Building Materials in the Operational Phase

Impacts of Direct Carbon Exchanges and Hygrothermal Effects

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Summary

How sustainable are the various building materials, and what are the criteria for assessment? The scope of this article is to explore in what ways responsible and conscious use of materials can yield environmental benefits in buildings. In particular, it discusses how material properties related to thermal and hygroscopic mass can be utilized for achieving energy efficiency and good indoor air quality, and how these gains can be included into the context of life cycle assessment (LCA).

A case study investigates and compares carbon impacts related to three design concepts for an exterior wall: (A) concrete/rock wool; (B) wood studs/wood fiber; and (C) wood studs/hemp lime. The thermal performance of concepts B and C are modeled to comply with concept A regarding both thermal transmittance (U-value) and dynamic heat flow (Q_{24h}) using the design tool WUFI Pro. An environmental cost-benefit analysis is then accomplished in four steps, regarding (1) manufacturing and transport loads, (2) carbon sequestration in plant-based materials and recarbonation in concrete/lime, and (3 and 4) potentially reduced operational energy consumption caused by heat and moisture buffering. The input data are based on suggested values and effects found in the literature.

The summarized results show that wall A has the highest embodied carbon and the lowest carbon storage and recarbonation effects, whereas wall C2 has the lowest embodied carbon and the highest carbon storage and recarbonation effects. Regarding buffering effects, wall A has the highest potential for thermal buffering, whereas wall C has the highest potential for moisture buffering.

Introduction

Environmental Assessments of Building Materials

Building materials and components are usually assessed on a cradle-to-grave basis, evaluating the environmental impacts from extraction, production, transport, waste handling, and, eventually, also maintenance and replacements in the service life of the building. Life cycle assessments (LCAs) deal with calculating the impacts throughout the life cycle and may also include energy consumption during occupancy. Thereby, it is possible to estimate and compare impacts from materials as well as operational issues in the different phases of a building's life. In Norway, current tools for benchmarking of buildings include Statsbyggs Klimagassregnskap (carbon calculator by the Norwegian Public Construction and Property Management), limited to assessing greenhouse gas (GHG) emissions, and BREEAM NOR, the Norwegian version of the UK Building Research Establishment Environmental Assessment Method (BREEAM) using ten evaluation criteria.

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Impacts from materials are less understood and reflected in building legislation than impacts related to energy consumption, but responsible material use can yield great benefits (Hammond and Jones 2008). LCA studies show that, in parallel with increased building standards, a shift in the importance of life cycle phases is in change (Thormark 2002; Blengini and Di Carlo 2010). Thus, to continue environmental improvements in the built environment, it is imperative to not only design buildings for energy efficiency, but also to anticipate the development of low-carbon building materials that can replace high-impact counterparts.

Measures related to materials can generally be more robust in mitigating climate change than those facilitating energy efficiency because they achieve results in the present instead of postponing the effects into an uncertain future. A report by the Center for International Climate and Environmental Research in Oslo "Why Delaying Climate Action Is a Gamble" states that, for a given temperature target, if we decide to delay emissions reductions, we must be willing and able to undertake much more substantial emission reductions than with early action. In fact, probably delaying action will put some of the lower long-term temperature targets out of reach (Kallbekken and Rive 2005). The impact of carbon reductions today is considered more valuable than possible reductions later, and thus savings of the present material supply may become a more important step in climate mitigation than savings of future energy supply. Indeed, carbon savings achieved by substituting materials work independently of the frequency of use and also independent of user involvement in the operational phase. Recent studies show that there are considerable deviations between thermal modeling and actual energy use in low-energy dwellings (Gram-Hanssen 2010; Langseth et al. 2011), thus reflecting that user behavior can undermine technical performance estimated in energy balance calculations. Also, future changes caused by new users or user needs causing rebuilding or demolition and new-build may appear earlier than expected, so that investments in energy-efficient building envelopes and equipment may not reach their payback time. The choice of low-impact building materials are independent of these issues and will save carbon, disregarding eventual poor building energy management, change of use, or obsolescence.

LCA can be a useful tool in comparing buildings from a top-down perspective and in assessing which life cycle phase is important. The results can give valuable information with regard to development of green buildings and legislation. However, although a range of tools for assessment have been developed internationally, there is no overall agreed baseline of information of what should go into an LCA regarding materials contributions. This can be an advantage for manufacturers of building materials, because environmental arguments can be suited to fit the beneficial properties of their specific product.

Direct Exchanges with Carbon

A discussion that is difficult to settle is whether or not wood and other crop-based materials should be credited for carbon sequestration. Crops need carbon dioxide (CO_2) for their growth and thus act as carbon reservoirs until the material burns or decomposes, and as much as 1.8 kilograms (kg) of CO_2 are transformed and stored in 1 kg of dry wood (Berge and Stoknes 2004).[1] This uptake should, however, be considered in the broader context of land use and forestry. The United Nation Framework Convention on Climate Change (UNFCCC) has, for many years, discussed harvested wood products (HWPs) as a mitigation option. In the Durban 2011 meeting, it was decided to include HWPs in national reporting from 2015 (FCCC 2012). It is here recommended that storage of carbon in forest products be included in a national inventory only where a country can document that existing stocks of long-term forest products are, in fact, increasing (UNFCCC 2003). In Norway, this is definitely the case because the annual growth is about three times the annual removal (Statistics Norway 2010). The methodology for reporting is not yet decided, but different models and approaches are discussed (Bache-Andreassen 2009). It becomes clear that if carbon sequestration is taken into account in the assessment of building materials, it can play an important role. In the *Green Guide to Specification*, underpinning BREEAM in the UK, carbon sequestration is accepted for plant-based materials (Doran and Anderson 2011), but in the Norwegian assessment tools for materials such as EcoProduct, underpinning BREEAM NOR, it is, so far, neglected.

Also, other materials have chemical exchanges with carbon. Cement and limes emit CO_2 during the calcination process in manufacturing, but later reabsorb carbon in their life cycle. How much carbon reacts with the casts, blocks, mortars, and plasters depends on the material composition and on the exposure to air (Pade and Guimaraes 2007). About 40% of the CO_2 emitted in the calcinations process during the production of cement can potentially be reabsorbed (Paine 2011), whereas, for the more porous limes, the maximum uptake can be 75% to 80% (Berge 2009; Lawrence 2011). Demolition and recycling generally lead to greater exposure to air, eventually causing the materials to achieve their full potential of recarbonation. These processes can be seen as positive contributions to climate mitigation as they "neutralize" negative impacts from manufacturing. Although the carbonation process in concrete traditionally is regarded as unwanted because it deteriorates the steel reinforcement normally embedded in concrete, it is now also highlighted as a life cycle benefit (see, e.g., Engelsen et al. 2007; Norcem 2012).

Design Issues

An LCA cannot give a full evaluation of each specific building's environmental performance because it uncovers little of how they are designed and used. A host of design issues are of importance for a building's life cycle load. Regarding energy use, passive design principles, such as area efficiency, flexibility, and climate adaptation, are important in curbing a buildings energy demand for heating and cooling, but these effects will not be reflected through energy modeling. Regarding material use, detailing to avoid moisture deposits and condensation will lead to better performance and durability of materials, and further, possibilities for extended use of components can be obtained through facilitating for reuse or recycling. However, none of these issues can be easily quantified in terms of environmental impact.

During the use phase, utilizing the operational qualities of each material can also lead to high environmental performance. Obviously, insulation materials safeguard high thermal resistance of the building envelope and will thus reduce heating needs. But, in addition, materials' heat and moisture capacities can help in buffering thermal and damp loads and thus lead to reduced need for heating, ventilation, and air-conditioning (HVAC) systems. These last points call for a holistic understanding of building physics and material mechanics to be pursued by the design team.

Need for Holistic Understanding

Although building materials are commercially promoted by pointing out various life cycle exchanges with carbon as well as highlighting their beneficial operational qualities, there is no consensus on how to include these effects for assessments. This lack of standardization may lead to confusion and misleading guidance. A recent investigation report about carbon assessments of buildings and building materials for the Norwegian Ministry of Local Government and Regional Development concludes that there is no evidence for prioritizing one building material to the other regarding environmental impacts (Rønning et al. 2011). In spite of the fact that a number of studies, as well as the carbon inventory of *Statsbyggs klimagassregnskap*, demonstrate great differences in manufacturing loads, it is assumed that that the negative impacts in production may be compensated for in the life cycle due to life cycle effects, such the use of thermal mass. The natural following question is how the benefits of building materials' various properties can be quantified and compared. We need more knowledge about how materials contribute in the operational phase and about how to integrate these effects in LCA models.

Functional Units

When comparing the sustainability of various building materials, a first-hand principle is to keep track of what the materials are actually used for. It is necessary to look beyond the cradle-to-gate inventories that show the impact of production per kg and introduce a functional unit for each service, where the impact per *desired effect* is given. According to a text book on the Ecology of Building Materials (Berge 2009), building materials can be broadly divided into three groups according to their intended use, which are structural materials, sheeting materials, or climatic materials that modify heat and moisture transfer.

Structural and Sheeting Materials

Structural materials provide structural support for the building through foundations, walls, and roof. The main function is to transfer external loads to the ground without material decay. Various structural materials have different designs for the components decided by their inherent properties. However, the interesting question with regard to LCA is not the design of the component or its mass, but the environmental load per service unit. In a report by the Norwegian Institute of Wood Technology (NTI), the energy use consumed to produce a primary beam per square meter (m^2) of covered floor space was assessed (NTI 1990). Table 1 shows the result. The impact varies between 24 kilowatt-hours (kWh)/m^2 for a beam in timber lattice and as much as 600 kWh/m^2 for a beam in aluminum extracted from ore.

Table 1 Embodied energy of different structural materials, related to energy consumption given in kilowatt-hours per square meter (kWh/m^2) covered floor area

Structural materials	*Embodied energy kWh/m^2 covered area*
Timber lattice	24
Laminated timber	30
Concrete	75
Steel	155
Aluminium (from ore)	600

Note: One kilowatt-hour (kWh) $\approx 3.6 \times 10^6$ joules (J, SI) $\approx 3.412 \times 10^3$ British Thermal Units (BTU). One square meter (m^2, SI) $\approx$ 10.76 square feet (ft^2).
Source: NTI 1990

Sheeting materials provide protection and add finish to structural and climatic materials. The service of sheeting and boards will depend on the desired properties, such as vapor permeability, air tightness, and visual appearance. Thus, the functional unit will reflect environmental load per m^2 of surface with a certain property according to specification.

Climatic Materials

The term climatic materials denotes a group of materials that modify the climatic conditions in a building regarding air, noise, heat, and moisture. Thermal insulation in the building envelope typically reduces heating needs and is thus important for curbing operational energy use. However, various insulation materials have quite different environmental loads in their life cycle, and the literature shows great differences between the alternatives when comparing the material types with regard to their delivered heat resistance. Thus, large carbon savings can be gained by substituting commonly used materials (Bribián et al. 2011). Table 2 shows a comparison of insulation materials with respect to embodied carbon related to a fixed thermal transmittance of U = 0.15 watts per square meter Kelvin (W/m^2K). The result varies between 1.5 kilograms carbon dioxide equivalents (kg CO_2–eq) for cork and 24.6 kg CO_2-eq for polystyrene foam (Walker 2011).

Building Elements

Naturally, there are more criteria than carbon impact to be considered when choosing materials for a building. Different building types are designed to function as whole systems, and the components are assembled to take care of a range of demands. Elemental constructions, such as external walls, ground floors,

Table 2 Embodied carbon of different insulation materials, related to a fixed thermal transmittance of U = 0.15 watts per square meter Kelvin (W/m^2K) as a functional unit. Figures are based on ICE (2008) and do not include stored carbon in bio-based materials

Insulation	*Embodied carbon kg CO_2 -eq; $U = 0.15\ W/m^2K$*
Cork	1.5
Mineral wool	8.9
Fiberglass	12.0
Flax	13.6
Polyurethene rigid foam	19.6
Polystyrene foam	24.6

Note: kg CO_2-eq = kilograms of carbon dioxide equivalents. CO_2-eq: Carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of carbon dioxide as the reference. One watt (W, SI) ≈ 3.412 British Thermal Units (BTU)/hour ≈ 1.341 × 10^{-3} horsepower (hp). One Kelvin (K) increment = 1 degree Celsius (°C) = 1.8 degrees Fahrenheit (°F).

Source: Walker 2011

and roofs, can be used as functional units to ensure like-for-like comparisons. For example, in the *Green Guide to Specification*, to assess the relative impact of a range of external walls, each wall must achieve the functional unit of 1 m^2 to satisfy the current building regulations and a thermal transmittance (U-value) of 0.3 W/m^2K. Thus, the impact of a building is found by multiplying the impact per unit by the quantity of each unit.

However, this apparently straightforward approach has some shortcomings. According to the information paper "Carbon footprinting and labeling of construction products" by the Building Research Establishment (BRE), materials that do not fit into an established building element category or functional units that differ from the norm can be difficult to assess. Also, the approach may deter innovative whole-building, low-impact design solutions and does not integrate operational impacts within the same workflow (Doran and Anderson 2011). One of the missing links in this picture is how to assess the operational benefits derived from building materials. Although thermal insulation values are typically integrated into functional elements for the building envelope, other effects connected to heat and moisture regulation are less commonly discussed.

Heat and Moisture Regulation in Buildings

The insulation of a building's envelope is usually regarded as the primary service provided by materials to safeguard sustainable operation in the life cycle. Thermal modeling is based on the U-value, which reflects the conduction through every material layer when the heat flow has reached steady state. However, materials with heat and/or moisture capacity will also influence the heat transfer in different ways, and practical tests show that the actual heat flow through exterior walls, as well as the overall energy consumption, can deviate considerably from the one predicted by the U-value due to the thermal capacity as well as hygroscopic properties of the materials (Pritchett et al. 2008). Table 3 shows some definitions of terms used.

Dampening of Heat Flow through Walls

First, the heat flow through the building envelope can decrease as a result of using materials that not only have low heat conductivity, but also provide heat capacity. This is because heavy materials store heat and thus induce a time lag when outside temperatures drop or rise (Lechner 1991). The heat flow is *dampened*. The energy transfer during 24 hours can be simulated by imposing a sudden temperature drop in the external environment while the internal environment is maintained at the same level. The time integral of heat flux at the internal surface of the wall over 24 hours following the temperature drop (Q_{24h}) can then be determined and presented per square meter of wall surface area in kilojoules per square meter (kJ/m^2).[2]

A dampening effect can also occur through phase change in materials. Latent heat storage is the process where materials absorb and release thermal energy at the transition between solid and liquid state or between liquid and gas state. When heat flows from inside to outside, the flow will be slowed down because of phase changes of vapor in the pores of the material (Bevan and Woolley 2008). The practical thermal inertia is the sum of the sensible heat storage and the latent heat storage. Generally, insulation materials based on biomass have about twice the practical heat capacity of mineral-based insulation and thus will perform better in practice (Cripps et al. 2004). Also, plant-derived composites, such as hemp-lime, have particularly interesting properties as a lightweight construction material combined with heat storage.

Thermal Buffering

Second, materials with heat capacity exposed in the interior can have an effect for the energy consumption in a building because these materials will offset and thus *buffer* the thermal loads during the day and result in reduced need for heating and cooling. Two material properties are of interest regarding thermal buffering; in addition to heat capacity, which roughly follows the density of the material, it is the thermal conductivity. The moisture content of the material may influence both these properties (e.g., the heat capacity as well as the conductivity of wood will rise as a result of increased moisture content). When combined with the diurnal temperature variation of 24 hours, the effective thickness of the material layer can be calculated, and further, the effective heat capacity per m^2 can be defined (Dokka 2005; Ma and Wang 2011).

Phase change materials (PCMs) are materials with a large capacity for accumulating latent heat and have been developed to meet the need for thermal buffering in lightweight buildings. Compared with sensible storage materials, such as water, masonry, and concrete, PCM stores much more heat per unit volume. However, an important limitation to commonly used PCMs, such as hydrate salts, is their durability and performance loss with repeated thermal cycles (Haase and Andresen 2007). Also, the embodied carbon of prefabricated PCM panels can be

Table 3 Definition of terms

Terms	*Definitions*
Heat/thermal conductivity	The property of a material's ability to conduct heat
Heat/thermal capacity	The amount of heat required to change a substance's temperature by a given amount
Sensible heat	Heat exchanged in a thermodynamic system where the effect is a change of temperature
Latent heat	Heat exchanged without change of temperature (e.g., during phase change of materials)
Hygroscopic capacity/moisture buffer value	The amount of water transported in or out of a material per open surface area, during a certain period of time, when subjected to variations in relative humidity of the surroundings

significantly higher than for, as an example, poured concrete (Haavi and Gustavsen 2011).

Concrete producers promote the effect of thermal inertia assuming it can give concrete buildings higher energy efficiency than buildings in wood (see, e.g., Byggutengrenser 2009). However, again, the question with regard to the delivered service of heat buffering is the environmental load per service unit. Less carbon-intensive materials, such as natural stone and earth, can also deliver heat buffering. Although, for example, rammed earth may not have the same high thermal capacities as concrete, the environmental load in production is much less. In addition, earth materials can buffer moisture as well.

Moisture Buffering

Hygroscopic materials are beneficial for several reasons. In addition to the potential for increasing the thermal resistance of insulation through phase change, the use of hygroscopic materials in the interior will result in moisture buffering. Because of changed humidity conditions, the use of hygroscopic materials can result in better indoor air quality (IAQ) or it can keep the same IAQ at a lower ventilation rate and within a wider temperature range. Energy use for HVAC systems can therefore be reduced, and the moisture buffer effects may also have an impact of size, efficiency, and cost of equipment (Padfield 1998). Also, because of latent heat exchange with the indoor air, a direct heat gain can be obtained from using hygroscopic materials in the interior (Osanyintola and Simonson 2006).

As a measure of the ability to buffer moisture, the concept of moisture buffer value (MBV) is introduced (Rode 2005). MBV indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity (RH) of the surrounding air. The property depends on active thickness of the material, its vapor permeability, and its moisture storage capacity, and the units for MBV are grams per square meter percent relative humidity ($g/m^2\%RH$).[3]

Another favorable effect of using hygroscopic materials is the reduced risks for condensation in constructions. Crop-based materials typically store 20% to 30% of their own weight, whereas mineral wool stores only 2.5%. As the risk of interstitial and surface condensation decreases, this effect can result in prolonged technical lifetimes of building materials.

Summarized Benefits Provided by Thermal and/or Hygric Mass

Materials with sensible or latent heat capacity:

- Increased practical heat resistance in insulation materials because of thermal dampening in exterior walls
- Heat buffering when exposed in the interior; time-lag effect can reduce energy use for heating and cooling

Hygroscopic materials:

- Increased practical heat resistance in insulation materials because of hygric dampening (phase change) in exterior walls
- Moisture buffering when exposed in the interior; improving indoor air quality, reducing energy use directly (reduced heating and cooling through latent heat exchange) or indirectly (lower ventilation rates and wider indoor temperature range)
- Decreased risks for moisture deposits/condensation in construction and on interior surfaces; can result in prolonged technical lifetimes of materials

Case Study

Different climatic conditions as well as the function and use of a building will influence the design and choice of materials. Therefore, there cannot be an optimal set of material properties to fulfill all requirements in any given situation. In this section, a case study will shed light on the issues that can arise from viewing, and potentially quantifying, materials as service providers.

The aim of the study is to explore in what ways responsible use of building materials can yield environmental benefits that are quantifiable in a life cycle perspective. The functional unit is 1 m^2 exterior wall, and three design concepts are compared in an environmental cost-benefit analysis regarding material choice and related environmental issues of production and operation. Manufacturing and transport loads are viewed together with carbon sequestration in plant-based materials and recarbonation in concrete and lime, and together with potentially reduced operational energy consumption caused by heat and moisture buffering. The assessment is limited to GHG emissions, and the life cycle is set to 60 years.

Some simplifications and generalizations have been necessary. Regarding heat and moisture buffering, it is assumed that the walls form part of a sample building that is optimized for these effects to take place. Generally, the scope of heat and moisture buffering will vary as a function of climate, building type, and choice of HVAC systems. However, in this study, it is considered that the potential energy savings suggested in the relevant literature are actually achieved in the sample building.

Data for the assessment are based on published sources of research as far as possible. In some cases, the research is sparse and the input data are based on unpublished sources or discussions with field experts. A main point of the study is to present a scheme for comparison of exterior walls and to visualize how the environmental profiles of the three concepts can vary during the production and operational phase. Although some inputs to the assessment are based upon estimations that may be modified as new research gives more specific data, it is believed that the results can lead to some fruitful discussions.

Energy Performance

Three principally different design concepts for an exterior wall were compared. The walls consist of (A) concrete/rock wool, (B) wood studs/wood fiber, and (C) wood studs/hemp-lime. The constructive and climatic layers of the walls were included in an analysis where the performance, with regard to energy efficiency, was assessed in two ways, using the design tool WUFI Pro. First, the U-value of each concept was set at 0.18 W/m^2K, which complies with the Norwegian building code. Second, the energy flow during 24 hours (Q_{24h}) was determined for wall A, and then the other two concepts were designed to comply with the same Q_{24h} value. Accordingly, walls A, B1, and C1 were matched regarding U-value, and walls A, B2, and C2 were matched regarding Q_{24h}. The five resulting wall designs with material layers and thermal characteristics are displayed in figure 1.

WUFI Pro simulates hygrothermal performance with one-dimensional heat and moisture transport. The total thermal transmittance of the wall, which consists of thermally homogeneous (i.e., insulation, and so on) and thermally inhomogeneous (i.e., wood studs) layers parallel to the surface, was calculated as the arithmetic mean of the upper and lower limits of the resistance, as described in technical standard BS EN ISO 6946:1997 (BSi 2007). The thermal conductivity of the insulation layer was then increased in the WUFI model until the overall thermal transmittance matched that calculated using the BS EN ISO standard, which incorporated the wood studs.

The Q_{24h} value was determined by imposing a sudden temperature drop from 20°C to 0°C in the external environment, whereas the internal environment was maintained at 20°C. The time integral of heat flux at the internal surface of the wall over 24 hours following the temperature drop is determined and presented per m^2 of wall surface area (i.e., kJ/m^2). Figure 2 presents the heat flux through the internal surface for each wall following the temperature drop. Q_{24h} (%) is the ratio of the energy transferred to the energy that would be transferred (over 24 hours) if the steady state were achieved instantaneously. Accordingly, a low ratio would indicate a greater buffering effect, making regulation of the internal environment at a constant level a less energy-intensive proposition (Evrard and De Herde 2010). The energy transferred in 24 hours for wall A (157.2 kJ/m^2) was selected as a "baseline" value, and further simulations of walls B and C were undertaken to establish the thickness of insulation required to meet the target value of approximately 157 kJ/m^2.

The thermal and hygric properties of the component materials were taken from the database of construction materials within the WUFI software, with the exception of the hemp-lime material, which was based on data presented previously (Evrard et al. 2006; Evrard and De Herde 2010).

In the UK, hemp-lime is used at a relatively low target density of 275 kilograms per cubic meter (kg/m^3) to improve thermal performance; however, the moisture transport data for the material at this density are not available. These simulations used the higher density (480 kg/m^3) and, correspondingly, higher thermal conductivity ($\lambda = 0.09$ watts per meter Kelvin [W/mK]) presented in Evrard and De Herde (2010)[4] to be consistent with the porosity and liquid transport coefficient data, which have been determined for the higher-density material. The relatively high thermal conductivity for this hemp-lime material necessitates much greater thickness of material to achieve the target U-value of 0.18 W/m^2K. However, at this wall thickness (540 millimeters [mm]),[5] the Q_{24h} value for the hemp-lime construction was almost zero. With a hemp-lime mix more common in the UK (density = 275 kg/m^3), the conductivity has been measured to $\lambda = 0.067$ W/mK ± 2.5% (Duffy 2012). This means that an exterior wall with 370 mm low-density hemp-lime would achieve $U = 0.18$ W/m^2K.

Other performance characteristics were not considered. Different load-bearing capacities as well as fire classification and interior surface qualities of the three walls imply that these walls may be chosen for different building types. However, for this study, the detailing of the material layers are chosen so that the thermal performance, as a building envelope as well as the effects regarding heat and moisture buffering, can be easily visualized. The main point is to present a scheme where the studied issues can be compared. Figure 1 presents the five resulting walls (A, B1, B2, C1, and C2) and summarizes the results of the WUFI simulations.

Four Areas of Assessment

The exterior walls are assessed within four areas of life cycle impacts. The first assessment regards the embodied carbon of the materials, reflecting manufacturing loads and transport to the building site. The second assessment regards the sequestered carbon in plant-based materials and recarbonation in lime and concrete. The third assessment regards thermal buffering and the potential reduced energy impact caused by using materials with heat capacity in the interior, and the fourth assessment regards moisture buffering and the potential reduced energy impact caused by using hygroscopic materials. The first assessment is thus considered to measure the environmental costs of the

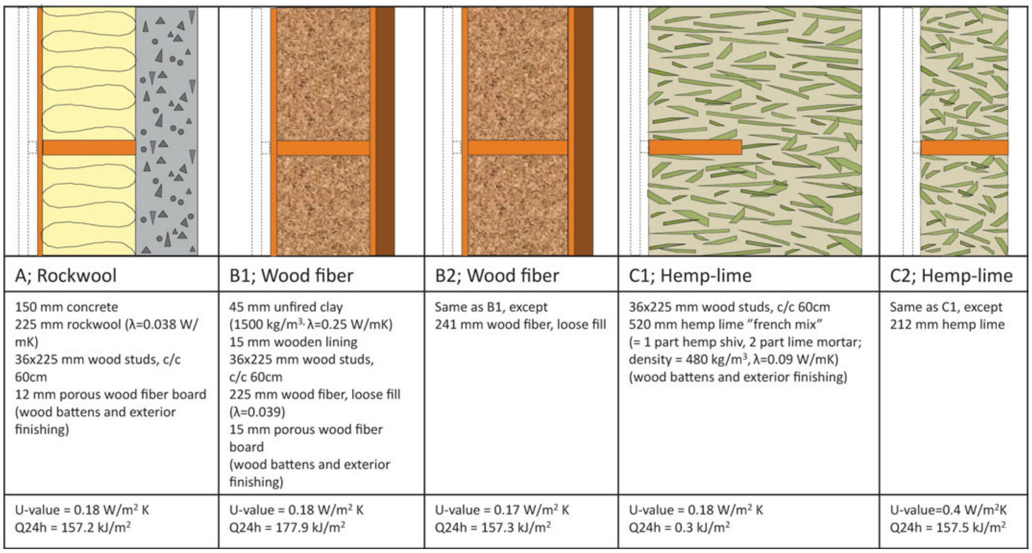
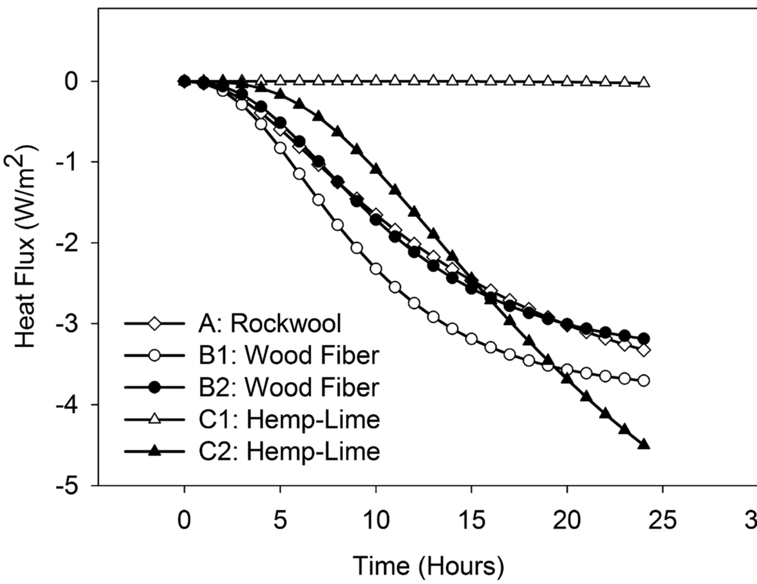


Figure 1 Design, material layers, and resulting thermal characteristics of the exterior walls compared in the study. Abbreviations: λ = thermal conductivity; W/mK = watts per meter Kelvin; U-value = thermal transmittance; W/m^{2}K = watts per square meter Kelvin; Q_{24h} = energy transfer during 24 hours; kJ/m^2 = kilojoules per square meter.



	A; Rock-wool	B1; Wood fiber	B2; Wood fiber	C1; Hemp-lime	C2; Hemp-lime
Q_{24h} %	51%	57%	54%	0%	23%

Figure 2 Heat flux through the internal wall surface for each wall type over a 24-hour period following a sudden 20-K temperature drop. Lower part shows Q_{24h}(%), which is the ratio of the energy transferred to the energy that would be transferred (over 24 hours) if the steady state were achieved instantaneously. Abbreviations: W/m^2 = watts per square meter; K = degrees Kelvin.

materials, whereas the other three assessments are considered to show different environmental benefits that the materials may provide.

The full depths of the walls are needed to provide a suitable overall heat resistance, whereas for the heat and moisture buffering effect, only the inner layer of the walls is needed. Calculated regulation depths for heat buffering are shown in table 4. Regulation depths for moisture buffering are generally assumed to be thinner than for heat buffering, and thus it is considered that enough mass is available for both heat and

Table 4 Technical properties and the resulting thermal regulation depth and effective area-specific heat for the three interior layers compared in the study. Conductivity is based on samples in a dry state and at a mean temperature of 10°C. The method only considers sensible heat exchange, not latent heat

Interior layer	*Mass-specific heat kJ/kgK*	*Density kg/m^3*	*Conductivity W/mK*	*Thermal regulation depth m*	*Effective area-specific heat kJ/m^{2}K*	*Energy reduction*
Concrete	0.85[a]	2,200[a]	1.80[a]	0.061	113.4	15%
Unfired clay	0.85[b]	1,500[b]	0.25[b]	0.027	34.9	4.6%
Hemp-lime	1.55[c]	480[c]	0.09[c]	0.021	16.0	2.1%

Notes: Mass-specific heat; kilojoules per kilogram and degree Kelvin (kJ/kgK). One cubic meter (m^3, SI) ≈ 35.3 cubic feet (ft^3).
Density: kilograms per cubic meter (kg/m^3).
Conductivity: watts per meter and degree Kelvin (W/mK).
Thermal regulation depth: meter (m).
Effective area-specific heat; kilojoules per square meter and degree Kelvin (kJ/m^{2}K).
[a]WUFI database.
[b]WUFI database, Oti et al. 2010.
[c]Evrard and De Herde 2010 and Shea 2012.

moisture buffering to take place in all three walls. More detailed descriptions of assessment methods are presented below.

Waste impacts are not regarded. Although the environmental impacts connected to the different phases of waste handling (e.g., demolition, transport, recycling, and landfill) play an important role in the life cycle of building materials, it is considered outside the scope of this study. However, for a full evaluation and comparison of different material options, the waste aspects should be included.

For the purpose of visualizing the effects of heat and moisture buffering by walls A to C, a sample energy need for heating and cooling at 45 kWh/m^2 is regarded for a 12-m^2 (3 × 4 m) room. The energy consumption is not modeled, but relates to a standard for low-energy nonresidential buildings (Dokka et al. 2009). Here, the requirements for maximum energy need for offices are set at 30 kWh/m^2 for heating and 15 kWh/m^2 for cooling. The related exterior walls have a minimum requirement for U-value ≤0.18 W/m^{2}K, and this value now also complies with the current Norwegian building regulations (Tek 10). The energy consumption is then allocated to wall and ceiling area, instead of floor area. Assuming a ceiling height at 2.6 m and a window area at 20% of the floor area, this equals 11.8 kWh per m^2 wall.

Electricity is considered as the energy source for heating and cooling loads. The carbon emission factor for Norwegian electricity in a 60-year perspective is considered at 132 grams of carbon dioxide equivalents per kilowatt-hour (g CO_2-eq/kWh), as recommended by BREEAM NOR and the Norwegian Research Center on Zero Emission Buildings. This factor is related to the European Union goal of reducing GHG emissions of electricity production (Selvig 2011).

Embodied Carbon

GHG emissions are calculated as kilograms of carbon dioxide equivalents per square meter (kg CO_2-eq/m^2) wall area. The emission factors for the material layers are based on the Norwegian Statsbyggs Klimagassregnskap, the University of Bath Inventory of Carbon and Energy V2.0 (ICE 2011), or other relevant sources. The emission factor for energy consumption in the production of materials vary among the sources, but is mainly based on the current European mix at ±400 g CO_2-eq/kWh. GHGs are calculated for each layer of the wall and include transport from production facility to building site. Different waste factors for the various materials in construction phase are also considered.

Sequestered Carbon and Recarbonation

Carbon sequestration is considered for the layers of biomass materials used in walls A to C (wood studs and lining, wood fiber boards, wood fiber loose fill, and hemp fiber) and calculated according to the mass content in a 1-m^2 wall. As described in the *Introduction*, 1.8 kg of CO_2 is stored in 1 kg of (dry) wood. Because the embodied carbon of Norwegian wood products is considered to be 0.026 kg CO_2-eq/kg (Selvig 2012), the sequestration thus amounts to as much as 6,923% of the emissions related to manufacturing. Further, 1.8 kg of CO_2 is also considered to be stored in 1 kg of (dry) hemp fiber.

Because a standard method of accounting for carbon sequestration is not yet defined, a sensitivity analysis was performed. A calculation was run using only half the effect; instead of 1.8 kg, only 0.9 kg of CO_2 was considered stored in 1 kg of biomass. The results for the wood products show that the sequestration then is reduced to 3,462% of the emissions related to manufacturing.

Recarbonation in concrete is assessed for wall A. According to ICE V2.0, the production of a typical concrete mixture of medium strength (32/40 megapascals) leads to emissions in the order of 0.132 kg CO_2-eq/kg. The emissions are mainly related to the production of Portland cement and consist of emissions caused by processing energy as well as direct chemical emissions released during the calcination of limestone. It is assumed that the content of sand and aggregates only contributes with a small amount of the embodied carbon in concrete, and that the amount of chemically released CO_2 is about 53%. It is then considered that 40% of the CO_2 emitted can potentially be reabsorbed, and that a concrete wall of medium strength will recarbonate 0.8 mm per year (Paine 2011). Thus, in a 60-year perspective, wall A will recarbonate 48 mm from each side, which equals 64% of the wall. Further recarbonation in the end-of-life phase is not considered. In sum, the concrete in wall A will reabsorb 0.132*0.53*0.4*0.64 = 0.018 kg CO_2-eq/kg. This equals 13.6% of the embodied carbon in concrete.

Recarbonation in lime is considered for the hemp-lime composite in wall C. The production of lime mortar emits 0.190 kg CO_2-eq/kg (Berge 2009), and it is considered that 60% of the emissions are chemically released. It is then generally considered that 80% of these emissions can be reabsorbed in a lifetime of 60 years (Lawrence 2011). Thus, the lime in wall C will reabsorb 0.190*0.6*0.8 = 0.091 kg CO_2-eq/kg. This equals 48% of the embodied carbon in lime mortar.

Thermal Buffering

As described in the *Introduction*, thermal buffering is effectuated by heat capacities of interior surface materials. Dokka (2005) and Ma and Wang (2011) describe a method for calculating the effective heat capacity per m^2 for various surfaces, and this method is used for the three interior materials involved: concrete, clay sheets, and hemp-lime. The effective heat capacity per m^2 is defined through the equation $C'' = c\rho d$, where c is the specific heat capacity (in kilojoules per kilogram Kelvin [kJ/kgK]), ρ is the density (in kg/m^3), and d is the effective thickness (in meters [m]); thus, the effective area-specific heat is in kilojoules per square meter Kelvin (kJ/m^2K). Table 4 shows the results.

Dokka (2005) also quantifies effects in terms of reduced energy need caused by heat buffering. The study compares a heavy and a light construction for an office and a dwelling in the Oslo climate and concludes that energy need for heating can be reduced with 7% to 13% for the two building types. Energy need for cooling in the office building is reduced by 33% for the heavy construction, as compared to the light construction. A Ph.D. thesis by Høseggen (2008) presents a literature study on the effects of thermal buffering. It refers to studies from various climates and building types and concludes that energy need for heating can be reduced with 15% for dwellings and 20% for offices, and that energy need for cooling can be reduced with 5% to 36%, depending on climate and building type.

The conclusions in Dokka's (2005) and similar studies are based on simulations of specific cases and cannot be directly transferred to buildings in other climates and with different HVAC systems, window areas, internal heat gains, insulation values, and so on. Thermal mass is considered as one out of several means to achieve an overall energy design, and the approaches for this will naturally vary. However, when comparing the effects of various materials, these estimations are used as a point of reference for how much the energy need potentially can be reduced by conscious and efficient use of thermal mass. An estimate of a maximum 15% total reduction of energy need for heating and cooling is used in the calculations.

Further, a correlation is assumed between effective heat capacity per m^2 and the achieved heat-buffering effect. Because concrete is considered a good heat-buffering medium, it is assumed that an energy reduction of 15% is obtainable for wall A (concrete as interior surface). Then, the potential energy reductions for the other two walls are defined according to their ratio of effective area-specific heat. As a result of heat buffering, wall B can thus potentially save 4.6% and wall C 2.1% of the operational energy for heating and cooling. Important to note, however, is that this method only considers thermal buffering caused by sensible heat exchange, and not latent heat exchange.

Moisture Buffering

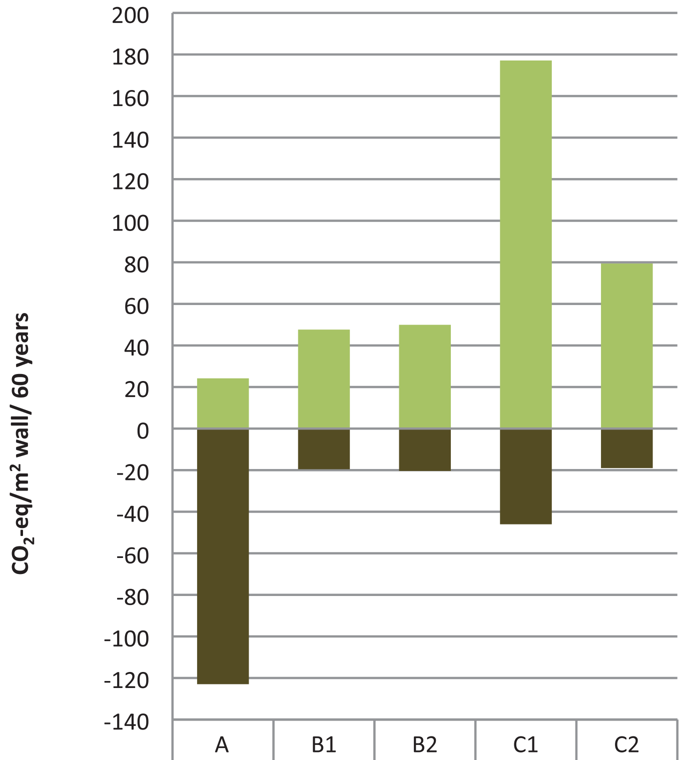
Moisture buffering is effectuated by hygroscopic capacities of interior surface materials. The issue of potential energy savings is less investigated for moisture buffering than for heat buffering. However, Osanyintola and Simonson (2006) describe and quantify direct and indirect effects of moisture buffering in a 12-m^2 bedroom with spruce panel on the walls and ceiling. The effects are modeled for climates in Finland, Belgium, Germany, and Italy. The study suggests a potential reduction in the consumption of heating energy at 7% to 8%, when applying hygroscopic materials in buildings, and 10% to 30% effects for cooling (Osanyintola and Simonson 2006). An estimate of a maximum of a 10% total reduction of energy need for heating and cooling resulting from moisture buffering is used in the calculations.

A correlation is assumed between MBV and the achieved moisture-buffering effect. The assessments of energy reductions in Osanyintola and Simonson (2006) are based on interiors with spruce panels. The MBV of spruce is 1.16 g/m^2%RH (Rode 2005), whereas MBV of concrete is 0.38 g/m^2%RH (Rode 2005). The MBV for unfired clay is 1.49 g/m^2%RH (derived from Rode 2005; Padfield and Jensen 2011), and the MBV of hemp-lime is 2.11 g/m^2%RH (Evrard and De Herde 2010). Assuming that the interior surface with the highest MBV (wall C: hemp-lime) can potentially achieve 10% energy reduction, the energy reductions for the other two walls are defined according to their ratio of MBV. As a result of moisture buffering, wall A can thus potentially save 1.8% and wall B can save 7.1% of the operational energy for heating and cooling. Table 5 shows the results.

Table 5 Moisture buffer value (MBV) for the three interior layers compared in the study. MBV is given in grams per square meter and percent relative humidity (g/m^2%RH)

Interior layer	*MBV g/m^2%RH*	*Energy reduction*
Concrete	0.38[a]	1.8%
Unfired clay	1.49[b]	7.1%
Hemp-lime	2.11[c]	10%

[a]Rode (2005).
[b]Derived from Rode (2005) and Padfield and Jensen (2011).
[c]Evrard and De Herde (2010).



	A	B1	B2	C1	C2
Sequestered carbon/ Re-carbonation	24	48	50	177	79
Embodied carbon (manufacturing loads)	-123	-20	-20	-46	-19

Figure 3 Embodied carbon and sequestered carbon/recarbonation in the five walls. Negative values indicate embodied carbon, assessed as GHG emissions resulting from manufacturing and transport (Norwegian average) to building site. Positive values indicate sequestered carbon and recarbonation. Sequestered carbon is assessed for the layers of biomass materials in all walls, whereas recarbonation is assessed for concrete in wall A and for lime in walls C1 and C2. Abbreviations: GHG = greenhouse gas; CO_2-eq/m^2 wall/60 years = carbon dioxide equivalents per square meter wall per 60 years.

Results

Embodied Carbon and Sequestered Carbon/Recarbonation

Figure 3 presents the results of embodied carbon related to the manufacturing process, as well as the walls' potentials regarding carbon sequestration in biomass and recarbonation in concrete and lime.

As expected, concept A has the highest embodied carbon (123 kg CO_2-eq/m^2), out of which the layer of reinforced concrete contributes the most. The concrete recarbonates 6 kg CO_2-eq/m^2 during 60 years, and the wooden parts in the wall store 18 kg CO_2-eq/m^2. In summary, carbon storage and recarbonation make up for about 20% of the manufacturing loads when viewed in a 60-year perspective. In the sensitivity analysis with only half effect for carbon sequestration in biomass, the wooden parts in wall A store 9 kg CO_2-eq/m^2. In summary, carbon storage and recarbonation then make up for about 12% of the manufacturing loads. Interesting to note, still most of the contribution stems from the carbon sequestartion in the wooden parts.

Concept B has lower embodied carbon ($\pm$20 kg CO_2-eq/m^2), and most layers consist of biomass materials, which store more carbon than is emitted during manufacuring. Therefore, the potential of carbon storage is about 240% of the manufacturing loads. In the sensitivity analysis, where the effect of carbon storage is reduced, the potential of carbon storage is about 122% of the manufacturing loads.

For concept C, the two methods of determining thermal performance lead to quite different thicknesses of the hemp-lime and thus more diverging results. Embodied carbon for C1 is 46 kg CO_2-eq/m^2, whereas for C2, it is 19 kg. Because this concept both sequesters carbon in the hemp shiv and the wooden studs, and, in addition, the lime recarbonates, the total sequestration/recarbonation amounts to 177 kg CO_2-eq/m^2 for wall C1 and to 79 kg CO_2-eq/m^2 for wall C2. Thus, this concept stores about 400% of the carbon emitted during manufacuring. In the sensitivity analysis, this percentage is reduced to 208% for wall C1 and 225% for wall C2.

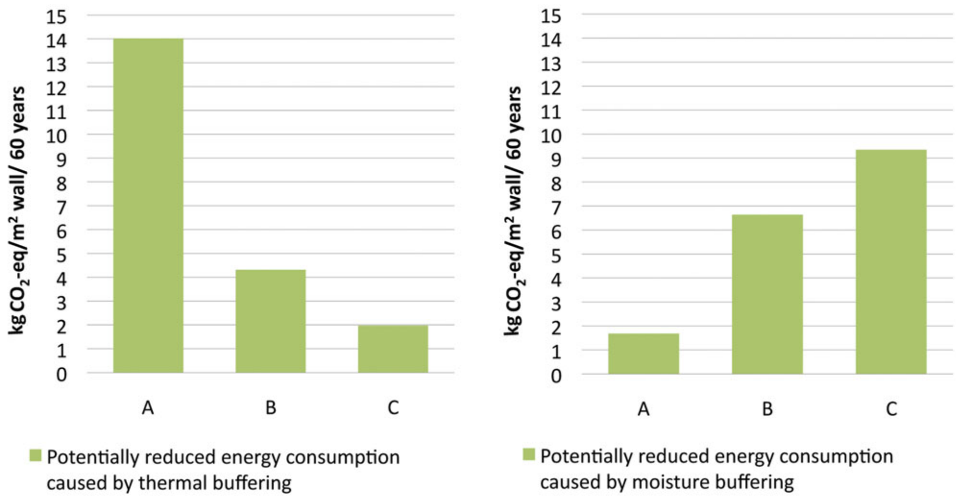


Figure 4 Potentially saved GHG emissions resulting from reduced energy needs caused by thermal and moisture buffering during 60 years of operation. The energy source is electricity with carbon factor at 132 g CO_2-eq/kWh. Abbreviations: GHG = greenhouse gas; CO_2-eq/m^2 wall/60 years = carbon dioxide eqvivalents per square meter wall per 60 years; g CO_2-eq/kWh = grams carbon dioxide eqvivalents per kilowatt-hours.

Buffering Effects

In the analysis of buffering effects, only the internal layers of the exterior walls contribute. In concept A, the internal layer is concrete; in concept B, it is unfired clay; and in concept C, the internal layer is hemp-lime. The potentially saved GHG emissions in 60 years of operation is shown in figure 4 and result from reduced energy need caused by thermal and hygric buffering effects, as descibed in the *Introduction*.

Concept A has the highest potential for thermal buffering (14 kg CO_2-eq/m^2), whereas concepts B and C contribute with about 4 and 2 kg CO_2-eq/m^2. Regarding moisture buffering, the walls have different profiles; concept A has the lowest potential for moisture buffering (1.7 kg CO_2-eq/m^2), whereas concepts B and C contribute with 6.6 and 9.4 kg CO_2-eq/m^2 respectively.

Discussion

The three design concepts show quite different profiles when comparing the environmental costs and benefits. Regarding embodied carbon versus carbon sequestration/recarbonation in the five walls (figure 3), the results show that carbon sequestration in biomass materials can be higher than the embodied carbon. Thus, if carbon sequestration was included in carbon accounting, it would make a great impact and greatly favor biomass materials. Recarbonation in lime and concrete make less overall impact. In concept A, where a 150-mm concrete wall recarbonates in 60 years, most of the benefit still results from carbon sequestration in the wood studs. The result is still valid with half the effect of carbon sequestration in wood used in the sensitivity analysis.

Regarding the potentials for reduced operational energy consumption caused by heat and moisture buffering, the results also vary greatly between the concepts. The internally exposed concrete in concept A buffers thermal loads well, but has little hygroscopic capacity, whereas concepts B and C have less potential for thermal buffering but have good moisture buffer capacity. The calculations on thermal buffering effects are based on specific heat capacity (kJ/m^{2}K) for each material. If, also, latent heat exchange was considered, the thermal buffering effect of hemp-lime would be higher. The interesting question with regard to LCA is what the total environmental costs are. If one material layer solves more than one task, this should be rewarded.

When looking at these potentials for energy savings, as compared with the environmental investments in production of the materials, the gain is, overall, modest. It is therefore questionable whether thermal and hygroscopic buffering can outweigh high impacts of production. Nevertheless, the advantages that materials provide should be utilized for benefits in the operational phase. The question is what the needs are in each specific building project and how these needs can be met through relevant material choice. Good environmental practice will be to choose materials on the basis of their abilities as service providers and, simultaneously, with a view to impacts in production, such as GHG emissions.

Analytical Framework

The analyses combine different areas of research, but are based on a common functional unit for the assessments (kg CO_2-eq/m^2/60 years). A problem of allocating different issues, such as embodied and sequestered carbon as well as thermal and moisture buffering down to 1 m^2 of exterior wall is that it will not necessarily represent a real situation. A prerequisite for achieving energy reductions through choice of materials is relevant design regarding climate and building type. In this assessment, it is simply assumed that the m^2 in question forms part of a building where these effects actually take place. The effects on heating and cooling needs could be lower or they could be higher than shown in the calculations. Generally, in climates with cooling needs, the effects of both thermal and moisture buffering are generally greater than in climates with heating needs alone. Therefore, with other allocation frameworks, and, in particular, in climates with great cooling needs, the aspects of thermal and moisture buffering could become far more significant.

The method of simulating thermal performance is decisive for the results, and, in particular, this is demonstrated for concept C. In real buildings, which are subject to the diurnal variation of the external climate, an evaluation of the transient energy performance is clearly of interest. The simulations highlight the need to evaluate more than just the steady-state thermal performance and indicate that hemp-lime is capable of achieving comparable energy performance for a modest (230-mm) wall thickness, which belies its steady-state thermal transmittance characteristic.

The emission factors for electricity are also decisive for the results. A considerably lower emission factor is used for operational energy (132 g CO_2-eq/kWh) than for production of materials (±400 g CO_2-eq/kWh). This is reflecting that more carbon-intensive energy sources are typically used for the production of materials than for households, and also that a lower emission factor in general is expected within a time span of 60 years. If a higher emission factor was used for operational energy, the results for thermal and moisture buffering would increase accordingly.

Other effects related to materials, such as waste loads, could have been included in the analysis as well. Biomass materials are biodegradable and can be burned for heat recovery if not chemically treated. Thus, if the waste phase was considered, biomass materials would probably have further gained carbon credits. It is important to point out that some of the calculation and allocation methods used in this study represent a first attempt to bridge different areas of research, and that a set of simplifications had to be made. Refinement of the methodology, as well as connection to whole-building LCA, can hopefully be pursued in future publications.

Implications

Generally, aspects of material choice other than insulation values and their simulated consequences for operational energy consumption are generally missing in building regulations and environmental assessment schemes. In future building design, however, both heat and moisture buffering provided by materials may become in greater demand. More research pointing out the negative effects of dependency on HVAC systems to solve all energy and IAQ challenges may shift the focus to materials as replacing or accompanying service providers.

Many low-cost and traditional building materials are interesting in this respect because they are inherently low carbon, easily available, and generally present little challenges in waste handling. Also, in terms of hygrothermal performance, natural building materials display some interesting characteristics and can often provide a range of services. More research on these material types and their environmental profiles throughout the life cycle seem like an important step to make for a greener construction industry in the future.

Conclusions

The choice of building materials has implications for a building's environmental profile not only through manufacturing loads and direct exchanges with carbon, such as carbon sequestration and recarbonation, but also through the building's operation. Proper use of thermal and hygric mass can lead to reduced energy consumption caused by thermal dampening as well as heat and moisture buffering. In this analysis, these effects are allocated to 1 m^2 of exterior wall for the purpose of visualizing the potentials within the same functional unit.

Three design concepts were investigated, and the thermal performance simulated both in terms of U-value and dynamic heat flow during 24 hours (Q_{24h}). Accordingly, walls A, B1, and C1 were matched regarding U-value, and walls A, B2, and C2 were matched regarding Q_{24h}.

The results show that concept A (concrete/rock wool) has the highest embodied carbon and that its potential for carbon storage and recarbonation is 12% to 20% of the manufacturing loads when viewed in a 60-year perspective. For concepts B (wood studs/wood fiber) and C (wood studs/hemp-lime), the potentials for carbon storage and recarbonation are 122% to 240% and 208% to 400% of the manufacturing loads, respectively. Regarding buffering effects, concept A has the highest potential for thermal buffering (14 kg CO_2-eq/m^2/60 years), whereas concepts B and C have the highest potential for moisture buffering (6.6 and 9.4 kg CO_2-eq/m^2/60 years, respectively). The assessments of heat and moisture buffering depend on relevant building design with regard to climate and building type.

The results of the analyses give some indicative answers regarding building materials as service providers. The greatest effect is carbon sequestration in biomass and would lead to a change of perception if included in carbon accounting schemes. However, with other allocation procedures, and, in particular, regarding climates with cooling needs, buffering effects may also become significant. Clearly, the assessments do not represent any final conclusion, but rather suggest a layout for gathering more knowledge on these issues.

LCAs are, by nature, top-down exercises. Because all buildings are unique to their environment, there are limitations to the usefulness of upscaling standardized solutions. Architectural design, as an interdisciplinary practice, rather represents a bottom-up approach, which is decisive for the overall sustainability of buildings in their life cycles.

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Notes

1. One kilogram (kg, SI) ≈ 2.204 pounds (lb).
2. One kilojoule (kJ) = 10^3 joules (J, SI) ≈ 0.239 kilocalories (kcal) ≈ 0.948 British Thermal Units (BTU).
3. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces (oz).
4. One meter (m, SI) ≈ 3.28 feet (ft).
5. One millimeter (mm) = 10^{-3} meters (m, SI) ≈ 0.039 inches.

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