurate measurements of their thermal properties more challenging.

In this thesis, the numerical method involved developing a model that handled moisture differently compared to commercial software, as detailed in subsequent chapters. The developed model underwent benchmarking against WUFI [178], a widely used software, and demonstrated similar results regarding temperature and humidity when analysing mineral wool. Figure 26 provides a comparison between the *Paper II* model and WUFI.

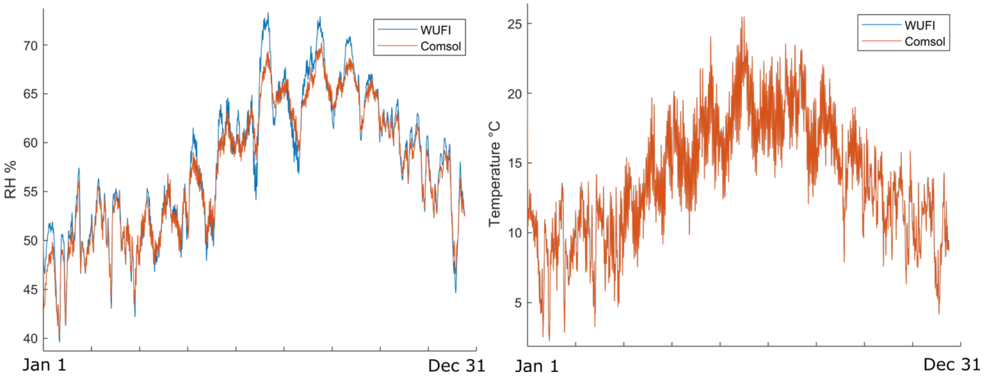

Figure 26: Comparison between WUFI and the model developed in Paper II. To the left is relative humidity [%], and to the right is temperature [°C]. The comparison was made with the numerical element closest to the centre of a modelled ‘wall' subjected to a reference year.

Model

A numerical coupled heat and moisture model was developed using COMSOL Multiphysics 6.0 [181], a finite element program known for its robust capabilities. COMSOL stands out among commercially available software due to its open equation manager and advanced output differentiation. This feature allows for separating latent heat effects from other energy balance terms, providing more accurate insights. Additionally, COMSOL's flexibility enabled the modelling of vapour within material pores, improving the fidelity of the simulations. Utilising this model, executed from MATLAB [182], numerous simulations were conducted to assess the impact of sorption properties on heat flux through a wall. One-dimensional models are commonly preferred when evaluating hygrothermal behaviour [183], and COMSOL has demonstrated effectiveness in modelling hygroscopic materials [184].

Moisture transport was assumed to occur solely within the voids of the pores. Steady-state conditions were examined to demonstrate the magnitude of latent heat of evaporation and its potential impact on heat flux under varying moisture and temperature conditions. The two primary drivers of latent heat, temperature and relative humidity, were manipulated. Outdoor temperature variations altered the temperature difference, while the indoor temperature remained constant at 21°C. In a steady state, the amount of latent heat remains unaffected by the absolute thickness of the wall. Nonetheless, to demonstrate the magnitude of latent heat compared to conductive heat flux, walls with different insulation capacities were compared. Simulated walls were assigned different thermal conductivity values to achieve varying insulation capacities without modifying the underlying model. While the model did not incorporate changes in thermal conductivity with relative humidity, such changes are typically minor and consistent across materials within the hygroscopic range [185].

Furthermore, full-year simulations were conducted using weather data from various European cities. Temperature and humidity inputs were obtained from cities located at similar longitudes but different latitudes, including Kiruna (67°), Stockholm (59°), Lund (55°), Kassel (51°), and Rome (41°), offering a range of climatic conditions representative of Europe. See an overview of the temperature and humidity conditions in Figure 27-29.

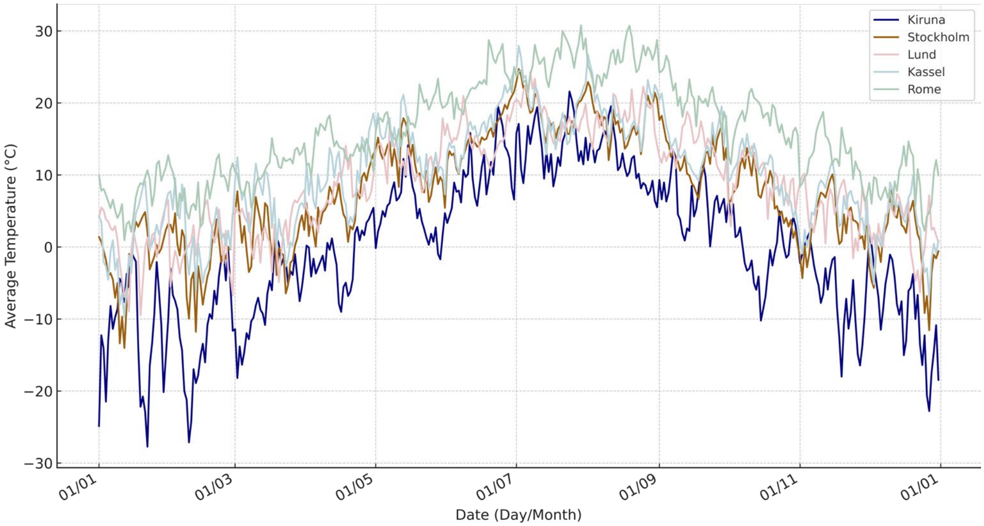

Figure 27: Daily average temperature [°C] in the Meteonorm data for the cities modelled in *Paper II* [135].

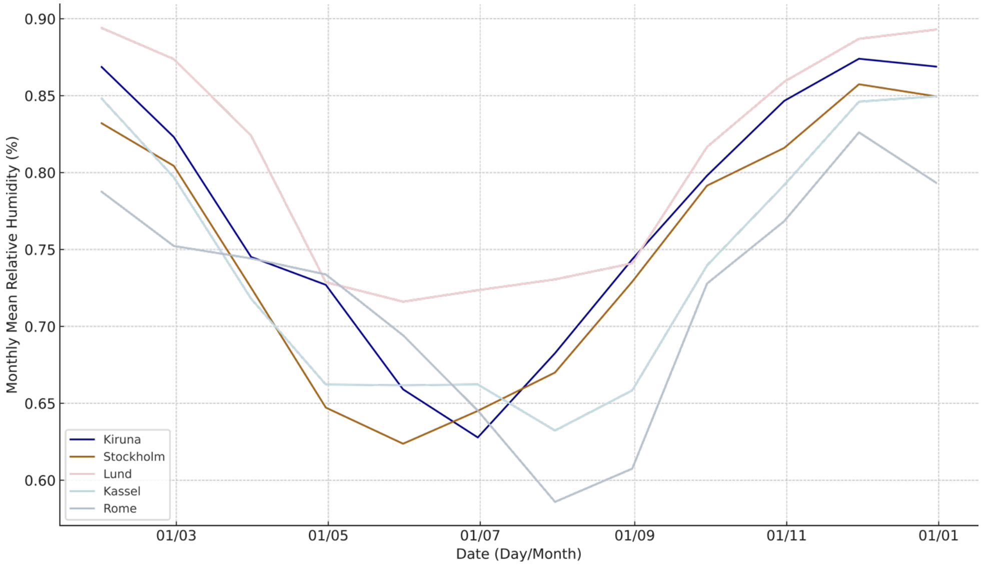

Figure 28: Monthly average relative humidity [%] in the Meteonorm data for the cities modelled in *Paper II* [135].

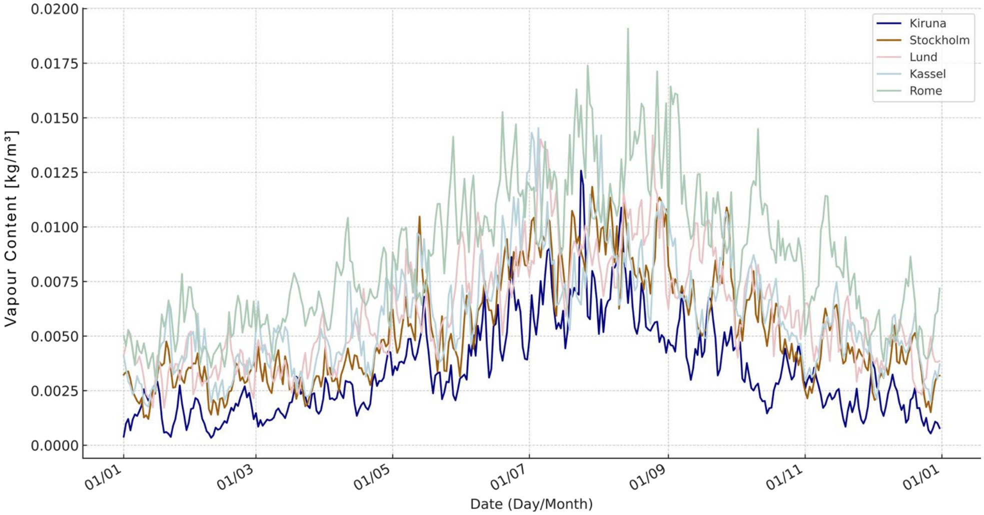

Figure 29: The calculated daily average vapour content [kg/m³] for the cities modelled in Paper II is calculated using the formula suggested in [186].

Typically, indoor and outdoor air have similar vapour content, occasionally affected by occupants' activities that introduce interior moisture loads. Maintaining constant vapour content leads to a relative humidity gradient when there is a temperature disparity. Temporary increases in vapour content due to events like rain or ground moisture on the exterior or activities like cooking, showering, or just occupant transpiration indoors can elevate moisture transfer through the wall. These variations in vapour content can significantly influence latent heat, affecting heat flux compared to pure conductive heat transfer. Dynamic simulations also explore vapour transport within the material.

Two types of moisture loads were analysed to understand their influence: interior moisture loads and simulated five-hour rain events occurring every third day, with outdoor relative humidity set at 99% during the rain event. To assess the impact of sorption properties on latent heat, the sorption isotherm was varied under dynamic conditions. The wall remained constant as a 170mm insulating material, but different sorption isotherms representative of materials such as EPS, mineral wool, wood fibre insulation board, and wood were applied.

Blind evaluation of experiments

Temperature and humidity data measured in the full-scale experiment detailed in *Paper IV* served as boundary conditions for a numerical assessment conducted using the model introduced in *Paper II*. Two one-dimensional numerical coupled heat and moisture models were created for the specimen walls, modelling either the thermal insulation or timber stud interfaces. The entire specimen walls were comprehensively analysed by integrating the results obtained from the stud and insulation models. A graphical interpretation of this is seen in Figure 30.

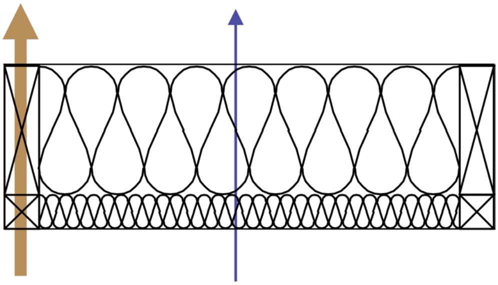

Figure 30: Graphical interpretation of how the two modelled situations in the 1D model would look in a wall: one 1D model through the timber stud (bronze arrow) and one model through the insulation (blue arrow).

All materials within the walls were represented using the 'Building Materials' module, where moisture transport was confined within the material, mirroring the approach adopted by other hygrothermal software models, as outlined in [187] and compliant with international standards [188]. In addition, another model (*Paper II*) was made, where the insulation layers were modelled using the "Hygroscopic Porous Medium" module instead. This module allows for modelling both the material and its pores, enabling a more specialised approach to model materials, particularly those with hygroscopic properties [189]. The primary distinction between the two models lies in including latent heat within the material. Depending on the sorption properties of the constituent material, these two modelling approaches yield significantly different results, as demonstrated in *Paper II*.

It is important to note that the models were constructed without considering factors such as air infiltration or construction defects and, therefore, may underestimate actual heat transfer. Additionally, the thermal conductivity of materials was not adjusted as a function of relative humidity; instead, the models accounted for the pores and the conductivity of their contents. All material values were selected based on information provided in the manufacturer's datasheets. The only variation between pairs of wall specimens in the numerical model was the thermal insulation material used.

Results of the Appended Papers

This section provides a comprehensive summary of the appended papers, emphasising the results. For a deeper understanding and additional context, please refer to the appended papers, which include further background, methodology, evaluation, and discussions.

Paper I – Development of a Dynamic Hot Box Test Setup with Variable Outdoor Climate

As described in the chapter "Bio-based Insulation", there is often a discrepancy between the design and actual energy use of buildings. As described in the chapter "State-of-the-art", there is anecdotal evidence suggesting that timber buildings generally have lower energy consumption than predicted. Traditional methods of measuring thermal conductivity under steady-state conditions often fail to capture real-world scenarios where temperature and humidity fluctuate. To address this, the study proposed a Dynamic Hot Box test method, allowing for the simulation of varying outdoor climates, mainly focusing on moisture. The setup involved a climate chamber representing outdoor conditions and an insulated metering box for indoor conditions. The working hypothesis for this paper was that hygroscopic materials with more considerable moisture buffering capacity have different energy performance when used in actual structures under natural climatic conditions compared to standard tests of thermal insulation performance. The dynamic Hot Box and TPS experiments are explained further in the 'Experimental Methods' chapter.

The paper aimed to develop a Hot Box to successfully test steady-state and dynamic conditions. The developed Hot Box was tested and benchmarked with three different insulation materials: mineral wool (stone wool, typical façade insulation), XPS (extruded polystyrene, typically found in foundations) and a bio-based (wood fibre insulation batt, which can potentially be used to insulate timber-framed walls). The latter shows promising performance, potentially outperforming predictions.

The results from the steady-state experiments are shown in Figure 31. For non-hygroscopic insulation materials, i.e. mineral wool and XPS, the declared performances are close to the measured values obtained using the TPS method. For the bio-based insulation, the thermal conductivity from the TPS test was 40 % higher than the declared value, which is most probably because the declared ‘indoor condition’ thermal conductivity is not a measured value but rather an estimated value from recalculation of test results done with a completely dry specimen. To investigate this, one specimen was dried at 105°C and then measured with the TPS. The dry specimen had a thermal conductivity of 0.041 W/mK, which is still higher than the declared value of 0.038 W/mK, as the producer claims it should be in an indoor climate. Also, the characteristics of the specimen were changed entirely. The material felt burnt and became very brittle, unlike a material used for construction.

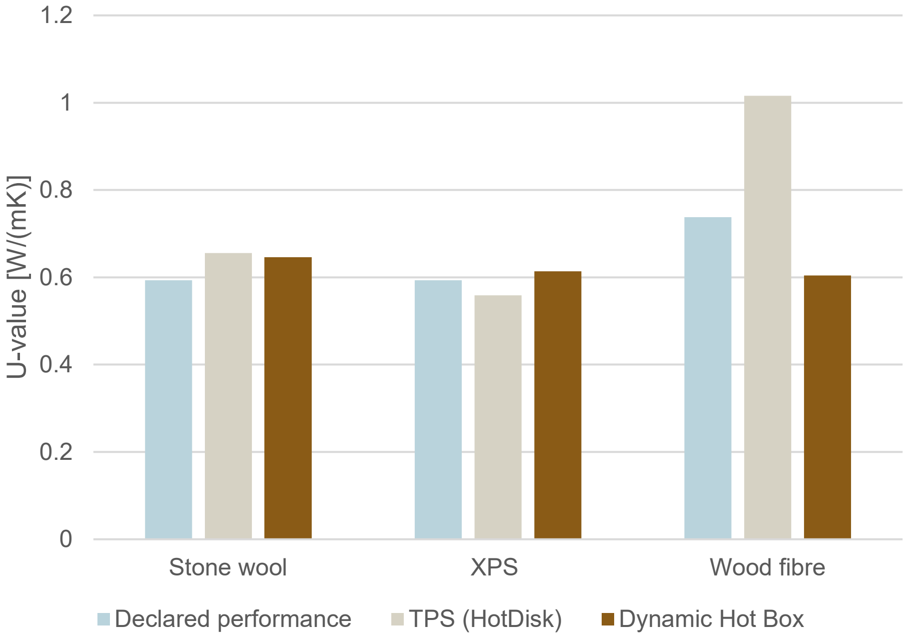

Figure 31: Compares the thermal transmittance derived from the thermal conductivity from either the manufacturer's declared performance or TPS measurements with the results from dynamic Hot Box tests.

Apart from steady-state tests, tests with dynamic conditions were carried out to simulate diurnal changes in the outdoor climate, either with dynamic temperature or with dynamic humidity. The cycle time for the dynamic tests was set to ten hours to simulate a colder night.

Dynamic outdoor climate with diurnal changes does not result in apparent differences in the performance compared to the steady-state tests, as seen in Figure 32. For the dynamic temperature tests, mineral wool and biobased insulation performed better, and XPS performed worse than in steady-state conditions. One explanation could be the larger thermal mass for mineral wool and biobased insulation, as seen in the TPS measurements.

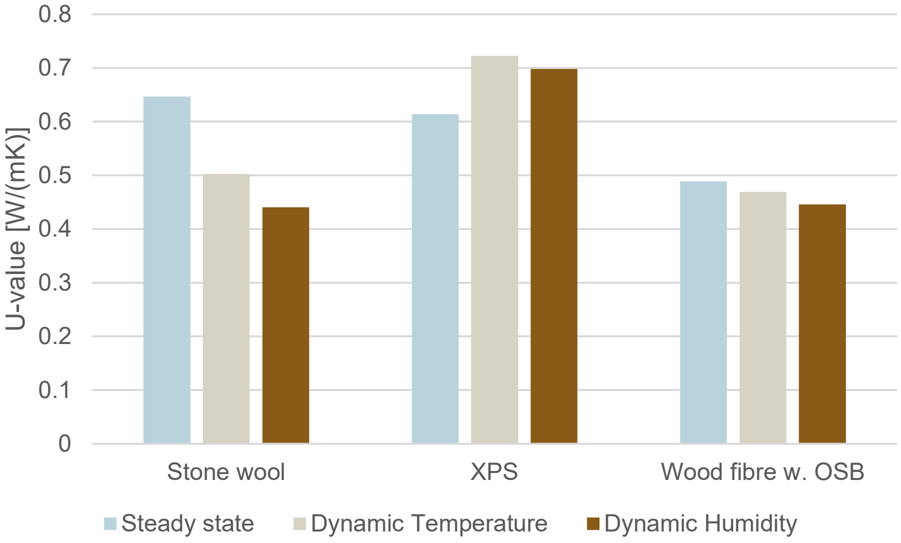

Figure 32: Comparison between the different testing methods with the dynamic Hot Box. When comparing materials, note that the dynamic temperature test is practically a test of thermal inertia. The dynamic humidity test did not work satisfactorily and is primarily a steady-state test with a smaller temperature gradient.

Maintaining steady boundary conditions, particularly with dynamic humidity, presented significant challenges, emphasising the complexities of experimental research. The study highlighted the necessity of considering factors such as air tightness and external influences on insulation performance, which has implications for future research and development. Despite limitations, the developed ‘Dynamic Hot Box’ method proved to be a practical approach for evaluating insulation performance under varying conditions. While the climate chamber struggled to control humidity sufficiently to create a cyclic climate for the porous test specimens, higher exterior temperatures were needed for reliable humidity control. Nonetheless, the dynamic Hot Box method performed well for dynamic temperature tests. This method has the potential to promote the adoption of bio-based materials, contributing to improved energy efficiency and reduced carbon footprint in building construction.

Paper II – Investigating the Potential of Latent Heat in Hygroscopic Insulating Materials

Paper II is about hygroscopic insulation materials' capacity to contribute to building energy efficiency. It is common that energy models only focus on the thermal properties of materials and thermal flows through the building envelope, without considering moisture loads or hygrothermal behaviour of building materials. A relevant difference between bio-based insulation materials and their polystyrene or mineral wool-based counterparts is that the former is more hygroscopic, with a generally high moisture capacity. The study aimed to validate anecdotal experiences suggesting lower energy consumption in buildings insulated with bio-based materials compared to energy simulation models' projections. The focus was on understanding the role of latent heat and moisture transfer, particularly in hygroscopic insulation materials like cellulose, wood, or hemp fibre insulation. It is hypothesised that latent heat and moisture transfer from the higher hygroscopicity of bio-based insulation materials could account for the discrepancy between modelled energy needs and measured energy needs in the operational phase.

Using numerical simulations conducted in COMSOL, a model of an exterior wall assembly with hygroscopic insulation materials was created. Parameters such as moisture buffering capacity, insulation thickness, and indoor/outdoor climate variations were investigated. The output being evaluated was the heat flux through the wall from the interior side.

The study found that latent heat significantly influenced energy transfer in steady-state simulations. The results indicated that hygroscopic materials exhibited a potential for reduced energy needs for space heating, especially in scenarios with more significant temperature and humidity differentials between indoor and outdoor environments, as seen in Figure 33. Walls with higher insulation thicknesses and hygroscopic properties showed reduced heat loss, with some even exhibiting a net gain in heat energy.

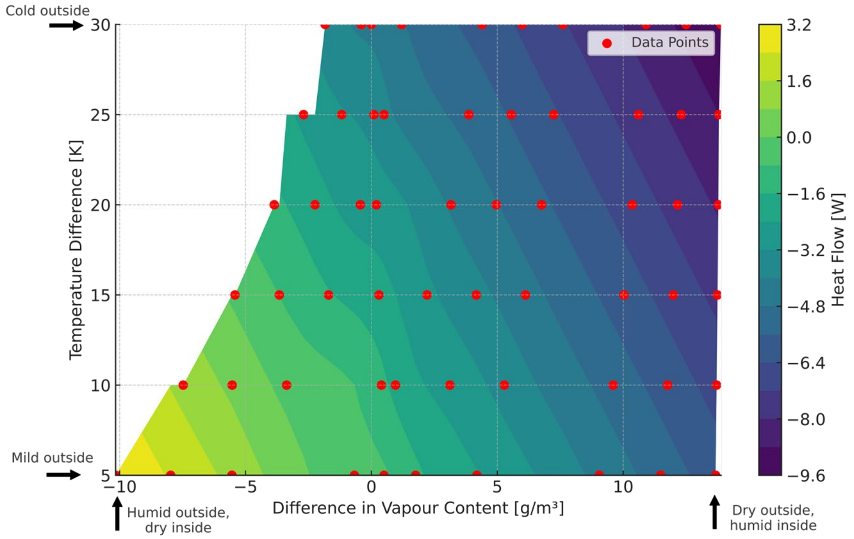

Figure 33: Summary of steady-state results from *Paper II* for an exterior ‘wall’ made out of 265mm insulation. Negative heat transfer is the heat going out through the wall. A negative difference in Vapour content means the vapour content is higher outside than inside. The temperature inside is constant at 21°C.

Dynamic simulations for different European cities further underscored the importance of considering latent heat in energy simulations. The study revealed that neglecting latent heat could lead to an underestimation of energy needs for space heating by approximately 30%. Additionally, an increase in hygroscopic properties of insulation materials was found to decrease heat flux, indicating potential energy savings. However, the study acknowledged limitations, such as static material parameters throughout simulations, which might not accurately represent real-world conditions where thermal conductivity can increase with higher moisture content. See Figure 34 for a summary of the dynamic simulations. The findings suggest that incorporating latent heat and moisture transfer considerations, particularly in hygroscopic insulation materials, can provide valuable insights for improving energy efficiency in building designs.

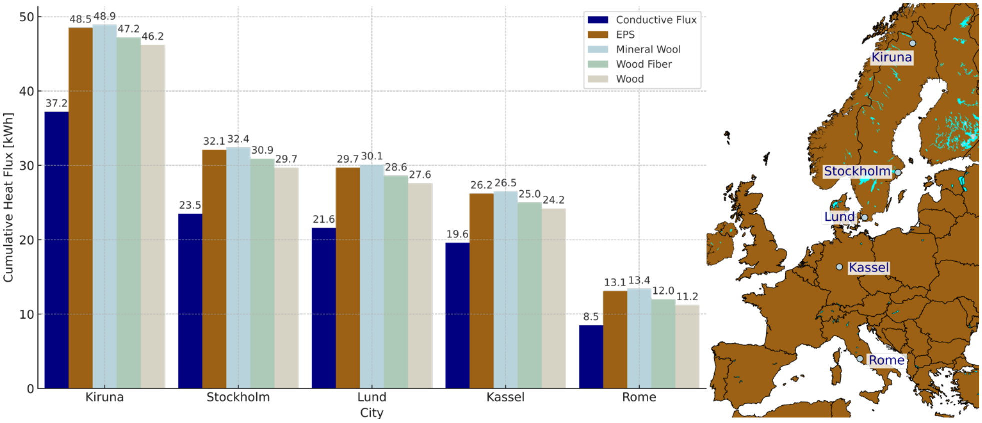

Figure 34: Summary of the simulations from *Paper II*, using climate data from different European cities. The heat flux presented is the cumulative heat flux over a year. The conductive heat flux (blue bar) is compared to the heat fluxes for the different materials in the Hygroscopic Porous Medium model. Note that the sorption properties were the only difference between the 'materials'.

Paper III – Hygrothermal properties and performance of bio-based insulation materials locally sourced in Sweden

This paper assessed the hygrothermal properties of three bio-based insulation materials: eelgrass, grass and wood fibre. All three materials have the potential to be locally sourced in Sweden. Stone wool was also included and used as a reference material. See Figure 35 for photographs of the four materials.

Figure 35: Samples of the insulation materials investigated in this paper. Clockwise, starting in the top left corner: eelgrass, grass, wood fibre, and stone wool (reference material).

Hygrothermal material properties were measured with dynamic vapour sorption (DVS), transient plane source (TPS), and sorption calorimetry. The insulation materials' moisture buffering was also assessed, and their thermal insulation capacity was tested on a building component level in the Hot Box developed in *Paper I*, which exposed the materials to a steady-state climate.

The results from the sorption test are shown in Figure 36. Sorption properties of bio-based insulation materials differ significantly from those of stone wool, and there is quite a large difference between them. In contrast, the moisture buffer value (data not shown here) was similar for all the bio-based materials, even if they had different sorption isotherms. This suggests that the sorption rate is as important a parameter as the sorption isotherms. Nevertheless, these findings contradict the sorption calorimetry test results (data not shown here), where the wood fibre showed a significantly lower sorption rate at lower relative humidity.

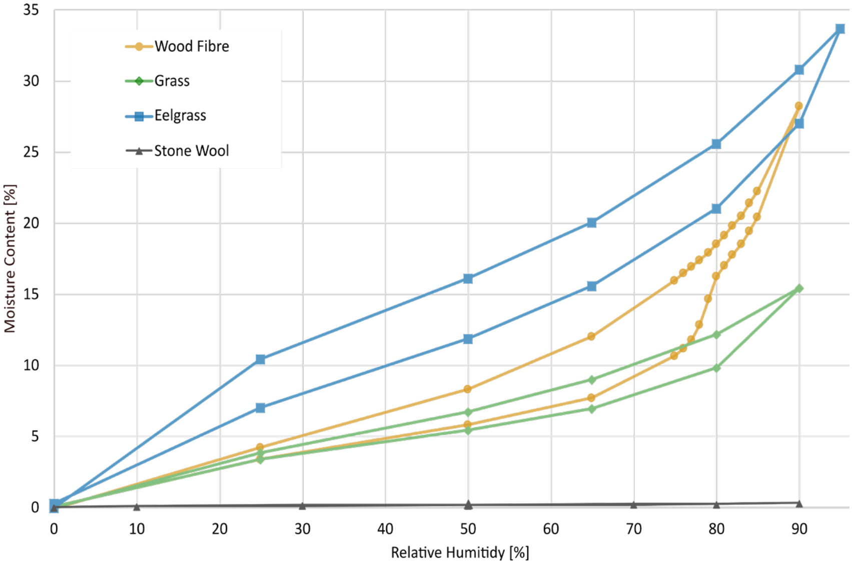

Figure 36: Sorption isotherms from the DVS. The lower curve shows absorption, and the upper curve shows desorption. Figure from *Paper III*.

The analysis of the thermal properties is shown in Figure 37. In the TPS test, all bio-based materials showed a higher thermal conductivity than the manufacturer declared, and the Hot Box experiments showed that the bio-based insulations have a very different insulating capacity than the one derived from the thermal conductivity. This reinforces the hypothesis that only measuring the thermal conductivity of hygroscopic insulations is not an accurate way of estimating their energy performance in a wall.

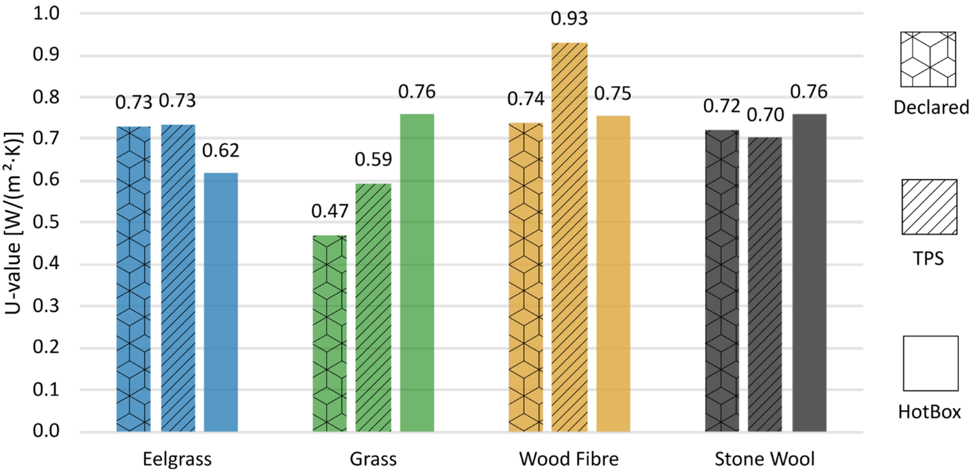

Figure 37: Comparison of thermal transmittance (U-Value) from the expected U-value from declared thermal conductivity, measured thermal conductivity from the TPS tests and the measured U-value from the Hot Box test. Figure from *Paper III*.

Seven hygrothermal properties (sorption isotherms, thermal conductivity, thermal diffusivity, volumetric heat capacity, mixing enthalpy, moisture buffer value, and U-value) of three novel bio-based insulation materials (eelgrass, grass, and wood fibre) and conventional mineral wool were measured in the laboratory. These results can be used as input for numerical simulations of the hygrothermal performance of buildings with bio-based insulation materials.

Paper IV – Assessing the Energy Performance of Wood Fibre and Mineral Wool Insulation through a Co-Heating Test

A paired co-heating test compared conventional mineral wool's performance with wood fibre insulation. Four walls, where one pair faced north and one pair faced south, were subjected to the Swedish climate over one year, with the only difference between the walls being the choice of insulation material (wood fibre or mineral wool). Despite the wood fibre insulation having higher thermal conductivity, the measured energy use within the pairs was similar, which shows that wood fibre insulation is feasible to use in modern construction from an energy point of view. Although on the south side, the wall with wood fibre insulation performed better than the wall with mineral wool insulation, on the north side, the opposite was found. This suggests that increased hygroscopicity provides bio-based insulation with very different energy performance and implies that significant diurnal changes play a role. Though numerical models did not satisfactorily replicate the experimental results in absolute numbers, the model developed in *Paper II* could capture the different trends. The results from *Paper IV* are summarised in Figure 38.

Experimental U-values were higher than the theoretical values across all wall specimens and insulation types, with the smallest discrepancy observed in the wood fibre insulation on the southern wall and the largest on the north-facing wall. Notably, the south-facing wood fibre insulated wall outperformed its mineral wool counterpart despite having a higher theoretical U-value, likely due to the advantageous hygroscopic properties of the wood fibre in conjunction with hygrothermal lag and latent heat. This beneficial effect was not observed on the north side, where conditions influenced by minor diurnal temperature variations and relative humidity changes approximated a steady state. The performance variation between the two insulation materials, where the wood fibre demonstrated superior results despite its higher declared thermal conductivity, suggests that hygroscopic insulation can effectively reduce space heating needs when appropriately utilised in mild temperate climates.

No apparent performance gap was found in the experiment, which strengthens the hypothesis that the residents' behaviour is the key to the performance gap. However, the lack of performance gap in this study could also be explained by building quality and good airtightness.

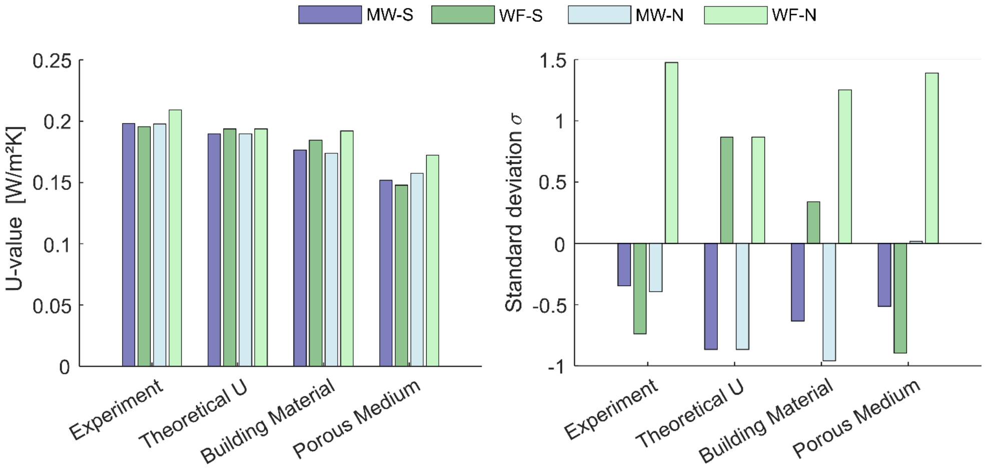

Figure 38: Comparative analysis of experimental, theoretical, and numerical results – insights into methodological variances. Standard deviations from the mean values highlight method discrepancies and trends within the results. MW-S: mineral wool facing south, WF-S: wood fibre facing south, MW-N: mineral wool facing north, WF-N: wood fibre facing north. Figure from *Paper IV.*

Although advanced energy models were found to be insufficient in accurately predicting energy use, the more advanced hygroscopic porous medium model did show the tendencies seen in the experiment. Therefore, the hygroscopic porous medium model has the potential to be used as a future tool for modelling hygroscopic insulation materials.

Finally, using wood fibre insulation in a code-fulfilling timber-framed stud wall that meets the Swedish building code (BBR) requirements is feasible as it performs similarly to its mineral wool counterpart. However, it is more complicated to accurately predict the hygrothermal performance of walls with wood fibre insulation compared to walls with mineral wool.

Commentary and Discussion

Paper I

Many of the anecdotal examples of bio-buildings using less energy than designed originate from homeowners or material manufacturers, which, from a scientific point of view, carry little weight. *Paper I* aimed to develop a test setup for dynamic conditions. Before testing, the idea was to test different climates to investigate any potential discrepancies found between theoretical values and the value obtained from the Hot Box. However, disagreements between conductivity measurements and Hot Box measurements were already found in steady-state conditions for wood fibre insulation. Still, as the study aimed to develop a Hot Box that could handle dynamic conditions, they were naturally added to the paper. The dynamic outdoor climate with diurnal changes did not result in apparent differences in performance compared to the steady-state Hot Box test for the included materials. In hindsight, dividing the dynamic part into a 'humidity' and 'temperature' test complicated things without adding value. The 'dynamic temperature' experiment was practically a test of hygrothermal mass, and the humidity test was a stress test for the climate cabinet. In reality, temperature and relative humidity are always correlated. A drop in temperature will increase relative humidity. The humidity test was also done around 0°C, where the amount of vapour in the air is meagre, so the theoretical difference in vapour content was 4.6g/m^3 (95%) and 2.42g/m^3 (50%). In the test, the climate chamber had difficulty regulating humidity at low temperatures, making the practical difference even lower than the theoretical.

Paper I mentioned the connection between the metering box and climate cabinet as a point of improvement. This was improved to some extent by adding a layer of flexible polyurethane foam around the opening, and the leakage was reduced in future testing, including *Paper III*. The heat-loss-coefficient for the setup was 3.05 W/K in *Paper I* and 2.29 W/K in *Paper III*, a reduction of 25%. *Paper I* also discusses the difference in air tightness between the materials, which added an unnecessary parameter. For *Paper III,* the tested materials were fitted with an exterior wind barrier to reduce this uncertainty. The improved connection and the wind barrier on the specimen also remedied the problem of slightly drifting humidity on the exterior side, seen in *Paper I* but not in *Paper III.*

Paper II

Early data from what would become *Paper IV* showed inconsistent results, where the biobased wall performed better than the mineral wool counterpart on the south side, where the opposite was found on the north. This inconsistency or uncertainty in the results made it necessary to compare them with some numerical tool. With the background explained in ‘Bio-based Insulation‘ and the uncertainty regarding the thermal performance of biobased materials, a search for a numerical model began. The existing models and software often have a minimal equation editor, if accessible at all. The testing of different modelling environments and programs eventually developed into *Paper II.*

Paper II partly uses the COMSOL module “Building Material” and partly the module “Hygroscopic Porous Medium.” Both model versions were benchmarked against one of the most used commercially available software, WUFI, with a non-hygroscopic insulation material. This was a time-efficient way of benchmarking, as WUFI has been the target of numerous ‘reality checks’, e.g. [190–195]. Regardless, the developed model should have been verified using measured data. The model's poor fit in *Paper IV* is likely due to the lack of fine-tuning. Yet, for a blind evaluation, the developed model predicted the trends in the result accurately. This suggests that the *Paper II* model could be developed further to make accurate predictions of the energy performance of hygroscopic walls.

Furthermore, changing just the sorption isotherm for the insulating materials is only possible in numerical models. Comparing the methodology in *Paper II* with the measured data in *Paper III* or from the literature, it is apparent that other parameters, such as porosity, thermal conductivity, or heat capacity, will naturally change when using actual materials.

The model in *Paper II* assumed direct contact with the air on both sides of the insulation, which in reality would not be the case as typical walls usually consist of several layers, often a vapour barrier on the interior and a weather barrier on the exterior side. However, this is precisely how the materials in *Paper I* were tested, which partly could explain the results found there. *Paper II* showed the potential of latent heat in a steady state when a moisture gradient was present, and *Paper I* showed that the most hygroscopic material had the lowest U-value. This was also somewhat seen in *Paper III*, even though the specimens had an exterior weather barrier.

Figure 39 shows a simple experiment that practically indicates the potential of latent heat and hygrothermal lag. Two specimens of mineral wool and wood fibre insulation are conditioned at 15°C and 30% relative humidity in a climate room before being subjected to a drop in temperature, which correlates with a spring/autumn night. The materials are the same as the ones used in *Paper III*, with the mineral wool having a lower thermal conductivity and volumetric heat capacity. Still, even if the material has some differences in properties, it is as close to the *Paper II* situation as is practically feasible. The experiment shows that the mineral wool specimen drops in temperature faster than the wood fibre specimen. It is important to note that the wood fibre would remain colder for longer in the case of a temperature increase and drop in relative humidity.

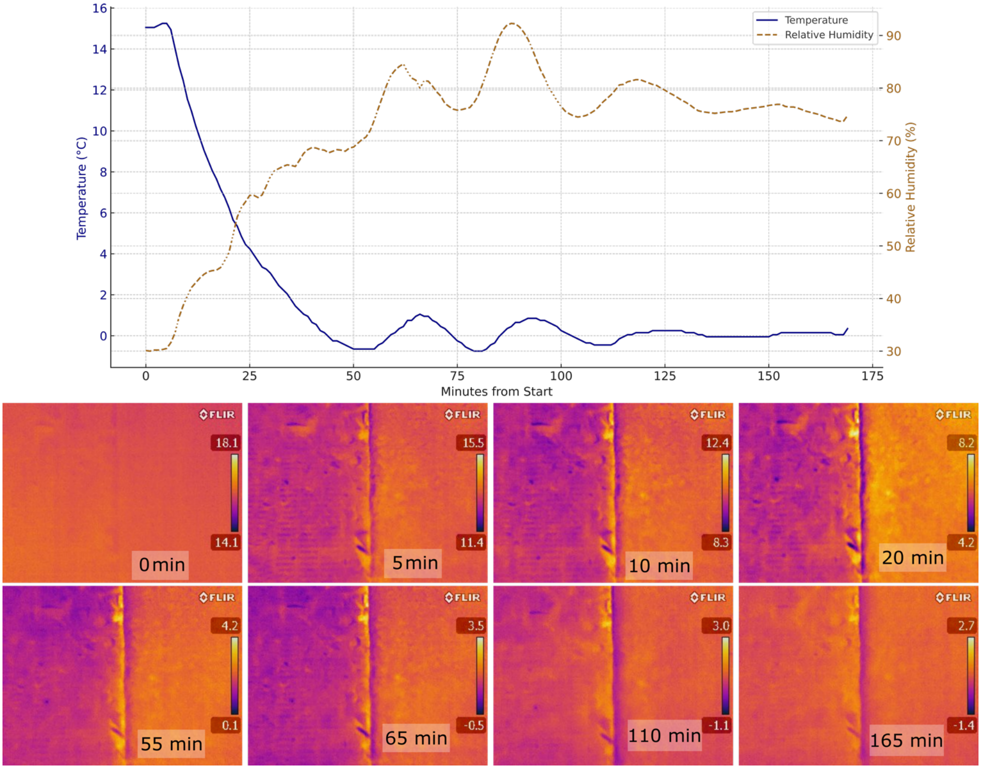

Figure 39: A simple experiment with a thermal camera and a climate room shows a mineral wool (left) and wood fibre (right) specimen conditioned at 15°C and 30% relative humidity being subjected to a sudden drop in temperature. The climate room was set to 0°C and 90% relative humidity (practically, it cannot control humidity below 10°C). Values on the pictures indicate when the thermography is taken.

Paper III

Papers I and *IV* tested the performance of wood fibre insulation and investigated the hygrothermal performance of other non-biomaterials, leading to the conceptualisation of *Paper III*. As there are many more bio-based insulation materials than wood fibre, the choice of materials in *Paper III* was consciously made to achieve a spread of other biological raw materials.

From *Paper III,* the most noticeable result was how much more hygroscopic the tested bio-based insulation materials are than stone wool. The three different bio-based insulation materials have significant differences in the sorption isotherms and substantial differences in their hysteresis. As *Paper II* shows, these differences in sorption properties greatly influence energy performance. This is necessary to consider in future models, as most models only have one sorption curve per material and do not model hysteresis, which is required [130,196]. Also, comparing the DVS and MBV tests from *Paper III*, it is clear that equilibrium is not reached after 8 hours. In numerical software, such as in *Paper II*, porous materials like those in *Paper III* would condition very fast (typically twice as fast), highlighting the increased complexity of hygroscopic insulation materials. The lack of differentiation between sorption and desorption would be extra noticeable for a material like the wood fibre from *Paper III*, where the effect of the fire-retardant salt on the isotherm is noticeable. The increased absorption isotherm could not be seen as a corresponding decrease in the desorption. This added salt also made the conditioning before the tests complicated, as too high of a drying temperature, the sorption properties would change. This is likely what is seen and commented on in *Paper I*, even though the materials were from different manufacturers.

For the sorption calorimetry in *Paper III*, the wood fibre sample could not be measured at lower relative humidity, as it absorbed moisture slowly. This effect is not seen in the moisture buffer tests, which start at 33% relative humidity. The reason is that the sorption calorimetric method does not work well with samples with ‘delayed sorption’ [197]. It is uncertain if this is the case in *Paper III*, as ‘delayed sorption’ is assumed negligible for finely divided materials. Still, the wood fibre insulation gave odd results, indicating delayed sorption, possibly related to the so-called non-Fickian behaviour seen in many studies using wooden materials [198,199].

For the eelgrass insulation in *Paper III*, there was an apparent difference in density between the sides, likely from the manufacturing process where heat is applied on one side in the press. This highlights the importance of quality control, as the reference group and industry generally care about the characteristic value. Speculatively, quality control is even more critical when using non-synthetic raw materials as the variation in the production is likely more significant. This might partly explain why the manufacturer's values and the measurements in *Papers I* and *III* differ.

The difference between the TPS tests in *Paper I* and *Paper III* is the conditioning of the specimens and the conditions during the experiments. In *Paper I*, the materials were conditioned and tested in laboratory conditions. In an additional test series, the bio-based insulation was dried at 105°C and placed in a plastic bag during testing. For *Paper III*, the specimens were dried at 60°C in a vacuum oven and tested at very dry conditions. However, the results from the TPS tests between the papers are similar. Note that the insulations tested in the papers are not exactly the same type, even though the raw materials are the same (for wood fibre and stone wool).

In *Paper III,* TPS experiments were conducted in a ‘dry box’ to maintain stable conditions, but conditions varied slightly. The drying agent was placed in the box with the sample, leading to a systematically higher relative humidity in the last measurement series than in the first. However, no systematic trends in the results could be seen due to this. Of curiosity, the wood fibre specimen was kept in the ‘dry box’ after the planned measurements without replacing the drying agent, leading to increasing relative humidity. Continuous measurements were taken during this time, which are shown in Figure 40 and Figure 41. Just before the last measurement (repeated three times), a glass of water was placed, and there was some deliberate spillage in the ‘dry box’. The extra tests were not intended to be included in *Paper III* as it was more of a curiosity test and should not be interpreted as a scientific experiment. For instance, the sensors were not moved after any of the tests as described in *Paper III*. Regardless, the data shows more significant differences compared to previous research [137–140]. This showcases the influence of the hygroscopic behaviour on energy performance, where noticeably, the same heating effect leads to different increments in temperature (higher thermal conductivity) in the TPS tests.

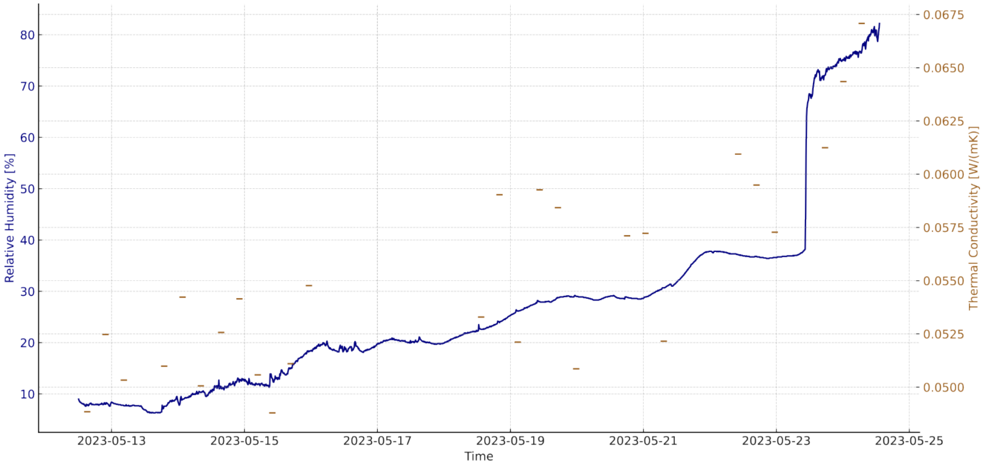

Figure 40: Relative humidity (blue curve) in the 'dry box' during the testing of wood fibre insulation in *Paper III* and the following period. Thermal conductivity measurements at the corresponding time (bronze markers). Note that the measurement time has been exaggerated by ×10 to be visible in the figure.

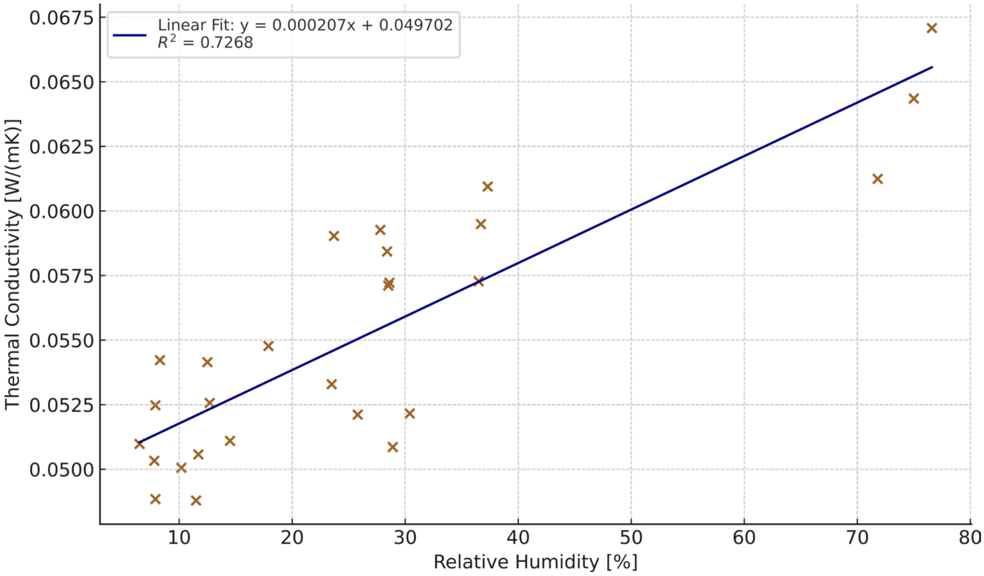

Figure 41: Scatter plot of the simple experiment done immediately after measurements of *Paper III*, including a linear regression. The linear regression shows somewhat higher thermal conductivity values than those of previous research. However, note that the experiment is more exploratory rather than investigative.

The manufacturers' declared thermal conductivity is compared to the results from the TPS and Hot Box experiments using the standard method of calculating an expected U-value from the thermal conductivity [200]. For both *Papers I* and *III,* the TPS test's thermal conductivity accurately assesses the insulating capacities of the non-hygroscopic materials, which is not the case for the more hygroscopic bio-based insulation materials. There is a significant difference between the thermal conductivity and the measured U-value. The wood fibre in *Paper I* and eelgrass and wood fibre in *Paper III* perform significantly better in the Hot Box compared to that derived from the thermal conductivity measurements. However, unexpectedly, the opposite is found for the grass insulation. The calibration test was done with the stone wool insulation, and with the grass specimen being almost twice as thick, the leakage and the resulting U-value are likely overestimated. Using the same or similar thicknesses between material specimens would have reduced this uncertainty. Comparing the Hot Box experiments from *Paper I* and *III, Paper I* shows lower U-values for stone wool and wood fibre. This is partly due to the different areas used. *Paper I* uses the exterior area, whereas *Paper III* uses the internal. Also, note that the tested materials are different even though they are called the same in the papers.

Paper IV

In *Paper IV*, experimental results showed somewhat higher U-values than the theoretical U-values, which is in contrast to *Papers I* and *III* and also to previous research where uninhabited test houses often showed a lower U-value in-situ than theoretical, independent of insulation material [113,138,176,201]. The lack of interior moisture is similar to those studies and the experiments conducted in *Papers I, III, and IV*.

The southern wall with wood fibre insulation performed the best in the experiment, even though the wood fibre insulation had a higher declared lambda-value than the mineral wool insulation. Both the materials tested in *Paper IV* are from the same batch as the stone wool and wood fibre used in *Paper III*, and the difference in measured thermal conductivity is even more significant.

This difference could be due to the hygrothermal lag or latent heat in connection with solar radiation working beneficially within the wall and reducing the heat loss through it, as seen in previous research where a lower U-value was found for a bio-based wall in dynamic conditions [202]. *Paper IV* focused primarily on the aggregated performance over the entire duration of the co-heating period. Detailed analysis of diurnal fluctuations could help explain some of the findings. For example, there are periods with a notable difference in time between the heating peaks for the two southern specimens (MW-S and WF-S). Here, the bio-based wall specimen has a longer time between the coldest temperature and the daily 'peak' energy use than the mineral wool specimen, indicating a more extended time constant due to hygrothermal lag. This effect is most noticeable when there is a considerable temperature difference between night and day. However, this effect is not statistically significant over the entire heating period and is practically not seen on the northern side. Figure 42 shows the specimens during the first week of March, where there are large differences in temperature night and day, and where this difference in hygrothermal lag and contribution of latent heat is very noticeable on the southern wood fibre specimen. Figure 43 shows the specimen during the first week of January when the difference between night and day is negligible. Furthermore, with the colder temperatures, the air holds significantly less vapour, leading to a lower potential of hygrothermal lag and latent heat, which could explain the results. A definite answer is complicated, as this behaviour was not statistically significant for the entire period. Additionally, moisture transport in insulation materials is complex. Some studies even show contradictory drivers of moisture, e.g., temperature, not relative humidity [203].

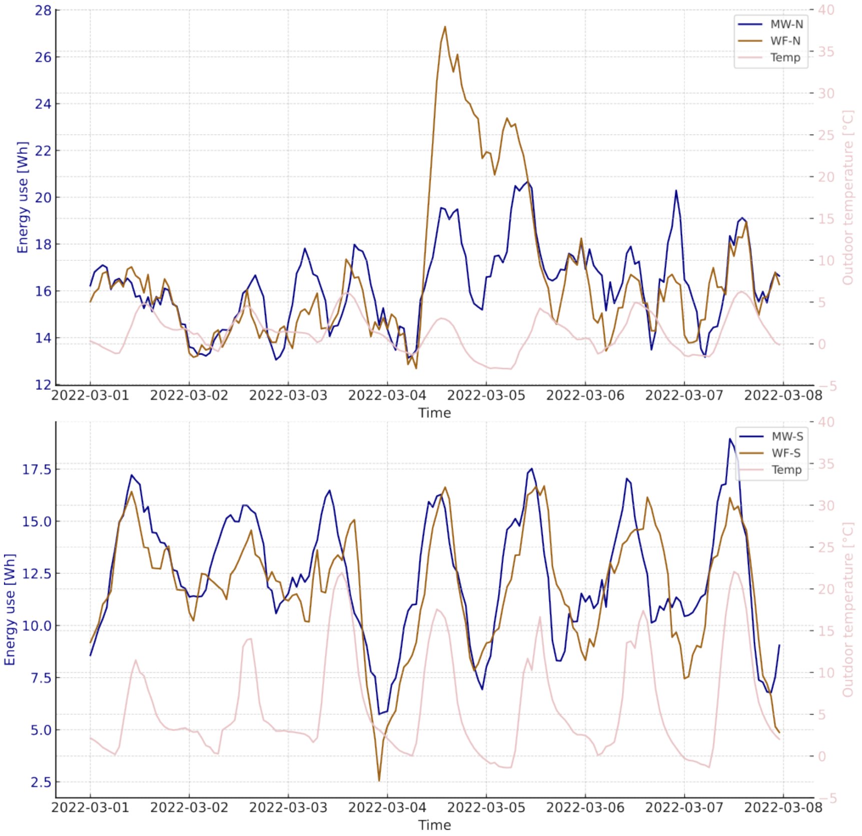

Figure 42: Plotted is the 6-hour moving mean of the calibrated energy used during a week during spring with fluctuating climate and significant differences between day and night. The northern specimens are on top (MW-N and WF-N), and the southern specimens are below (MW-S and WF-S). Notice the difference in temperature on the two sides and the time of the peak in energy use of the two walls.

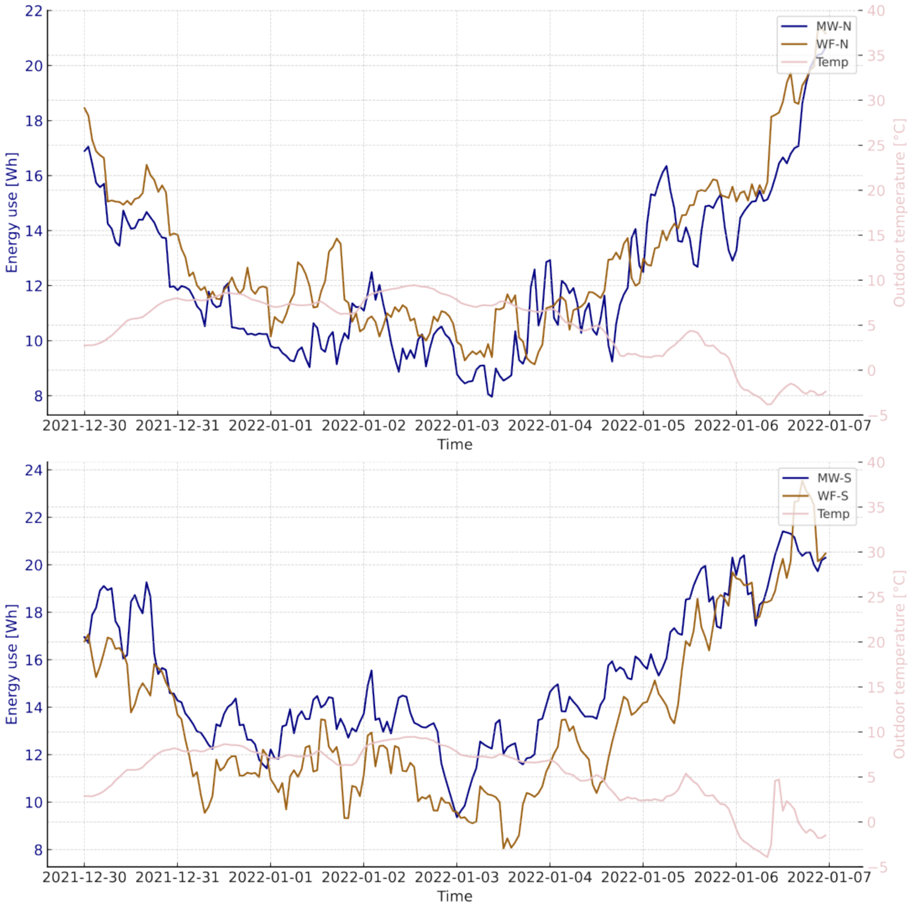

Figure 43: Plotted is the 6-hour moving mean of the calibrated energy used during a week during winter with steady climate and minor differences between day and night. The northern specimens are on top (MW-N and WF-N), and the southern specimens are below (MW-S and WF-S). Notice the difference in temperature on the two sides.

The numerical models could have fitted the experimental results better, even for a blind evaluation. One reason for this is that the models only consider material data from data sheets, and minor variations in material data significantly impact the result [204]. This difference would be even more significant if the data from *Paper III* were used instead, especially for the wood fibre insulation.

However, when looking at the trends, the hygroscopic porous medium model appears to be most similar to the experimental results: the wall with wood fibre insulation facing south has the lowest U-value and wood fibre facing north having the highest, with only minor differences between the two mineral wool walls. The difference between the theoretical U-value and the measured in-situ is typically assumed to be 20% larger than in-situ. This is supported by several studies [205] that found a 17% difference in the U-value between the Heat Flow Meter and co-heating test and an 18.5% difference between modelled or measured U-values [206]. If that ‘in-situ factor’ had been added to the model results, the model from *Paper II* would have had the best fit for the experimental results.

With some fine-tuning and model verification, the hygroscopic porous media model could be a promising alternative to conventional models for assessing the hygrothermal behaviour of walls with hygroscopic insulation. However, in this study, when analysing absolute values, the model performed worse than the theoretical values based on a steady state. When analysing the numerical results during shorter periods, it was evident that the models react faster to changes in climate than the experiment. This could partly be because the model domain is limited to the specimen and does not include the thermal cell. Also, the model was a blind evaluation with no retroactive model fitting, meaning that the result depends on accurate input and assumptions.

Differences in areas and air leakage for the thermal test cells were considered in the calibration test and the weight factor. The calibration test was conducted over a month, and preferably, it should have been longer, as sufficient time is vital to assess buildings with a large thermal mass [207]. An alternative to triangulate the leakage would be to do the same as in *Paper I* and also add a calibration test where the leakage is even more significant. This could have been done by turning the radiators off in the test house and increasing the gradient over the test cells.

Conclusions

Paper I

A Hot Box test setup was developed using an insulated metering box and a climate chamber. The climate chamber allows for the simulation of different outdoor climates in terms of temperature and humidity. Three materials were benchmarked under steady-state conditions: Mineral Wool, XPS and Wood Fibre insulation. The non-hygroscopic materials strongly agreed with the thermal conductivity obtained through a TPS apparatus (HotDisk). However, the correlation is weaker for wood-fibre insulation, likely due to factors other than the thermal conductivity that affect the insulation's capacity. The wood fibre insulation showed a significantly lower U-value when tested in the Hot Box compared to that derived from its thermal conductivity.

Paper II

Latent heat and its influence on heat flux were studied using a numerical model that integrates heat and moisture dynamics within a finite element software. The behaviour of a wall that allows for diffusion was analysed under steady-state conditions, with varying humidity levels both outside and inside. The findings indicate a substantial beneficial heat gain from latent heat in reducing heat flux from the interior side of the wall during ‘cold climate’ steady-state conditions. However, latent heat consistently increased heat flux in year-round simulations under realistic conditions compared to purely conductive heat flux. This phenomenon could contribute to the often-observed discrepancy between predicted and actual energy usage in buildings. Additionally, due to its hygroscopic properties, wood fibre insulation could reduce heat flux by about 10%, potentially more with increased interior moisture. These results suggest that appropriately using hygroscopic insulation materials can lead to energy savings.

Paper III

Seven hygrothermal properties (sorption isotherms, thermal conductivity, thermal diffusivity, volumetric heat capacity, mixing enthalpy, moisture buffer value, and U-value) of three novel bio-based insulation materials (eelgrass, grass, and wood fibre) and conventional mineral wool, were measured in the laboratory. These results can be used as input for numerical simulations of the hygrothermal performance of buildings with bio-based insulation materials.

The measured sorption properties of bio-based insulation materials differ significantly from those of stone wool and among the different bio-based materials. However, the moisture buffer value was similar for all the bio-based materials, even if they had different sorption isotherms. This suggests that the sorption rate is a more critical parameter than the isotherms in building applications, especially regarding diurnal changes. This is inconsistent with the sorption calorimetry test, where the wood fibre showed a significantly lower sorption rate at lower relative humidity.

In all the TPS tests, bio-based materials showed a higher thermal conductivity than the manufacturer declared. The Hot Box experiments showed that bio-based insulations have a very different insulating capacity than those derived from thermal conductivity. This highlights that only measuring the thermal conductivity of hygroscopic insulations is not an accurate way of estimating their thermal performance in a wall. In contrast, the Hot Box results correlated well with the U-value derived from the thermal conductivity measurements for the non-hygroscopic synthetic insulation.

Paper IV

In full-scale tests, the U-values were higher than the theoretical values for all wall specimens and insulation types. The smallest difference between the experimental and theoretical U-values was for the wood fibre insulation in the southern wall, and the largest was for the wood fibre insulation facing north. On the south-facing side, the specimen with wood fibre insulation performed better compared to the wall with mineral wool, even though it has a higher theoretical U-value. This effect is not seen on the north side. This could be due to the hygroscopic properties of the wood fibre insulation. On the South side of the building, the heat loss was smaller due to the hygrothermal lag and latent heat together with solar radiation. The opposite was seen on the North side, where the diurnal changes in temperature difference and relative humidity changes were smaller, and the situation was closer to a steady state. Thus, hygroscopic insulation could positively influence the amount of space heating required when used correctly in mild temperate climates.

Although advanced energy models were found to be insufficient in accurately predicting energy use, the more advanced hygroscopic porous medium model did show the tendencies seen in the experiment. Therefore, if improved further, the hygroscopic porous medium model has the potential to be used as a future tool for modelling hygroscopic insulation materials.

General conclusions

With the results from this thesis, it is clear that bio-based insulation materials perform differently in actual buildings than just deriving the U-value from thermal conductivity. In most cases, bio-based insulation performs better than predicted in the case of ‘cold climates’, although this is not always true. As thermal performance is the most critical property of insulating materials, the results from this thesis can further promote the use of bio-based insulation materials. This will help the industry reduce its carbon footprint in their coming climate declarations while still building energy-efficient buildings.

Finally, using wood fibre insulation in a code-fulfilling timber-framed stud wall that meets the Swedish building code (BBR) requirements is feasible as it performs similarly to its mineral wool counterpart. However, it is more complicated to accurately predict the hygrothermal performance of walls with wood fibre insulation compared to walls with mineral wool. Furthermore, a practical conclusion from the industry is that bio-based insulation's general uncertainty must be reduced before a large-scale implementation. This is especially important regarding diffusion open walls and moisture safety.

Ongoing and future research

Several companies within the reference group have built houses with different bio-based insulation types and ongoing building envelope monitoring during the project (see Figure 44). These results will be analysed further and are intended to be used as the ‘true’ value for a blind evaluation round-robin. This round-robin will hopefully give valuable insight into different numerical models and how to improve their accuracy.

Figure 44: Wall element insulated with cellulose loose-fill for a test house by DEROME/A-hus.

As numerical models become more complex, it is essential to investigate which parameters to include. Including both the sorption and desorption curves, with some hysteresis model, will likely improve the accuracy of most software when assessing bio-based insulation. However, this is very complex and not yet fully understood [208]. Furthermore, more material data is needed if models require more input, especially sorption measurements for more materials. A test house built by OBOS/Myresjöhus with sensors and different types of insulation between the studs presents an excellent opportunity to see how accurate numerical software is. Material parameters can be tested in the laboratory to the extent needed, and measured values could be compared to those obtained by simulation. One wall with different insulation materials (wood fibre, hemp, and stone wool) is shown in Figure 45.

Figure 45: Wall for a test house built by OBOS/Myresjöhus. The insulation type (stone wool, hemp, and wood fibre) varied within the same wall element. Temperature and humidity sensors were built into the wall and will be monitored during the building's first years.

A limitation in this thesis was that the developed model kept all material parameters static throughout the simulation. The model achieves increased thermal conductivity with higher relative humidity because the pores have a higher vapour content. However, most bio-based materials have some moisture uptakes within the cell structure, likely changing the material's thermal conductivity. This would be interesting to study further. Also, the vapour resistance factor of materials influences heat transfer [209]. Depending on the hygroscopicity of the insulation material, this effect could be very different, which would be interesting to study further.

The wood fibre sample could not be measured at lower relative humidity for the sorption calorimetry, as it absorbed moisture slowly. This effect is not seen in the moisture buffer tests, which start at 33% relative humidity. It would be interesting to study the sorption rate for different materials at lower relative humidity and correlate it with vapour permeability.

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