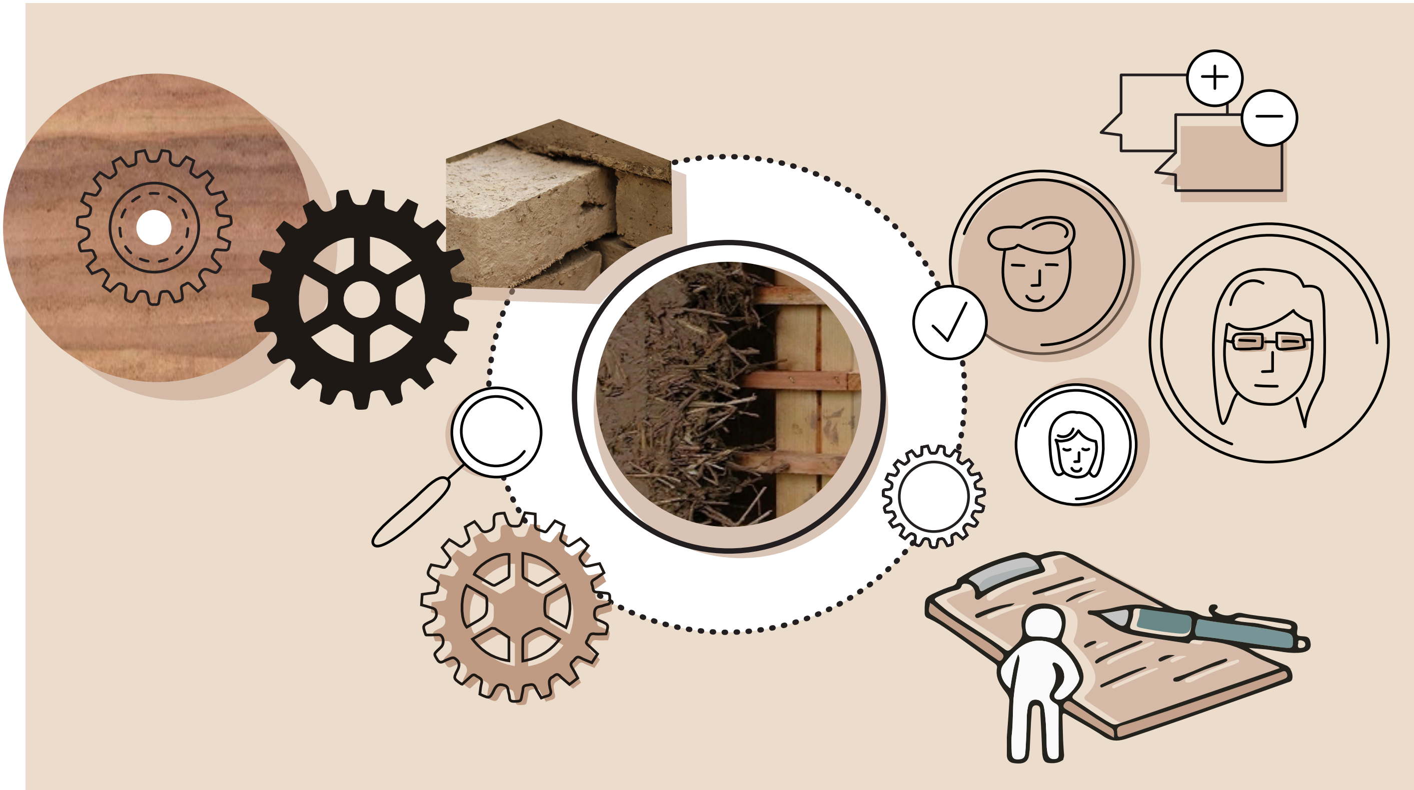
Natural Buildings

Integrating Earthen Building Materials and Methods Into Mainstream Construction



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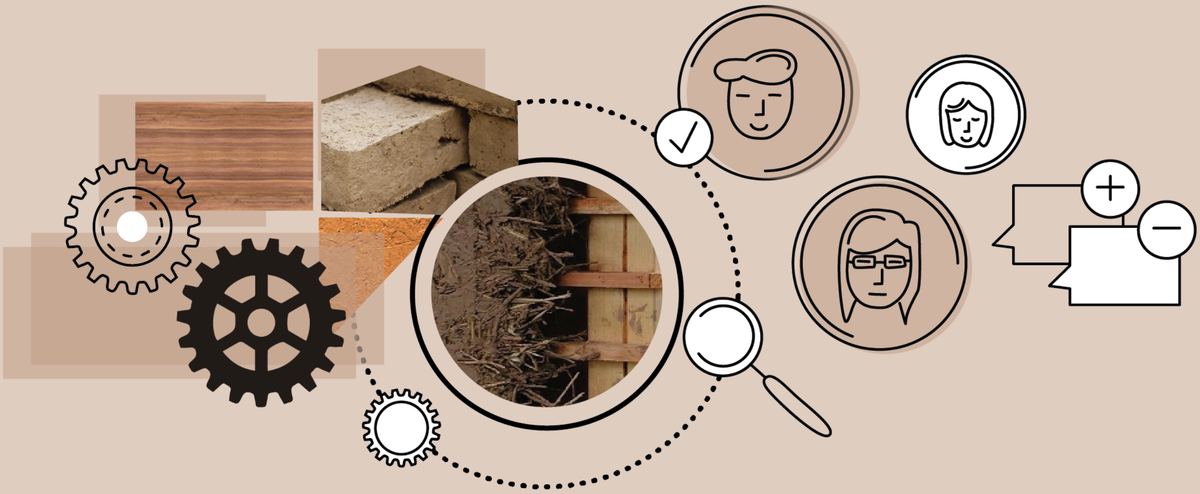
Rammed Earth House Entrance | hyperSity Architects, 2016, China

Imagine yourself entering into your new home. The walls are naturally plastered with breathable clay. The floor is a warm, smooth earthen surface. It feels primal and warm but looks elegantly modern. The scent is clean like a rain forest. The temperature and humidity feel like a perfect bright sky day. It is as if the outdoors were entered into a relaxing indoors… And it is not located in the rural land, 2-hour drive from the city's commodities, as one might think. Rather, your home is one of the many new-norm natural, healthy, and passive 6 floor apartment homes, located 5-minute walk from the city center.

Inspired by Bruce King's visionary book on zero-carbon architecture (King, 2017)



Abstract

Earthen materials are critically needed for modern building to dramatically reduce carbon-intensive and extractive construction practices, and to improve comfort, health, and community engagement. Light straw clay, rammed earth, and cob assemblies provide high thermal inertia and high hygrothermal performance, resulting in optimal indoor environment for occupant's comfort and health.

Despite their advantages, earthen materials are not widespread. For some, there is a perception that earthen materials are "poor-mans materials" and low-tech. For others, the technical data is inadequate to quantify their true performance for different climates. Lastly, earthen materials are not comprehensively represented in building codes and standards.

To address both the benefits and gaps, this thesis completes performance and policy assessments to mainstream implementation of earthen materials in the construction industry. The dissertation undertakes: (1) Perception analysis that identifies how negative perception on earthen building can be revised; (2) Technical analysis through environmental Life Cycle Assessment (LCA) of earthen materials compared to conventional building materials in six climates; and (3) Policy repair analysis for earthen building codes and standards towards the development of comprehensive earthen building codes.

The perception analysis reveals the importance of health and indoor quality data to influence homeowners, of environmental data for policymakers, and the importance of reducing building permitting barriers, especially for compressed earth block and rammed earth assemblies.

The environmental LCA shows that earthen assemblies significantly reduce environmental impacts compared to the benchmark assemblies of wood and concrete assemblies. Using in-depth LCI and LCA analysis, the thesis quantifies that the embodied energy demand is reduced by 62-71% by shifting from wood or concrete to earthen assemblies. In addition, the embodied global climate change impacts are reduced by 85-91%, the embodied air acidification is reduced by 79-95%, and the embodied particulate

pollution is virtually eliminated. The operational impacts are shown to be highly dependent on the hygrothermal properties and climate zone, but in all cases, earthen assemblies outperform conventional assemblies with light straw clay and insulated rammed earth the top performers for all 6 climates.

Finally, the policy repair analysis provides strategic solutions to address the unfamiliarity and under-development of earthen building codes, by use of successful precedents from around the world. The concluding recommendations are to advance the permitting processes in the absence of local earthen building codes and to establish a national organization for Earthen Building to lead and contribute to the development of an international comprehensive earthen building code. This doctoral thesis contributes critically needed environmental quantification and policy recommendations to catalyze the advancement of healthier and more environmentally sound commitments to earthen construction worldwide.

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My sincere thanks go to Prof. Vivian Loftness, Prof. Kent A Harries, and Prof. Erica Cochran Hameen, without whom I could not have undertaken this research. Their expertise, which spans many fields of sustainable architecture and nonconventional material engineering, has been invaluable.

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I thank all the wonderful earthen building people within and outside the US who were cooperative in assisting me with my research and for answering my surveys and in-depth interviews.

Thanks to my mother, Dr. Dora Ben-Alon, who provided me with the inspiration to pursue an academic career, and for encouraging me to keep on writing every day. I thank my father, Moshe Ben-Alon, who showed me the wonders of building construction and took me to his construction sites since childhood.

And of course, many thanks to my wonderful husband Eyal and my sweet son Yuval, who kept on loving me despite my long hours at the computer.

Thank you.

מילות הוקרה

אני מודה למנחים שלי, פרופ' ויויאן לופטנס, פרופ' קנט א. האריס ופרופ' אריקה צ'וקרן האמין, על תרומתם הבלתי נדלית למחקר זה. מומחיותם הרב-תחומית בנושאי אדריכלות ברת-קיימא והנדסת חומרים טבעיים עזרה למחקר זה ללא שיעור.

תודותיי לדר' גוון די-פיאטרו, המרצה בתחום הערכת מחזור חיים סביבתי בקרנגי מלון, שלימדה אותי את רזי המקצוע.

תודותיי לביה"ס לאדריכלות באוניברסיטת קרנגי מלון, על תמיכתם הכלכלית במענקי מחקר, מענקי נסיעה לכנסים, ומענקים לסדנאות, שעזרו לי ללמוד את אמנות הבנייה באדמה, ברחבי ארה"ב ומרכז אמריקה. העבודה עם הידיים הייתה חשובה ועזרה לי להבין את החומריות ואת דרכי הבנייה עם האדמה.

אני מודה מקרב לב לכל המשתתפים במחקר – המרואיינים וכל מי שענה על הסקרים – אנשי האדמה ברחבי העולם. תודה לכם שתרמתם מהידע שלכם ועזרתם ביצירת מחקר זה.

תודותיי לאמי, דר' דורה בן-אלון, שעוררה בי את ההשראה למסלול האקדמי, ועודדה אותי לאורך הדרך, והפצירה בי לכתוב, לכתוב, לכתוב. תודה לאבי, אינג' משה בן-אלון, שנטע בי את האהבה לבניין, ולקח אותי לאתרי הבנייה שלו מאז היותי ילדה קטנה.

וכמובן – תודה ענקית לאיילוש אהובי, ולבני המתוק יובל, על תמיכתכם ועל שהמשכתם לאהוב אותי למרות העבודה הארוכה על המחשב.

תודה.

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Key Terminology

Earthen Building – Earthen building is both the design, construction process, and the structure that is the result of such a design process. An earthen structure is a structure that is made largely from soil. Since soil is a widely available material, it has been used in construction since prehistoric times. It may be combined with other materials, compressed and/or stabilized to add strength.

Earthen Building Materials – The materials common to the various types of earthen building. These materials would mostly refer to clay and sand but can include other biological and/or geological minimally processed materials such as fibers, bamboo, wood, aggregates, and recycled materials.

Earthen Building Methods – Earthen building methods are the process and product that occurs when mixing earthen building materials and placing them into an earthen building. Earthen building materials can be mixed with water and, in some cases, straw or another fiber, and then sculpted, formed, tamped, or pressed, to form blocks and/or monolithic walls. The various earthen building methods include cob, rammed earth, light straw clay, adobe, Compressed Earth Blocks (CEB), and earthbags.

Environmental Life Cycle Assessment (LCA) – The compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006a).

Life Cycle Inventory (LCI) – LCI is the straight-forward accounting of everything involved in the LCA analysis. It consists of the details for all the resources and activities that flowed in and out of the product system boundary, including raw materials, energy by type, and emissions.

Life Cycle Impact Assessment (LCIA) – The LCIA is the LCA's "what does it mean" step. In LCIA, the LCI is analyzed for environmental impact.

Heating and cooling loads are the total energy loads required to provide comfort conditions in the home; all other loads are kept constant between building simulations.

Heating and Cooling Energy Use is the total energy required on site to meet the heating and cooling loads, accounting for other issues such as the efficiency of the heating and cooling system and fuel type (e.g. gas versus electricity).

Heating and Cooling Energy Demand is the total energy required in source to meet the heating and cooling energy use, accounting for local energy system inventories, fuel production mechanisms and transportation (e.g., electricity from grid, natural gas from combustion site).

Standard – A generic term encompassing consensus documents that include test methods, practices, specifications and model codes.

Building Code – A series of ordinances enacted by a jurisdiction or entity establishing minimum requirements that must be met in the construction of buildings. Building Codes are conventionally model codes adopted with or without (locally relevant) revisions.

1 Introduction

1.1 Research motivation

The vast majority of modern buildings are constructed from highly processed, and often toxic materials such as synthetic insulation and concrete. Making and processing these building materials account for approximately 15% of global warming impacts, 20% of global energy demand, and up to 40% of global solid waste (King, 2017). Overall, through their use phase, buildings are responsible for more than 40% of global energy used, and as much as one third of global greenhouse gas (GHG) emissions. Essentially, it has been shown that relying on these conventional building materials at a global level is draining our planet's resources, and that "the building sector has the greatest potential for delivering significant and cost-effective reductions in GHG emissions (United Nations Environmental Program, 2009).

Specifically, new residential homes, both single family and multifamily, continue to be constructed in the US, and are responsible to a large share of national energy consumption and GHG emissions. Approximately one million new homes are being built each year in the US, of which 75% are 1-2 story single-family houses, as illustrated in Figure 1 (US EIA, 2018).

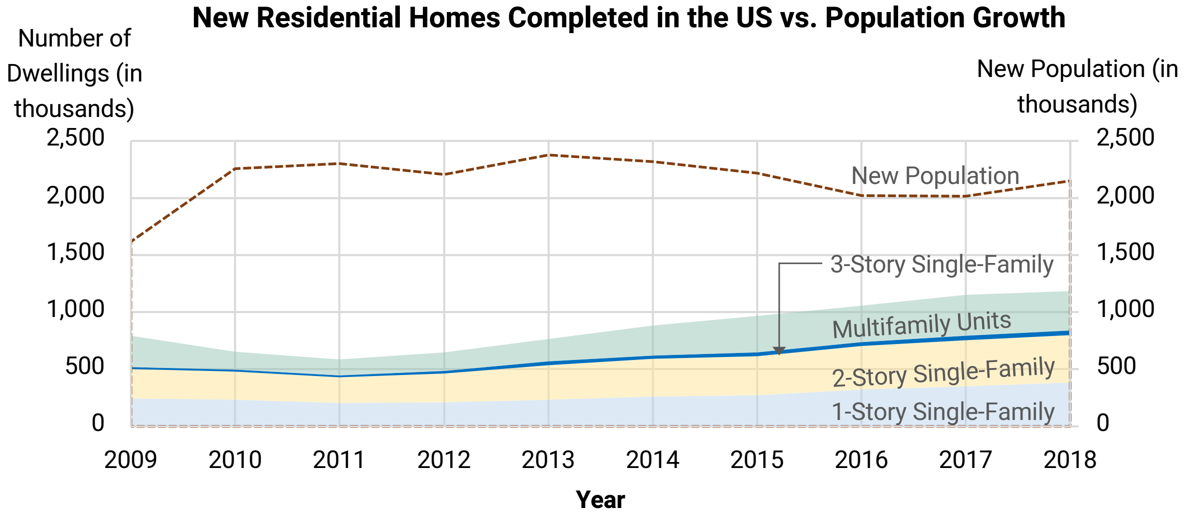


Figure 1: New residential homes completed in the US between 2009-2016 (US EIA, 2018)

These low-rise single-family houses alone are responsible for 16 quadrillion Btu and 1.2 Gt of energy-related CO_2, which accounts for 16% of national energy requirements and 22% of national GHG emissions (US EIA, 2011, 2017, 2018), of which approximately 5% account for embodied values that include raw materials extraction, manufacture, and transportation (Upton et al., 2008). On a global scale, US single family houses (with less than 5% of the world's population) account for a staggering 3% of global energy use and GHG emissions (European Commission, 2016; US EIA, 2016). In terms of building materials, modern constructions in general, and US residential construction in particular, are mostly made of wood, synthetic insulation, steel, and reinforced concrete, meeting a wide variety of building codes and standards. These building codes and standards (that were initially developed to ensure individual safety and general public welfare) are currently neglecting larger, ecologically based risks to natural systems upon which everyone's safety and health ultimately depend (Eisenberg and Yost, 2004).

As a consequence, additional non-mandatory regulatory and rating systems have been developed to encourage materials and resources considerations in projects, as shown by the growing numbers of L.E.E.D™ certified projects (MacDougall, 2008; Shutters, 2015). Parallel to the interest in green rating systems and in "sustainable building" there has been a growing interest in "ecological," and "natural" building materials and methods. These later concepts have seen a tenfold increase in published research papers when compared to the previous decade (MacDougall, 2008; Pacheco-Torgal & Jalali, 2011). As opposed to "green" or "sustainable" materials and methods, "ecological" and specifically "natural" building materials and methods are defined as minimally processed, low carbon, and readily available materials that enhance their local environment, rather than only mitigate negative impacts (Van der Ryn and Cowan 2007). Examples of natural building materials include natural fibers like straw and hemp, and earthen materials like sand and clay.

1.1.1 The case for earthen building materials and methods

In contrast to other natural building materials, earth exhibits various advantages; it provides high thermal inertia and offers better structural capacity in compression. As opposed to trees and crops, earth is usually abundant in and around the construction site. As opposed to cellulose-based natural materials, it has better resistant to fungi, insects and rodents. Furthermore, it allows a diversity of forms and styles, from sculptural monolithic assemblies to modular components (Racusin and McArleton, 2012).

Earth is considered one of the oldest building materials. While earthen building materials still shelter approximately a third of the world's population, particularly in developing countries (Kahn, 1990; Wanek et al., 2002), they have also been undergoing a new Renaissance in developed countries, with dozens of books being published in the last two decades that address re-implementation of earthen building methods such as rammed earth, earthbags, and cob, mainly by authors from within Europe (Figure 2, Table 1).

From an environmental point of view, the broader implementation of earthen building materials could result in lower embodied energy and fewer GHG emissions than conventional building materials (MacDougall, 2008; Morel et al., 2007). In many cases, earthen building methods incorporate waste materials or by-products with excellent properties. Other benefits of earthen building materials include their low toxicity, and recyclability at the end of life that allows a cradle-to-cradle supply chain (Morel et al., 2007; Pacheco-Torgal and Jalali, 2011).

Figure 2: Contemporary earthen building materials and methods book covers from European authors: (M. R. Hall et al., 2012; Minke, 2012; Röhlen and Ziegert, 2011; Schroeder, 2016)

Due to their high thermal inertia, earthen building materials are particularly advantageous in warmer climates, especially when the diurnal changes offer warm days and cool nights. However, the advantages of earth as a thermal mass can also be used in cold climates by placing a mass wall within an insulated envelope; the wall can store and retain passive (solar) or active indoor heat within the building interior, and then release this heat slowly over a period of time (for instance, over a cold night) (Racusin and McArleton, 2012).

In addition to their thermal mass properties, earthen building materials exhibit good hygrothermal properties due to their porosity. Recent research has shown that various earthen building materials are able to regulate both indoor temperatures and indoor humidity to achieve optimal levels for occupants health (Allinson and Hall, 2010; Brambilla and Jusselme, 2017; Liuzzi et al., 2013; Serrano et al., 2016).

In light of these environmental and health benefits, earthen building materials and methods are a critical future that while clearly justified, require demonstration, and code permission possibilities.

1.1.2 Barriers to the broader implementation of earthen building

Despite their benefits and the bottom-up interest in earthen building, there are still many barriers and unrealized opportunities for the use of these materials and methods in mainstream construction (Figure 3). First, earthen building technical data is highly variable, making it challenging to quantify their true performance for different climate conditions (Miccoli et al., 2014; Woolley, 2006). Second, there is a broad, and often mistaken, perception of these materials as low-tech and as having poor performance (MacDougall, 2008; Spisaková & Macková, 2015). Lastly, one of the main barriers that is especially evident in the case of earthbags and cob is the lack of complete and user-friendly codes and regulations that could give rise to the conventional implementation of, for instance, affordable homes (Eisenberg and Yost, 2004; Swan et al., 2011).

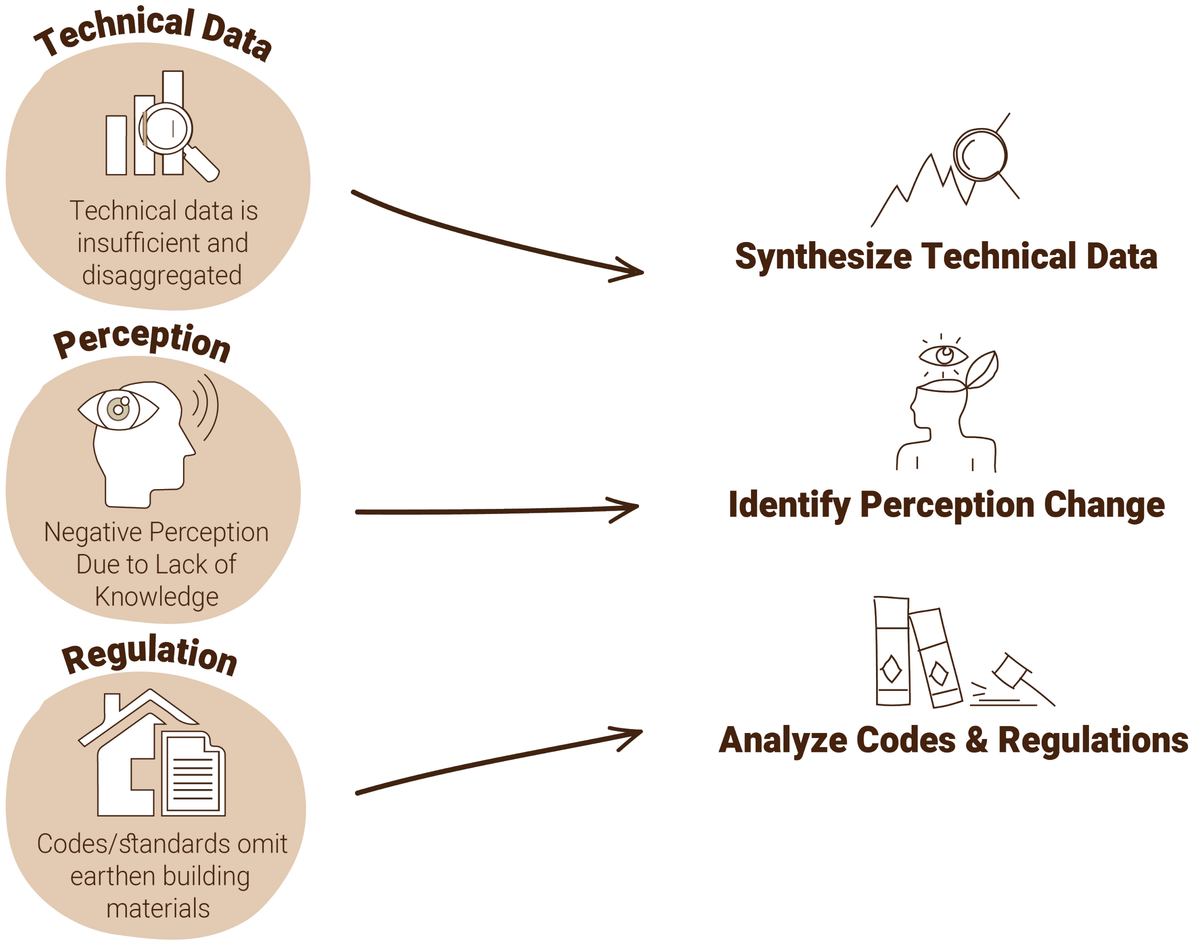


Figure 3: Three steps on the path to overcoming barriers and to a broader implementation of erathen building materials and methods

These concerns are broadly echoed in the literature. Woolley (2006) concludes that public policy incentives, particularly formal codes and regulations, should be developed for earthen materials, accompanied with financial incentives, in order to give rise to real-estate investments. Similarly, Swan, Rteil, and Lovegrove (2011) suggest that future research should (1) aggregate the existing experimental engineering studies, (2) provide analytical and numerical insights that could facilitate the design process and allow the inclusion of earthen materials in building codes, and (3) provide life cycle analysis of earthen construction assemblies.

1.2 Purpose statement, objectives, and hypotheses

1.2.1 Purpose statement and research perspective

In light of the benefits of, and barriers to, using earthen building materials and methods (as detailed in sections 1.1.1 and 1.1.2), this dissertation focuses on providing practical measures that could be used to catalyze the implementation of earthen building in mainstream construction. The current existing literature is divided by research in a variety of disciplines; architectural design, structural engineering, thermal performance and step-by-step guides. This leads to a disconnection that might stall continuing understanding of earthen materials and methods, their applicability, and limitations (Figure 4). Therefore, the suggested research perspective will incorporate dialogues from a variety of disciplines while using a top-down approach that lies at the intersection of Architecture, Engineering, Construction Management (AECM) and building policy.

Figure 4: Earthen building research suffers from disconnection between the various disciplines, such as seen in many cob projects (Photo credit: Maccabe, 2010)

1.2.2 Research objectives and significance

This research develops performance-based and policy-based assessments that could be used by policy makers and give rise to a top-down implementation of earthen building materials and methods. The main goals of this research are: (1) to analyze the factors that affect interest in, and barriers to, using earthen building materials among experts and end-users, (2) to develop a comparative environmental Life Cycle Assessment (LCA) of different earthen building assemblies and compare them to conventional building assemblies, and (3) to examine which improvements are necessary in earthen building codes and standards that could be used by policy makers and earthen building advocates. As part of the second and third steps, an additional deliverable was to synthesis known earthen building performance data from the literature, including thermal and structural parameters.

Significantly, this research contributes to the AECM industry and to the code development community by catalyzing the implementation of low-impact, sustainable building materials and methods. One of the long-term implications this research hopes to achieve are the development of a complete, safe, and user-friendly earthen building representation in building codes, worldwide.

1.2.3 Research hypotheses

The main research hypotheses that this dissertation addresses are as follows:

Overall Research Hypothesis:

Earthen building materials and methods suffer from technical, perceptual, and regulatory gaps that could be addressed; they are environmentally urgent because they environmentally outperform conventional residential constructional materials and methods (concrete and wood assemblies) in dry warm and hot climates.

In order to undertake this main research hypothesis, the following sub-hypotheses are addressed:

Research Sub-Hypothesis 1:

Strategies to overcoming negative mistaken perception of earthen building materials and methods can be formulated by analyzing the motivation and perceived barriers of end-users.

Research Sub-Hypothesis 2:

Over their cradle to end-of-life life cycle, earthen wall assemblies (light straw clay, cob, and rammed earth) exhibit **fewer environmental impacts** than conventional wall assemblies (concrete and wood) for residential buildings in dry warm and hot climates.

Research Sub-Hypothesis 3:

In the absence of a complete building policy, **regulatory barriers are the greatest impediment** for earthen building implementation, and these can be addressed through a **policy performance analysis among experts and end-users**.

2 Background on Earthen Building

This chapter reviews the existing literature regarding Earthen Building Materials and Methods. It begins with definitions related to earthen building, and proceeds to an overview of main earthen materials and techniques in regard to their history, production techniques, advantages, importance, environmental Life Cycle Assessment (LCA), and existing codes and standards. The last part of this chapter reviews the main barriers to using earthen materials, the limitations of existing studies, and suggests directions for future studies.

2.1 Defining earthen building in the context of modern building evolution

Earthen building receives different definitions within the literature, often considered a traditional and vernacular building method that utilizes clay as the main component. However, a consistent definition of earthen building is still missing. In light of the advancement of earthen materials and methods in the last few decades, there is a need to be re-examine and define the possibilities of earthen building materials as a viable alternative in sustainable construction.

2.1.1 Natural building in the context of sustainable design evolution

Throughout history, various shelters were developed in different cultures by improving materials, energy, water, and waste solutions, from generation to generation, adjusting to new needs and opportunities. The evolution of human building behavior followed the path of building our shelters out of locally abundant materials (Kahn, 1990); the building components were always mined and curated from the nature nearby: earth, stone, trees and grasses (Wanek et al., 2002).

It is only in the last few centuries that our relationship to buildings has changed. Cementing materials started playing a vital role in the ancient world: the Egyptians obtained cementing material by burning gypsum; the Greeks used lime by heating limestone; and the Romans developed water-resistance cement by adding crushed volcanic ash to the lime (Lechtman and Hobbs, 1986). These techniques were re-developed and patented in western Europe between the 18th-19th centuries as “Roman Cement” and “Portland Cement” (Hewlett, 2003; Wanek et al., 2002).

This last development of Portland Cement, accompanied with the industrial revolution and steel production improvements, changed the way building materials are produced and techniques are used for construction. These changes that followed industrialization started as a wave in Western Europe and are still spreading into less-developed parts over the world. Thousands of new building products gradually developed and replaced local traditional materials in ways that reduce labor and allow an increase in the pace and amount of construction. Nevertheless, these new products required the extraction, transportation, and manufacture of (often toxic) products in ways that contribute to global environmental deterioration (Wanek et al., 2002). As a result, construction of these modern buildings result in the consumption of large amounts of fossil fuels and non-renewable materials (Woolley, 2006).

In light of the environmental degradation that is the consequence of modern building evolution, 'sustainable' and 'green' building practices have been receiving tremendous interest throughout the world in the past decades, in both research and practice. This rise can be shown by the increase in academic research on sustainability in buildings, where a quick search on Google Scholar for the term "Sustainable building design" results in 287 papers for the years 1995-2000, 548 papers for the years 2000-2005, 1,500 papers for the years 2005-2010, and 3,190 papers for the years 2010-2015.

However, the growing interest in sustainable building has been accompanied by a growing number of various interpretations regarding what makes a building system sustainable. One of the most widely-accepted definitions, outlined by the US Green Building Council, defines a sustainable building as *a building system that aims to amplify its positive and mitigate its negative effects, throughout its entire life cycle* (U.S. Green Building Council and Kriss, n.d.). In his work, Berardi (2013) identifies the necessity for a more precise definition of a sustainable building system. Berardi (2013) concludes, following a thorough analysis of the different existing definitions, that sustainable building should be defined as *a building system that contributes "through its metabolism, and by doing this it favors a* ***regenerative resilience*** *of the built environment among all the domains of sustainability*". Therefore, sustaining a mutually beneficial relationship with the natural world is critical for future generations to thrive. These should be brought to the forefront in the decision-making processes of a building system's design and construction.

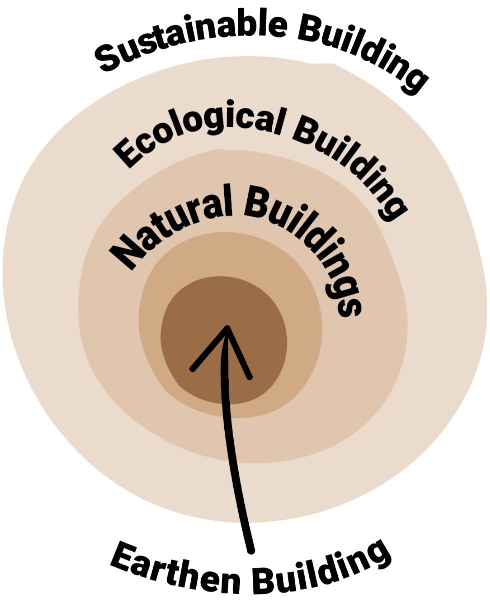
Within this context, the question for designers, engineers, and contractors of the built environment seems to be the following: how can buildings be made in a way that promise such ***regenerative resiliency*** of our local ecology? One key approach that provides means for solving this problem is the ecological building concept, following methods that adhere to the natural building processes.

While sustainable building is broadly defined to reduce negative and increase positive impacts, ecological building defines how these aims should be fulfilled to ensure resiliency for future generations. According to the ecological building concept, a sustainable building system fulfills its mission *by integrating itself with living processes and by sustaining a mutually beneficial relationship between the* ***natural and the built worlds*** (Van der Ryn and Cowan, 2007). Natural building takes these concepts even further to a more specific context by focusing on the incorporation of local, minimally processed natural materials. In addition, according to the natural building approach, a sustainable building system fulfills its mission *by ensuring* ***environmental, social, and economic*** *sustainability: first, by using minimally processed materials; second, by producing structures that ensure occupants' health and indoor environment quality; and third, by providing building techniques that are affordable and accessible for community engagement* (Evans et al., 2002; Wanek et al., 2002).

2.1.2 Earthen building as a subset of the natural building paradigm

The relation between sustainable building, ecological building, and natural building can be identified as illustrated in Figure 5; sustainable building includes various approaches, among others is ecological building, and natural building is a specific case of the ecological building domain. One way to think about the overlaps and connections between these three approaches is to consider material selection. A sustainable building could contain high performance assemblies with materials that have high embodied environmental impacts, such as concrete insulated with polystyrene. An ecological building could have materials with low embodied environmental impacts but some toxic emissions, like reclaimed tires. A natural building, on the other hand, would incorporate toxin-free, raw materials, with low embodied environmental impacts, like straw and clay.

There are various natural building materials and application techniques. In essence, natural building materials divide into those that are biological, such as plants and animal products, and to those that are geological, such as soil and stone (Racusin and McArleton, 2012). Each material (or mix of materials) and its method of application is appropriate for certain environmental, climatic, and cultural conditions.



While many builders become enthusiastic experts in a subset of the natural building specific methods, it is important to emphasize that the underlying aim of ecological and natural building concepts is to maintain a holistic approach to design. There are a wide range of materials and building systems, and the best results will be sometimes be derived from a combination of multiple approaches (Woolley, 2006). For instance, straw-bale walls that have high thermal resistance should be used to insulate. Earthen walls that exhibit high thermal inertia should be used to absorb and release heat gradually. According to passive design principles, these techniques could be combined in a single structure in a form of a hybrid section (e.g., straw bale insulation layer attached to an earthen thermal mass layer), or placement of each material on different walls according to orientation.

Figure 5: Natural building as a specification of ecological building and sustainable building

Furthermore, location of the material origin can dictate usage. Straw bales come from renewable crops and are the by-product of the grains industry and therefore should be used in areas that are proximate to grain fields. In contrast, earthen walls should be built in areas where clay-rich soil is abundant and can be locally mined.

2.1.3 Re-defining earthen building in the context of sustainable contemporary construction

Earthen building is defined in the literature as either traditional and vernacular building methods (Niroumand et al., 2017), that utilize natural building materials (Wanek et al., 2002). However, neither of these definitions is entirely accurate. Some earthen building techniques are traditional and vernacular (e.g., adobe), some were developed in the past few decades (e.g., compressed earth blocks), and some were used traditionally but nowadays receive a new architectural interpretation (e.g., rammed earth) (Ciancio and Beckett, 2015; Serrano et al., 2016). In addition, earthen materials and methods sometimes contain small amounts of non-natural materials (e.g., small amount of stabilizers, or polypropylene bags such as seen in earthbags (Wojciechowska, 2001)).

Earthen building needs to be re-defined, from an up to date, broader view. Generally, earthen building can be defined as *construction methods of building elements in which graded soil (i.e. earth) is used as the main component*. More specifically, in recent decades, material science has come to know much more about how clay works as a natural binder in building materials (used essentially in all earthen mixtures, that are often referred to as clay-based concrete (King, 2017)). Indeed, the study and use of geopolymers is presently booming. Earthen building materials can be defined as a *natural alternative to concrete, where clay is used as a binder (rather than cement), sand and aggregate are used as compressive strength providers, and natural fibers are used as a tensile strength provider (rather than steel rebar).*

Figure 6: Successfully permitted Stoltz Bluff Eco-Retreat, Vancouver, Canada

2.2 Overview of the main earthen building techniques

Cob

Cob is an earthen building method that combines earth, natural fibers such as straw, and water. This mixture is produced in a plastic state and implemented wet to build monolithic load bearing or freestanding walls. The term cob comes from England (probably due to the similarity of a cob batch to a lump or rounded mass). Cob is sometimes referred to as monolithic adobe and has many other names worldwide, such as bauge (France), lehmweller (Germany), pasha (Turkey), terre crue (Italy), and zabour (Yemen) (Hamard et al., 2016; Watson and McCabe, 2011).

In the literature, there are many publications that deal with cob in the context of building restoration (mainly in the UK, e.g., Saxton, 1995 ; Berlant, 1998). However, recent research has focused on new ways to implement cob in contemporary practice (Evans et al., 2002; Pullen & Scholz, 2011; and Weismann & Bryce, 2006, to list a few).

Figure 7: The Smiling House by US cob pioneers (Smiley and Evans, 2005), and retrofitted cob LEED Platinum structure (Studio D'Arc, 2012)

Cob is advertised as an affordable building method due to its use of locally available materials, but also due to the manual and approachable construction method that can be implemented by home-owners (Armstrong, 2015). Cob requires no extensive training and can be assembled by almost anyone, even children. Cob building easily lends itself to form different curves, shapes, and sculptural details (Evans et al., 2002). Another advantage of cob is the presence of straw that imparts a ductile failure mechanism to cob, a quality that suggests appropriate behavior in seismic areas (Miccoli et al., 2014). To the contrary, cob construction, when implemented manually, cob can be labor intensive and slow. It was traditionally considered in England as "the slow process" (Watson and McCabe, 2011). One way to address this disadvantage is to spread the labor across more workers by making cob-building a community effort, where everyone can contribute – from expert builders to children and elders (Evans et al., 2002).

Figure 8: Production of cob mix: manual mixing vs. tractor-cob (Watson and McCabe, 2011)

Another way to address the above disadvantages is to use construction machinery and accessories, such as in the case of tractor-cob that uses a tractor for the cob mixing, as shown in Figure 8, and shuttered-cob that uses formwork within which the cob is placed, as shown in Figure 9. However, incorporating these techniques mitigates cob's environmental benefits and sculptural features to a degree.

Figure 9: Construction of cob walls: shuttered-cob in Merton, UK vs. sculptural free-form cob construction (Watson and McCabe, 2011)

Figure 10: The Great Wall of China, Jiayuguan Gate, built by the Ming Dynasty around 1372 (Preciado et al., 2017).

Rammed earth

Rammed earth combines small gravel aggregates, silt, sand, clay, and a small amount of water, all compacted by ramming into forms, similar to the ones used in concrete. Depending on the region, rammed earth is also referred to as Pise (France), Tapial (Spain), and Stampflehmbau (German).

Rammed earth dates back to ancient times, and it was used to produce some of the most well-known, monumental architecture, such as the Alhambra in Spain, the Pyramid of the Sun in Mexico, and portions of the Great Wall of China (Figure 10). The oldest rammed earth walls found date to 5,000 BC in Assyria (Minke, 2012), and 2,600 BC in China, as shown in Figure 11 (Niroumand et al., 2013).

Figure 11: Rammed earth in ancient China, 1320 BC (Schroeder, 2016)

In recent decades, rammed earth has experienced a revival; its reassessment began in the 1970s while taking a shift towards a more sophisticated marketplace (Easton, 2005). Today, rammed earth can be found in various projects, from residential cottages, to commercial projects (Figure 13).

Figure 13: Rammed earth residential house in Mexico (López Rivera, 2014) and 56,000 m^2 (600,000 ft^2) rammed earth project in Islamabad, Pakistan (Sirewall, 2019)

Prominent rammed earth books include design and construction techniques (Easton, 2007; McHenry, 1984; Minke, 2012, to list a few). In addition, recent studies deal with thermal and structural evaluation of rammed earth (e.g., Allinson & Hall, 2010b; Miccoli et al., 2014; Taylor et al., 2008b).

In comparison to other earthen building methods, rammed earth exhibits higher compressive strength due to its compaction, and is less susceptible to shrinkage on drying due to the low moisture content in the mixture. Therefore, as a monolithic system, rammed earth is more durable and has longer life than other earth building techniques (Minke, 2012).

Rammed earth often exhibits the distinctive layers of compacted soil resulting from the construction process. This might act either as an advantage or as a deterrent to its use, according to aesthetic interests of the clients and/or designers.

Figure 15: Econest kitchen light straw clay walls (Baker-Laporte and Laporte, 2015).

Light straw clay

Light straw clay is an earthen infill method that uses fiber (usually straw) as its main component, and clay slurry (very wet clay), earth, natural fibers such as straw, and water. The loose straw is lightly coated in clay and then packed into forms that are either temporary or permanent to serve as an insulating assembly, as shown in Figure 16. Light straw clay is not load bearing, but it can be mixed and packed to a variety of densities (Doleman, 2017).

Figure 16: Light straw clay workshop by The Year of Mud, and a sprouting drying wall (Baker-Laporte and Laporte, 2015; Jacob Schmidt, 2012),

Light straw clay was developed in Europe after World War II, as an evolution of the wattle and daub infill system that was used in half-timbered houses from the 12th century. Light straw clay is also referred to as light clay, straw clay, slip straw, rammed straw, and leichtlehmbau (Germany).

Studies on light straw clay mainly focus on its thermal and hygroscopic performance as an alternative insulation material. Light straw clay was shown to have a higher moisture buffering capacity than conventional wall systems such as insulated concrete. In the field, light straw clay is often offered as a viable healthy construction alternative, such as the EcoNest Home Prototype that is promoted for occupants with sensitivity to mold and chemicals, (Baker-Laporte and Laporte, 2015).

Beyond being an excellent insulation assembly, light straw clay exhibits additional advantages. It is compatible with conventional framing systems, making it a viable retrofit insulation, where existing walls can be furred out to any thickness. Additionally, the light straw clay mixture is plastic and is compatible with cob, adobe, and straw bale construction; it can be worked with around windows, doors, and other openings.

Light straw clay's main disadvantage is its long drying time that can result in mold if not appropriately paced. Therefore, in areas with high humidity, light straw clay will require thin wall sections to allow the moisture to dissipate from the wall system (Baker-Laporte and Laporte, 2015). As shown in Figure 16, a light straw clay wall will sprout as it dries, often providing an indicator of the wall being fully dry when the sprouts dry.

Figure 17: Adobe consrtuction details at Museum of New Mexico, Santa Fe, NM. Photo credit: Rymer (2018)

Adobe

Adobe is an earthen building method that combines earth, water, and in some cases added chopped fiber, all mixed and molded into forms, and used as bricks. The word adobe comes from the Egyptian word for mud, thobe. This word in Arabic became al-tobe, which later became adobe in Spanish. Depending on region, adobe is also referred to as clay lump (England), brique crue (France), lehmziegel (Germany), and madar (Yemen) (Elizabeth and Adams, 2005). Adobe is also known as unfired mud, clay, or sun-dried bricks.

Figure 18: Historical adobe examples: eight storey 500 year old homes in The City of Shibam, Yemen (left), historical adobe structure in Santa Fe, NM (right)

Adobe bricks are made by placing the adobe mixture into forms that are often made of timber. Adobe bricks usually have the same dimensions as fired bricks and they can used for walls, floors, vaults and domes (Minke, 2000).

Figure 19: Modern adobe homes: construction process (left) and final product (right) of adobe construction (Arizona Adobe Company, 2018)

Advantages of adobe include its easy assembly in a modular manner due to its dry form, as opposed to other earthen methods that are implemented wet. However, if not properly strengthened, adobe might exhibit deficient responses to horizontal loads, such as seen in seismic activity. This disadvantage is addressed worldwide by retrofitting techniques such as the use of polymer mesh for wall reinforcement, as seen in Figure 20 (Blondet and Aguilar, 2007).

Figure 20: Arizona Adobe company plant (left); and adobe reinforced with polymer mesh (right) ((Arizona Adobe Company, 2018; Blondet and Aguilar, 2007).

Figure 22: The Yellow Train School, made with CEBs, by Biome, Tamil Nadu, India. Photo credit: Vivek Muthuramalingam, 2013.

Compressed Earth Blocks (CEB)

Compressed earth blocks are a modern evolution of molded earth block (i.e., adobe) (Rigassi, 1995). CEB combine inorganic soil, water, and in some cases added chopped fiber, all mixed and compressed at high pressure to form blocks. This technique is sometimes referred to as pressed earth block, compressed soil block, or compressed earth brick. If the blocks are stabilized – by the inclusion of a binder – they are called Compressed Stabilized Earth Block (CSEB) (Garg et al., 2014).

Existing literature of CEB include production and building manuals (Stabilised Earth Block, 2001; Rigassi, 1995), as well as durability and mechanical properties (Garg et al., 2014; Lima et al., 2012; Obonyo et al., 2010). Recent CEB studies also include tests of their thermal and hygrothermal properties, with or without insulation (Brambilla and Jusselme, 2017; McGregor et al., 2014; Touré et al., 2017).

The production process of CEBs is similar to that of fired clay bricks, excluding the firing stage. CEB production can take place at various production scales: from small scale on-site production, to industrial factory production, as shown in Figure 23 (Rigassi, 1995).

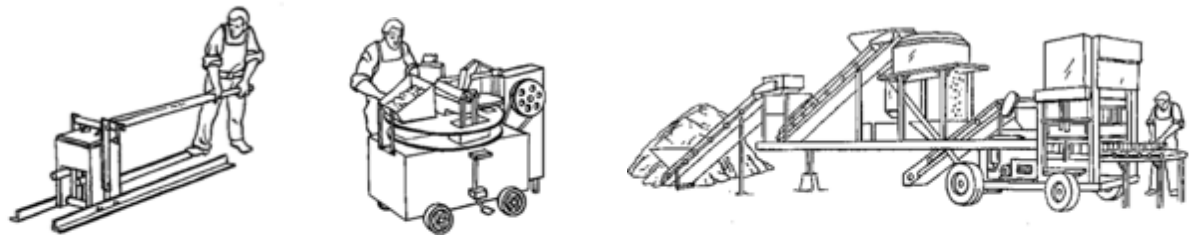


Figure 23: CEB production scales: on-site manual production (left), on-site motorized production (middle), and fixed factory production unit (right) (Rigassi, 1995).

The advantages of CEBs include the consistency of quality that is obtained due to using mechanical presses. This feature also contributes to CEBs' social acceptance and compatibility with building products standards. In addition, the use of CEB is adopted well in regions where traditional building relies on small masonry elements, and provides an additional technological resource to the community Figure 24 (Rigassi, 1995).

CEB appears to be well implemented in communities where local, affordable and natural materials are respected. It also provides potential for monetization within the community as well as providing a sense of pride in living in a modern home, as shown in Figure 24. CEB were shown to be successful fot making "a new way to honor the old ways" (Trees Water and People, 2018). On the other hand, there is a growing range and complexity of presses available on the market, making it necessary to acquire suitable training in order to ensure high quality control of CEB construction (Rigassi, 1995).

Figure 24: CEB homes in Crow Tribe reservation, Montana (Good Earth Lodges, 2018), and in Central America (Trees Water and People, 2018)


Figure 25: Earthbags in Junoot, Oman (Fazly, 2011)

Earthbags

Earthbags is an earthen building method that involves moist subsoil filled into sturdy sacks that are built up in courses to form walls and curved roofs. This technique was originally used in the past century for flooding control and military bunkers, due to its inexpensive and fast assembly together with the ability to keep water and bullets away. Using earthbags for houses and permanent construction has been a recent innovation; it was initially developed in the 1970s by Gernot Minke, who used bags filled with pumice to build walls, and was further enhanced and popularized in the 1990s by Nader Khalili, who coined the name "Superadobe" for his technique (Figure 26) (Hart, 2015).


Figure 26: Superadobe earthbag construction (CAL-Earth, 2019)

Today, earthbags construction is used worldwide, mostly by CAL Earth alumni who incorporate the Superadobe technique as emergency shelters in developing countries (

Figure 27), but also by other architects and builders who use earthbags in rectilinear structures.

Figure 27: Superadobe Earthbag examples from around the world (from upper left clockwise): Tanzania, Mexico, Colombia, Japan, Sierra Leone, and West Bank (CAL-Earth, 2019).

In the literature, earthbags are rarely reviewed and very few studies address their structural behavior (Canadell et al., 2016; Daigle et al., 2011).

Earthbags systems have various advantages when compared to other earthen building techniques. First, earthbags can be implemented both below and above ground, and they are less prone to moisture damage than other earthen techniques. Second, a wide variety of infill soils can be used in earthbags construction, including sand, silt, and other insulating materials such as pumice (Hart, 2015). This last advantages make earthbags more accessible to various geographical locations and more affordable than other earthen materials and methods that often require mining and transporting clay from a quarry. One of the main limitations of earthbags is that they are considered a “radical architecture”, which is implemented bottom-up. To-date, earthbag construction have been rarely used in modern conventional architecture or in commercial buildings.

Figure 28: Earthship interior, Taos, New-Mexico (Earthship Biotecture Institute, 2018)

Earthships

Although not part of the analysis in this dissertation, the earthship is a significant type of autonomous machine mostly built from earthen and reclaimed materials to create an off-grid habitat that integrates autonomous energy, water, and sewer systems. Earthship walls are comprised of a combination of earthen materials and reclaimed materials such as car tires, plastic bottles and cans. Earthship geometry and orientation are holistically designed to provide passive thermal/solar heating and cooling, solar and wind electricity, and water harvesting. The earthship technique and principles were developed by architect Michael Reynolds, in the past few decades, at the Earthship Biotecture, Taos, NM.

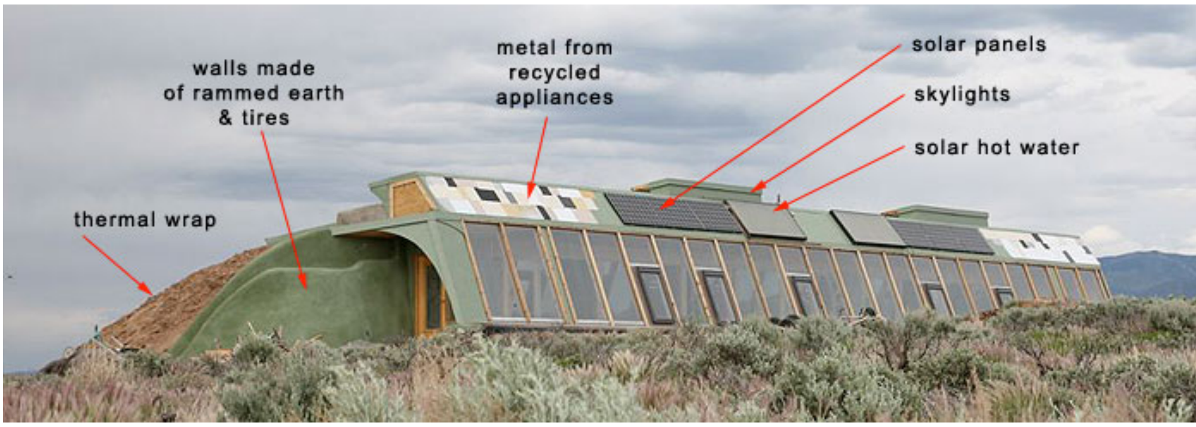


Figure 29: Features of the Global Earthship model (Earthship Biotecture Institute, 2018)

The advantages of earthship structures lie in their holistic design, featuring various recycled and passive strategies, as shown in Figure 29. Rather than having a singular approach for solving a certain problem, earthships provide a model to address various challenges. First, the challenge of material depletion is addressed by using natural and reclaimed materials. Second, the challenge of energy and water scarcity, as well as high utilities costs, are addressed by integrated autonomous electrical and water systems. Third, the challenge of food production and fertilizers are addressed by an integrated irrigation collection system that allows growing food locally. Lastly, the challenge of wastewater disposal is addressed by using a biological system that requires no chemicals but only a low-power pump. Most of all, earthships have been developed with the intention to allow accessible construction for people of socioeconomic class. It has also been successfully taught to people located in natural disaster areas (Freney, 2014).

Earthships have several disadvantages. First, earthship building permits are very challenging to obtain, similar to other underrepresented earthen techniques. Second, earthship applicability to an urban context can be very challenging due to the required orientation and thermal wrap. Lastly, earthships were developed to best perform in their original climatic environment, Taos New-Mexico, and may not be as optimized for climates others than those that are warm and arid (Kruis and Heun, 2007). Despite these disadvantages, earthships are a critical future that inspire new strategies for integrated decentralized energy systems, and innovative interpretation can be seen especially in Europe (Figure 30).

Figure 30: The Ardehuizen earthship ecovillage in Netherlands, self-sufficient use of microgrid (De Graaf, 2017)

2.2.1 Summary comparison of main earthen building materials and methods

A summary of the primary characteristics of the various earthen building techniques presented above is given in Table 1.

Table 1: List of earthen building methods and their key references and characteristics

	Also Known As	Raw Materials	Application	Key References
Cob	Monolithic Adobe, Puddled Earth, Topis (Spain), Zabour (Yemen), and Bauge (France).	Clay, sand, straw, water	Monolithically sculptures	(Evans et al., 2002; Snell and Callahan, 2009; Weismann and Bryce, 2006)
Rammed Earth	Taipa (Portuguese), Tapial (Spanish), pisé (French), hangtu (Chinese)	Clay, sand, gravel, water	Monolithically compressed	(Easton, 2007; Maniatidis and Walker, 2003; Taylor et al., 2008; P. Walker et al., 2005)
Light Straw Clay	Light clay, straw clay, slip straw, rammed straw, and leichtlehmbau (German)	Fiber (straw), clay, water	Infill	(Baker-Laporte and Laporte, 2015; Doleman, 2017)
Adobe	Mud bricks, In-situ adobe (when cast in place)	Clay, sand, straw/dung, water	Formed into Bricks	(Sanchez and Sanchez, 2001; Schroder and Ogletree, 2010; Varum et al., 2014)
Compressed earth blocks (CEB)	Cinva Bricks, Pressed Earth Bricks, Pressed earth block, Compressed soil block	Clay, subsoil, aggregate, water	Formed into Bricks	(Lima et al., 2012; Morel et al., 2007)
Earthbags	Sandbags (when used with sand), Eco-Dome, Super-Adobe	Earth, gravel, sacks	Tamped within bags	(Hart, 2015; Hunter and Kiffmeyer, 2002; Wojciechowska, 2001)
Earthships		Earth and upcycled materials, such as earth-packed tires	-	(Kuil, 2012; Preston Prinz, 2015; Reynolds, 1990)

2.3 Earthen building advantages and significance

Earthen building materials and methods exhibit limitations that should be addressed; for instance, they are labor intensive to construct (and thus might be costlier), and they are structurally weaker than conventional building materials (Hall et al., 2012), which places limits on their height. However, in the era of emerging design technology and structural knowledge, new opportunities are developed for the implementation of earthen materials in a modern environment. In order to be considered in mainstream construction, it is crucial to capture the advantages of earthen building.

2.3.1 Environmental advantages

Over the past few decades, it has been increasingly easy to extract, process, and transport building materials for construction (King, 2017). In this context, earthen building materials offer a much more sustainable alternative to conventional materials; Existing environmental Life Cycle Assessment (LCA) studies (that are further reviewed in section 6.1) illustrate that earthen materials and methods can potentially require less energy and emit less Green House Gasses (GHG) during their life cycle (Christoforou et al., 2016; Freney, 2014; Treloar et al., 2001). This is due to earthen materials' self-sustaining life cycle that begins with the utilization of raw soil, continues with natural processing, and ends with the reuse of recycled earthen materials, as shown in Figure 31.

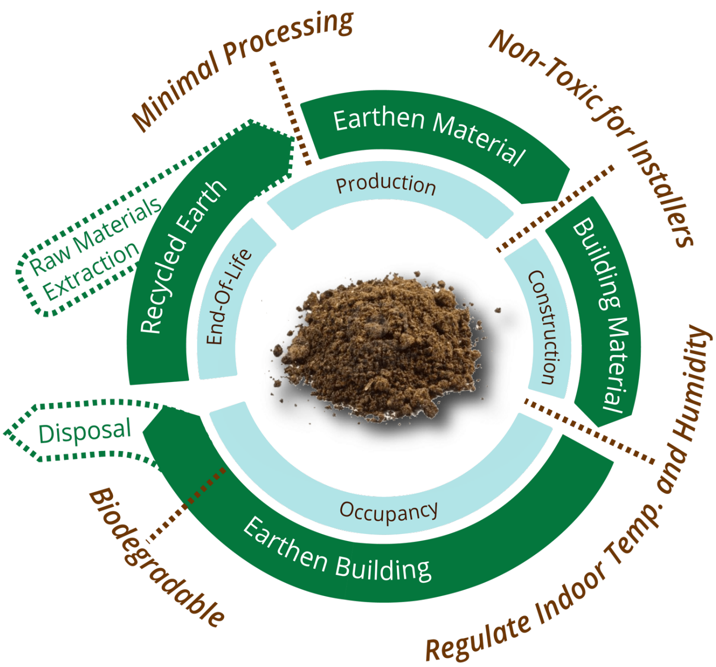


Figure 31: The life cycle of an earthen building component (image by Ben-Alon, with respect to (Schroeder, 2016)

In addition, we are also facing a challenge in regard to materials capacity – studies show that we do not have enough material capacity in the world to continue building the way we do in light of growing population and urbanization (Hendriks, 2001; King, 2017). From a climatic point of view, global climate change predictions (Rubel and Kottek, 2010) illustrate that demand for thermal mass may increase in order to prevent overheating in buildings. To date, the most used thermal mass (and building material in general) is concrete, which is essentially one of the main materials that requires reinvention; cement production, alone, is responsible for 6% of anthropogenic global emissions, and there is not enough cement-making capacity in the world for the predicted building demand (King, 2017). An additional constraint of modern conventional materials such as concrete is that the supply source does not reflect anticipated demand, driving up transportation cost. For example, the cement-production capacity in Germany exceeds that of all sub-Saharan Africa (Schmidt et al., 2012).

Relatively non-polluting and ubiquitous, earthen building materials and methods can be used as clay-based concrete, implementing clay as a natural binder rather than Portland cement. Unlike other binders, clay does not need to be activated by heat or chemical curing. Clay's binding forces are reversible, allowing earthen materials to be plasticized and reused. Clay does not require renewed energy input for its reuse, as opposed to, for instance, steel or glass. In addition, clay is biodegradable and can return to the earth in a cradle-to-cradle manner at the buildings' end of life (Hall et al., 2012).

Given these important benefits, earthen materials offer an imperative substitute to concrete in a world with raising energy costs, material depletion, and unpredicted changing temperatures.

2.3.2 Health and sociocultural advantages

According to a 1984 World Health Organization Committee report, approximately 30% of new and remodeled buildings worldwide are subject to occupants' disorders that are caused by poor indoor air quality (IAQ). Such poor IAQ can be caused by chemical contaminants that are found in building materials such as treated wood products and finishes, as well as by the biological contaminants, such as bacteria and molds, that result from inadequate ventilation and humidity buffering (US EPA, 1991).

In this context, earthen materials are non-toxic materials that are able to passively preserve indoor temperature and humidity within the comfort and health range. Earthen materials were shown to be able to buffer both indoor temperatures and relative humidity, due to their high thermal mass coupled with a high hygric mass (Hall et al., 2012). Earthen materials are able to keep indoor temperatures within the comfort range, especially in hot climates. Significantly, insulated earthen materials were shown to perform better than conventional insulating and mass systems. For instance, insulated compressed earth blocks (CEB) were shown to have significantly better indoor temperature stabilization as opposed to standard insulated lightweight timber frame with respect to internal heat gains. The insulated CEB wall system exhibited 32% more hours within the comfort range (21OC-26OC), as opposed to the standard insulated lightweight frame which overheated beyond 26OC and up to 30OC (Brambilla & Jusselme 2017). Similarly, an insulated rammed earth (IRE) wall system that was externally insulated with natural wood fiber panels was shown to achieve an 85% increase in thermal stability around the mean temperature of 22OC, resulting in 31% in heating, ventilating and air-conditioning (HVAC) energy savings, as opposed to conventional double brick wall system, under summer conditions (Serrano et al., 2016).

In terms of moisture buffering, earthen materials have a vapor sorption capacity that far exceeds other building materials. Due to their porosity, earthen materials are considered as 'breathing' materials, and studies have shown that they are able to maintain the 40-60% levels of relative humidity that are optimal for human health (Allinson and Hall, 2010; Pacheco-Torgal and Jalali, 2011). For instance, stabilized rammed earth (SRE) exterior walls were shown to be able to keep 50%-60% indoor relative humidity levels, as oppose to concrete walls with painted plasterboard that showed fluctuations in unconditioned indoor spaces between 40%-80% in warm weather (Allinson et al., 2010).

Furthermore, indoor air pollution also reduces occupant comfort. In this context, the ability of earthen assemblies to act as a buffer results in relative humidity falling in the optimal zone for minimal growth of bacteria, viruses, fungi, respiratory infections, ozone production, etc., as shown in Figure 32. To illustrate this ability, Darling et al. (2012) showed that clay wall coverings led to a 23-51% reduction in ozone concentration, and to a 29-72% reduction in aldehyde concentrations inside a structure containing both ozone and carpet, as opposed to painted gypsum boards.

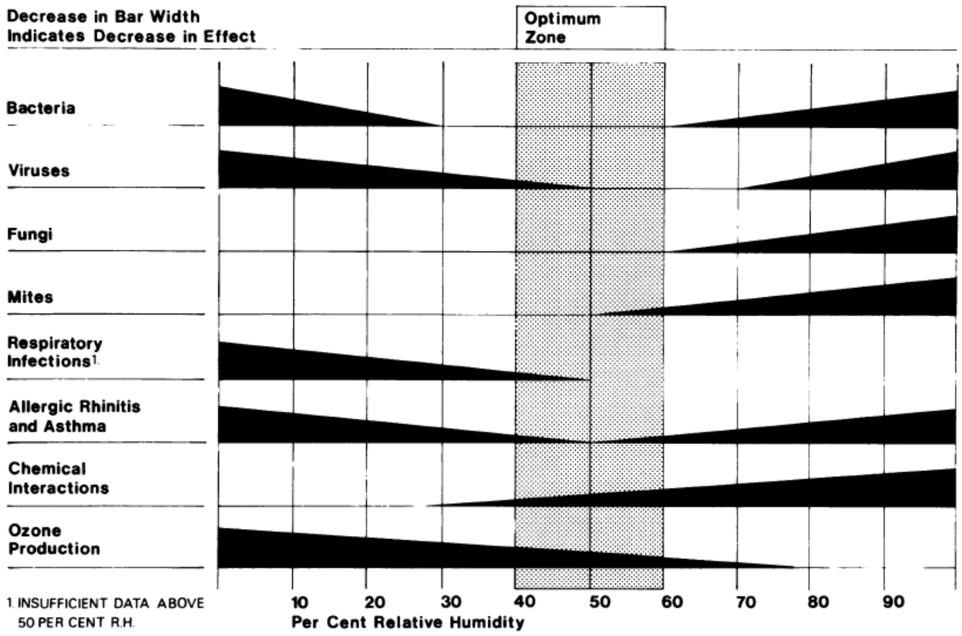


Figure 32: Optimum relative humidity range for minimizing adverse health effects (Arundel et al., 1986)

Their 'breathability' is also what makes earthen materials a good odor regulator. Tests have also shown that earthen walls are able to dampen high-frequency electromagnetic fields (emitted from antennas, radars, mobile phones, etc.), much better than other building materials (Röhlen and Ziegert, 2011). This attribute can be used to reduce electromagnetic radiation in spaces such as bedrooms, allowing a better sleep hygiene (Baliatsas et al., 2012).

Alongside their health benefits, earthen building materials and methods are important for sociocultural reasons. Approximately one third of the world population – mostly in developing countries – live in earthen structures. Many such regions are facing a continuous need for improvement of the existing living conditions and for reasons that range from natural disasters to population growth and emerging economy, the development of new housing infrastructure. However, it has been shown that exporting industrialized practices to developing regions does not work as well as the traditional local techniques.

Rather, enhancing traditional and local techniques might offer a better solution while preserving local identity (Jackson and Tenorio, 2010).

Many modern building codes that are based on heavily processed and/or commoditized materials such as concrete and steel products have been adopted by developing countries, leading to the exclusion of earthen techniques (Hall et al., 2012). Adoption of modern building codes eventually leads to the replacement of sustainable vernacular building practices that are associated with a smaller ecological footprint per capita, a goal that industrialized countries, ironically, are striving to achieve.

Earthen building faces various challenges in the context of globalization. In terms of enhancing traditional techniques, novel approaches to using earth in construction from around the world should be synthesized and formulated into guidelines that could then be used by local communities, allowing to preserve local techniques while enhancing performance and durability. This is especially significant in the context of earthquake resistance; many people in high seismic hazardous areas are living in earthen structures, e.g., Peru and Iran, as illustrates. In addition, improved traditional earthen materials were shown to be beneficial also in areas with seismic activity but with no previous earthen building experience, as illustrated in Figure 34.

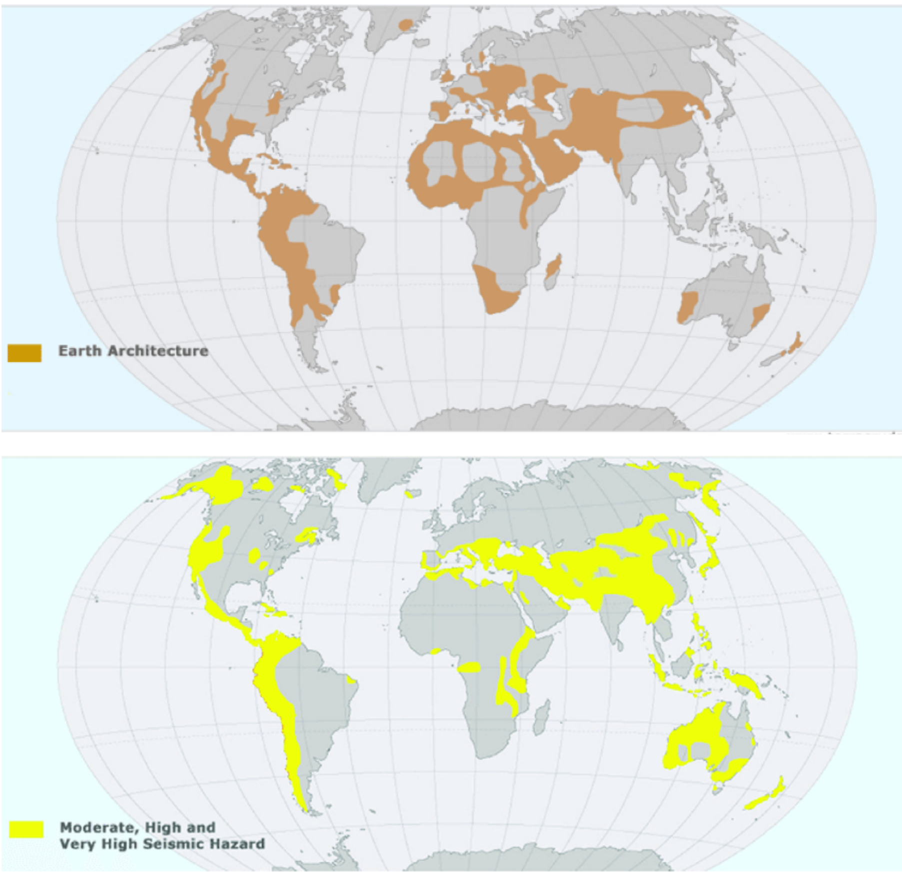


Figure 33: World Distribution of earthen building (up) and Moderate, High and Very High Seismic Hazard Zones of the World (right) (De Sensi, 2003)

Figure 34: Pegasus Children's Superadobe Project (left), survived the 7.6 magnitude 2015 earthquake as opposed to neighboring homes (right). (Cal-Earth News, 2015)

2.3.3 Economic and industrial advantages

There is an increasing demand for environmentally responsible building products, capturing a large share of the eco-marketplace. In North America, the Lifestyles of Health and Sustainability (LOHAS) market segment includes approximately 70 million U.S. adult consumers, who are willing to invest nearly 100 billion USD in green building products, especially in those that improve energy efficiency and reduce toxicity levels (French, 2003; Hall et al., 2012; Natural Marketing Institute, 2017). In addition, costly housing construction leads homeowners to seek affordable, and self-sustaining construction alternatives (Freney, 2014).

New housing construction is costly and requires longterm mortgage payments from homeowners. However, evidence shows that housing can be created affordably by incorporating earthen building materials and methods, mainly due to their on-site soil extraction and self-sufficient production process that in many cases require no additional costs for manufactured products (Hardin et al., 2003; Schroder and Ogletree, 2010). Many earthen techniques require little training and can be assembled by almost anyone, allowing the distribution of construction effort across a community (Evans et al., 2002).

However, there is a difference between owner-builder costs and commercial costs for earthen materials and methods. While the first is more simplistic economically, the latter is undertaken by a contractor and requires capturing costs of labor and learning curve effects (Hall et al., 2012). In terms of market economy, emerging earthen products[1] have been developed in the past few years such as the SIREWALL and Endeavour rammed earth wall systems that are successfully implemented in various large scale commercial wall systems (e.g., Nk'Mip Desert Cultural Centre in British Columbia, Figure 35), and CLAYTEC earthen plaster products that are used successfully in many commercial projects (e.g., the interior walls of Kolumba Museum in Cologne, a 2009 German Architecture Award winner, Figure 36).

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[1] Reference to commercial products in this document are made to provide examples for the reader and in no way implies endorsement of these products.

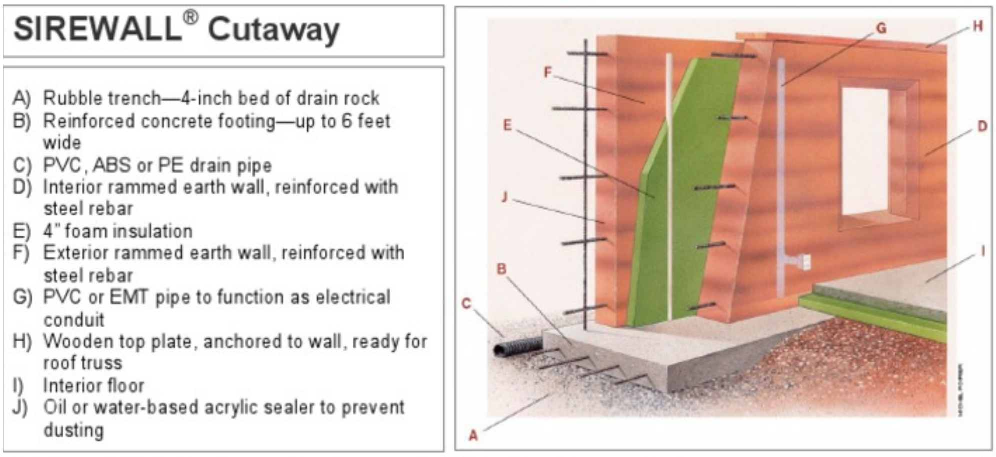


Figure 35: Nk'Mip Desert Cultural Centre utilizeing SIREWALL system (Sirewall, 2017)

Figure 36: CLAYTEC earthen plaster in Kolumba Museum, Cologne

2.4 Earthen building performance vs conventional materials

2.4.1 Selected performance parameters

The comparative assessment incorporates a selection of performance parameters of earthen building materials and methods. Three matrices were developed: a) a comprehensive list of technical, environmental, social, and economic assessment that should be used for earthen building, b) performance matrix of earthen materials versus wood and concrete, and c) a detailed performance matrix that compares among the different earthen building materials and methods.

Table 2 illustrates the selected parameters that are relevant to earthen materials according to (Schroeder, 2016). The majority of these parameters were used by the German Institute for Standards in their Earthen Building Codes (DIN 18123 for soil classification, DIN 18945 for earthen blocks, DIN 18947 for earth plasters, DIN 18946 for earth masonry mortar, etc.). Therefore, it is assumed that these parameters are especially relevant for the purpose of building policy (i.e., codes and standards) development. As Table 2 illustrates, each parameter group has several parameter areas and various specific parameters. In turn, each specific parameter could be relevant to one of more of the three earthen building life cycle phases (i.e., raw materials, earthen building material/product, and earthen building element/structure).

Table 2: Overview of main performance parameters that are required to assess earthen building. The selected parameters are marked in orange, • Test method/procedure known, o No test metho known (using the table from Schroeder, 2016)

Parameters			Earthen Building Life Cycle Phase		
Group	Parameter	Data point	Raw Materials	Material/Product	Element/Structure
Physical parameters	Structure parameters	Porosity	•	•	•
	Mass parameters	Bulk density		•	•
		Dry bulk density	•	•	
		Proctor density		•	
		Specific density	•	•	
	Grain size parameters	Grain size/ grain size distribution	•		
Chemical-mineralogical parameters	Acid-based reaction	pH value			•
	Type of clay mineral (class)	Activity	•		
		Cation exchange capacity	•		
	Natural additives	Lime	•		
		Water-soluble salts	•	•	•
		Organic Additives	•		
Material processing parameters	Plasticity	Moisture content	•		
		Liquid limit/plastic limit	•		
		Consistency	•		
		Cohesive strength/standard consistency	•		
Structural parameters	Deformation parameters, load independent	Moisture expansion; shrinkage (-) or swelling (+)	•	•	o

Parameters			Earthen Building Life Cycle Phase		
		Slump		●	
	Deformation parameters, load dependent	Modulus of elasticity/Poisson's ratio		●	O
	Strength parameters	Dry compressive strength		●	O
		Modulus of rupture		●	●
		Tensile adhesion strength			●
		Shear strength			O
		Wear resistance			O
Thermal and indoor air quality parameters	Hygric parameters	Capillary water absorption		●	O
		Frost test		●	
		Equilibrium moisture content			●
		Water vapor diffusion resistance factor			●
		Water vapor sorption			●
	Thermal parameters	Thermal conductivity		●	●
		Specific heat capacity		●	●
		Thermal transmittance coefficient			●
		Heat penetration coefficient			●
	Sound insulation parameters	Sound reduction index			●
	Fire protection parameters	Flammability (class)		●	●
		Fire resistance (class)			●
	Radiation protection parameters	Activity Concentration Index			●
	Limits for harmful substances	Metals/metalloids: TVOC; PAKL AOX; phenol index		●	●
Durability parameters		Erosion resistance			●
		Wind resistance			●
		Biological durability			O
		Susceptibility to aging			O
Architectural and aesthetic parameters	Surface effects	Quality grades Q (for finishes)			●
	Crack formation	Crack width control			●
	Color range				O
	Abrasion	Abrasion dust quantity			●
Economical and Construction Management parameters	Planning parameters	Construction trades			
		Activity sequencing			
	Scheduling parameters	Activities durations			●
	Cost parameters	Unit costs	●	●	●
		Other direct costs		●	●
		Variable and crashing costs		●	●
		Depreciation		●	●
	Quality control parameters	Foundations			●
		Floors			●
		Structural walls			●
		Nonstructural walls			●
		Ceiling			●
		Roof			●
		Plasters and finishes			●

Parameters			Earthen Building Life Cycle Phase		
Environmental parameters	Consumption of natural resources	Energy consumption (primary and cumulative)	●	●	
		Land use	●	●	●
		Recycling potential			●
		Heating value			●
	Environmental impact parameters	Global warming potential, CO_2-eq	●	●	●
		Human Health Particulate $PM_{2.5eq}$	●	●	●
		Acidification potential, SO_2-eq	●	●	●
		Overfertilization potential/ eutrophication, PO_4 potential	●	●	●
		Photochemical ozone creation potential POCP, C2H4-eq	●	●	●
		Tropospheric ozone precursor equivalent, TOPP-eq	●	●	●
		Risks for the local environment	●		●
End of life parameters	Material purity				o
	Disassembly and hauling parameters	Extraction class	●		
		Transport	●	●	●
		Risk potential	o		
	Reuse/recycling	Levels of harmful substances/assignment criteria LAGA			●

2.4.2 Earthen building materials vs. conventional materials

For the purpose of the earthen building performance-based assessment incorporated in this dissertation, physical, thermal, structural, and environmental parameters were selected from Table 2 according to the following criteria:

1. *Relevance to end-users' perception* – Environmental parameters that might influence end users' interest in using earthen building materials were selected.
2. *Relevance to policy decision makers* – Structural, thermal, and durability parameters were selected, rather than chemical-mineralogical and processing parameters that are mostly relevant to manufacturers and thus were not included.
3. *Availability of structural data and known test methods* - Available technical data in existing literature is a key requirement for the proposed performance-based assessment, mainly in the structural as well as in the building physics and indoor air quality parameters groups. Parameters with missing data sets were not included in the assessment, as well as parameters with unknown test procedures.

The performance of a building material describes its functioning in terms of declared characteristic properties. Depicted through levels, classes or short descriptions, these performance parameters can portray the main features of earthen materials as opposed to conventional assemblies.

2.4.3 Synthesizing the performance of earthen building materials vs. conventional assemblies

The performance of earthen building materials was studied extensively. However, knowledge is vast and scattered. Table 3 shows the main advantages (and weaknesses) of earthen materials (cob, rammed earth, and light straw clay) compared to conventional assemblies (timber frame and concrete masonry).

Table 3: Comparative performance-based assessment of earthen building materials and methods vs. conventional wood frame and concrete assemblies

	Performance Parameter	Earthen Building Materials			Timber Frame (Details for Conventional Wood Frame Construction, 2001)	Concrete Masonry (Farny et al., 2008) uninsulated (insulated)
		Cob	Rammed Earth	Light Straw Clay		
Physical	Density, kg/m³ (lb/ft³)	1,233, 1,458, 1,794 (77, 91, 112) (Goodhew, 2000, Table 8.1) 1,442 (90) (S. Goodhew and Griffiths, 2005; K. Heathcote, 2011)	2,002 (125) (K. Heathcote, 2011) 1,698- 2,195 (106-137) (P. Walker & Standards Australia, 2001, Table 2.6) 1,400-2,000 (87-125) (Bauluz and Bárcena, 1991) 1,698-2,323 (106-145) (Röhlen & Ziegert, 2011, Table 9.2)	240, 384, 400, 449, 529 (15, 24, 25, 28, 33) (Labat et al., 2016) 432 (27) (S. Goodhew and Griffiths, 2005)	NA	1,362-2,162 (85-135) (National Concrete Masonry Association, 2014)
Thermal	Thermal Resistance, m²K/W (ft² °F hr /BTU in)	0,06, 0.07, 0.05 (0.36, 0.38, 0.29) (Goodhew, 2000) 0.06, 0.07 (0.32, 0.38) (S. Goodhew and Griffiths, 2005)	0.02 (0.12) (K. Heathcote, 2011; Röhlen and Ziegert, 2011) 0.06-0.08 (0.32-0.48) (P. Walker and Standards Australia, 2001)	0.15, 0.14 (0.83, 0.80) (S. Goodhew and Griffiths, 2005) 0.21-0.36 (1.20-2.03) (Labat et al., 2016)	0.32-0.37 (1.8-2.1) (CISBE, 1999)	0.05 (0.28) (National Concrete Masonry Association, 2014)
	Specific Heat Capacity, kJ/kg°K (Btu/lb °F)	1.34, 0.921 (0.321, 0.220) (S. M. R. Goodhew, 2000, Table 8.1) 0.800 (0.191) (S. Goodhew and Griffiths, 2005)	0.599 (0.143) (Taylor et al., 2008) 0.908 (0.217) (Houben et al., 1994)	0.900 (0.215) (S. Goodhew and Griffiths, 2005)	0.841 (0.201) (S. Goodhew and Griffiths, 2005)	0.213-0.355 (0.0509-0.0848), depending on grouting (National Concrete Masonry Association, Atlas Block, 2008)
	Volumetric heat capacity kJ/m³K (BTU/ft³°F)	1655 (24,694) (S. M. R. Goodhew, 2000)	1830 (24,694) (Houben et al., 1994)	400 (5,968) (S. Goodhew and Griffiths, 2005)	10 (149) (S. Goodhew et al., 2005) (Rüdisser, 2015)	170-380 (2,536-5,670), depending on grouting (National Concrete Masonry Association, Atlas Block, 2008)
	Decrement factor time lag (hour)	13.84 for 400 mm (15.7 in) thick wall, 21.23 for 600 mm (23.6 in) thick wall,	10 for 300 mm (11.8 in) thick wall (Taylor and Luther, 2004)	18.41 for 600 mm (23.6 in) thick wall (S. Goodhew and Griffiths, 2005)	6.15, 6.7 (CISBE, 1999) (6.43)	8.9 (CISBE, 1999)

	Performance Parameter	Earthen Building Materials			Timber Frame (Details for Conventional Wood Frame Construction, 2001)	Concrete Masonry (Farny et al., 2008) uninsulated (insulated)
		Cob	Rammed Earth	Light Straw Clay		
		and 28.63 for 800mm (31.5 in) thick wall (S. Goodhew and Griffiths, 2005)				
	Hygrothermal performance, g/m^2 [lb/ft^2]	300 (0.0614) (Minke, 2000)			100 (0.0205) (Minke, 2000).	50 (0.0102) (Minke, 2000).
	Indoor RH amplitude			13.7% (Labat et al., 2016)		(22.6%) (Labat et al., 2016)
Environmental (Ben-Alon et al., 2019)	Embodied energy MJ_{eq}/m^2 ($kBtu/ft^2$)	86.4 (7.61) for 18 in (0.457 m) thick wall	71.1 (6.26) uninsulated, 95.7 (8.43) insulated with 2” extruded polystyrene, both for 18 in (0.457 m) thick rammed earth wall	100 (8.81) for 12 in (0.305 m) thick wall	241 (21.2) for 2x6 studs with fiberglass insulation	226 (19.9) uninsulated, 491 (43.2) insulated, for 8 in (0.203 m) blocks
	Global climate change $kgCO^{2}_{eq}/m^2$ ($lbCO^{2}_{eq}/ft^2$)	13.2 (2.71) for 18 in (0.457 m) thick wall	11.1 (2.28) uninsulated, 13.2 (2.69) insulated with 2” extruded polystyrene, both for 18 in (0.457 m) thick rammed earth wall	17.8 (3.64) for 12 in (0.305 m) thick wall	62.7 (21.2) for 2x6 studs with fiberglass insulation	53.1 (19.9) uninsulated, 74.8 (43.2) insulated, for 8 in (0.203 m) blocks
	Air acidification $kgSO^{2}_{eq}/m^2$ ($lbSO^{2}_{eq}/ft^2$)	0.00679 (0.00170) for 18 in (0.457 m) thick wall	0.00279 (0.000697) uninsulated, 0.0104 (0.00259) insulated with 2” extruded polystyrene, both for 18 in (0.457 m) thick rammed earth wall	0.0298 (0.00745) for 12 in (0.305 m) thick wall	0.0781 (0.0195) for 2x6 studs with fiberglass insulation	0.0607 (0.0152) uninsulated, 0.142 (0.0356) insulated, for 8 in (0.203 m) blocks
	Air particulate pollution $PM_{2.5eq}/m^2$ ($PM_{2.5eq}/ft^2$)	0.00247 (0.000230) for 18 in (0.457 m) thick wall	0.0014 (0.000134) uninsulated, 0.0026 (0.000242) insulated with 2” extruded polystyrene, both for 18 in (0.457 m) thick rammed earth wall	0.0262 (0.00243) for 12 in (0.305 m) thick wall	0.0574 (0.00533) for 2x6 studs with fiberglass insulation	0.130 (0.0121) uninsulated, 0.143 (0.0133) insulated, for 8 in (0.203 m) blocks
	Recycling potential	The majority of earthen building components can be reused by hydrating and plasticizing, with no additional heating or processing beside hydration and mixing (Röhlen and Ziegert, 2011)			Wood can be partially reclaimed, depending on the condition of the existing timber structure, including mold and mildew, presence of pests, bending, nails and other metal objects.	Concrete can be reused by crushing and using as an aggregate; however, this compromise the workability of the concrete. In addition, there is lack of proper standards for the specification of concrete that uses recycled concrete as an aggregate (Rao et al., 2007)

	Performance Parameter	Earthen Building Materials			Timber Frame (Details for Conventional Wood Frame Construction, 2001)	Concrete Masonry (Farny et al., 2008) uninsulated (insulated)
		Cob	Rammed Earth	Light Straw Clay		
Structural	Modulus of Elasticity MPa (psi)	76 (11,000) (Pullen and Scholz, 2011) 72 (10,371) (Rizza and Bottgar, 2015) 651 (94,420) (Miccoli et al., 2014)	4,143 (600,891) (Miccoli et al., 2014) 550-960 (79,800-139,200) (Schroeder, 2016)	Not load bearing	7,000-18,000 (1,015,300-2,610,700) along grain (Schroeder, 2016)	15,000 - 60,000 (2,175,600 – 8,702,300) (Schroeder, 2016)
	Modulus of Rupture, MPa (psi)	0.172 (25) (Pullen and Scholz, 2011) 0.979 (142) (Rizza and Bottgar, 2015)		Not load bearing	25-100 (3,626-14,503.7) (Mcaleavey et al., 1999)	0.158 (23) - 0.431 (63)
Economic	Unit cost, in USD/m^2 (USA/ft^2) wall surface	NA	0.3 m (12”) thick wall costs between $350-1050 ($32-100) when incorporated by a commercial construction firm (Röhlen et al., 2011)	NA	$500 ($45) (obtained from www.BuildingJournal.com)	0.3 m (12”) thick wall costs between $150-180 ($14-17) (Röhlen et al., 2011)
Others	Sound Transmission Class (STC)	57 (Racusin and McArleton, 2012)			33 (Racusin and McArleton, 2012)	55 (DuPree, 1980)
	Fire resistance	Fire resistant (DIN 4102-4, 2016; Schroeder, 2016)		Fire retardant (DIN 4102-4, 2016; Schroeder, 2016)	Combustible requiring treatment or oversizing (ISO type 1).	Semi Fire Resistive (ISO type 5).

2.4.4 Synthesizing the structural data of earthen building methods

Comparative analyses of the engineering properties and failure mechanisms of earthen techniques are limited, and the results are considerably scattered in the literature. Thus, an aggregated engineering data is shown in Table 4, using cob as a representative example.

Table 4: Engineering properties of cob, as recorded by laboratory tests

Parameter	Source	Test Method	Condition	n	Strength, MPa (psi)	Modulus MPa (psi)
Compression Strength & Modulus of Elasticity	Pullen and Scholz, 2011	ASTM C39		6	0.703 (102)	75.8 (11,000)
	Rizza and Bottgar, 2015	10 x 8 x 5 in. prisms tested parallel to long axis	conventional	4	0.608 (88)	71.7 (10,400)
			long straw added	4	0.283 (44)	37.2 (5,400)
			chopped straw added	4	0.524 (76)	64.8 (9,400)
	Miccoli et al., 2014	DIN EN 1052-1		1 Wall	1.59 (231)	651 (94,400)
	Saxton, 1995	ASTM C39		24	1.00 (145)	
	Kleinfelder, 2005	ASTM C39		6	0.827 (120)	
	Summit, 2016	ASTM C39		12	1.33 (193)	
Flexural strength / Modulus of Rupture	Pullen et al., 2011	ASTM C78		6	0.172 (25)	
	Rizza et al., 2015	Midspan flexure of 2 x 2 x 6 in. beams	conventional	4	0.54 (78)	
			long straw added	6	0.793 (115)	
			chopped straw added	6	0.98 (142)	
	Kleinfelder, 2005	ASTM C293		6	0.724 (105)	
Shear Strength & Shear Modulus ($G_{1/3}$)	Miccoli et al., 2014	ASTM E519		1 Wall	1.00 (145)	420 (60,900)

Specifically, it can be seen from Figure 37 that the compression tests result are scattered and depend not only on factors such as workmanship and weathering, but also on the testing procedure. Tests using small prisms or cylinders adapted from concrete test procedures such as ASTM C39 resulted in lower values than large wall specimens. This may be partially explained by the larger scale required for long straw stalks to fully affect the strength of cob specimens. In addition, for most of the tests, when the maximum load was reached, deformation was still possible since the specimen parts were still held together by the straw.

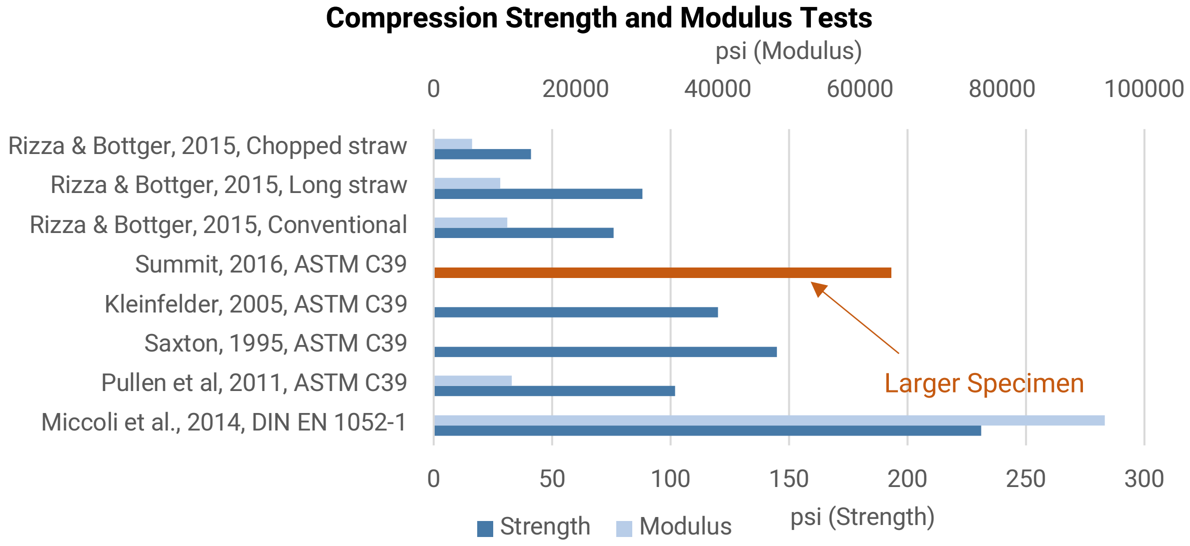


Figure 37: The various compression strength and modulus test results from existing literature

As per the existing rupture tests, Figure 38 illustrates fewer tests than the number of existing compression tests. It can be seen that most tests exceed the rupture requirement by NMAC, which requires a modulus of rupture of 50 psi. However, this is a value for bricks (approximately 8” by 16” by 6” tested in the flat position), and not for beams that are used in these tests. The test by Pullen et al. (2011) resulted in the lowest value, might be due to the smaller specimen size that is incorporated in the ASTM C78 testing protocol.

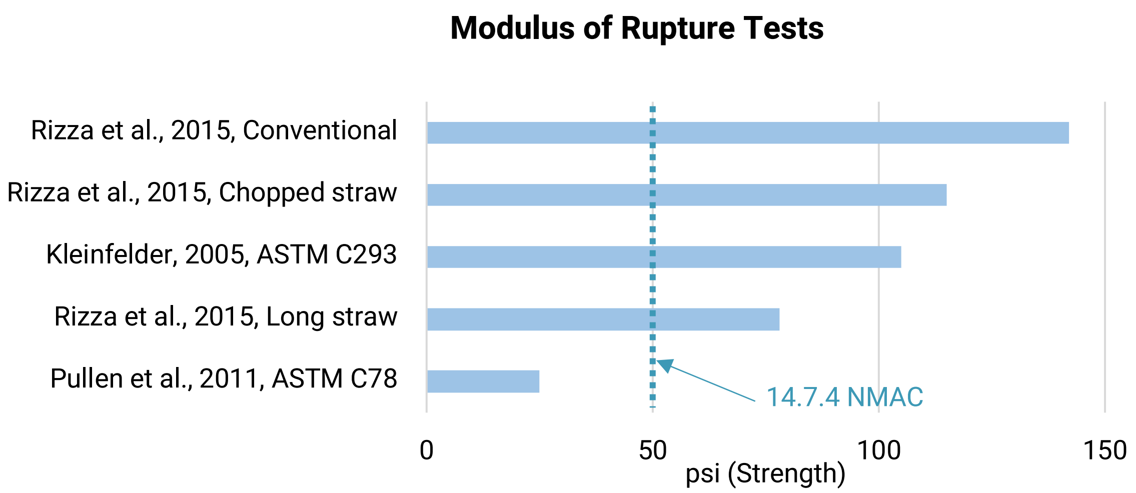


Figure 38: The various rupture strength and modulus test results from existing literature

Only one test was detected for shear, showing the major lack of existing cob shear tests. These tests are required to evaluate the failure mechanism of in earthquakes.

To conclude, cob material property tests results are highly variable and sensitive to test methods. Cob falls below standard requirements for adobe bricks although made from the same mixture, presumably due to the different specimen size (brick vs. cylinders or beams). Cob exhibits a certain ductility that proportionally increases the modulus of rupture. Overall, tests using small prisms or cylinders adapted from concrete test procedures such as ASTM C39 ASTM C78, or ASTM C293 result in lower values than small wall specimens. This may be partially explained by the larger scale required for long straw stalks to fully affect the strength of cob specimens.

One limitation of this preliminary study is the direct comparison of results from different test procedures. Standard test specimens for compression (ASTM C39) or flexure (ASTM C78 and C293) are intended to establish characteristic material properties and are conventionally based on reduced scale tests – such results comprise a lingua franca, of sorts, for engineers. Tests of multiple component wall units ("wallettes") (ASTM E519 and DIN 1052-1) are conducted at "full-scale" and provide system- and material-specific design properties of assemblies and thus capture additional effects such as workmanship. However, this limited comparison was performed due to the small number of studies, as well as with the intent to evaluate how various test procedure affect the different results.

For materials such as cob, which are expected to demonstrate considerable scale effects associated with the embedded straw, full scale component testing is preferred and should be developed as part of cob code/standard. A limitation therefore becomes cost. Standard tests are well-established, easily conducted almost anywhere in the world and require relatively inexpensive specimens (allowing a larger sample size) and test apparatus. Components tests are larger, more expensive (few samples) and require special test apparatuses (for example, ASTM E519). The engineering properties of cob are scattered and highly dependent on the selected test method. Specifically, standard concrete tests might not be adequate for cob testing, which should be tested in larger specimens to capture the woven straw mixture properties. Thus, regulatory development of cob requires defining these test procedures that should be adapted to cob's unique construction practices and mixture properties.

2.5 Identifying key gaps to the implementation of earthen construction

Current earthen construction is developing in a button-up manner, where pioneers and advocates are confronting technical, economic, and political constraints (Woolley, 2006). The mainstream construction industry is hesitant to adopt earthen building materials, and many professionals in the conventional building industry are unwilling to embark on what they perceive as non-proven materials and experimental techniques that lack standard approval, certificates, warranties (MacDougall 2016). This situation leads to lack of earthen building materials integration in mainstream construction, and the reasons behind this comprehensive challenge was not thoroughly distilled. Without knowing the mechanism behind the lack of implementation of earthen materials, solutions are hard to develop. For these reasons, it is necessary to acquire more information and regional examples through research. This is be done by assessing the in-depth situation at the field, obtained from earthen building professionals.

2.5.1 Conducting in-depth interviews to further identify additional barriers and required research

The main goal of the in-depth interviews was to gain detailed insights and examples of barriers to earthen building construction as well as explore the respondent's point of view about required research in the field. The in-depth interviews were one on one, providing an opportunity to generate rich understanding of respondents' perceptions, motivations, and views about earthen building motivation and barriers. In order to acquire data saturation, the in-depth interviews included 10 participants, an average between the sample sizes recommended by Dworkin, (2012), and Guest et al., (2006).

The process of conducting the in-depth interviews incorporated the steps recommended by Boyce & Neale (2006) and Kvale (1996), including: (1) thematic planning, (2) designing the interview protocol, (3) conducting the interviews, (4) transcribing, (5) analyzing, and (6) verifying the findings.

The 60-120 minute long in-depth telephone interviews included a semi-structured format to achieve conversational flow, in addition to a guiding questionnaire with open-ended questions, as shown in 0 A. Additionally, prompts were used to expand discussion and to elicit further views and experiences of the participants (Creswell and Creswell, 2017). Each expert was asked about the following subjects: (1) current barriers to implementing earthen building materials and methods in construction projects; (2) the role of each barrier among the other existing barriers; (3) suggestions to overcoming these barriers; (4) the conditions that have made previous earthen building projects successful; and, (5) suggestions for required contributions, especially in terms of academic research.

In-depth interviews recruitment and participants

Earthen building experts were recruited from a professional network group. Experts taking part in the interview needed to have earthen building practice for at least the past ten years. Overall, recruited interviewees including engineering, design, and regulatory experts, as detailed in Table 5. The interview screening and recruitment, as shown in (Appendix A: In-depth interviews), includes further details on the in-depth interviews objectives as well as benefits for the interviewees.

Table 5: Interviewees' profession, primary earthen building experience, and projects locations within the US

	Profession	Coding	Earthen projects	Projects locations within USA
1	Civil engineer	Eng1	Various techniques	All over USA
2	Civil engineer	Eng2	Cob	CA, AL, CO, HI, NM, OR, WA
3	Architect	Arch1	Various techniques	PA and MD
4	Architect	Arch2	Cob	CA
5	Architect	Arch3	Various techniques	VT
6	Architect	Arch4	Adobe	CA and NM
7	Builder and teacher	Teach1	Earthbags	CA
8	Builder and teacher	Teach2	Various techniques	OH
9	Builder and teacher	Teach3	Various techniques	CA and OR
10	Regulatory expert	Reg1	Various techniques	All over USA

The interviews were transcribed using an online software and then manually checked for errors.

Main earthen building gaps according to the literature

Five basic immediate barriers to the implementation of earthen building in mainstream construction were extracted from the literature:

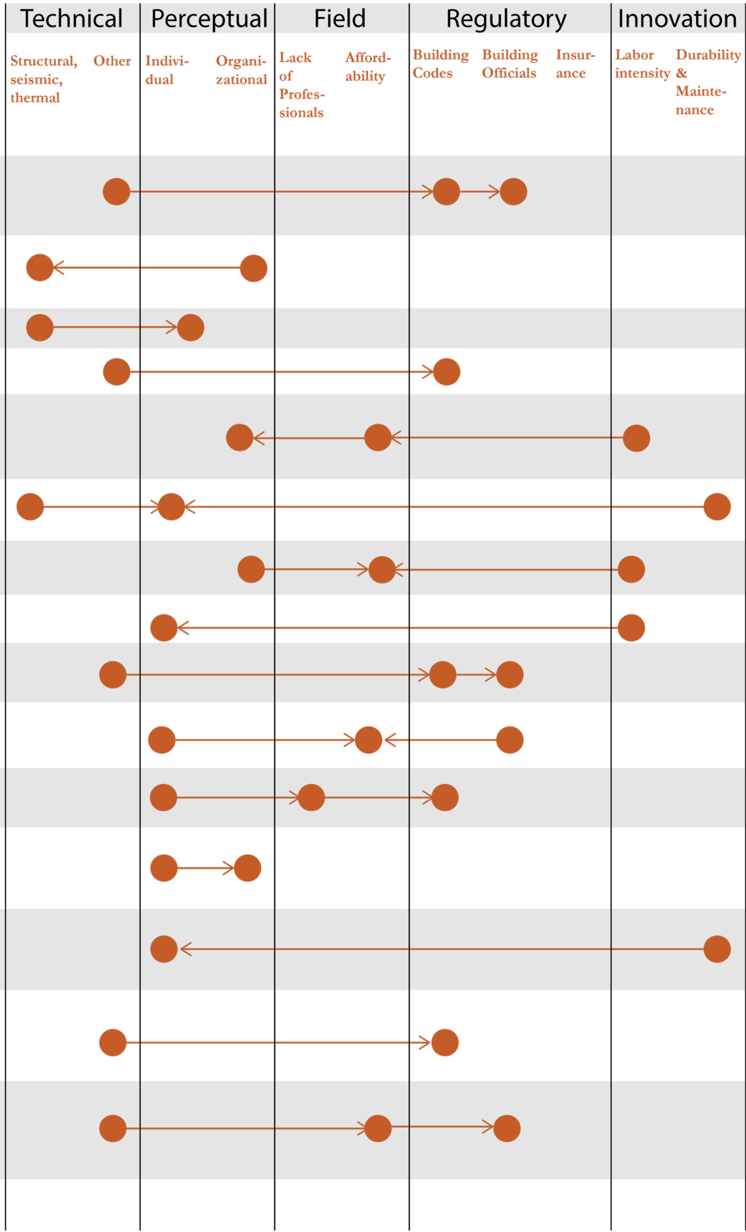
1. **Technical gap**, due to a growing body of research that has not yet been efficiently synthesized (Miccoli et al. 2014; Swan et al. 2011; Woolley 2006).
2. **Perceptual gap**, where earthen building is perceived as being 'low-tech' and having poor performance (Bristow, 2015; Colin MacDougall, 2008; Spisaková and Macková, 2015).
3. **Regulatory gap**, where earthen building techniques are omitted from building codes (Bristow, 2015; Eisenberg and Persram, 2009; Pullen and Scholz, 2011; Swan et al., 2011).
4. **Implementation gap**, due to lack of experience by the mainstream construction industry in using earthen building methods (Colin MacDougall, 2008; Swan et al., 2011).
5. **Innovation gap** and lack of earthen building innovative solutions (Woolley, 2006).

Using the identified gaps from the literature, each key challenge and its examples from the field were analyzed and assigned a flow of direction to assess perceived causes and effects.

In-depth interviews analysis

The main challenges were extracted and cited from each interviewee, and then analyzed as shown in Figure 53 according to their perceived causes and effects.

Arch1	"So I've had questions... from a fire marshal, who said, well, you need to show me that data on the fire rating for a clay wall. And so we had this conversation about whether you can light the dirt on fire in your yard, like dig a hole and make the dirt burn... I was trying to put it in a context that he has complete understanding of the material"
Eng1	"Nobody's done [earth] tubes like in a concrete lab at and test them for their compressive strength and do a comparison. How much do they shrink, how much strength do they develop and so on... We've done a lot of isolated tests, but people don't know what each other are doing because there's no central place where that knowledge gets gathered.
Arch1	"[A strong] misunderstanding... is that it's a mass material, not an installation."
Arch1	"I have not seen an actual fire testing, which is kind of silly that you would do fire testing on clay materials, that it would burn. There is that information for straw bale and it would be useful to be able to attach that to a set of drawings for earth…"
Arch3	"Takes more time to build [with earth]. I can build a stud wall in one day. I can drywall it in another day... that is fast construction. And cob, you can do three feet in a day if you've got lots of helpers…. It's time consuming. It is hard labor. It's really peaceful to most people. It's fun, but it's work. And then you have to wait for it to dry, which takes months for it to fully dry. And you're looking at a construction schedule with interest on a construction loan, which is 10, 12 %. That's money."
Arch4	"When you when you talk about adobe, even in California, it has like some definite negative connotations.... in the seismic country... Which I think are a little bit misleading. Obviously, there are safe and effective ways to do seismic adobe that's been proven by [researchers in] Peru. But the popular opinion maybe hasn't caught up with technology and research.
Arch1	"And their [conventional contractors'] whole entire goal is quickest turnaround, highest profit. So the barrier then to mainstreaming is how on earth do you tell a company like that you should build in a slow manner? [just to] motivate people, to move people?"
Teach3	"From a teaching standpoint, it's so much easier to teach you how to make cob and have even eight year olds participate. I'm not going to do rammed earth and have eight year olds understand what they're doing... cob and adobe are so user friendly."
Arch1	"[The barrier] from a building permit standpoint, with a permit official not having any idea how to look at an earthen material and know where in their experience and their knowledge of the building codes does this fall… So being able to provide them enough information so they know even how to think about it."
Arch1	"I just had an email today from someone who has been trying to build a straw bale home in Colorado, a very responsible thing to do, and they have been going around in circles with their permit official and their engineer, around and around until they just wear this person out and they decide not to pursue it."
Arch1	"Finding an engineer who understands earth enough or who wants to understand… an open minded engineer [that will be] willing to stamp something and engineer it for you… So sometimes you will go to an engineer and you will say, this is what I'm trying to do, and they're going to talk you out of it. You need to walk out the door and go call the next engineer on your list. To me, that's like a whole race."
Eng1	"The biggest barrier to the acceptance of earth and building is earth builders. It's the community of people in... the industrialized world...they are themselves now essentially the biggest impediment to the acceptance of earth because they're still living in sort of a cult like mentality of 'we're doing our thing over on the side here and building our adobe houses up into New Mexico or building rammed earth buildings and we're outlaws and we're proud of it'"
Eng1	"In fact, he's [David Easton, a rammed earth innovator] done a whole lot of research and he can make them [CEBs] made entirely with earth and industrial waste products. No cement, and they're strong enough. They meet all the performance specifications... But he says very often a client would say to him 'well put some cement in there anyway', they feel a little nervous... just can't believe it's going to work without the cement. It's kind of funny, but it's as if in the culture, not just for building professionals, the contractors and the architects, it's like people say, well, I've got to have some cement."
Arch4	"Structural engineers mostly don't know how to use it [the adobe section in the IBC]. You know, like the guidance in the code is really bizarre. It tells you that you can do it, but it's not very realistic. It's called empirical design for adobe masonry, but then it kicks you to TMS 402, which is this reference standard for design masonry structures, very technical manual. Once you get in there, it's never mentioned again. So, you know, it's like, OK, you want to design with adobe, just use this reference manual that never once uses the term adobe, and that's super confusing"
Reg1	"I was on a committee to try and do some code development for compressed earth blocks. Ultimately, what I found in the consensus, even within the compressed block community is that it's really complicated. There are so many different factors that go in to quality control and assurance of compressed earth blocks that there's really very little consensus even within block manufacturers, the machinery, the equipment manufacturers and folks in the field about what a good block is. Stabilized, unstabilized, to what extent it needs to be compressed. Can you over compress it? Water content and all kinds of like just about any single subject that comes up."



Eng2	"The [barrier] that's most difficult to solve is how to substantiate it [cob] as a structural material that could ostensibly pass code inspection. Getting code approval is also a barrier, but it's not going to be that big a deal if the backup material is there. So the toughest is to be able to take the material, the literature, the information that is available, and turn it into a structurally justifiable system."
Arch4	"Perception is a problem that's very regional. A lot of earthen structures in some places are considered valorized. It's like in Santa Fe… your home is worth so much more if it's made out of adobe. In other places, it's considered slum housing... those sort of cultural codes and kind of connotations that come with it, I think are very like community specific barriers."
Arch1	"[rammed earth] is just so expensive because the labor is so high or you need the engineering of the forms and you need a pneumatic machine and somebody who knows how to operate it"
Arch4	[Ben-Alon: And how come it's not mentioned in the IRC?] "I believe that's a legacy of when it was in the uniform building code. So the IRC is a more recent development. Basically, if you look back at the genealogy, it's got an immediate predecessor in the UBC [Uniform Building Code]... The IRC was created right about that same time as those consensus codes to sort of simplify things for residential construction."
Reg1	"As part of the Earth Builders Guild tag… we had this long term plan to try and insert all the good language into the IBC. But because we weren't familiar with how the process worked at the national level, we figured we would just take one that was really easy to demonstrate, and see how it went. So we made this code proposal to change the portion of the IBC that disallowed earthen mortars on unstabilized adobe bricks…. and I had heard that there was this proposed change by the Masonry Society…. we were not paying a whole lot of a attention. So I showed up and in Louisville, and I'm going through all of the proposed actions in my hotel room at like 6:00 in the morning…..and I'm like, oh my God, they actually want to take, you know, adobe out, like this entire section. Get it out of the IBC and put it into the IRC…. Apparently they thought that no one is using adobe for commercial construction. But this would be a big deal….even more perilous that there were two proposals: their proposal to adding it to the IRC and their proposal to delete it from the IBC were in two separate proposals so we were faced with the potential that the proposal to add it to the IRC could be declined and the proposal to remove it from the IBC could have been accepted and then it just would have vanished entirely… So we ended [spending] three crazy days trying to reconstruct this thing"
Arch4	"It's [code hearings] really heavy politics in a way that I didn't really expect. You go into the meeting and you think, oh, well, everything is just going to be evaluated on its basic terms just based on the language of the proposal. But in fact, what happens is that if you want to get something done there, there's all these different stakeholders from FEMA, to representatives of each of the insurance industries, SEAOC and these engineering societies, all of this stuff. And pretty much if you want to succeed, you need to make sure that you don't have opposition from any of them, or at least that everyone stay quiet in their seats"
Arch4	"Another barrier is - real vs perceived energy balance for Adobe. So that the issue is that the codes, as they try and increase the energy performance of buildings, are getting more and more of these [insulation] standards. It's all a really good idea. However, the quantification of high mass structures, and specifically adobe, is not really well known. There were a lot of studies that were done on this in New Mexico in the 70s and 80s, the publications are out there, but they haven't been built into the building codes. They're not in the energy compliance modeling software like energy pro - it doesn't include it. So what ends up happening is that you get into this situation where you have to treat a mass wall assembly basically on a thermal resistance basis only. So I have this 14 inch thick earthen wall which has an effective R-value of 3, right? And so what does that mean? You know, when you go into the city, sometimes they're like, OK, well, that's fine, just for walls, and add a six inch back insulation on the exterior, additional framing, and then a stucco, all that stuff that defeats the entire purpose. Even worse is when people are [adding] the insulation in the inside, which is entirely counterproductive because you're putting your mass on the outside of the conditioned envelope. Super bad."
Arch4	"In New Mexico, there's this trade off sheet that I truly like gives you an effective R value for mass walls. But it hasn't been published or updated, something like 20 years. So even though they [the jurisdiction that reviews permit applications in New Mexico] are very familiar with it, a lot of people that are submitting a permit don't know about it. So people end up getting penalized using this, and having to design really expensive systems and mitigations for a problem that doesn't really exist except that the math isn't there."
Arch4	"There is lots of problems with the [New Mexico Earthen] code. It was written, I think, in the late 80s or early 90s.... the language isn't super sophisticated. It leaves some big gaps for interpretation, both for a designer builder to do something that might be a really bad idea as well as for officials to misinterpret the code and not allow something that's a good idea."
Arch2	"The third [barrier] would be finding clients who are willing to go through the process, given what the process is now. Finding people who are willing to financially able to support it. Few and far between and easily deterred from the fanciful desire to build with cob. There is some fanciful desire, and then there's the reality"
Arch2	"The initial expense that clients are going to have to deal with is the engineering and architectural fees in order to get a design and plants which will be able to be submitted for building permit. So that's an expense that's not talked about in the fanciful approach, which is the approach that proselytizing for earth. Selling something which sounds really good, but which can't really be fully supported. So the selling of cob is that here is this thing and you can do and it's really cheap. But the reality is, that it's only real if you're willing to do it illegally, in the current climate of lack of approval."
Arch2	"Most people, they're busy making a living and most people who would be willing to have the resources if they're not independently wealthy, and are not going to be able to do the sweat equity approach, which keeps cob in the realm of being inexpensive. So then you going to wind up paying for professional construction, which is expensive. So the cheap part of it all is, that the materials are cheap and sweat equity labor is cheap. But if those are not available, then the cheap materials don't solve the problem of keeping it within the realm of affordability."

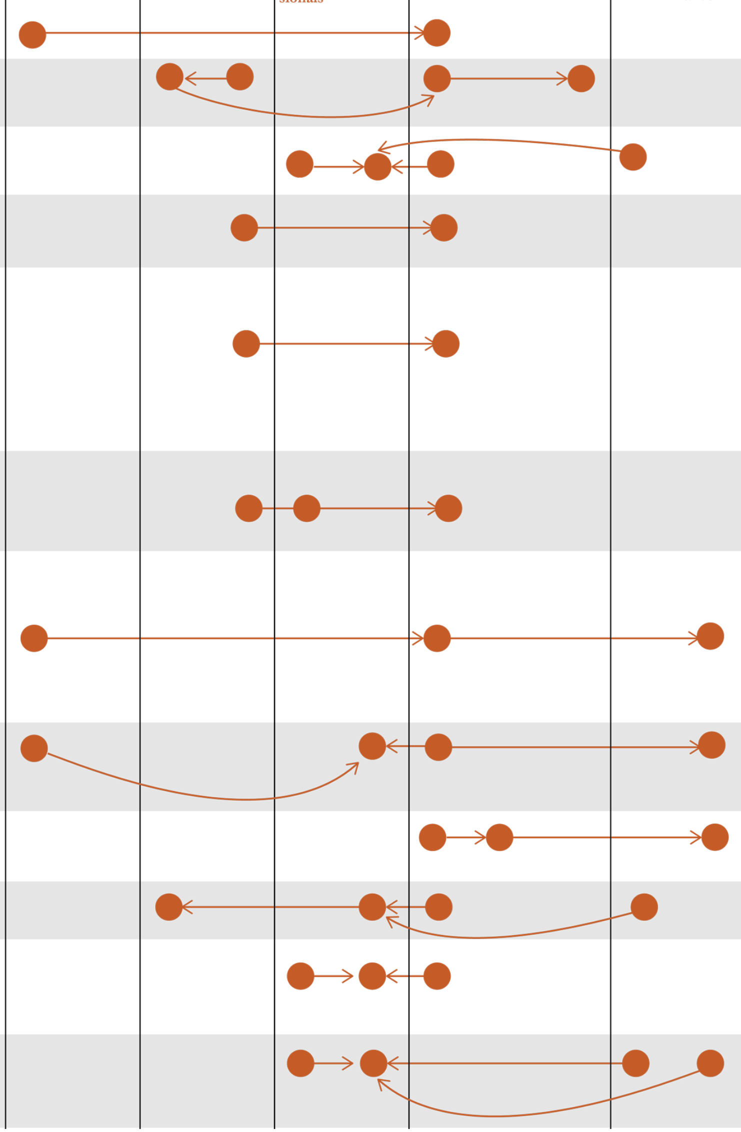


Figure 39: Overview of the in-depth interviews analysis, analyzing key challenges by experts interviewed according to their cause and effect

The causes and effects from Figure 53 were quantified and analyzed as shown in Figure 40-Figure 43, where the thickness of the flow lines represents number of instances from the examples by the experts interviewed.

Technical gap – scattered engineering data makes it challenging for earthen building advocacy that is grassroots with little funding

The technical gap was shown to be the most significant cause, largely leading to other gaps, as illustrated in Figure 40. Many interviewed experts highlighted the need for accessible, synthesized engineering data, which is currently scattered. While there is a growing body of research into the engineering properties of earthen building materials, this research has not yet been efficiently aggregated. It is therefore difficult to address the variability and accuracy of materials data, as well as to quantify earthen buildings' true performance for different climate and hazard conditions

While technical justification requires expertise, time and monetary resources, advocacy for earthen building regulations becomes challenging. For instance, some of the interviewees that deal with cob described their main challenge as the justification for including cob in code amendment meetings. This task requires advocates to synthesize existing performance data on cob, as well as to conduct and support tests to fill-in missing data that could validate cob, especially in earthquake zones, as further analyzed in Section 6 of this dissertation. Large amounts of technical data that is varied and scattered, as well as lack of organizational consensus on acceptable practices were shown to lead to a regulatory challenge. For instance, the following example illustrates the effects of the technical gap and organizational perception on the regulatory gap:

> "I was on a committee to try and do some code development for compressed earth blocks. Ultimately, what I found in the consensus, even within the compressed block community is that it's really complicated. There's really very little consensus even within block manufacturers and folks in the field about what a good block is. Stabilized, unstabilized, to what extent it needs to be compressed, can you over compress it, water content and just about any single subject that comes up."

A final, and often overlooked aspect of the technical gap is the skill required to draft proposed code language and amendments once a consensus has been reached (Harries et al., 2019).

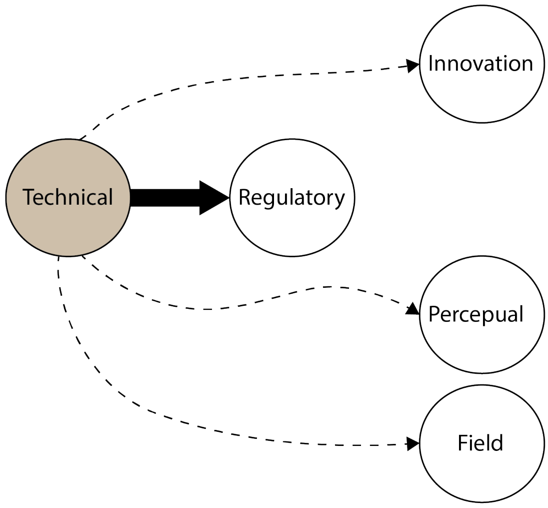


Figure 40: The effect of the technical gap on the other gaps

Perceptual gap – earthen building materials are gaining popularity but are still perceived as being "dirty"

Similar to the technical gap, the perceptual gap leads mainly to a regulatory gap, as illustrated in Figure 41. According to experts, earthen construction is gaining popularity, and there have been an increasing number of workshops and seminars to building with the various earthen techniques, targeted for individuals and communities. However, experts repeatedly mentioned that earthen building materials are still often perceived by both clients and contractors as being unreliable and "dirty". For instance, according to an interviewed structural engineer, homeowners are often skeptical in regard to rammed earth durability and ask to incorporate Portland cement for stabilization:

> "In fact, [a rammed earth product developer] has done a whole lot of research and he can make them [rammed earth blocks, aka CEBs] made entirely with earth and industrial waste products. No cement, and they're strong enough. They meet all the performance specifications. But he says very often a client would say to him 'well put some cement in there anyway', they feel a little nervous and just can't believe it's going to work without the cement. It's kind of funny, but it's as if in the culture, not just for building professionals, contractors, and architects, it's the people say, well, I've got to have some cement."

Furthermore, according to an interviewed builder, many projects that take place within US Native Nations reservations specify the use of CEB (that have an appearance similar to conventional bricks) due to their dual ability to provide a sense of connection to earth by using earthen materials, as well as a sense of pride by living in a structure that resembles a "conventional American house". This anecdote illustrates that perceptual challenges to using earthen materials could be addressed by making earthen assemblies resemble conventional techniques.

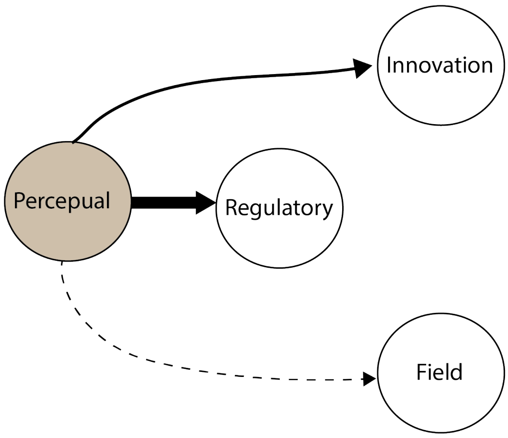


Figure 41: The effect of the perceptual gap on the other gaps

Regulatory gap – earthen building can be affordable but their omission from building regulations make it more expensive. Illustrated in Figure 42, the regulatory gap was shown to heavily effect the field gap. According to the in-depth interviews, earthen building can and should be affordable, however, omission from building codes (and from mandatory or at least code-compliant standards) inflate engineering and regulatory costs and therefore construction duration due to the required back-and-forth between construction professional and local code officials. As a result, residential earthen projects often are only possible for single-family rural owner-builder, or those with sufficiently high-incomes.

Interviewees also affirmed that these conflicts may result in bypassing regulations and compromised design. For instance, lack of organized regulatory resources for earthen building have led to experts moving away from earthen building best practices, as shown in the following example:

> "In New Mexico, there's this trade-off sheet that gives an effective R-value for mass walls. But it hasn't been published or updated for 20 years. So even though some [of the jurisdictions that review permit applications in New Mexico] are very familiar with it, a lot of people don't know about it. So [architects and engineers] end up getting penalized for using this sheet, and then having to design really expensive [conventional building] systems and mitigations for a problem that doesn't really exist except that the math isn't there."

Other examples of compromised design of earthen structures due to the regularly gap includes integrating steel reinforcement within clay walls (structurally ineffectual and a possible durability concern), placing earthen materials within a structural frame, and intentionally designing structures to a size that will not require code approval.

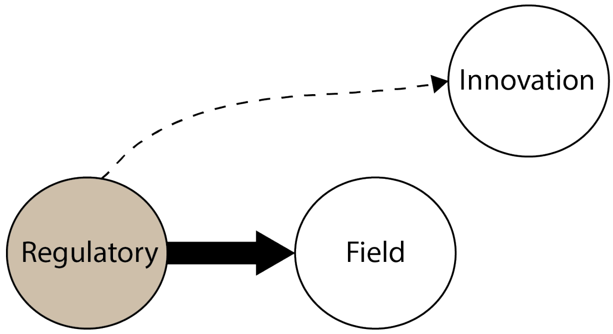


Figure 42: The effect of the regulatory gap on the other gaps

Implementation gap – lack of earthen building contractors and educated professionals

Ultimately, and unsurprisingly, all identified gaps – technical, regulatory, etc. – result in an implementation gap (Figure 36). The implementation gap shown to be more *effected* than *effecting*.

Experts described a lack of experience by the mainstream construction industry in using earthen building materials and methods. According to interviewees, lack of experienced and trained professionals lead homeowners who are interested in earthen building to either use other, more conventional materials, or to seek an independent construction path as owner-builders. Especially for earthen techniques that require machinery, such as rammed earth, experts were challenged in locating builders and engineers, as described by the following expert interviewed:

> "[Rammed earth] is just so expensive because the labor is so high and you need the engineering and you need a pneumatic machine and somebody who knows how to operate it"

Several interviewees highlighted that the conditions that made successful earthen building projects were good collaborations among professionals, specifically with the local code officials; regions with code officials that were knowledgeable or sympathetic to using earthen building, made very successful projects. It is also recognized that code officials in many – particularly smaller, less well-funded jurisdictions – are often not construction professionals themselves. In such cases, the officials are reliant on a clearly delineated code in order to make compliance decisions (a 'checklist' as it were). Ironically such jurisdictions are exactly those were earthen building may be expected to most appropriate and attractive.

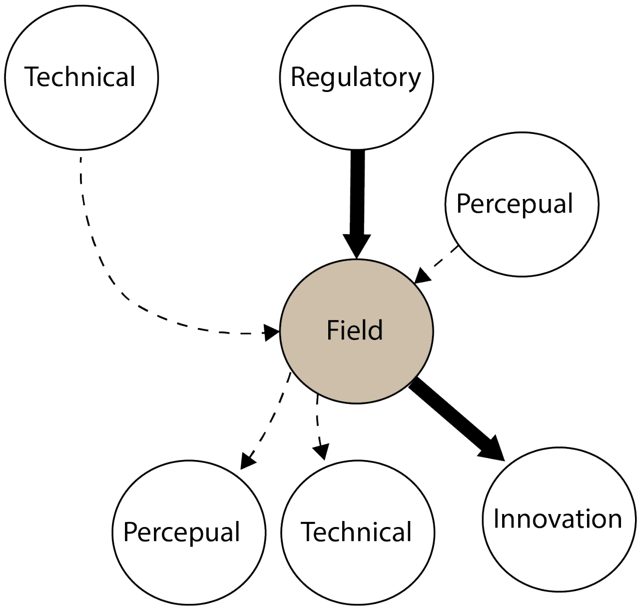


Figure 43: The correlation between the field gap and the other gaps

Innovation gap – lack of research, higher education, and technology development

According to the in-depth interviews, earthen building is constrained within a "traditional" niche, and in order to evolve, earthen construction requires more academic research about structural, durability, and construction methods enhancement.

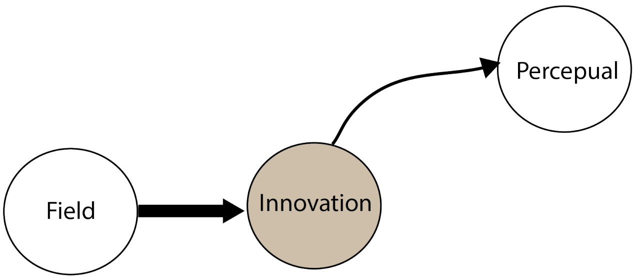


Figure 44: The effect of the regulatory gap on the other gaps

According to the experts, the demand for earthen building practice is not realized, leading to the lack of educated experts who might innovate the traditional building techniques and products. In terms of construction efficiency, experts suggested various ways in which earthen construction can be enhanced. For instance, experts included suggestions about mechanization, enhanced mixtures and quality control tests, using innovative technology such as 3D printing, incorporating BIM and machinery throughout the construction process.

In terms of structural integrity, experts mentioned the need to find new ways to reinforce earthen structures, as well as finding innovative ways to test soils and to naturally provide mixtures with added strength or stability.

The gap relationships and interdependencies

Following the in-depth interviews, the interdependency among the above gaps was observed and depicted as illustrated in Figure 45.

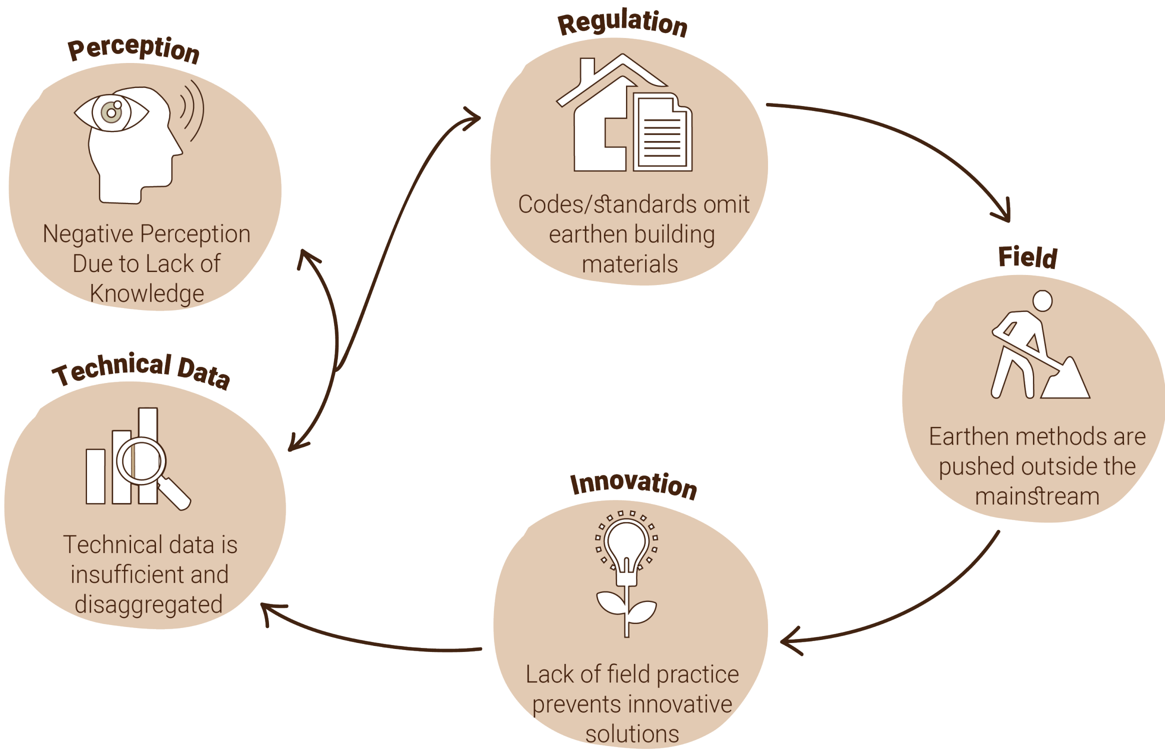


Figure 45: The cycle of key implementation gaps of earthen building materials

Accordingly, the technical and perceptual gaps are inter-reliant, and both lead to the regulatory gap. Lack of technical data leads to a poor reputation of earthen building materials, and vice versa. Negative perception results in fewer technical tests, and less research conducted on earthen building. In turn, insufficient engineering data and negative perceptions lead to omission from building codes , as well as to challenging building permit processes for earthen buildings. As a consequence, standard permitted structures are hard to achieve, leading to lack of experienced building professionals. Finally, demand for earthen building materials and methods is not realized, leading to the lack of educated experts who might innovate the traditional building techniques and products.

2.5.2 Summary of missing research

Existing earthen building literature is divided by research in a variety of disciplines: architectural design, structural engineering, public policy and construction. This leads to a disconnection that might stall continuing understanding of these materials, their applicability and limitations. Specifically, Table 6 shows that While literature is sparse in most areas, some earthen techniques have no known published studies.

Table 6: Earthen building matrix of existing studies and identification of missing areas of research

Method	Environmental Performance	Structural Performance	Thermal and Hygrothermal Performance	Architectural Design and Building Guides	Policy and Regulation
Adobe	(Christoforou et al., 2016; Shukla et al., 2009)	(Silveira et al., 2012; Varum et al., 2014)	(Revuelta-Acosta et al., 2010)	(McHenry, 1984)	(ICC, 2015; New Mexico Regulation & Licensing Department and NMAC, 2015; Pima County Development Services, 2013)
Rammed Earth	(Serrano et al., 2012; Treloar et al., 2001)	(Maniatidis and Walker, 2003)	(Allinson and Hall, 2010; Dong et al., 2014; M. Hall and Allinson, 2009)	(Maniatidis and Walker, 2003; P. Walker et al., 2005)	(New Mexico Regulation & Licensing Department and NMAC, 2015; Pima County Development Services, 2013)
Compressed earth blocks (CEB)		(Lima et al., 2012; Morel et al., 2007)	(Cagnon et al., 2014)	(Wanek et al., 2002)	(New Mexico Regulation & Licensing Department and NMAC, 2015; Pima County Development Services, 2013)
Cob		(Miccoli et al., 2014; Pullen and Scholz, 2011; Saxton, 1995)		(Evans et al., 2002; Weismann and Bryce, 2006)	
Earthbags		(Canadell et al., 2016; Daigle et al., 2011)		(Hart, 2015; Hunter and Kiffmeyer, 2002; Wojciechowska, 2001)	
Earthships	(Freney, 2014)		(Freney, 2014; Ip and Miller, 2009)	(Preston Prinz, 2015; Reynolds, 1990)	

2.6 Research methodology

This dissertation incorporates a mixed-method design. Using an explanatory sequential methodology, the following methods and procedures are employed:

Perception analysis using perception surveys – this step identifies what are the main challenges and factors that motivate end-users to implementing earthen materials and methods and how can negative perception be replaced.

Environmental assessment using LCA – this step quantifies potential environmental impacts of earthen building materials comparing these with conventional building materials.

Policy analysis using the online surveys and in-depth interviews – this step evaluates existing earthen building policy as well as develops recommendations for policy improvements.

Figure 46 illustrates the relationships between the studies and methods used.

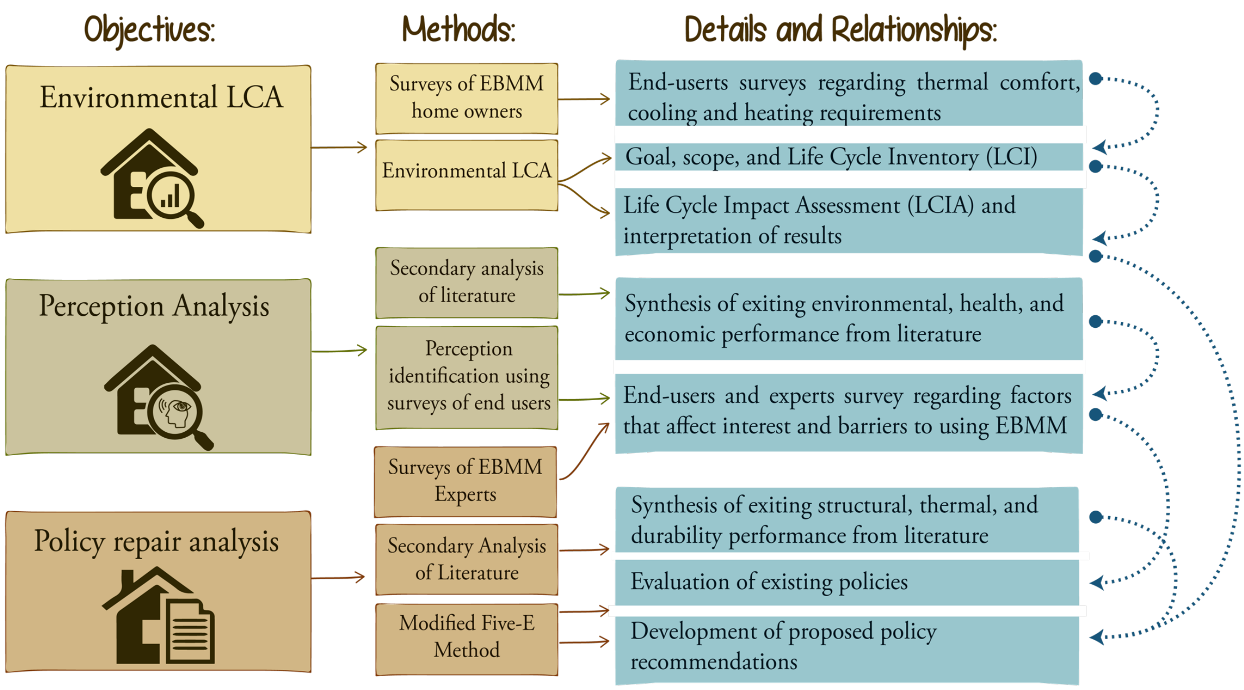


Figure 46: Overview of the research studies and their relationships

Data collection using surveys and interviews are used for each study: (1) for the perception analysis, in-depth interviews of experts are used to identify factors that affect interest and barriers to using earthen building materials and methods for the surveys, (2) for the LCA, surveys of homeowners are used to inform and validate the thermal performance of earthen houses and (c) for the policy analysis, experts surveys and in-depth interviews are used to analyze the role and causes of regulatory barriers.

2.6.1 Scope of each study

The climate focus of this dissertation is dry, both warm and hot climates, due to the suitability of earthen building materials to these climates in terms of thermal performance and durability (Racusin and McArleton, 2012). In order to choose specific climate zones and to identify relevant geographical regions, two climate classifications are used: Köppen-Geiger World Climate Classification, due to its broad representation of climates worldwide, and ASHRAE International Climate Zones that correlate to building envelope climatic criteria.

The LCA in this dissertation uses data that is relevant for the USA. In addition, other sections in this dissertation address areas outside the USA that are relevant to the dry warm/hot climate, including Australia, New-Zealand, South America, and some parts of Europe. In the US, addressed areas are Arizona, Texas, California, New-Mexico, Nevada, Utah, and some parts of Oregon. In addition, some areas of temperate climate are also included, such as Colorado, due to the historical use of earthen materials in temperate regions in Figure 47.

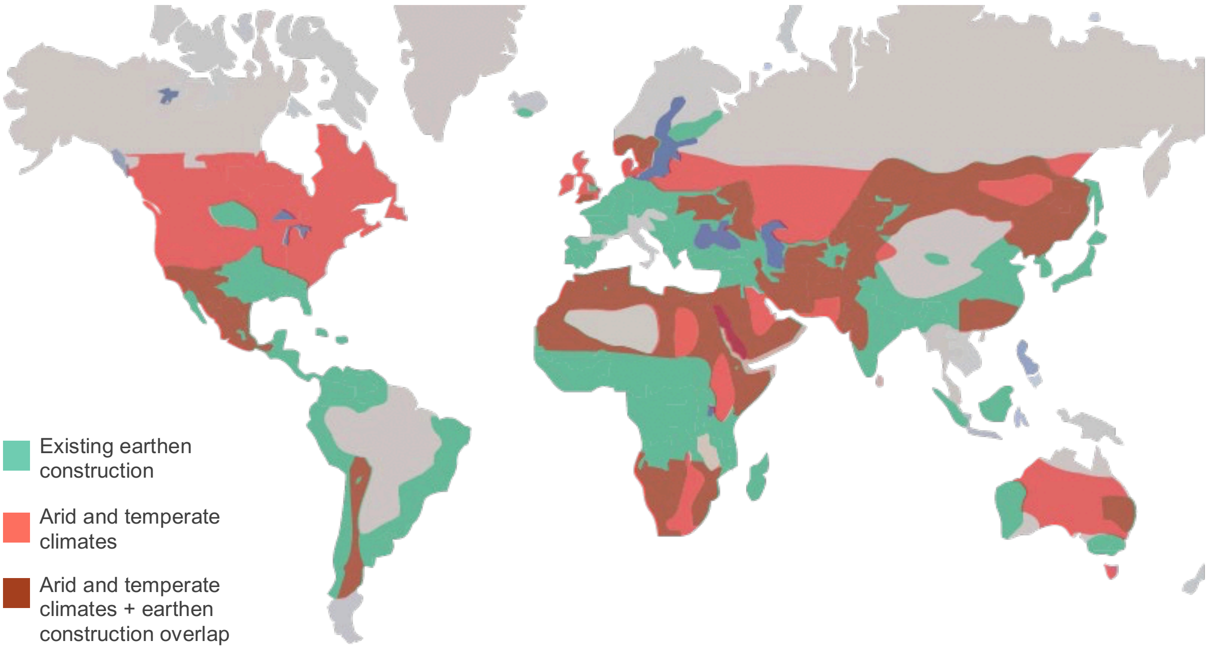


Figure 47: Current earthen architecture and climate zones (Gupta, 2019).

The perceptual, technical, and regulatory analysis are each designed to address a specific scope, as illustrated in Figure 48. For instance, the in-depth interviews, as well as the LCA, focus on the USA. The online survey is distributed to a global respondent audience. The policy analysis assesses earthen building codes from around the world, while focusing on recommendations for the USA context. Although this dissertation aims to analyze earthen building as a whole, for specific technical assessments, such as the thermal performance and LCA, residential construction is considered.

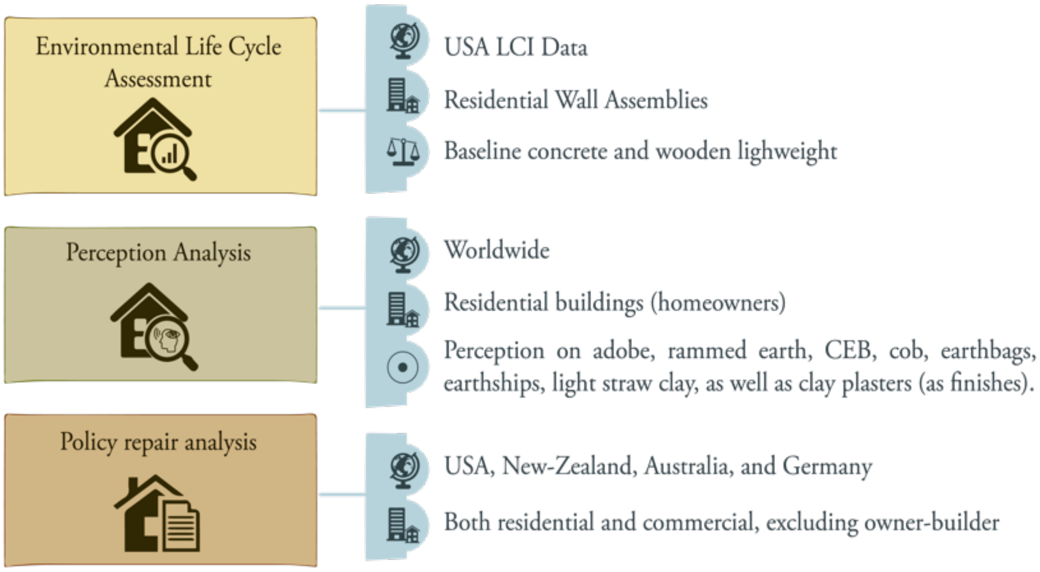


Figure 48: Scope parameters for each study

A further detailed list of the chosen parameters for each study is encompassed in Table 7 and include geographical scope, building type and density, building height, chosen earthen building materials and methods, and chosen baseline conventional assemblies.

Table 7: Detailed scope parameters for each stage in terms of geography, building type and building methods

	Environmental LCA	Perception Analysis	Policy Repair Analysis
Geographical Scope	LCI and LCIA focus on USA data and specifically on states located in South-West USA (e.g., CA, AZ, NM, TX, NV).	In-depth interviews include experts from USA. Online survey includes respondents from around the world	Analysis includes USA-based earthen building regulation such as ASTM E2392-M10 and NMC 14.7.4, while comparing to foreign codes.
Building Type and Density	LCI incorporates residential buildings. Medium urban/suburban density is considered for transportation and construction parameters.	Data is obtained from experts and homeowners of earthen structures in all densities.	Both residential and commercial building codes and standards are analyzed, in all densities excluding rural sections (i.e., limited density and owner-builder permits).
Building Height	Adobe, rammed earth, cob, CEB, and earthbags → limited to 1-2 floors Light straw clay, dry panels, and clay plaster → used as infill, height according to the structural frame		
Chosen earthen building types	Cob, rammed earth (both insulated and uninsulated), light straw clay	Analysis includes cob, rammed earth, adobe, CEB, light straw clay, as well as clay plasters (as finishes).	Regulation documents that relate to all earthen building techniques are analyzed. Some challenges relate to specific codes/standards and thus to specific techniques.
Chosen baseline	Conventional insulated wood frame, concrete masonry units (CMU) (both insulated and uninsulated)	–	Comparison to other earthen building codes/standards is limited to New Zealand Standards, Australian HB 195, German Lehmbau Regeln, and the Peruvian Earthen Building Code.

3 Perceptual Gap: Earthen Building Experts and Homeowners Survey

In order to identify perceptual barriers that hold back earthen buildings' broader implementation and to ascertain possible solutions to these barriers, it was necessary to assess the current relationships and perceptions among primary resources such as practicing professionals and people who live in earthen houses. This chapter presents the results of online surveys of earthen building experts and end users[2] and explores both the factual condition of earthen building in practice, as well as the participants' points of view, perceptions and experiences.

3.1 Perception surveys among experts and homeowners

The perceptual barrier to using earthen building materials is described in this section by reporting the results of 126 surveys. The surveys were used to collect data from a broad group of participants and were complemented by 10 in-depth interviews detailed in Section2.5.1.

3.1.1 Survey design and methodology

The surveys provide a method of systematic data collection for the purpose of describing attributes of earthen building construction. The design of the survey incorporated the steps proposed by Groves et al. (2009), as outlined in the next subsections: defining the survey constructs and target population, designing the survey structure, and collecting the data.

Defining the survey constructs and target population

In the context of the survey implemented in this research, the following research questions were addressed:

[2] University IRB approval was obtained prior to initiating study procedures.

1. What factors affect the motivation of end users to use earthen building materials and methods in the construction or renovations of their homes?
2. What is the role of regulatory barriers among other barriers to using earthen building materials and which regulatory sections and mechanisms are most cumbersome?
3. What is the thermal performance of earthen houses in terms of heating and cooling requirements?

The target populations of this survey, shown in Figure 49, are earthen building experts and end-users. Earthen building experts are defined as professionals, including policy advocates, engineers, designers, contractors, builders, teachers, and researchers, who focus on earthen building in their profession. Earthen building end users are defined as homeowners of earthen houses, as well as potential homeowners who are generally interested in earthen building materials for a future home or renovation of their current home.

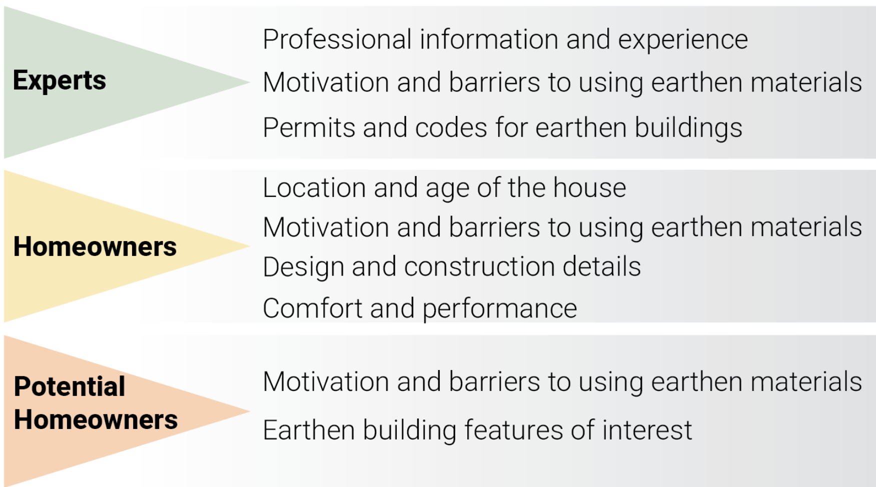


Figure 49: Summary of the survey sections for each respondent type

Survey structure and organization

The survey questions, as detailed in Figure 50, were designed according to recommended guidelines that were shown to maximize validity and minimize errors (Groves et al. 2009). The measurement error was minimized by avoiding excessive complex quantifiers, and the processing error by using Microsoft Excel and Tableau Analytics (Tableau, 2019) software package that updates automatically.

The survey was structured to provide a different set of questions to each of the targeted populations. As illustrated in Figure 50, all targeted populations were asked about their perceived motivation and barriers to using earthen building materials. Additionally, experts were also asked about their professional experience, and their perception of codes for earthen building. Homeowners were asked to answer a series of design and performance questions about their house. Potential homeowners were given a visual rating assessment of various earthen structures. Figure 50 provides a complete map of the survey, including the various questions in each section.

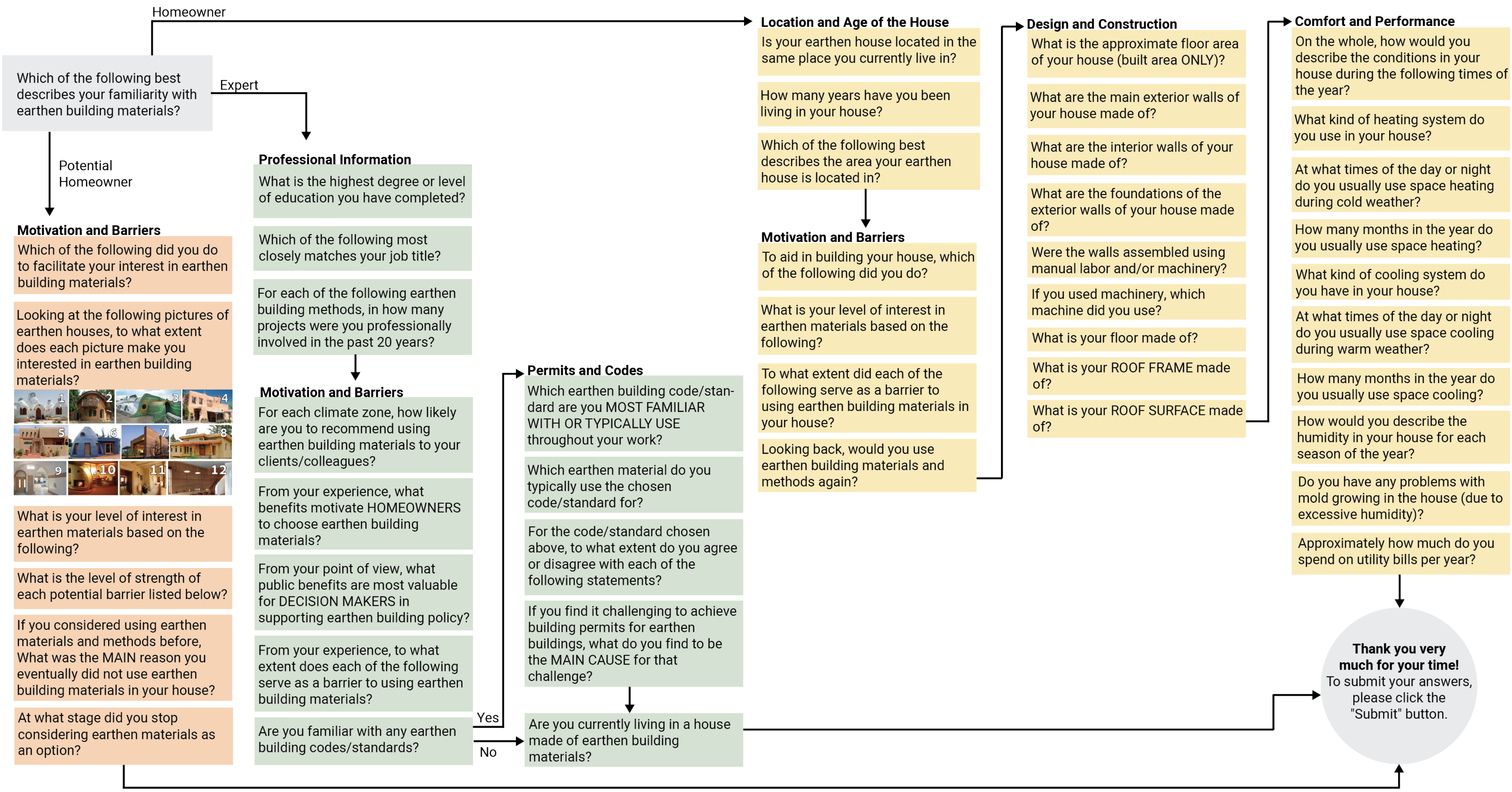


Figure 50: Structure of the perception survey, according to respondent type

Collecting the data

The questionnaire was designed within a Google Forms template and was distributed among respondents as described above. The questionnaire was expected to exhibit the following limitations and errors:

Limited questions format – the Google Forms questionnaire template offers a limited set of survey questions and does not offer open-source coding abilities. Therefore, survey questions were adjusted to the provided templates.

Limited sample type – Google Suite has a limited geographical coverage because it is restricted in several countries, such as China.

Limited administration method – the survey was administrated through a URL link within an email message, but some email may have been categorized as spam.

Measurement error - earthen building techniques and terms can be unknown or vary based on location.

The analysis of the survey data followed the steps, as suggested in Wilson & Stern (2001), including exploratory data analysis, deriving the main findings, and archiving.

3.1.2 Respondents distribution

In total, 126 individuals responded to the online survey from January to July of 2018. Figure 51 shows the geographical distribution of respondents according to their self-reported familiarity with earthen building.

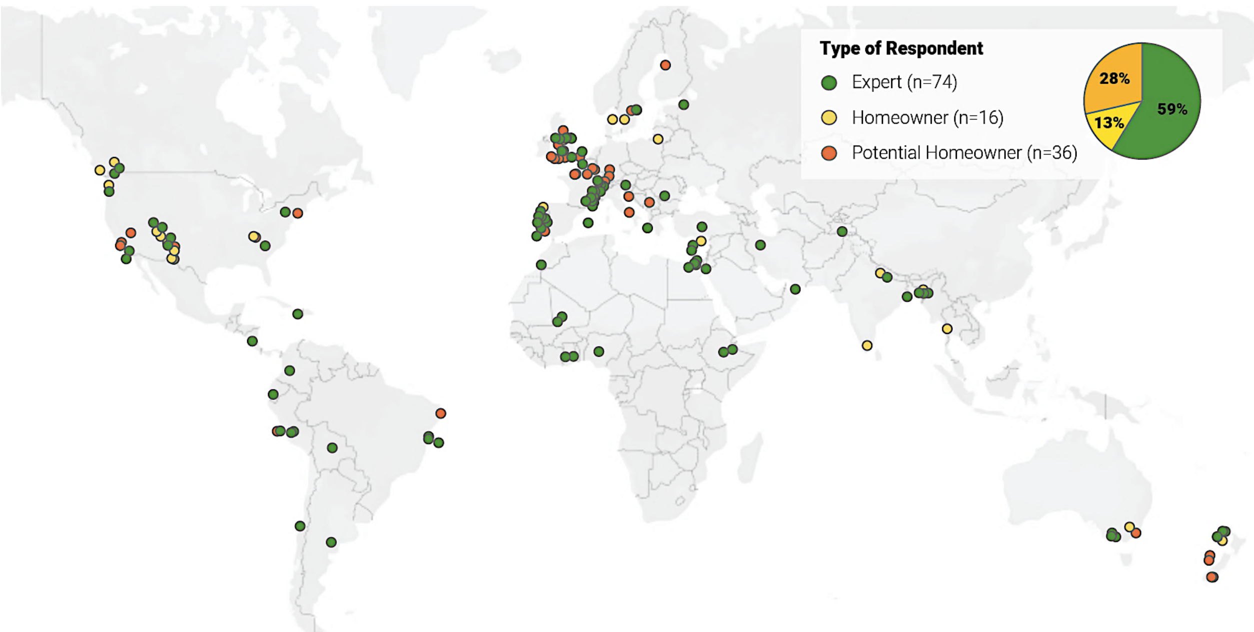


Figure 51: Geographical distribution of respondents according to their familiarity with earthen building

In general, respondents were located 52% (n = 65) from Europe, 17% (n = 22) from North America, and 31% (n = 39) from other regions, as shown in Figure 52. Specifically, for earthen building experts, 59% (n = 44) provided a geographical region in Europe, 16% (n = 12) in North America, and 25% (n = 18) in other regions. Additionally, 64% (n = 18) of potential homeowners reside in Europe.

The survey respondents included the following demographics: 59% (n = 74) [self-described] earthen building experts, 13% (n = 16) homeowners of earthen buildings, and 28% (n = 36) potential homeowners who indicated that they are familiar with earthen building materials and interested in applying them in their current or future homes. However, 26% (n = 19) of the experts indicated that they also live in an earthen structure, leading them to answer the homeowner's questionnaire in addition to the experts' questionnaire, increasing the total number of homeowners' responses to 35 and the total complete questionnaires to 145.

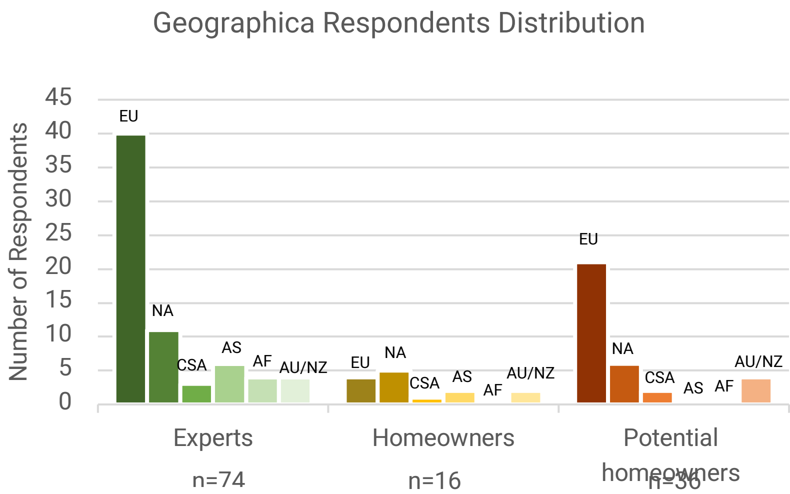


Figure 52: Distribution of respondents according to their geographical location: Europe (EU), North America (NA), Central and South America (CSA), Asia (AS), Africa (AF), Australia and New-Zealand (AU/NZ).

Overall, respondents were well distributed geographically, with a bias towards European locations, due to the distribution of the Call for Participants from a European academic institution, as well as traditional familiarity and earthen building codes available in Germany, UK, and France.

3.1.3 Barriers and motivation analysis

Perceived barriers to using earthen building materials and methods

The barriers to implementing earthen building materials and methods were first analyzed according to the different building techniques. Figure 53 shows that experts and end-users are mostly challenged by lack of design and construction professionals, as well as by obtaining building permits. These challenges were especially evident for Compressed Earth Brick (CEB) and rammed earth. The reported techniques which were the least challenging to apply are clay plaster, which does not require building permits, and adobe, which is often traditionally familiar or vernacular.

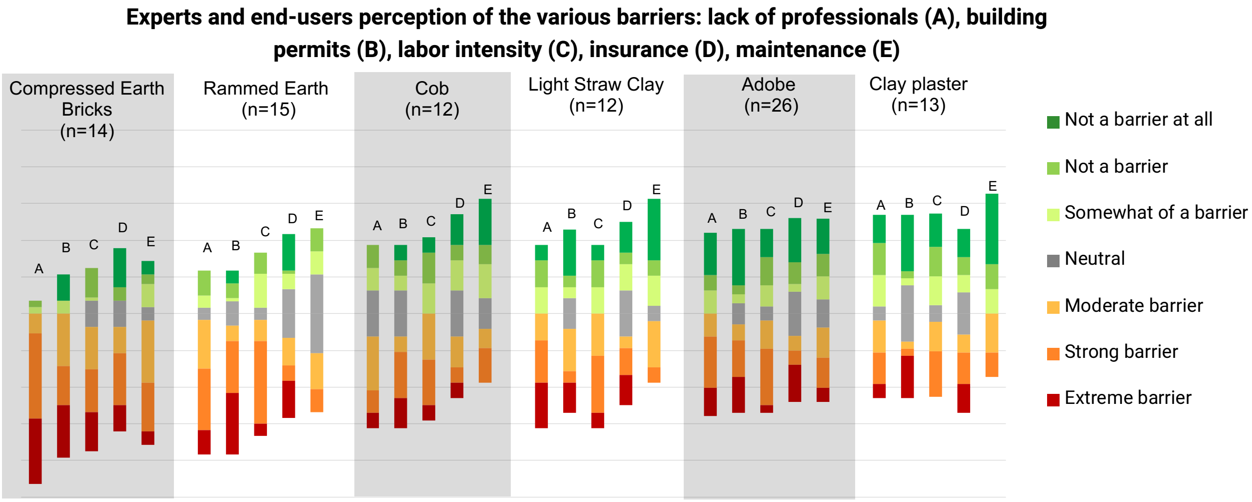


Figure 53: Experts and homeowners are mostly challenged by lack of professionals and building permits for compressed earth bricks

When analyzed according to respondent type, lack of design and construction professionals and difficulty of obtaining building permits were shown to be more significant among experts and potential homeowners. Unsurprisingly, homeowners who already finished constructing their homes were shown to be least challenged by obtaining building permits and lack of professionals, as shown in

Figure 54.

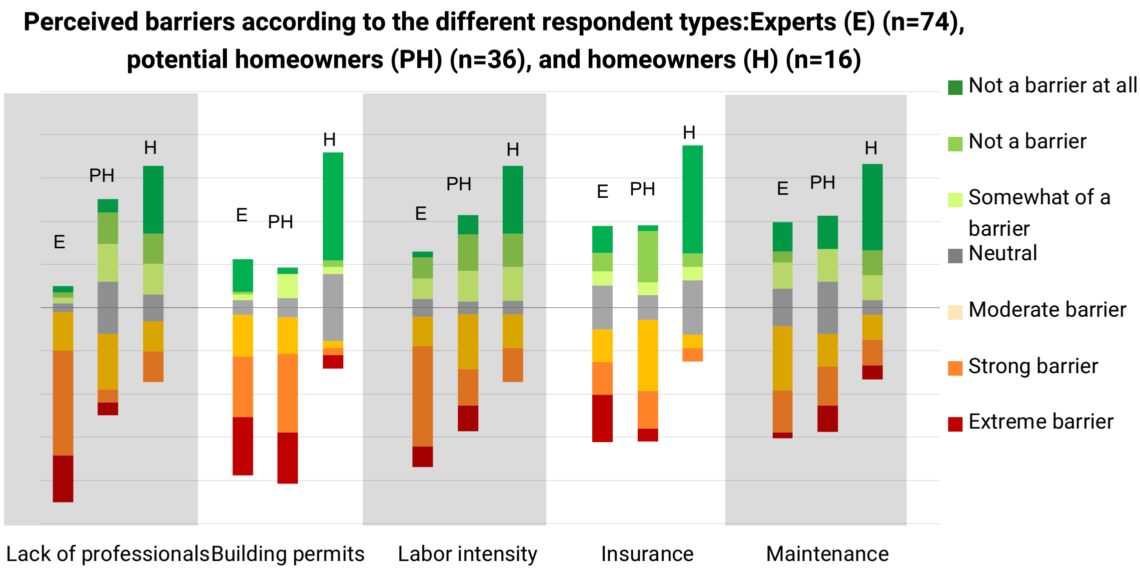


Figure 54: Experts and potential homeowners perceive the regulatory barrier as significant, whereas homeowners are challenged by insurance, maintenance, and labor intensity

The 'Motivation and Barriers' part of the survey allowed respondents to identify other barriers that were not specified in the survey questions. As part of this option, experts repeatedly mentioned that poor perception and lack of awareness of the benefits of earthen building are significant barriers. Specifically, as detailed in Table 8, experts mentioned that a significant barrier is "poor public perception" and "peoples' aversion to dirt". Experts also elaborated on the relation between poor perception and socioeconomic prejudice, for instance, an architect of rammed earth and adobe from a seismically active region mentioned that "unfortunately, most people feel unsafe and poor in earth buildings"; and an architect of adobe, earthbags, and clay plaster from South East Asia added that "people do not treat earthen building as a permanent and standard building, they think only poor [people] use earth as a building material." Lastly, some experts mentioned that another barrier is the lack of available technical data, and "lack of information on new developments and recent good examples".

Additionally, some homeowners provided additional comments on the challenges of acquiring raw materials. For instance, a homeowner of an insulated wooden structure plastered with clay located in Lithuania mentioned challenges finding suitable clay. Another homeowner of a straw bale structure with cob and clay plaster mentioned that importing sand for the construction of their home was required.

Table 8: Additional barriers to implementing earthen building materials in housing projects

	Respondent	Comment
Technical Gap	Builder/contractor from Sweden	"low knowledge and experience"
	Builder/contractor from Austria	"Lack of information on new developments and recent good examples"
	Structural engineer from Switzerland	"Knowledge that it is actually available…"
Perception Gap	Researcher from Ethiopia	"social status (perception)"
	Cob builder/contractor from Scotland	"lack of awareness about earth building"
	Researcher from North America	"cultural prejudice (poor man's resource, fragile)"
	Rammed Earth Consultant and CEO of National Earth Building Organization	"Really this is a combination of many factors which fall into two categories, ignorance and unfamiliarity. Ignorance is everything from earth as an option which is not 'mud huts' to designers who have no training. Unfamiliarity, we don't see this every day"
	Rammed earth and clay plaster architect from Russia	"Viewed as less strong and expensive cause of lots of labor involved"
	Cob and light straw clay structural engineer from Germany	"Public perception"
	Adobe researcher from North America	"Competition from other materials such as cinder blocks"
	Rammed earth and adobe architect from Iran	"Unfortunately, most people feel unsafe and poor in earth buildings."
	Cob builder/contractor from Canada	"People's aversion to dirt"
	Adobe and earthbags architect from Bangladesh	"People do not treat earthen building as a permanent and standard building, they think only poor use earth as a building material"
	Cob architect from Switzerland	"the mentalities"
	Cob architect from France	"ignorance of the general public, incompetence of the prescribers"
Regulatory Gap	CEB researcher from France	"Lack of standards"
	Rammed earth researcher in academia from New-Zealand	"The absolute worst barrier to adoption is a lack of construction standards or official guidance. Without that, all structures must be assessed by Structural Engineers, i.e. incurring a much higher cost than an equivalent masonry building. However, for maintenance, if the material is stabilised then evidence suggests that maintenance isn't too great a concern."

Respondent	Comment
Rammed earth building project manager from Belgium	“Hard to find engineers for structural calculations. Hard to do the "unknown"”
Adobe researcher from Cyprus	“Lack of international standards, building codes”

Factors that motivate homeowners to use earthen building materials and methods

As part of the survey, respondents were asked to rate the benefits of earthen building. Experts were asked to rate the extent to which each benefit motivates homeowners. Additionally, homeowners and potential homeowners were asked to rate their own motivation factors. Figure 55 illustrates the results according to homeowners (as perceived by experts), homeowners (as perceived by themselves), and potential homeowners.

According to experts, the most significant factors for homeowners in their choice for using earthen building materials and methods are aesthetics and indoor air quality. This result corresponds with the answers of homeowners themselves, who rated indoor air quality, following by environmental factors (global climate change and resource depletion) as the most significant motivating factors in their choice of earthen materials. Although potential homeowners’ perceptions were distributed in a more uniform manner among the various earthen building benefits, results still show that the majority of attention was given to environmental sustainability factors, followed by indoor air quality and aesthetics. In contrast, the least significant factors motivating homeowners (according to both experts and homeowners) in choosing earthen building materials are affordability and [reduced] utility bills. This observation additionally suggests a bias in the respondents toward those who are more-financially secure.

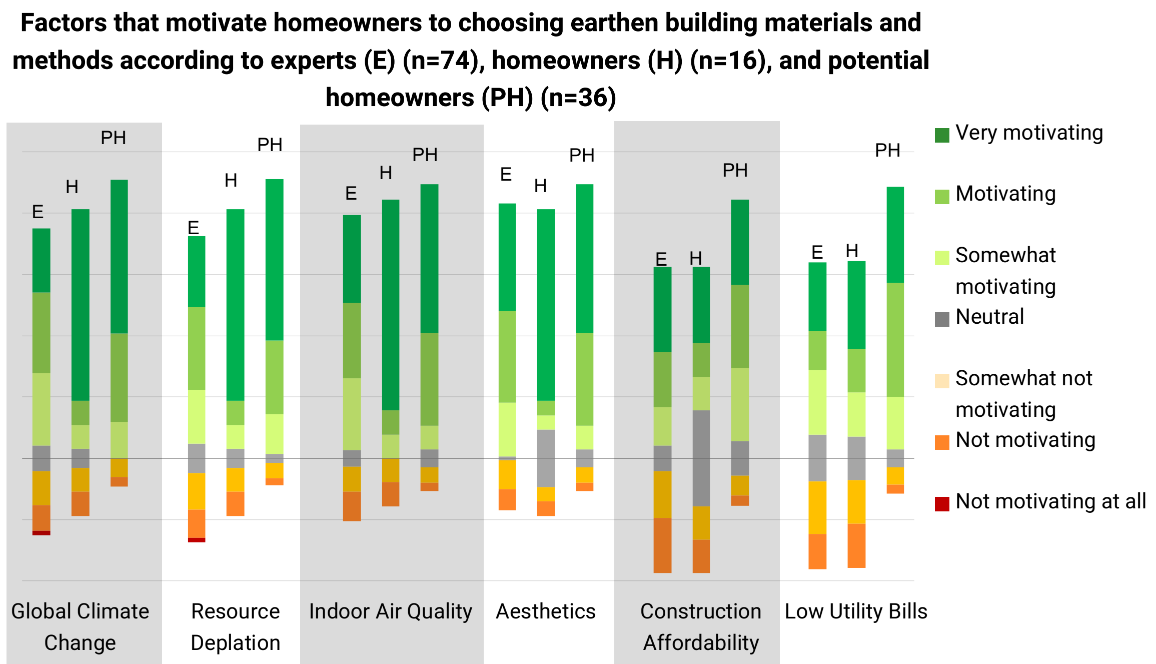


Figure 55: Homeowners and potential homeowners are motivated by environmental and health benefits rather than construction affordbility and reduced utility bills

Despite motivating considerations, homeowners are notably challenged by obtaining building permits, as shown in Figure 54. These results suggest that in order to advance earthen construction, environmental and health advantages that could attract more potential homeowners should be promoted, and efforts should be made to overcome permitting barriers.

Experts were also given the option to add comments regarding other perceived benefits of earthen building. Almost one-third of the participating experts (n = 22) added a benefit that correlates with the ability to self-build and to engage local communities in the building process in a way that enhances local economies. For instance, in three responses from European professionals, a rammed earth and adobe contractor commented that "it is the peoples' building-material. Everybody is able to handle it and it is of great value that people can use their hands for practical purpose"; an earthen building architect added that a valuable benefit of earthen building is the "participation of communities on construction site"; and a CEB and rammed earth architect commented that earthen building is capable of "giving a new competence to local communities, for new construction and for repair of existing construction... good for local economy".

Table 9: Additional factors that motivate homeowners to choosing earthen builidng materials

	Respondent	Comment
Self-Build Benefits	Rammed earth researcher, Australia	"...in Australia, for example, earth building was more expensive as labour was difficult to secure (can't use local untrained labour for commercial projects) ... Another advantage is acoustic insulation - v quiet in a rammed earth house!"
	Adobe architect from the UK	"Earth products are locally available"
	Cob builder/contractor from Scotland	"**accessible** skills and materials for **self-build**"
	Rammed Earth Consultant and CEO of National Earth Building Organization	"Fashion, lifestyle, **self build**, access to planning permission, sick of cement"
	Adobe, cob, and light straw clay structural engineer from Germany	"Ease of use, short learning curve to owner participation/**self building**"
	Building project manager in Israel	"They can take part in the construction"
	Researcher from Princeton, did adobe, cob, and rammed earth projects in Peru and Ecuador	"Tradition and heritage preservation"
	Adobe researcher from New-Zealand	"Simplicity of the construction techniques"
	Adobe, rammed earth and light straw clay architect, Russia	"Easy repair"
	Cob architect and researcher in CA, USA	"design freedom allowed with cob"
	Rammed earth and clay plaster architect from Russia	"Easy to learn to use"
	Adobe researcher from North America	"**Community engaging** activity"
	Adobe, cob, and light straw clay builder/contractor from North America	"Local employment opportunities, less transporting of goods."
	Builder/contractor from Sweden	"to be able to control the process of building better."
	Builder/contractor from Austria	Nice to work with, very flexible and adaptable in the use with other materials.
	Cob, rammed earth, and light straw clay architect from Switzerland	"**Participation** of communities on construction site"
	Rammed earth building project manager from Belgium	"no VOCs, vapour open, thermal inertia, Open construction process"
	Cob building project manager from Portugal	"Ability to **self build**"
	CEB architect from Portugal	"In Portugal some still think as a **self construction.**"
	Cob and light straw clay builder/contractor from North America	"Being desperate from a mass consumption model"
	Adobe and CEB researcher from Argentina	"**Self-construction**"

	Respondent	Comment
Comfort & Health Benefits	Rammed earth and CEB researcher, Brazil	“feel that it is part of Nature”
	Adobe builder/contractor, NM USA	“more comfortable to live in”
	Adobe, cob, rammed earth, earthbags, and light straw clay builder/contractor, BC Canada	“Health and spirituality”
	Adobe researcher from Cyprus	High thermal capacity
	CEB researcher from France	Hygrothermal regulation indoor

3.1.4 Experts perception analysis

Experts professional experience

Seventy-four respondents self-described as earth building experts. Experts were asked to provide their geographic location, level of education, and job title. As shown in Figure 56, six professions related to the construction industry were identified among participating experts. Researchers in academia made up the majority of experts with 37% (n=27), following by 31% (n=23) architects/designers, 15% (n=11) builders/contactors, 8% (n=6) building project managers, 5% (n=4) teachers, and 4% (n=3) structural engineers. Additionally, experts’ level of education included a majority of 44% (n=32) graduate or professional degree, following by 36% (n=26) PhD, and 16% (n=12) with a bachelor’s degree. The high portion of responses gathered from academia could be a result of the purposive survey distribution, which was initially realized using a call for respondents from within academia.

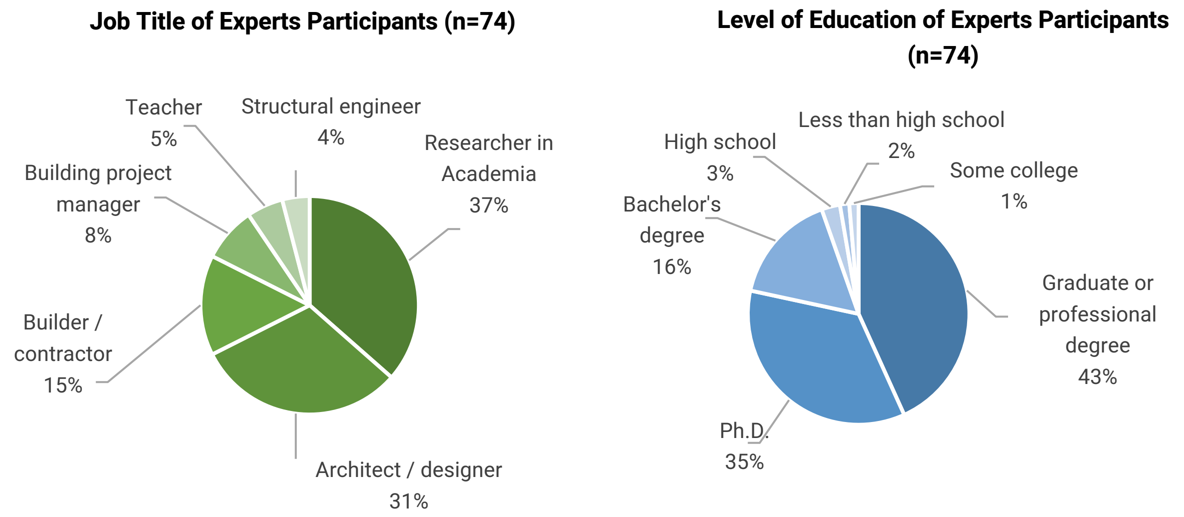


Figure 56: Experts participants are mostly researchers are architects/designers with graduate or professional degree

Experts were shown to be mostly experienced in clay plaster and adobe residential projects. Figure 57 highlights the most experienced techniques: clay plaster, adobe, rammed earth, and cob, for residential projects; and clay plaster, rammed earth, and CEBs for commercial projects.

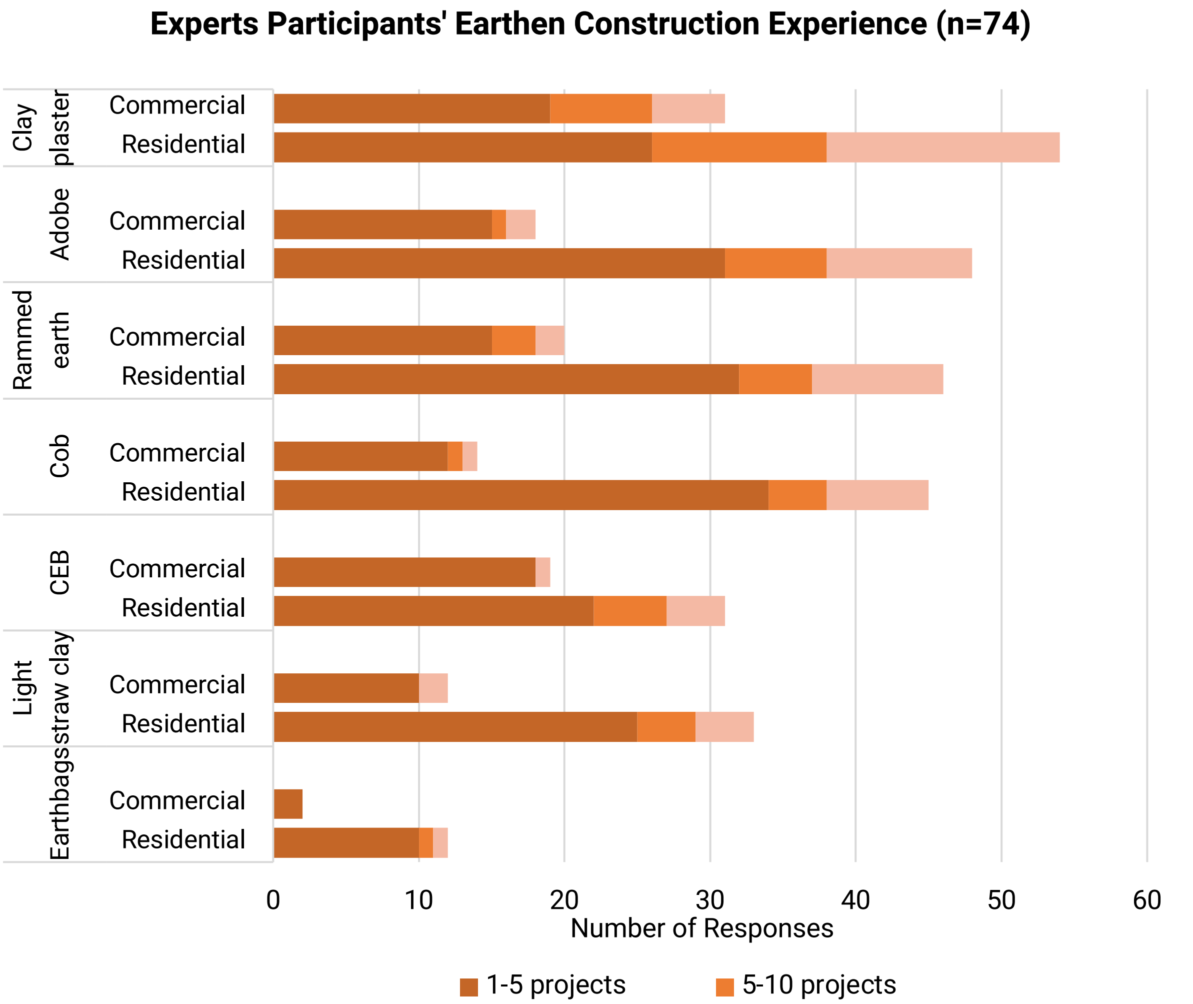


Figure 57: The majority of experts participants are experienced in residential construction of clay plaster, adobe, rammed earth, and cob

Experts climatic context was analyzed according to their geographical location, overlapped with the Köppen-Geiger World Climate Classification, as shown in Figure 58.

The distribution of experts suggests the majority of experts are located in temperate climates (34% of experts), followed by desert climates (23%). This result is counterintuitive to the assumption that earthen buildings are mostly associated with dry warm and hot climates and is a result of the high number of European respondents, where earthen materials are also traditionally used.

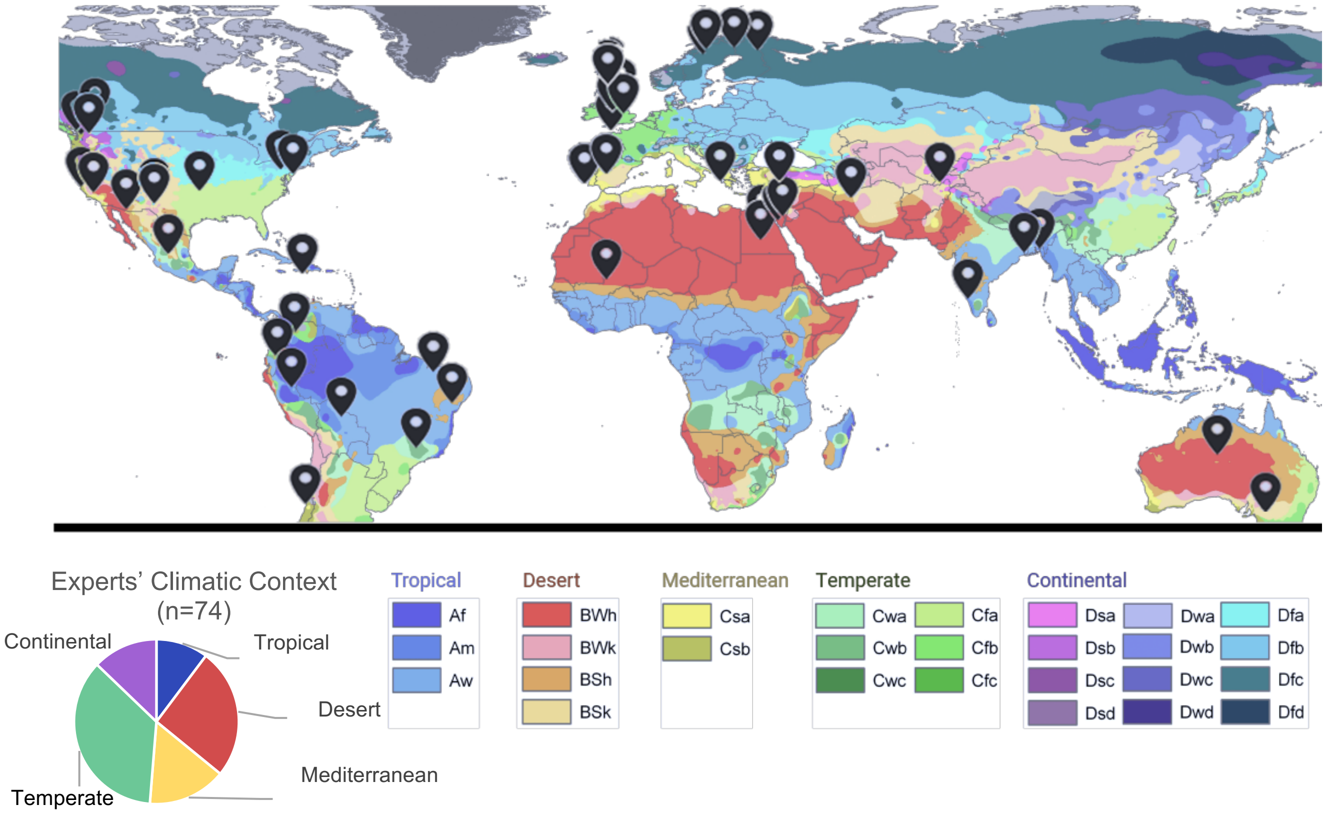


Figure 58: Experts respondents are mainly from temperate, desert, and mediterranean climates (Beck et al., 2018)

Likelihood of recommending earthen building materials in various climate zones

Experts were asked about the likelihood that they would recommend using earthen materials and methods for four broad climate zones. As depicted in Figure 59, experts reported to generally tend to recommend earthen building materials in all climates, whereas the climate that received the least positive responses is Marine, probably due to expected combination of precipitation and salt, both of which are regarded as major earthen building erosion factors.

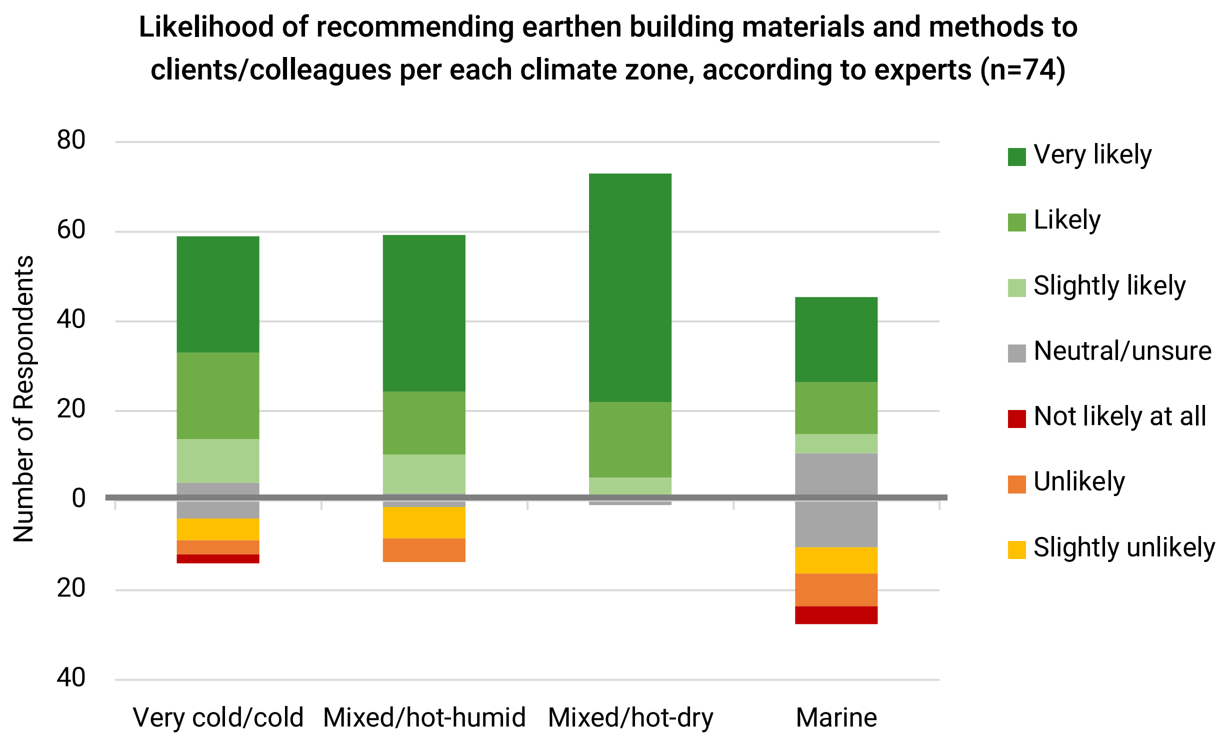


Figure 59: Experts are most likely to recommend earthen building materials in mixed hot and dry climates

Valuable factors for decision makers in supporting earthen building policy

Experts were asked to rate the extent to which each earthen building benefit is of value to decision makers in supporting earthen building policy. As depicted in Figure 60, the most important factors for decision makers were reported to be global climate change and resource depletion while the least significant was affordability.

These results indicate that economic factors are least significant as motivating factors when applying earthen building materials and methods (once again illustrating a potential bias toward wealthier locations and respondents), while environmental sustainability, health, and aesthetics, might represent the most attractive and valuable benefits. In addition, the results appear to indicate that in order to promote earthen materials among decision makers, environmental sustainability factors should be addressed.

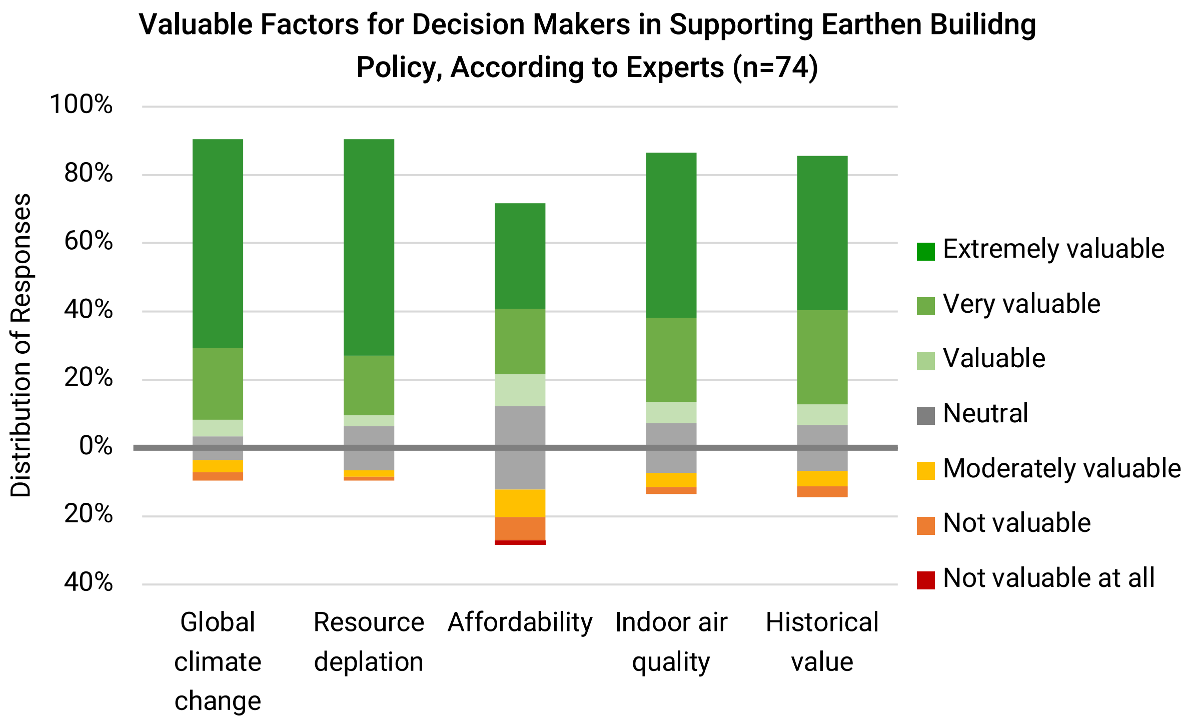


Figure 60: According to experts, environmental factors (global climate change and resource depletion) are the most valuable for decision makers in supporting earthen building policy

Experts added their comments regarding additional public benefits that are valuable for decision makers in supporting earthen building policy. One comment given by multiple experts (n = 10) was the benefit of job creation and the role of earthen building in a circular economy. As detailed in Table 10, experts highlight the connection between ease of use, local community involvement, and development of local jobs and social equity.

Table 10: Additional valuable public benefits that are valuable for decision makers in supporting earthen building policy, according to experts

Respondent	Comment
Rammed earth and adobe architect from Iran	"This method can involve local community in building and make job."
Architect from New-Zealand	"some earthen techniques are very suitable for owner builder programmes"
Rammed earth building project manager from Belgium	"Open construction process: different economical model, cheaper"
CEB and light straw clay researcher from France	"Development of local and durable jobs"
Researcher from Ethiopia	"local job creation and less hard currency needed to import building materials"
CEB and rammed earth architect from Portugal	"The possibility of giving a new competence local population, for new construction and for them to know who to repair and restore their houses, good for local economy"
Rammed earth and clay plaster architect from Russia	"Easy to learn to use"

Respondent	Comment
Adobe researcher from North America	“Community engaging activity”
Adobe, cob, and light straw clay builder/contractor from North America	“Local employment opportunities, less transporting of goods.”
Adobe, cob, and rammed earth builder/contractor from Sweden	“It is the peoples building-material. Everybody is able to handle it and it of great value that people can use their hands for practical purpose.”

Familiarity and perception of earthen building regulations

Figure 61 shows the distribution of experts' familiarity with existing earthen building codes and guides. 24% (n=18) of surveyed experts reported to be generally unexperienced in using building codes whereas 76% (n=56) of experts reported using building codes for their earthen projects. Of the experts who use building codes, 27% (n=15) had been applying conventional material codes to their earthen building projects. The remaining experts reported to be mostly using earthen codes from Germany (Dachverband Lehm, 2008), New-Zealand (NZS 4297: Engineering Design of Earth Buildings, 1998; NZS 4298: Materials and Workmanship For Earth Buildings, 1998; NZS 4299: Earth Buildings Not Requiring Specific Design, 1998), or New-Mexico (New Mexico Regulation & Licensing Department and NMAC, 2015). These results suggest that within the earthen building community, building codes are often unfamiliar or not applied. No dominant earthen code/standard/ guide was identified.

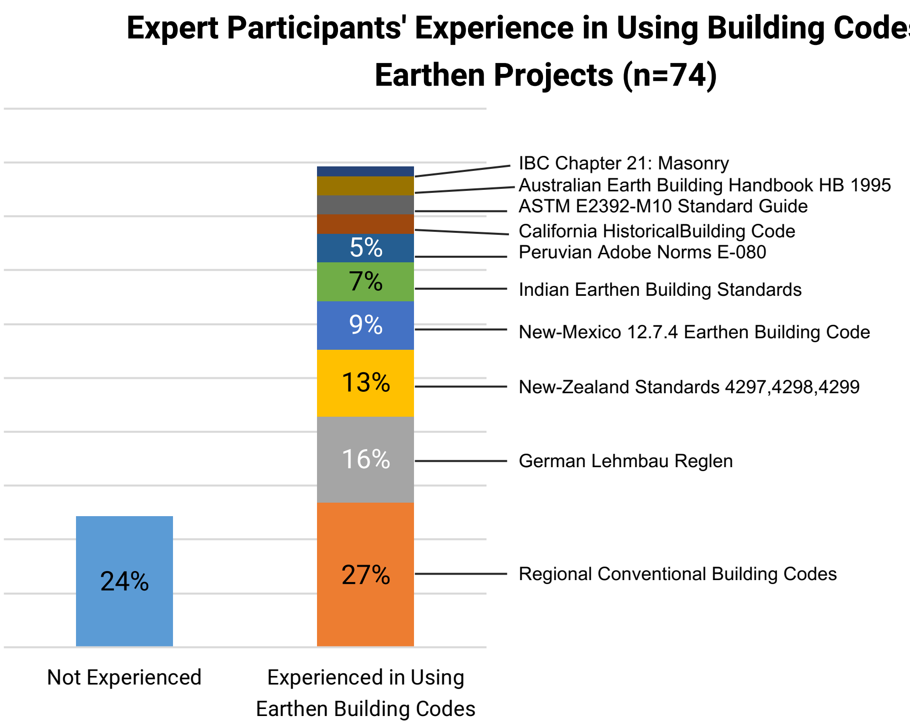


Figure 61: Experts are mostly experienced in using conventional building codes for earthen building projects

Experts rated the quality of the earthen building code/standard/guide they used. Figure 62 shows that, according to experts, earthen building codes are generally representative of the various earthen techniques in a user-friendly manner, with highest ratings given to the New-Zealand Earthen Building Standards (NZS 4299: Earth Buildings Not Requiring Specific Design, 1998; NZS 4297: Engineering Design of Earth Buildings, 1998; NZS 4298: Materials and Workmanship For Earth Buildings, 1998). However, experts indicated that using earthen building codes/standards results in a costlier and longer permitting process compared to conventional building projects, with the greatest impact stemming from the use US-based earthen codes/standards, specifically the NM code (New Mexico Regulation & Licensing Department and NMAC, 2015). This observation may be less a function of the code documents themselves, and more a reflection of the permitting environment in the United States. Furthermore, experts stated that, in general, building officials are unfamiliar with earthen building codes/standards. Specifically, the German Earth Building Regulations (Dachverband Lehm, 2008) are rated as the least familiar to building officials (admittedly, they are only available in German), followed by the New-Zealand Earthen Building Standards. Many experts reported a different geographical location from the code country of origin; for the German Earth Building Regulations, 78% (n=7) are from Europe but none from Germany, and for the New-Zealand Standards, 43% (n=3) are located in New-Zealand.

Quality rating for different codes/standards, according to experts participants, in terms of representation (A), user-friendliness (B), cost to permit (C), time to permit (D), and familiarity among building officials (E)

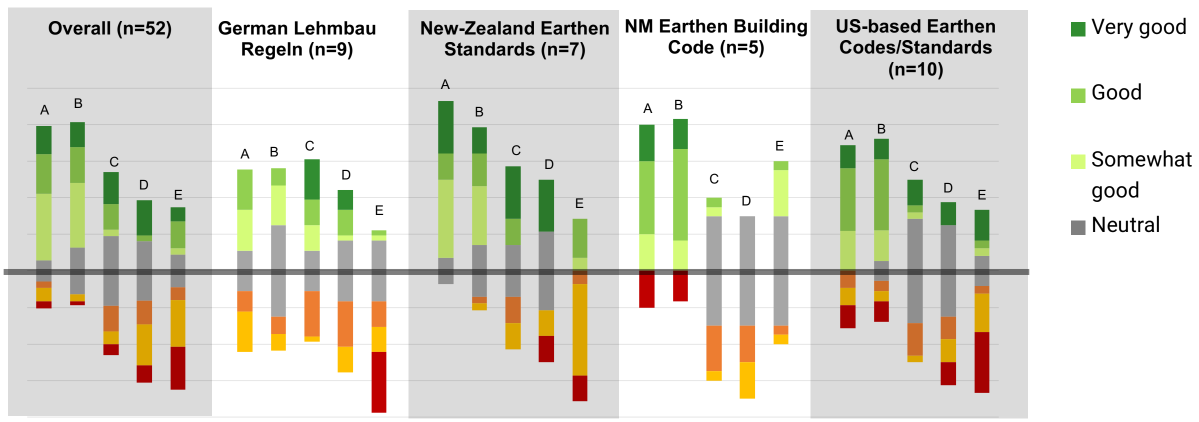


Figure 62: According to experts, earthen building codes/standards are not familiar among building officials, and result in a costlier and longer permitting process

3.1.5 Potential homeowners visual perception analysis

This survey section was designed to gather information from people who are interested in using earthen building materials in their future home or for the renovation of their current home. As illustrated in Figure 63, potential homeowners from around the world participated in the survey.

Figure 63: Distribution of the potential homeowners who participated in the survey

Potential homeowners were given a visual rating assessment with 12 images of earthen houses[3].

Figure 64 shows the images that were included in this part of the questionnaire. The images feature various earthen techniques, ranging from exterior curved and rectilinear structures, to indoor spaces. Potential homeowners were asked to rate each image and to respond to the question "to what extent does each figure make you interested in earthen building materials"

The results, as shown in Figure 64, indicate that potential homeowners prefer earthen materials in the interiors, as well as solid colors and shapes. Radial shapes and colors that are typically associated with earthbags were the least favored by homeowners. Interior warm spaces that include earthen heaters, rammed earth walls, and the presence of clay plaster were voted as the most favorable.

[3] The author received designers' and photographers' permission to use the images for the purpose of this dissertation

	1	2	3	4	5	6
Technique	**Earthbags**	**Earthbags**	**Earthbags**	**Adobe**	**Rammed Earth**	**Cob**
Elements	Exterior colourful and curved wall	Exterior colordul dome	Exterior dome	Exterior wall	Exterior wall	Exterior curved wall
Style	Radical	Radical	Vernacular	Vernacular	Contemporary	Vernacular

	7	8	9	10	11	12
Technique	**Earthbags**	**Cob**	**Adobe**	**Rammed Earth**	**Cob**	**Adobe**
Elements	Interior vault	Exterior wall	Exterior wall	Interior wall	Interior curved wall	Interior wall
Style	Vernacular	Contemporary	Contemporary	Contemporary	Contemporary	Vernacular

Figure 64: The differentearthen building images used in the potential homeowners visual assessment

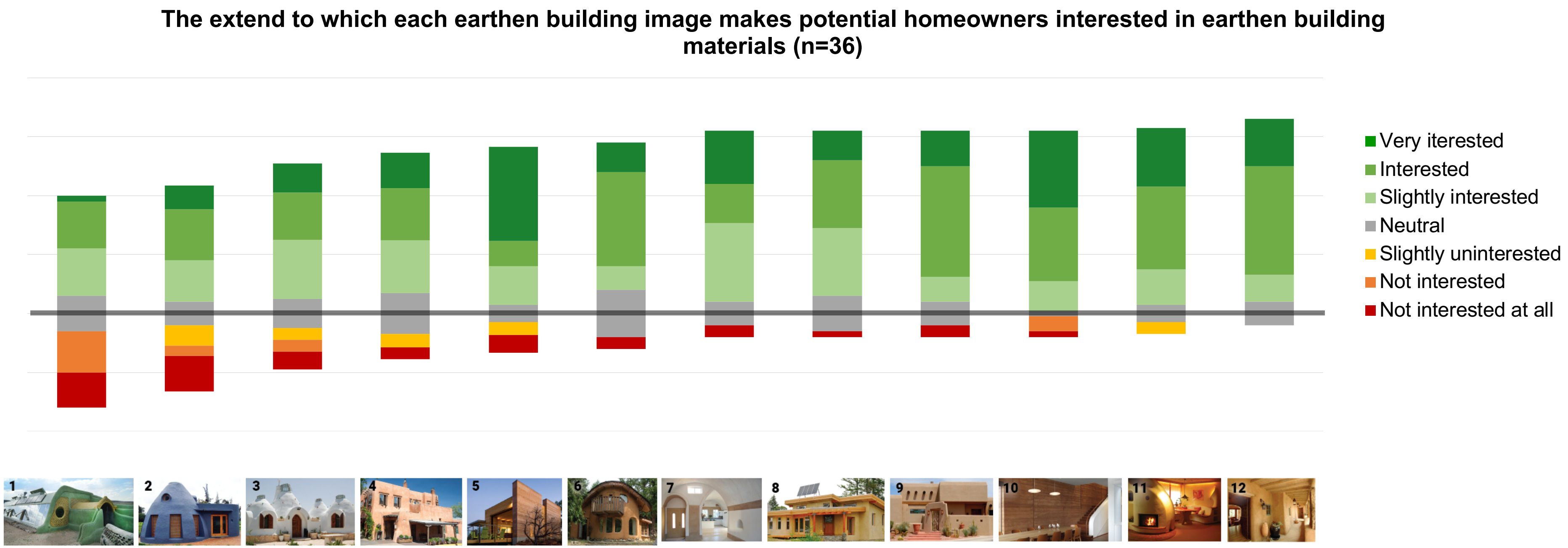


Figure 65: Potential homeowners prefer earthen materials in the interiors, as well as solid colors and shapes

3.1.6 Homeowners comfort and home performance analysis

This survey section was designed to gather information regarding a wide range of performance and comfort topics. As illustrated in Figure 66, 35 current occupants of earthen homes from around the world participated in the survey. Of the 35 responses, 13 were from Europe, 10 from North America, four from Asia, three from Australia and New-Zealand, and one from Central America. 10 of the respondents indicated that their homes do not contain earthen building materials as the main feature. For instance, some structures were identified as lightweight wood frame with clay plaster. The number of responses to each question does not necessarily sum to 35 because respondents either chose not to answer a question or selected multiple responses to the same question.

Figure 66: Distribution of the earthen building homeowners who participated in the survey (n=35)

Design and construction aspects

Eleven questions were aimed at understanding design aspects of the earthen homes including floor area, as well as wall, roof, and floor materials. 83% (n=29) of responses indicated that they used manual labor techniques to construct their home and only 17% (n=6) reported using a combination of manual techniques and machines. Specified machinery included mechanical mixer, block compressing machine, tractor, rammer, and excavator for sight leveling. As shown in Figure 67, most homes had modest floor area, with 67% (n=20) reporting a home within the range of 25-137 m^2 (270-1470 ft^2) floor area. As shown in Figure 68, 58% (n=19) of the homeowners reported building their home on a concrete footing, whereas other homeowners used either stone, gravel, or stabilized earth foundations.

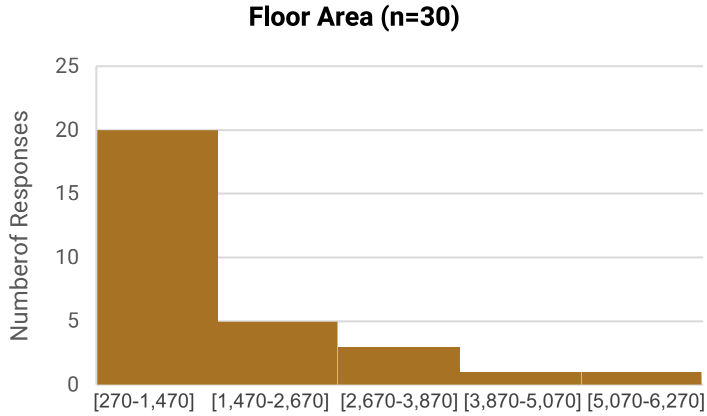


Figure 67: Homeownersreported relatively small-medium floor areas

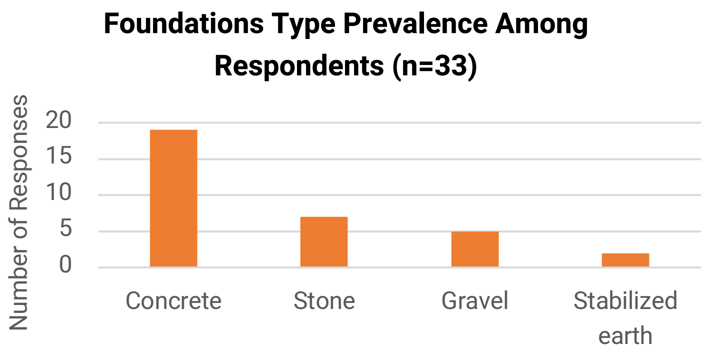


Figure 68: Homeowners reported using mainly concrete footing for their earthen house

Of the earthen homeowners, 31% reported having adobe in the exterior walls of their home. Other houses included a wide variety of techniques: cob, hybrid straw bale and earthen mass, clay plaster on top of different surfaces, rammed earth, light straw clay, and compressed earth bricks. Insulation types reported included 24% (n=8) straw bales, 9% (n=3) light straw clay, 6% (n=2) blown cellulose, and 6% (n=2) sheep's wool. 55% (n=18) of the homes were reported to have no supplemental insulation. None of the homeowners reported synthetic insulation in their home.

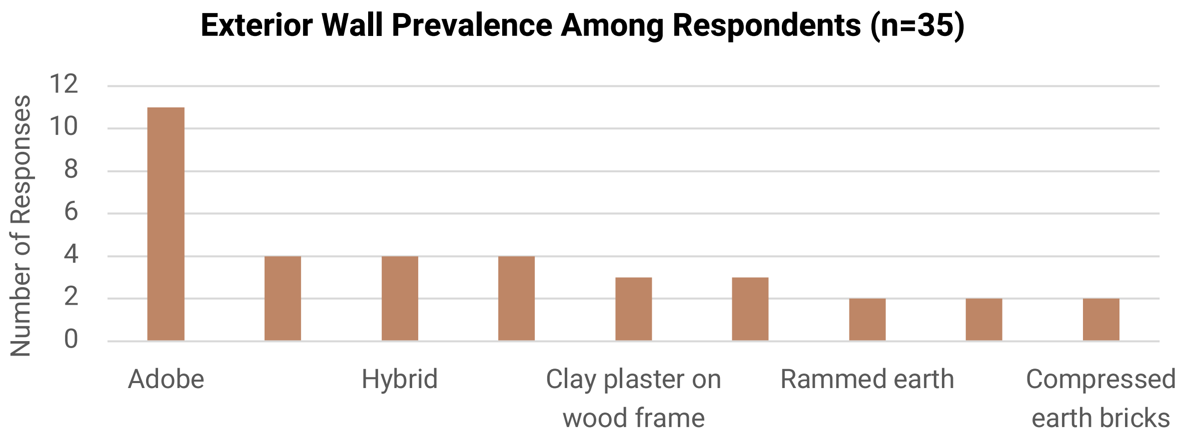


Figure 69: Homeowners reported mostly having adobe exterior walls, followed by clay plaster on a range of surfaces

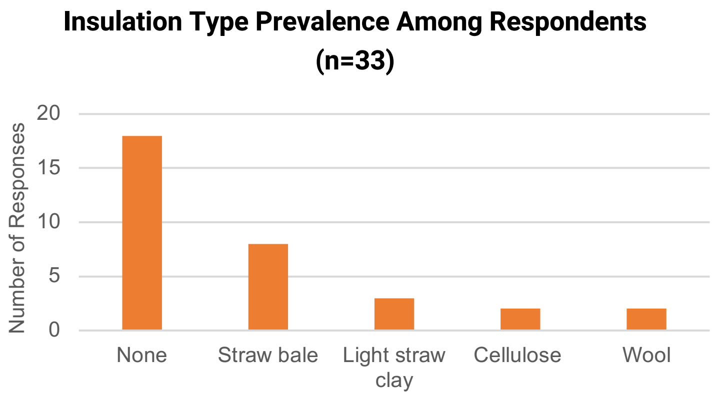


Figure 70: Homes are mostly uninsulated (55%), and no homes in the study contain synthetic insulation

As illustrated in Figure 71, 51% (n=18) of the homes reported using clay plaster as a finish material on the interior walls; adobe was also highly reported, presumably because of its ease of assembly. Flooring types were reported to be 76% (n=26) mass, as shown in Figure 72, in which concrete and earthen floors consisted of the most reported flooring materials.

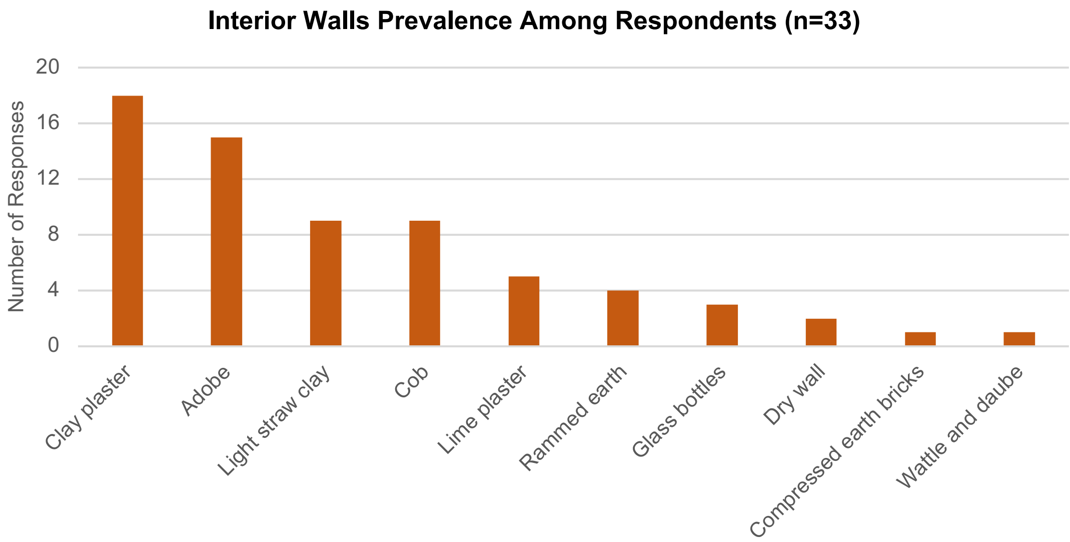


Figure 71: Interior walls are mostly adobe finished with clay plaster

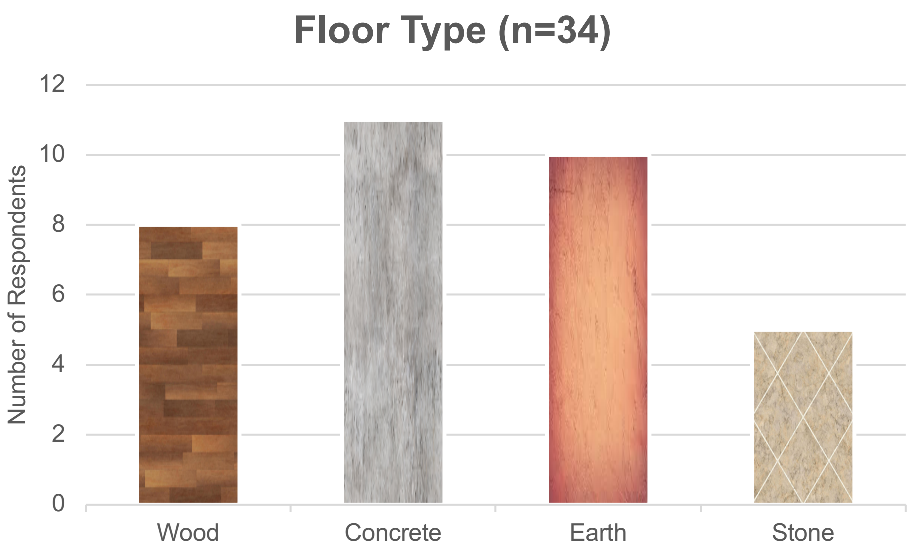


Figure 72: The analyzed earthen houses have mainly concrete and earthen mass floors

Comfort and thermal performance

Respondents were asked to provide their country and city in order to establish their climate zone and the survey included four questions that solicited the occupants' comfort levels in each season of the year. Respondents were also asked to provide their heating and cooling system types, as well as their usage pattern during the day and throughout the year.

This series of questions allowed for the analysis of thermal performance of the earthen houses for both heating and cooling seasons in each ASHRAE climate zone. As shown in Figure 73, 75% (n=26) of homeowners reported that their house has no cooling system. These results might indicate that earthen homes reduce the need for cooling, for all climate zones. A Few passive cooling systems were indicated to be "activated" (manually) by the owners for several months per year. Passive cooling strategies included shading and open windows. 51% (n=18) homeowners indicated using wood-burning stoves to provide heat in winter. Among the passive strategies, homeowners indicated using solar air heaters, earth air tubes for tempered ventilation, trombe walls, and sunlight.

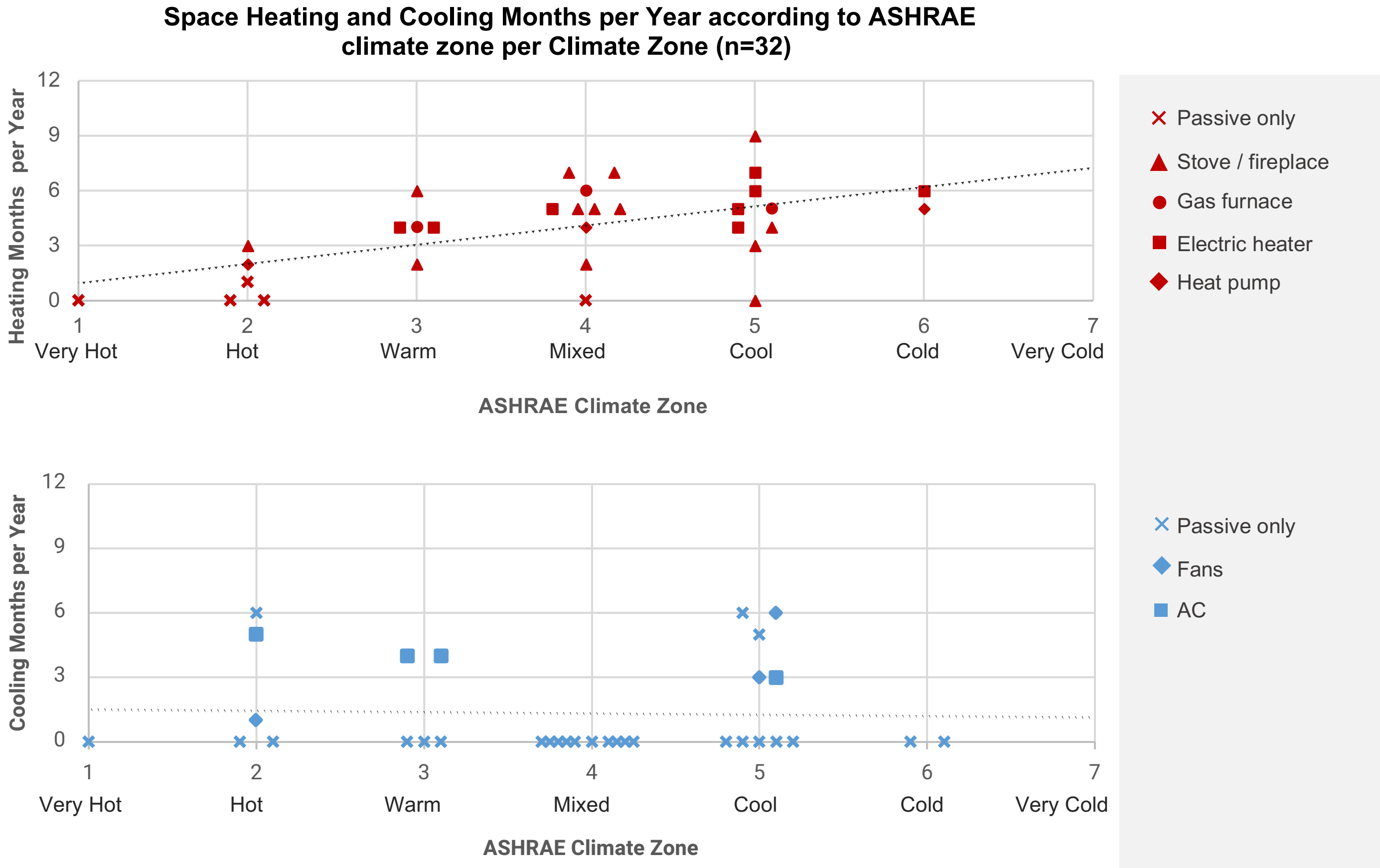


Figure 73: Earthen homes reduce the need for cooling, for all climates

Occupants' perceived thermal comfort was assessed using a series of questions for each season of the year. An overall comfort score was evaluated, showing that 91% (n=32) of homeowners are comfortable within their home during winter days, 86% (n=30) during winter nights, 89% (n=31) during summer days, and 94% (n=33) during summer days. In terms of perceived humidity comfort, 52% occupants reported to be comfortable, 59% of which have uninsulated homes.

Perceived thermal comfort levels were analyzed according to the inclusion/absence of insulation, as well as the presence of passive heating or cooling.

Figure 73 illustrates the difference between perceived comfort levels for insulated vs. uninsulated earthen homes, as reported by the homeowners. These results indicate that insulated mass assembly may provide a slightly higher perceived comfort. Additionally, the results show that insulated earthen assemblies are more likely to be suitable for passive cooling.

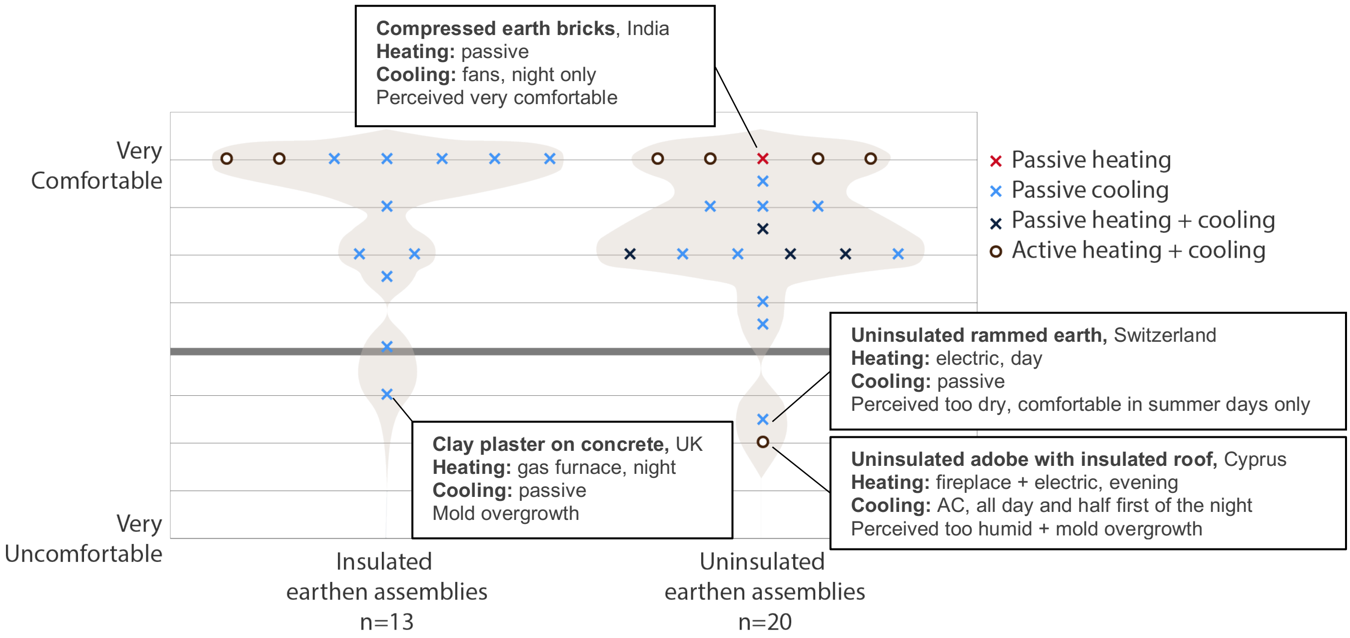


Figure 74: Occupants' comfort levels for insulated and uninsluated earthen homes

3.1.7 Conclusions

The earthen building experts and end-users perception survey study gathered information regarding a range of barriers to, and motivating factors for, the implementation of earthen materials, as well as design and performance aspects of earthen homes, from 74 experts: 35 homeowners (including 19 experts), and 36 potential homeowners, from around the world.

The main results of the barriers and motivation study include the following findings:

- Earthen building experts and potential homeowners are most challenged by obtaining building permits (also insurance, which might be a side effect of the permitting issue).
- For existing earthen building homeowners, labor intensity and maintenance are the greatest barriers, presumeably because they have already passed the hurdle of obtaining a building permit. They are now faced with maintaining their home.
- Compressed Earth Bricks (CEBs) and rammed earth methods suffer mostly from lack of design and/or construction professionals.
- Light straw clay showed the best results for low maintenance, and adobe and clay plaster showed best scores overall, with the least perceived barriers.

Experts that participated in the survey included architects, structural engineers, builders, contractors, teachers, and researchers. These experts were shown to be most experienced in clay plaster, adobe, rammed earth, and cob, in mostly residential projects. Specific to the expert respondents, the analysis generated the following findings.

- Among the expert respondents, the most used code was the German code following by the New Zealand standard series. However, 24% earthen building experts reported using conventional building codes to permit their earthen projects. This finding might indicate that even within the earthen building community, earthen building codes are either unavailable or unfamiliar. It might also be that permitting authorities are unfamiliar and therefore require projects to be "fit" into existing code frameworks.
- Experts identified that using earthen building codes result in a costlier and longer permitting process compared to conventional building projects, with the greatest impact stemming from the use US-based earthen codes.
- Experts rated the New Zealand standard as the most representative of the various earthen techniques, and the New Mexico code was shown to be the most user-friendly.

Another small segment of the survey included the visual preferability assessment of earthen structures among potential homeowners. The result of this assessment indicated that potential homeowners prefer earthen materials in the interiors, as well as solid colors and shapes, rather than the more colorful and irregular options. This observation might indicate that future earthen building development should prioritize earthen finish materials and possibilities for solid earthen colors and assembly shapes.

Overall, the following conclusions about the path to changing negative perception and advancing earthen building policy wer drawn:

- **Building regulation hurdles should be overcome.** According to the results of , this mission may begin with dawing from the benefits that were identified for each existing earthen building code: New Zealand earthen standards were promoted for their representiveness of the various earthen techniques, while the New Mexico code was most user friendly and familiary among code officials; presumably because it is cited from within the IRC (ICC, 2018). The German Lehmbau Regeln was shown to provide the best permitting process that does not incur higher cost and delay.

Increasing awareness about earthen building should be approached differently for each target group:

- **For homeowners and potential homeowners**, health and indoor air quality advantages should be investigated and promoted, mainly for finish materials such as clay plaster that were the most attractive in the visual assessment. For instance, future research about contaminant reduction and thermal comfort derived from clay plaster, should be catalyzed.
- **For decision makers,** environmental advantages should be enumerated to highlight the urgency of earthen construction.

- The earthen homeowners' comfort and their home's energy performance results show that earthen homes reduce the need for cooling, in all climate zones. Additionally, these results showed that insulation over earthen walls increased comfort levels, but only slightly. This last observation also showed that insulated earthen assemblies were more likely to be suitable for passive cooling. These results may provide significant recommendations for thermal performance and comfort guidelines for earthen structures, indicating that future research should demonstrate and justify these thermal benefits.

4 Technical Gap: Earthen Building Life Cycle Assessment (LCA)

4.1 Critical literature review of earthen building LCA

4.1.1 Introduction to LCA in the building sector

Environmental Life Cycle Assessment (LCA) is an important method for evaluating the environmental impacts of a product. LCA is defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006a). Developed in the 1960s, LCA methods evolved rapidly due to various environmental crises, such as the energy crisis on the 1970s. By the 1990s, life cycle thinking became a credible approach to evaluating the environmental impacts of products, leading to changes in public policy, environmental management, and design decisions. As a consequence of the increasing popularity of LCA during the 1990's, the International Organization for Standardization (ISO) developed a series of standards to guide LCA practitioners and to ensure the cohesion and accuracy of LCA studies (Freney, 2014; Matthews et al., 2015).

The methodological framework for conducting LCA should include the following steps (ISO, 2006b): 1) Definition of the study goal and scope, including functional unit and method of LCA 2) Life Cycle Inventory (LCI) data collection; 3) Life Cycle Impact Assessment (LCIA); and 4) Interpretation of the results. There are various ways in which an LCA study can be conducted, from the Economical Input-Output based matrix approach (EIO-LCA) that can be easily obtained but is extremely generalized, to process-based matrix models that often require expensive software and are resource intensive but are more accurate. Another approach that is often used is the hybrid model that combines the best features of process and EIO models (Matthews et al., 2015). The hybrid approach is used in many different sectors, including the building sector.

In the context of the building sector, LCA has become a powerful tool that is used to evaluate numerous building products and processes, while contributing to sustainable building development (Khasreen et al., 2009; Martínez-Rocamora et al., 2016). However, progress in LCA development is slower in the building sector than other industries, especially due to buildings' complicated production process and assumption-based future usage. Particularly, transparent datasets for buildings are missing and existing LCA studies are often not comparable among each other (Martínez-Rocamora et al., 2016). A significant challenge is therefore the acquisition of accurate, location-specific, and updated building Life Cycle Inventory (LCI) data, which is still missing for many construction materials and assemblies (Freney, 2014; Khasreen et al., 2009; Martínez-Rocamora et al., 2016).

4.1.2 Missing earthen building LCA studies

Although the environmental LCA of earthen building materials has not been comprehensively studied, it has been argued extensively that earthen materials can potentially require less energy and emit less Green House Gasses (GHG), due to their self-sustaining, cradle-to-cradle life cycle, as shown in Figure 75 (Schroeder, 2016).

The few existing earthen LCA studies include the environmental impacts evaluation of adobe bricks (Christoforou et al., 2016; Shukla et al., 2009), earth plasters (Melià et al., 2014; Morela et al., 2001), earthships (Freney et al., 2012; Kuil, 2012), earthbags (Cataldo-Born et al., 2017), and rammed earth (Serrano et al., 2012; Treloar et al., 2001). There has been limited work focused on the environmental impacts of cob and the few existing cob LCA studies present simplified breakdown studies. For instance, the embodied energy of cob in Canada was evaluated using only secondary online resources (Kutarna et al., 2013). Similarly, an embodied CO_2 inventory analysis of a small cob structure in rural Nicaragua was not extended to a full impact assessment (Estrada, 2013). Lastly, to date, the author has been unable to find LCA studies for light straw clay.

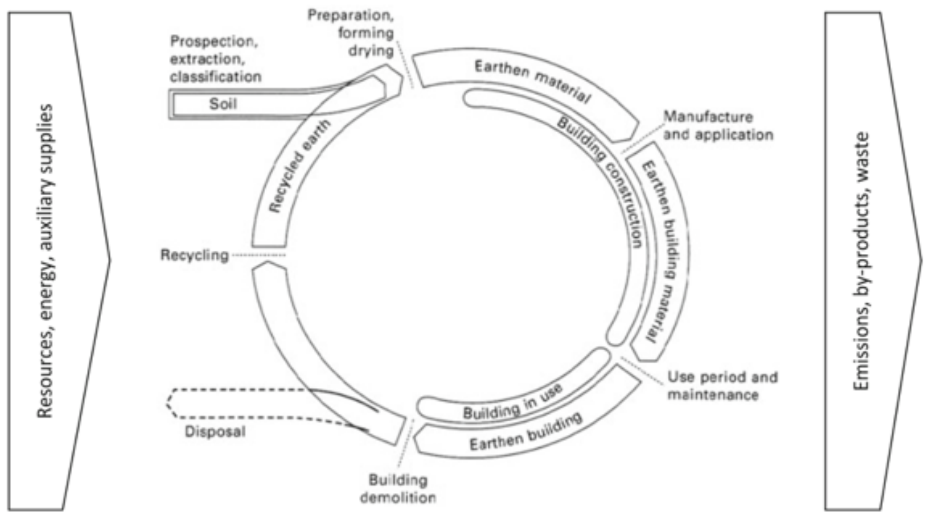


Figure 75: Life cycle diagram of earth as a building material (Schroeder, 2016)

Recent research into earthen building LCA show some of the environmental advantages of earthen building materials. For example, in a single-structure study in New-Delhi, India, Shukla et al. (2009) estimated the embodied energy associated with a stabilized adobe structure. The results of the study show that the energy payback time (EPBT) for the adobe house was only 1.5 years. However, the study does not follow the LCA methodology of ISO (2006b) and thus lacks an established research goal, system boundaries, LCA method, and impact assessment method. In this sense, this study makes a meaningful initial attempt to capture the environmental impacts of earthen construction, however without the use of proper LCA methodology.

On the other hand, Christoforou et al. (2016) presents a very rigourous LCA study for adobe in Cyprus. GaBi software (that has an extensive database for European countries), and CML impact assessment factors (Institute of Environmental Sciences of Leiden University et al., 2001) were used. This study clearly shows that one of the main environmental advantages of adobe (and earthen buildings in general) is their local production that reduces industrial production and transportation requirements. In addition, the study included comparative results to other bricks and to stabilized rammed earth. This comparison showed that the non-stabilized adobes have the lowest embodied energy per kg, in both scenarios of on-site as well as factory production. However, the study incorporated cradle to gate (construction site) only and did not include construction and operation processes in the system boundaries. An additional limitation of the study was the decision to use a functional unit of 1kg of material, which does not allow comparison between various *in situ* wall systems. Correspondingly, the LCA used in this dissertation will use a functional unit of 1 square meter of a wall system, that will be then expanded to a functional unit of a complete *in situ* wall assembly.

Another study, conducted in the Netherlands, (Kuil, 2012), compared the environmental life cycle impacts assessment of conventional houses, passive houses, and earthships. Kuil addressed both embodied and operating energy of each building alternative using Simapro software and ReCiPe impact indicator (which is normalized for Europe). The results show that both conventional houses and passive houses are far more suitable than earthships for Dutch conditions. The study had the following limitations: transportation of materials was not included in the model; an endpoint indicator (health problems) was used rather than using a midpoint indicator (emissions) that has higher certainty. Additionally, the study did not consider reduction of water consumption or renewable energy. Predominantly, the study assumed that the operating energy is the heating energy that compensates for heat loss. Earthship construction is a technique that is designed to passively reduce heat gain (making it a technique that is used in warmer climates); explaining the absence of earthships in the Netherlands reported by Kuil. Ultimately, this required the use data for earthships built outside of the Netherlands. In other words, the study results reflect the fact that earthships are less appropriate in colder climates such as in the Netherlands that require greater insulation (that can be achieved with, for instance, light straw clay or straw-bales).

Existing earthen structure LCA studies display limitations and only some of the studies include comparison to conventional materials and methods, making it hard to use these studies to extract environmental management or design change recommendations. In addition, these studies do not allow future comparison between the various earthen assemblies, due to the location-specific, inventory-specific, and process-specific data used for each case.

According to (Schroeder, 2016), in order to evaluate the action strategies required for sustainable earthen building, an environmental LCA is required. According to Swan et al. (2011), in order to enhance codes and practice for earthen construction in North America "Cost/benefit analyses are needed, including life-cycle analysis of construction assemblies". Within this context, the challenge is the development of a whole earthen materials LCA study that evaluates the various earthen assemblies in a manner permitting comparison to other building materials. This objective requires both to produce up to date, location specific data for missing studies, and to convert and re-evaluate data from existing studies. To achieve this, the present study provides a comparative analysis of a suite of earthen – as opposed to conventional – residential building assemblies.

4.2 Environmental Life Cycle Assessment (LCA) methodology

The presented environmental impact assessment uses the environmental Life Cycle Assessment methodology, as defined by the ISO series of LCA standards (ISO, 2006a, 2006b).

ISO describes a four-stage process:

Stage 1: Goal and Scope. The goal and scope of the study is defined, leading to the establishment of a "system boundary" which defines what will and will not be included in the study.

Stage 2: Life Cycle Inventory (LCI). The LCI data are developed based on the inputs (e.g., materials, energy use) and outputs (e.g., emissions to air, water, soil) of the system.

Stage 3: Life Cycle Impact Assessment (LCIA). The LCIA is used to analyze the data collected in the previous stage. Environmental impact "indicators" (e.g., energy demand, global climate change) are used to predict potential impacts to human health and the environment.

Stage 4: Interpretation. This is the final phase of the LCA in which the LCI and LCIA data is discussed and critiqued. Systematic processes for evaluating assumptions are conducted, limitations discussed, and conclusions drawn.

This Section details the rationale for assumptions and procedures adopted in this dissertation for each of the stages outlined.

4.2.1 Stage 1 - Definition of the LCA Goal, Scope, Functional Unit, and Approach

The goal and scope of the LCA are defined by identified gaps in the available literature. In essence, previous studies do not include comparative results and use functional units that cannot be readily incorporated in field work. Furthermore, existing earthen building LCA studies do not include cob or earthbag construction methods. Therefore, the presented LCA study aims to develop a comprehensive earthen building LCA that evaluates various earthen assemblies and other conventional building materials and methods in a comparative manner using operational function units, a hybrid Economic Input-Output (EIO) and process-based LCA.

4.2.2 Stage 2 - data collection and Life Cycle Inventory (LCI)

The proposed LCA requires to both produce up to date, location specific data for missing LCA studies, as well as to convert and re-evaluate data from existing studies. In order to conduct the presented LCA, the following inputs and LCI processes were evaluated:

1. *Production stage* – processes of extracting and transporting raw materials (from mines and fields), including water (wells or local water system) are obtained using SimaPro v8.4 life cycle assessment software (Pré Consultants, 2014), incorporating both process and IO LCA databases. Transportation distance of raw materials is acquired based on interviews with earthen building experts.
2. *Operation stage* – thermal performance and the associated heating and cooling energy requirements are obtained through a static and dynamic, thermal and hygrothermal, simulation in EnergyPlus. Additionally, the inventory and impact assessments are evaluated using environmental indicators from SimaPro life cycle assessment software.

In addition, conventional materials and existing earthen building LCA data are converted and re-evaluated from existing studies.

4.2.3 Stage 3 - Life Cycle Impact Assessment (LCIA)

The LCIA includes comparative impact results, using the data collection and the flow of substances from the LCI stage. This LCIA approach considers a set of impact categories, each of which is configured to account for a given list of substances, and then reports the impact in the common unit for that impact category. Selection of impact categories is not prescribed by any standard and consequently many approaches have been developed to address differing environmental and geographical conditions.

Common LCIA methods used in the US are the Cumulative Energy Demand (CED) and TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) methods. These tools enable the assessment of environmental impacts using factors that were evaluated according to US energy grid, water, and land use (Bare, 2012; Rolf Frischknecht et al., 2015). The CED and TRACI impact factors characterize the inventory of fuels and sources of energy, as well as air emissions.

According to Bengtsson and Howard (2010), LCIA impact categories should be chosen to represent four damage categories: climate change, resource depletion, ecological quality, and human health. To address this recommendation, this LCA study adopts primary impact categories of energy use (MJ_{eq}), global warming potential (kg CO_{2eq}), air acidification (kg SO_{2eq}), and human health (HH) respiratory effects (kg $PM_{2.5eq}$).

The Cumulative Energy Demand (CED) version 1.09 impact factors (Table 11) were used to characterize the inventory fuels and sources of energy, and the TRACI version 2.1 impact factors (Table 12) were used to characterize the inventory emissions (Bare, 2012).

Table 11: Impact factors according to CED 1.09 model

Energy Impact Factors			
Energy Source	**Source Units**	**Conversion Factor**	**Conversion Unit**
Natural Gas	$1m^3$	38.29	MJeq
Crude oil	1kg	45.8	MJeq
Gas, mine, off-gas	$1m^3$	39.8	MJeq
Coal, brown	1kg	9.9	MJeq
Coal, hard	1kg	19.1	MJeq

Table 12: Impact factors according to TRACI 2.1 model

	Global Warming	Acidification Air	HH Particulate Air
	[kg CO_2eq/kg substance]	[kg SO_2 eq/kg substance]	[$PM_{2.5eq}$/kg substance]
Ammonia, NH_3	-	1.88	0.0667
Carbon Dioxide, fossil	1.00	-	-
Carbon Monoxide, CO	-	-	0.000356
Methane, CH_4	25.0	-	-
Nitrous Oxides, NO_x	298	-	-
Nitrogen Dioxide, NO_2	-	0.700	0.00722
PM2.5	-	-	1.00
PM10	-	-	0.228
Sulfur Oxides, SO_x	-	1.00	-
Sulfur Dioxide, SO_2	-	1.00	0.0611

4.2.4 Stage 4 - Interpretation of the results

The interpretation stage of the LCA includes the systematic evaluation of the obtained LCIA results, as well as their sensitivity analysis. Importantly, this stage identifies significant issues that arise from the LCI and LCIA results, as well as an evaluation of the methods in terms of completeness, sensitivity, and limitations. A discussion about the limitations and assumptions that may have affected the results should be done and the evaluation in "relation to the defined goal and scope" presented (ISO, 2006a).

The sensitivity analysis in this LCA study was used as a systematic procedure for assessing the choices made throughout the LCA. The tested assumptions include transportation, material excavation choices, as well as allocation costs and weights.

4.3 Stage 1 - Definition of the LCA goal, scope, functional unit, and approach

4.3.1 Goal and scope

The main goal of the presented study is to enumerate the potential environmental impacts of building and living in an earthen structure compared to various conventionally built homes. Specifically, this study considers four earthen wall assemblies (cob, light straw clay, and insulated and uninsulated rammed earth) and three conventional assemblies (light timber frame, and insulated and uninsulated concrete masonry). The environmental impacts accounts for energy savings and emissions reductions of earthen assemblies for a single-family housing unit in warm-hot climates in the US. Accordingly, as described in greater depth in Chapter 5, this dissertation uses ASHRAE climate zone classification and accounts for dry warm-hot climate zones 2B (e.g., Tucson, AZ) and 3B (e.g., Los-Angeles, CA). Additionally, due to the broad use of cob in temperate and colder climates, climate zones 4C (e.g., Portland, OR) and 5B (e.g., Denver, CO) were considered as well.

4.3.2 Target Audience

The main audience of the study are policy makers and earthen building advocates that might use the results to motivate their endeavors to implement earthen materials within building codes/standards and ultimately bring the use of cob into mainstream construction projects. An additional audience includes earthen building experts, construction companies and architects, and those educating and collaborating with potential homeowners seeking more ecological building approaches. Furthermore, the study targets generally environmentally conscious homeowners and governmental departments looking at energy standards for housing policies.

In light of the target audience groups, the study's impact could be both top-down (by influencing policy decision makers, firms, and government), as well as bottom-up (by influencing local advocates, experts, and potential homeowners).

4.3.3 Functional unit

The chosen functional unit is 1 m^2 (10.75 ft^2) of load bearing exterior wall suitable for up to 2-story residential construction having an insulation value meeting or exceeding the requirements of the International Energy Conservation Code (ICC, 2018) for climatic zones 1-4. The functional unit was designed according to construction guidelines and common practice.

The functional unit was selected to provide building professionals and homeowners an applicable and multipliable measure that allows them to extrapolate the results to larger areas of wall during the design and construction processes. However, in order to make the results attractive and practical, a further functional unit of a prototypical dwelling was considered and discussed in the LCA study interpretation section.

4.3.4 System boundaries

This LCA accounts for the cradle to end-of-life portion of the life cycle; it considers the extraction and processing of raw materials, manufacture of building materials, transportation of the building materials to the construction site, and operation of HVAC for space conditioning for a 50-year life. Onsite construction energy and emissions are beyond the system boundaries (Figure 76).

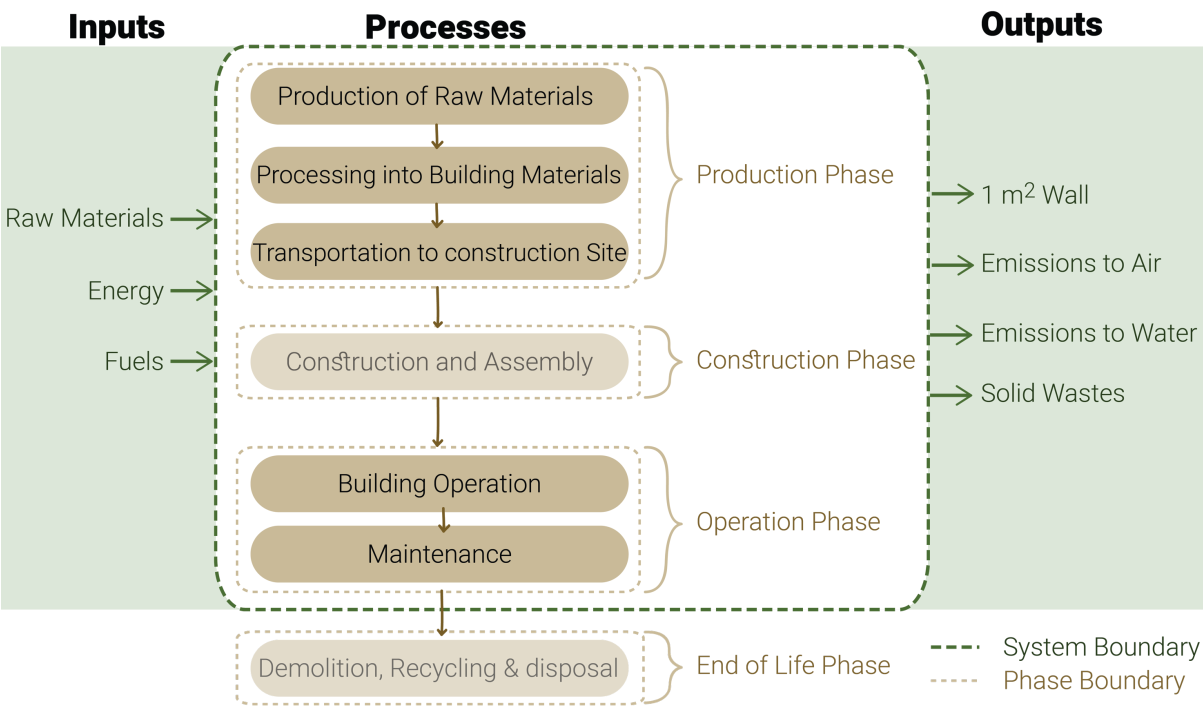


Figure 76: Boundaries of systems studied

There are many uncertainties regarding maintenance requirements for different earthen wall materials and assemblies and little research addressing this issue. As indicated by earthen building experts and homeowners in the perception survey (Chapter 3), maintenance requirements depend heavily on the building quality and workmanship, quality control of the materials and products, climate, occupant's behavior, and design details. Given the lack of information about maintenance of the various earthen walls, this aspect of the study was limited to the application of embodied values for component renewal, such as surface plaster, every 10 years (as seen in, for instance, (Monteiro and Freire, 2012)).

Acquisition of end-of-life stage data presents significant challenges for various reasons. First, very little useful data is available about the fine details and proportions of the various materials' salvage abilities. Second, future reuse and recycling practices (50 years from now) are unknown, making the results unable to provide accurate predictions. Given these challenges, the end-of-life stage is limited to a discussion-based assessment, given treatment rates and assumptions for all materials.

4.3.5 LCA approach

ISO 14044 (2006b) details three main types of LCA approach:

"Micro-level decision support" in which an LCA is typically related to specific products and decision support on a micro-level

"Meso/macro-level decision support" in which an LCA supports decision making at a strategic level (e.g. raw materials strategies, technology scenarios, policy options) with the aim to change available production capacity.

"Accounting" in which a purely descriptive documentation of the system's life cycle under analysis (e.g. a product, sector, or country) is presented, without being interested in any potential additional consequences on other parts of the economy.

The approach taken in this LCA is a "Meso/macro-level decision support" approach, which matches the aims of this dissertation in which comparisons are being made to promote strategic earthen policy enhancements and inclusion.

To support this approach, this LCA uses attributional modelling, using system expansion and allocation. For example, this LCA study uses economic allocation for straw, to best capture a viable future scenario where straw is used as a valuable building material rather than an as a less valuable byproduct of cereal production (Guinée, 2002; Owens, 2015).

Due to the significant impact that heating and cooling energy can have on environmental impacts of a home, this dissertation includes a thermal analysis for various climatic contexts. The aim of the operational stage part of the study – presented in Chapter 5 – was to develop a simulation model that could accurately predict indoor air temperature and thus energy loads of both earthen and conventional residential structures in warm and temperate climate zones in the US. The developed model offered a reasonable estimate for heating and cooling energy required for the context of the LCA study.

EnergyPlus software (US Department of Energy, 2014) was used to model the thermal performance of the assembled earthen walls (cob, rammed earth, insulated rammed earth, and light straw clay) and compare these to conventional assemblies (light wood frame, concrete masonry, and insulated concrete masonry). Significantly, whereas many thermal performance studies include static calculations and account only for the thermal resistance of the envelope, this study included a dynamic simulation that included a myriad of thermal and hygrothermal characteristics for each assembly, as well as air temperature, radiant temperature, and relative humidity for each climatic context.

4.3.6 Assumptions and limitations

The following assumptions and conditions delimit this LCA study:

- The geographical context of the study is primarily warm-hot climates in the US as defined by ASHRAE climate zone classifications 1-3; additional cases in zones 4 and 5 are also considered.
- This LCA study uses location-specific inventory databases as much as possible. Existing inventory databases were selected from US-LCI (NREL, 2012) where possible. Other inventories were selected from EcoInvent with relevance to the US geographical context (Wernet et al., 2016).
- To assess operational values, as described in Chapter 5, the functional unit was expanded to an entire residential structural wall envelope; however, the roof, floor, glazed area, footing, and other systems were assumed to be identical in all structures. In practice, these components might vary among and between the various dwellings due to common practice.
- The operational values and complete-building analysis are limited to the DOE residential structure template (Kneifel, 2012).
- HVAC for the operational stage was assumed to be available and operable 24 hours a day. It is assumed that electric AC is used for cooling and gas furnace for heating.

4.4 Stage 2 - data collection and Life Cycle Inventory (LCI)

The study includes both previously studied and unstudied wall systems. For the concrete masonry units (CMU) and lightweight wood frame systems, existing LCA studies are used and LCI data for these systems was taken from these existing resources. On the other hand, for the earthen wall systems that were not extensively studied, LCI was developed independently.

The development of the earthen assemblies LCI is depicted in Figure 77 and accounts for the constituent materials in each earthen building mixture. The developed LCI includes a process-based LCA, using financial-based allocations. In order to achieve an accurate assessment, energy and emissions inventories were taken from primary sources whenever possible, and every process was documented. North American data were used whenever available. All data used in the analysis is from 1997 or later. The majority of the data was adapted to fit the situation in southwest USA (which corresponds to the climatic context of this dissertation); however, some information could not be found and, instead, data specific to a greater or different geographical area was used.

In terms of system functionality, all wall assemblies were considered to be used as load bearing, in order to be directly comparable. For light straw clay that is used as a wall infill, a lightweight wood frame structure was considered. Cob, rammed earth, and CMU can be used as either infill or load bearing walls for the low-rise structures considered in this dissertation.

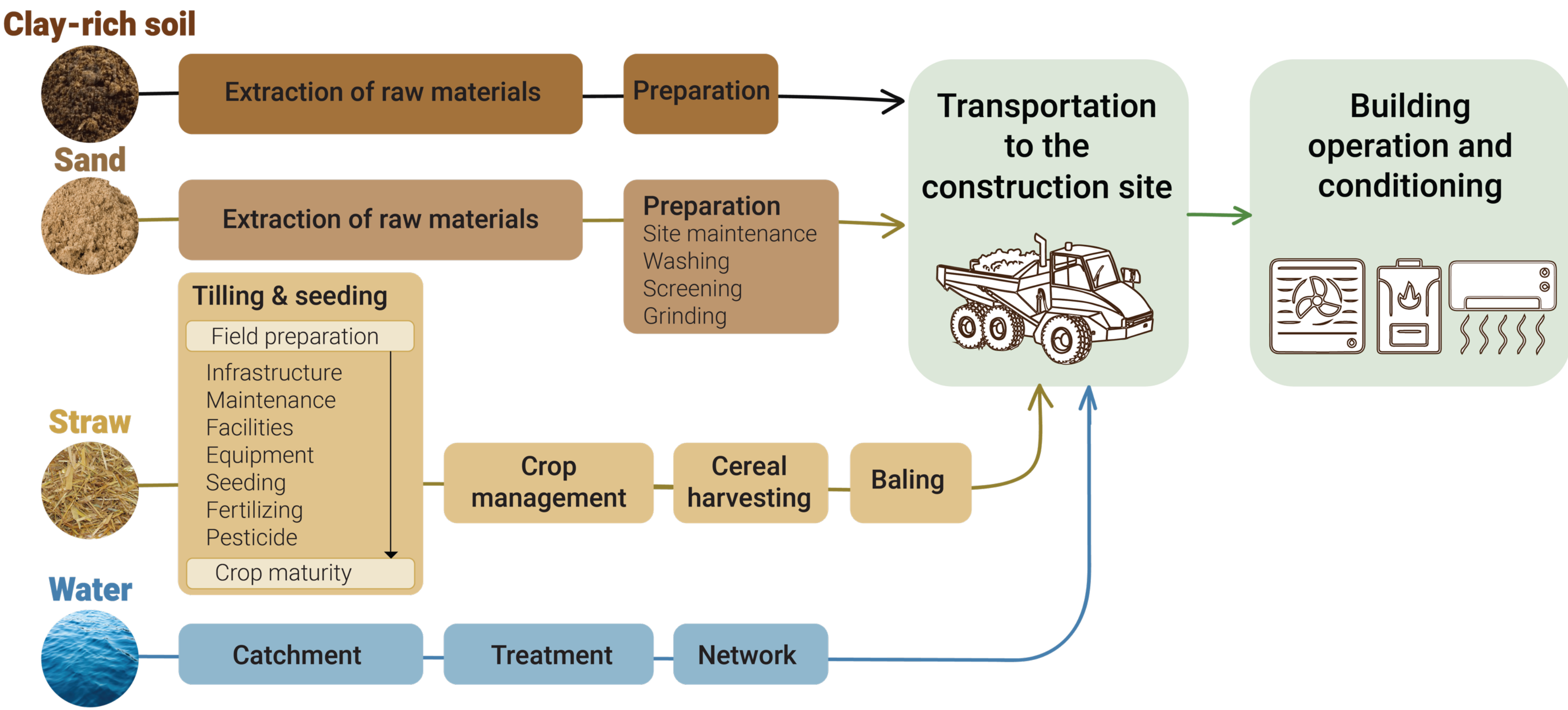


Figure 77: System boundaries of the developed cob LCI

4.4.1 Details of the chosen wall systems

Cob

The chosen cob wall section was designed according to typical sections by Fordice, (2009), cob architect and head of the Cob Research Institute. Illustrated in Figure 78 the wall section follows the recommendations from the Getty Report on adobe structures in seismic areas (Tolles et al., 2002). It is assumed that once cob walls are specified within building codes, they should have a maximum height of 2.44 m (8 ft) for an unreinforced, load bearing, wall (Cob Research Institute, 2019b). Additionally, it is assumed that cob wall minimum thickness is 305 mm (12 in.) at the top of the wall, and 610 mm (24 in.) thick at its base, resulting in an average wall thickness of 457 mm (18 in.). The insulation value of this wall is 0.51 W/m·K (R-11.4 $^{\circ}$F·ft^2·hr/Btu).

Rammed earth

The rammed earth wall section, illustrated in Figure 78, was designed according to common practice as well as code requirements (New Mexico Regulation & Licensing Department and NMAC, 2015; Pima County Development Services, 2013). Rammed earth mixture requires mainly clay-rich soil, sand, and gravel, with no added fibers. The mixture is achieved by mixing the dry materials with a small amount (8%) of water to achieve optimal compaction. The study assumes 20% gravel and 8% water content (Jaquin et al., 2009). Additionally, the rammed earth wall was assumed to have no plaster, which is the common practice due to the desired sedimentary aesthetic effect of rammed earth components. Lastly, the rammed earth wall thickness was assumed to be 457 mm (18 in.), according to the exterior rammed earth wall thickness in NMAC (2015). The insulation value of this wall is 0.62 W/m·K (R-9 $^{\circ}$F·ft^2·hr/Btu).

Light straw clay

The light straw clay wall section, illustrated in Figure 78, was designed based on the IRC light straw clay appendix (IRC, 2015a). The incorporated section includes a light straw clay infilled lightweight timber frame. It was assumed that the building methods utilized blind studs using 51x152 mm (2x4 in.) studs, per section AR103.2.4 in (IRC, 2015a). This LCA study assumes an overall core density of the light straw clay to be of 192 kg/m^3 (12 pcf) (Piltingsrud and Design Coalition, 2004) based on an 85% straw content (IRC, 2015a) and an overall thickness of 305 mm (12 in.). The insulation value of this wall is 0.28 W/m·K (R-21.8 $^{\circ}$F·ft^2·hr/Btu).

Concrete Masonry Units (CMU)

The benchmark concrete wall system, illustrated in Figure 78, was chosen according to Lstiburek (2010). The CMU wall includes the following layers: from interior to exterior, 13 mm (½ in.) gypsum board, 203 mm (8 in.) CMU blocks, and 15 mm ($^2/_3$ in.) Portland cement-based stucco. Two alternatives were considered: an uninsulated assembly and an insulated assembly that provided an additional 51 mm (2 in.) of R-15 extruded polystyrene insulation between the CMU and gypsum board. Although the uninsulated CMU wall does not adhere to energy code requirements (ICC, 2018, Table 402.1.2), it was still considered in this dissertation due to its relevance to other geographical and building practice contexts, such as those prevalent in Central America and the Middle East. The insulation value of this wall is 0.74 W/m·K (R-8 °F·ft^2·hr/Btu) for the uninsulated assembly and 0.23 W/m·K (R-23.8 °F·ft^2·hr/Btu) for the insulated assembly.

Light-frame wood

The conventional wood frame wall system, illustrated in Figure 78, was chosen according to the U.S. Department of Energy's Building America Research Benchmark Definition (Hendron and Engebrecht, 2009). Illustrated in Figure 78d, the wall system represents a typical light-frame wood residential house in the US, as defined by the National Renewable Energy Laboratory (NREL). The original benchmark section was modified slightly to represent warmer US climates as appropriate for the South-West USA by Lstiburek, (2010); stucco rendering was used rather than vinyl cladding. The chosen cavity insulation is R-21 fiberglass batt (Hoeschele et al., 2015). The wall includes the following layers: from interior to exterior, 13 mm (½ in.) gypsum board, 51x152 mm (2x6 in.) dimensional lumber, cavity insulation in the form of a 150 mm (5.9 in.) fiberglass batt, 13 mm (½ in.) plywood sheathing, and 15 mm ($^2/_3$ in.) stucco. The insulation value of this wall is 0.34 W/m·K (R-17.4 °F·ft^2·hr/Btu).

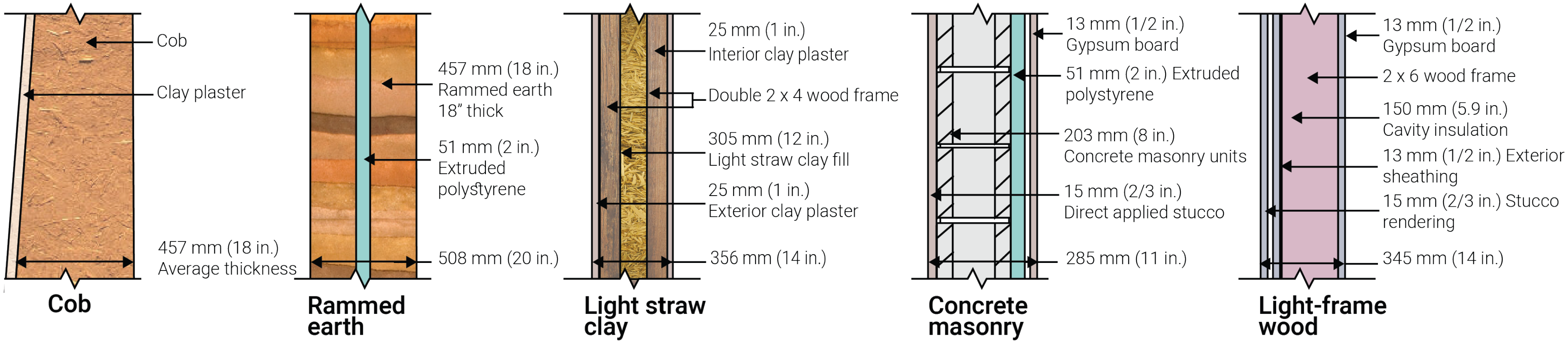


Figure 78: Section drawings of the compared wall systems (from left to right): cob, rammed earth, light straw clay, concrete masonry units, and lightweight wood frame wall systems.

4.4.2 Constituent materials embodied LCI analysis

As illustrated in Figure 78, the various wall assemblies require different constituent materials and building products. Each of the cob, rammed earth, and light straw clay wall systems incorporate clay-rich soil. Depending on the assembly, gravel, sand, fibers, and water will be used in the mixture. Cob and light straw clay require a layer of clay plaster. Additionally, light straw clay is incorporated within a lightweight timber frame. Similarly, the CMU assembly requires gypsum board, CMU bricks, and stucco, whereas the lightweight timber frame requires exterior sheathing and cavity insulation.

The following subsections detail the inventory data used for each of these constituent materials.

Straw

Straw production is a co-product of wheat production, and thus the associated inputs and outputs must be allocated between the two products. Two allocation procedures were considered: economic value and mass. Though physical quantity-based allocation is typically preferred, economic allocation was chosen as it best captures the scenario of straw as a valuable building material rather than an a less valuable byproduct of cereal production (Guinée, 2002; Owens, 2015). Wheat straw prices were drawn from both the field and from literature (Table 13) and represent the average experienced wheat straw price according to four cob experts located in southwest USA. This average price reflects how, according to experts, straw is typically purchased directly from local farmers, and prices often vary according to availability.

Table 13: Prices used for the market-based economic allocation of the wheat and straw production and harvesting processes

Component	Unit	Price from primary source	Price from field experts	Price used for the LCI (average)
Wheat straw	$/square bale	3.30 (USDA, 2016)	13.0, 3.50, 12.0, 7.50	7.96
Wheat grain	$/bushel	6.10 (NASS et al., 2017)	–	6.10

For the straw modeling, four main stages were assessed: producing the straw (tilling and seeding, crop management), harvesting, baling, and transporting the bales to the construction site (Figure 77).

For each stage, system processes were identified to compound the inventory:

- *Growth stage* – the evaluation data includes tilling and seeding of the field from its initial preparation to when the crop matures, and crop management. This stage was modeled by the US LCI unit process of "Wheat grains, at field, U.S.", which offers results per output of 1 kg of wheat grains and 1.3 kg of wheat straw (NREL, 2012). The unit process was converted to a system process using US LCI process matrix. It was assumed that 85% of planted acres are harvested. In addition, the inventory was allocated between the grains and straw based on cost allocation (USDA, 2016).

- *Harvesting stage* – this stage was modeled by the EcoInvent process of "Combine harvesting {CA-QC} | Alloc Def, S." (R. Frischknecht et al., 2005). The machinery and infrastructure components are specific to the U.S., sourced from the American Society of Agricultural and Biological Engineers. However, the emission rates are representative of the world ("GLO" geographic location) and diesel consumption is representative of Quebec, Canada. Process is per output of 1 hectare of field harvested. The inventory was manipulated to transform the output to be per 1 straw bale by converting average wheat yield to average straw yield (1.3 kg of straw per 1 kg of grains), as well as by converting the average straw yield to average number of bales per acre, using a density of 110 kg/m^3 (7 lb/ft^3), as required by the building code (IRC, 2015b).

- *Baling stage* – this stage was modeled by the EcoInvent process of "Baling {CA-QC} | Alloc Def, S." (R. Frischknecht et al., 2005), which follow the same geographic specificity as the harvesting process. The process is per output of approximately 2.5 million large bales of 360 kg each. The inventory was manipulated to transform the output to be per 1 small straw bale by calculating the total mass represented by the original output and converting to number of small bales using the assumed straw bale density.

- *Transportation stage* – transportation was modeled by the US LCI unit process of "Transport, combination truck, diesel powered" (NREL, 2012), which was converted to a system process using US LCI process matrix.

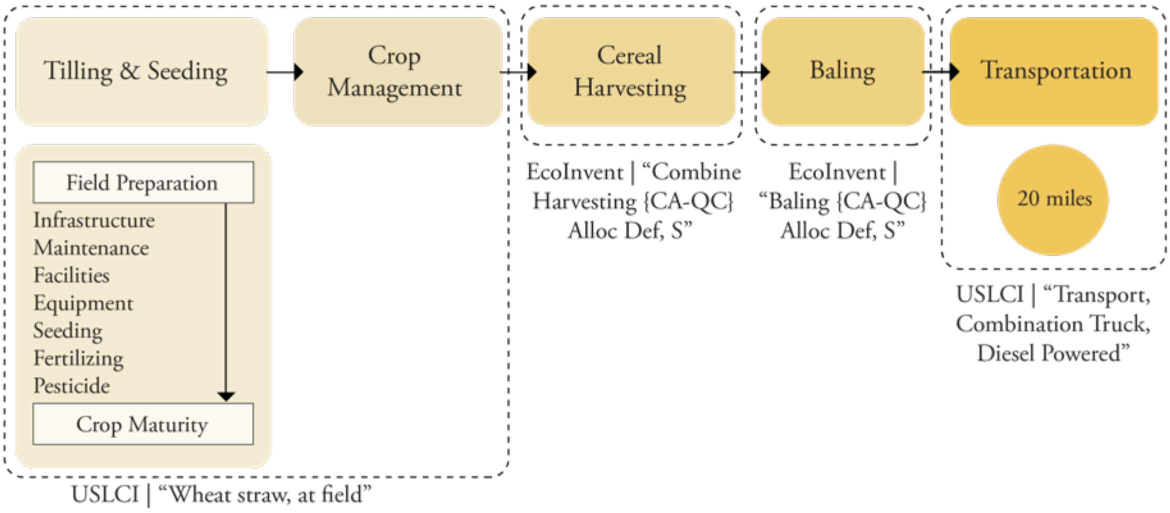


Figure 79: Processes incorporated in the straw LCI

Table 14 shows that growing the straw requires the highest amount of energy. This finding corresponds with a previous study that depict the high primary energy inputs in biomass production, due to the need of fertilizers and pesticides, as opposed to motor fuels (Offin, 2010). Overall, the amount of energy required for the production and transportation of one bale is 25.4 MJ and its prominently derived from natural gas and oil consumption, as seen in Table 14 and Table 15.

Table 14: Straw energy use by operation

By Operation	Growth	Harvesting	Baling	Transportation	Total to Construction Site
MJ/bale	21.8	2.91	1.1 x 10^{-6}	0.66	25.3

Table 15: Straw energy use by fuel type

By Fuel Type	Coal	Natural gas	Oil	Others	Total to Construction Site
MJ/bale	2.14	11.4	11.8	0.07	25.3

Table 16: Straw air emissions

kg/bale	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NO_x	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Growth	7.83 x 10^{-1}	5.88 x 10^{-3}	1.12 x 10^{-1}	NA	3.50 x 10^{-3}	NA	3.68 x 10^{-4}
Harvesting	2.00 x 10^{-2}	5.47 x 10^{-5}	6.31 x 10^{-5}	8.90 x 10^{-6}	3.62 x 10^{-10}	4.52 x 10^{-4}	2.91 x 10^{-5}
Baling	6.29 x 10^{-9}	1.37 x 10^{-11}	1.77 x 10^{-11}	2.38 x 10^{-12}	4.20 x 10^{-12}	1.38 x 10^{-10}	8.04 x 10^{-12}
Transportation	4.70 x 10^{-2}	2.22 x 10^{-5}	3.19 x 10^{-4}	1.54 x 10^{-5}	2.80 x 10^{-6}	2.46 x 10^{-4}	5.74 x 10^{-6}
Total to Gate	8.50 x 10^{-1}	5.96 x 10^{-3}	1.16 x 10^{-2}	2.43 x 10^{-5}	3.51 x 10^{-3}	6.98 x 10^{-4}	4.03 x 10^{-4}

Sand and gravel

Sand and gravel were assumed to be extracted from a quarry, which produces both sand (35%) and gravel (65%). It was assumed that the sand and gravel are similarly priced (as listed in Acme Sand & Gravel, 2016), and that they are extracted from the same riverbanks, as well as crushed, sorted, screened, and washed in the same facility, going through the same blade mill and then sorted (Moshgbar, 2017). Thus, 1 kg output was used for either output with no allocation. The embodied energy and air emissions of the sand and gravel extraction and preparation was performed using the EcoInvent process of "Gravel and Sand Quarry Operation {RoW}, Alloc Def, S" (R. Frischknecht et al., 2005). The activities included in the production of the sand and gravel are the digging and extraction of raw materials, internal process (transport, washing, screening, grinding), infrastructure for the operation (machinery), and the land-use of the mine (Figure 80). It is assumed that the quarry is located 35 km (20 miles) from the construction site (based on an interview with two architects and an earthen building contractor (Appendix D)).

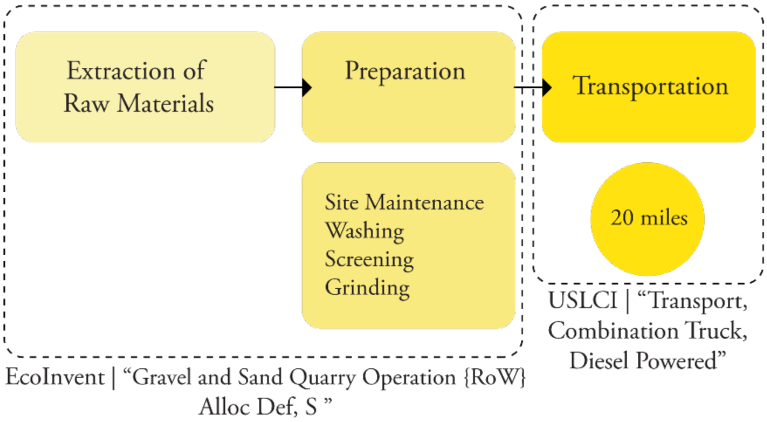


Figure 80: Processes incorporated in the sand LCI

The LCI analysis shows that both the production and transportation of sand requires an approximately equal amount of energy, which is mostly derived from crude oil (Table 17). Overall, the amount of energy required for the production and transportation of 1kg of sand is 0.0956 MJ.

Table 17: Sand energy use by operation

By Operation	Production	Transportation	Total to Construction Site
MJ/kg	0.0549	0.0407	0.0956

Table 18: Sand energy use by fuel type

By Fuel Type	Coal	Natural gas	Oil	Others	Total to Construction Site
MJ/kg	0.0205	0.0105	0.0619	0.00272	0.0956

Table 19: Sand air emissions

kg/kg sand	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NO_x	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Production	1.35×10^{-3}	1.50×10^{-6}	1.64×10^{-5}	9.01×10^{-12}	5.59×10^{-7}	7.85×10^{-6}	1.85×10^{-6}
Transportation	2.87×10^{-3}	1.36×10^{-6}	1.95×10^{-5}	9.39×10^{-7}	3.45×10^{-6}	1.50×10^{-5}	3.51×10^{-7}
Total to Gate	4.22×10^{-3}	2.86×10^{-6}	3.59×10^{-5}	9.39×10^{-7}	4.01×10^{-6}	2.29×10^{-5}	2.20×10^{-6}

Clay-rich soil

Earthen construction often employ clay-rich soil from the byproduct soil (spoil) of the foundation excavation (Reeves et al., 2006). However, clay soils might vary from site to site, or might be unsuitable or unavailable on the construction site. Therefore, some large-scale projects use clay-rich soil that is purchased from a quarry, which is the scenario considered in this LCA study. The clay-rich soil used in this LCI was extracted and prepared in a quarry and then transported to the construction site. The embodied energy and air emissions of the clay-rich soil was performed using the EU27 Input Output Database process of “Clay and Soil from Quarry”, as shown in Figure 81 (EU-27, 2010). It is assumed that the extracted soil consists of at least 50% clay, to provide the approximate recommended clay content of 20% when mixed with sand in the earthen mixture. It is also assumed that the quarry is located approximately 35 km (20 miles) from the construction site, following an interview with two earthen building architects and an earthen building contractor from Section 2.5.

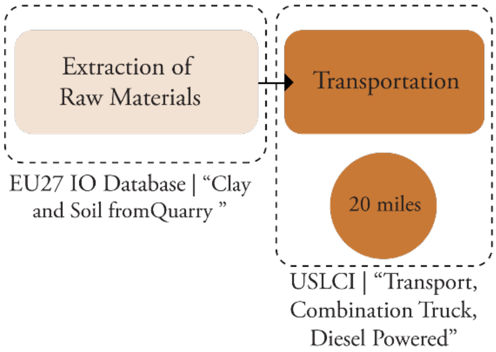


Figure 81: Processes incorporated in the clay-rich soil LCI

The LCI results for the clay-rich soil shows that the production stage requires twice as much energy than the transportation to the construction site (Table 20). Overall, the amount of energy required for the production and transportation of the soil is 2.64 MJ.

Table 20: Clay-rich soil energy use by fuel type

By Operation	Production	Transportation	Total to Construction Site
MJ/kg	0.0767	0.0407	0.117

Table 21: Clay-rich soil energy use by fuel type

By Fuel Type	Coal	Natural gas	Oil	Electricity	Total to Construction Site
MJ/kg	0.00116	0.0108	0.0876	0.0177	0.117

Table 22: Clay-rich soil air emissions

kg/kg soil	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NO_x	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Production	4.15×10^{-3}	4.74×10^{-6}	1.79×10^{-5}	9.38×10^{-6}	7.00×10^{-7}	2.39×10^{-5}	NA
Transportation	2.87×10^{-3}	1.36×10^{-6}	1.95×10^{-5}	9.39×10^{-7}	3.45×10^{-6}	1.50×10^{-5}	3.51×10^{-7}
Total to Gate	7.03×10^{-3}	6.10×10^{-6}	3.74×10^{-5}	1.03×10^{-5}	4.15×10^{-6}	3.89×10^{-5}	3.51×10^{-7}

Clay plaster

A 25 mm (1 in.) layer of clay plaster is used as the finish material for the cob and light straw clay wall surfaces. It is assumed that a layer of lime stucco is not needed to protect the wall systems from moisture due to the warm/hot dry climatic scope of this work (Minke, 2012). In addition, for the cob, it is assumed that the interior side of the wall is plastered manually using the cob mixture, with chopped straw.

The clay plaster was assumed to have a density similar to the cob mixture, due to their similar content. The process used for modeling the clay plaster production is EcoInvent “Clay Plaster {RoW} Production | Alloc Def S”, which consists of 55% sand, 25% clay, and 20% water (R. Frischknecht et al., 2005). The clay plaster LCI models the extraction of raw materials, mixing of raw materials, transportation to the packing site, packing, and storing (Figure 82). Then, the product is transported to the construction site, which is assumed to be located approximately 80 km (50 miles) from the storage facility. This assumption corresponds with the various locations of clay plaster distributers in the US (e.g., Americal Clay, 2017)

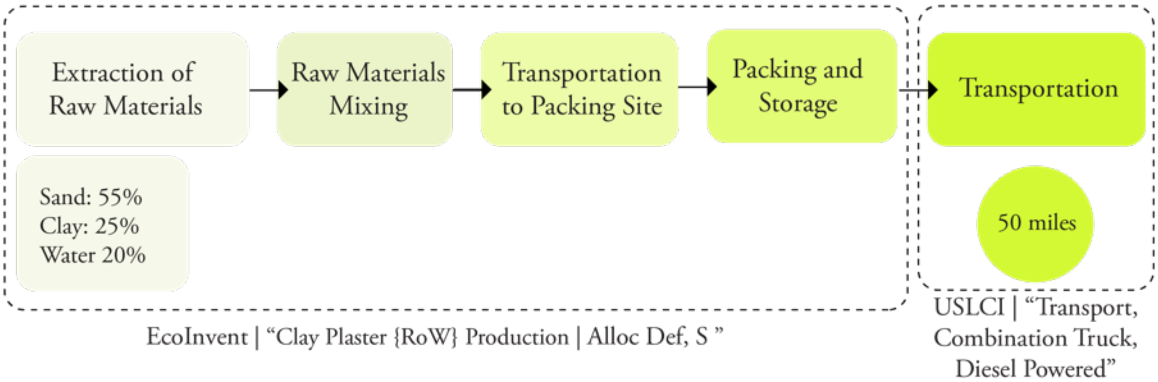


Figure 82: Processes incorporated in the clay plaster LCI

The LCI analysis of the clay plaster shows that its production requires approximately 3 times more energy than its transportation (Table 23). Overall, the amount of energy required for the production and transportation of 1 m^2 clay plaster is 11.7 MJ.

Table 23: Clay plaster energy use by operation

By Operation	Production	Transportation	Total to Gate
MJ/m^2	8.88	2.86	11.7

Table 24: Clay plaster energy use by fuel type

By Fuel Type	Coal	Natural gas	Oil	Total to Gate
MJ/m^2	1.14	2.57	8.02	11.7

Table 25: Clay plaster air emissions

kg/m^2 of 25 mm plaster	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NO_x	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Production	2.27×10^{-1}	3.14×10^{-4}	1.67×10^{-3}	2.16×10^{-9}	1.50×10^{-4}	1.28×10^{-3}	3.72×10^{-4}
Transportation	2.02×10^{-1}	9.54×10^{-5}	1.37×10^{-3}	6.59×10^{-5}	2.42×10^{-4}	1.05×10^{-3}	2.46×10^{-5}
Total to Gate	4.28×10^{-1}	4.10×10^{-4}	3.04×10^{-3}	6.59×10^{-5}	3.92×10^{-4}	2.33×10^{-3}	3.97×10^{-4}

Tap water

Water for the onsite mixing processes is assumed to be obtained from the tap. Tap water production was considered using the EcoInvent process for Tap water {RoW}| tap water production, conventional treatment | Alloc Def, S. Though the geographical representation employs a global average, this system process accounts for average global consumptions, infrastructure, and energy use for water treatment and transportation.

Table 26: Tap water energy use by operation

By Operation	Total to Construction Site
MJ/kg	0.00585

Table 27: Tap water energy use by fuel type

By Fuel Type	Coal	Natural gas	Oil	Others	Total to Gate
MJ/kg	0.00295	0.00148	0.000782	0.000641	0.00585

Table 28: Tap water air emissions

kg/kg water	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NO_x	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Total to Gate	4.16×10^{-4}	1.72×10^{-6}	1.00×10^{-6}	3.07×10^{-10}	2.29×10^{-13}	2.97×10^{-7}	1.58×10^{-6}

Dimensional Lumber

The dimensional (sawn) lumber embodied energy and emissions were obtained from an existing LCI cradle to gate study by Puettmann et al. (2013), which focused on softwood lumber production from the US Pacific Northwest. The lumber considered for the purpose of transportation is southern pine wood, with a density of approximately 560 kg/m^3 (35 pcf) (The Engineering ToolBox, 2016). The production phase of the lumber includes harvesting the trees, transporting them to the mill, drying, sawing, packing and storage in a storage site.

The LCI analysis of the dimensional lumber shows that wood production requires the bulk of the energy consumed, approximately three times more energy than its transportation (Table 29). Emissions from the forest resources LCI are small relative to manufacturing emissions. Overall, energy use and emissions in this LCI were dominated by the drying process and are a function of the fuel burned. In total, the amount of energy required for the production and transportation of 1 m^3 dimensional lumber is 1366 MJ.

Table 29: Lumber energy use by operation

By Operation	Forestry Operations	Wood Production	Transportation	Total to Construction Site
MJ/m^3	128	1215	22.8	1366

Table 30: Lumber energy use by fuel type

By Operation	Coal	Natural gas	Oil	Total to Construction Site
MJ/m^3	240	796	329	1366

Table 31: Lumber air amissions

kg/m^3 lumber	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NO_x	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Forestry Operations	4.505	0.003	0.082	0.002	0.006	0.041	0.003
Wood Production	46.7	0.339	0.201	0.052	0.166	0.069	0.364
Transportation	0.806	0.000	0.005	0.000	0.001	0.004	0.000
Total to Gate	52.0	0.342	0.288	0.054	0.173	0.114	0.366

Gypsum board

The gypsum board embodied LCI was obtained from an existing LCI database by Athena Sustainable Materials Institute & Venta (1997), modeled for Canada. The inventory data for west Canada was chosen when possible, assuming that it the most relevant to west USA. The evaluation data includes the extraction and transportation of the raw gypsum, the manufacturing of the paper, board, and board stucco, as well as the transportation from the plant to the market. A significant amount of energy is used to dry the extracted gypsum (which must be calcinated) before the board manufacturing, and more than half of the total embodied energy is attributed to the kiln drying during the board manufacturing (Table 32). Gypsum board production is not very carbon intensive given the amount of heat energy that is required for the calcination of the gypsum and drying of the final product (S. A. Matthews, 2011). This is probably due to the use of natural gas for the kiln heating processes (Athena, 1997). Overall, the production of 1 m^2 of 13 mm (½ in.) thick regular gypsum board requires 50.2 MJ.

Table 32: Gypsum board energy use by operation

By Operation	Gypsum Extraction	Raw Materials Transportation	Manufacturing	Transportation to Market	Total to Construction Site
MJ/m^2	0.266	10.5	38.6	0.856	50.2

Table 33: Gypsum board energy use by fuel type

By Fuel Type	Diesel	Natural gas	Oil	Electricity	Total to Construction Site
MJ/m^2	8.89	28.6	9.80	2.92	50.2

Table 34: Gypsum board air amissions

g/m^2 of 13 mm board	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NO_x	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Gypsum Extraction	13.42	0.0194	0.153	0.0165	0.00410	0.0841	4.64

g/m² of 13 mm board	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NO_x	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Raw Materials Transportation	753	2.01	7.70	1.63	0.258	2.95	
Manufacturing	1948	5.96	2.83	0.0550	0.0430	0.532	1.75
Transportation to Market	60.5	0.0873	0.69	0.0744	0.0186	0.379	
Total	2775	8.08	11.4	1.77	0.324	3.94	6.39

Concrete Masonry (CMU) blocks

The CMU LCI was assessed using an existing inventory analysis produced for the Portland Cement Association by Nisbet et al. (2002), targeting the US. The evaluation data includes the cement and slag cement manufacture, aggregate production, transportation of fuel, cement, and aggregates to the plant, concrete plant operations, and concrete block curing. Energy to produce cement dominates energy from other steps of the block production process (Table 35).

Table 35: CMU energy use by operation

By Operation	Cement Manufacturing	Aggregate Production	Raw Materials Transportation	Concrete Plant Operation	Concrete Block Curing	Total to Construction Site
MJ/100 CMU	812	85	92	187	49	1225

Table 36: CMU energy use by fuel type

By Operation	Diesel	Natural gas	Coal	Oil	Electricity	Others	Total to Construction Site
MJ/100 CMU	279	109	481	1	137	219	1225

Table 37: CMU air emissions

kg/100 CMU	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NOx	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Cement Manufacturing	0.301	0.394	0.00600	0.00500	0.134	0.382	0.301
Aggregate Production	0.00500	0.0280	0.00500	0.00100	0.0280	0.281	0.00500
Raw Materials Transportation	0.0100	0.0600	0.0110	0.00200	0.0600	0.00900	0.0100
Concrete Plant Operation	0.0630	0.0110	2.00×10^{-4}	NA	0.00300	0.0760	0.0630
Concrete Block Curing	0.0110	0.0300	4.00×10^{-5}	4.00×10^{-5}	0.00100	NA	0.0110
Total to Construction Site	0.390	0.523	0.0222	0.00804	0.226	0.748	0.390

Portland Cement-Based Stucco

The energy and carbon assessment of the exterior Portland Cement-based stucco was obtained from an existing LCI by Athena Sustainable Materials Institute & Venta (2001), which was developed in Canada. The modeling takes into account 3-coat Portland cement-based stucco with a total thickness of approximately 20 mm (0.8 in.). The most significant amount of the embodied energy and carbon is used to manufacture the cement (Table 38). Overall, the production of 1 m^2 stucco requires 17 MJ.

Table 38: Portland cement stucco energy demand by operation

By Operation	Raw Materials Extraction	Raw Materials Transportation	Processing	Transportation	Total to Construction Site
MJ/m^2	0.487	0.183	15.7	0.873	17.2

Table 39: Portland cement stucco energy demand by fuel type

By Operation	Diesel	Natural gas	Coal	Oil	Electricity	Others	Total to Construction Site
MJ/m^2	1.38	10.3	2.91	0.467	1.79	0.400	17.2

Table 40: Air emissions per 1 m^2 of 20mm (0.8 in.) PC stucco,

g/m^2	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NOx	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Raw Materials Extraction	34.5	0.0497	0.393	0.0424	0.0106	0.216	2.12
Raw Materials Transportation	13.2	0.0747	0.0462	0.0598	0.00683	0.00791	0.000
Processing	2519	2.00	10.0	0.0181	0.0154	0.465	2.00
Transportation	61.7	0.0890	0.704	0.076	0.0189	0.387	0.00
Total to Construction Site	2628	2.21	11.2	0.196	0.0517	1.08	4.12

Plywood Sheathing

The plywood sheathing LCI was obtained from an existing study by Matthews (2011). In this LCA study, the author incorporated NREL LCI database for the modeling of a 13 mm (½ in.) plywood sheathing. The modeling of plywood includes both the harvesting and reforestation of the wood, debarking and conditioning of the lumber, drying, pressing and trimming. The majority of the embodied energy is consumed during the plywood manufacturing operations. Plywood sheathing require a large fraction of grid energy that is used during manufacturing. Some of the other carbon intensive fuels are replaced by the use of natural gas.

Table 41: Plywood sheathing enrgy use by operation

By Operation	Extraction	Transport	Manufacture	Total
MJ/m^2 wall	1.94	6.46	35.3	43.7

Table 42: Plywood sheathing enrgy use by fuel type

By Operation	Diesel	Natural Gas	Petroleum	Electricity	Total to Construction Site
MJ/m^2 wall	12.2	4.95	0.753	25.7	43.6

Table 43: Air emissions per 1 m^2 plywood sheathing 13 mm (½ in.)

kg/1 m^2	Carbon Dioxide, CO_2	Nitrous Dioxide, NO_2	Methane, CH_4
Extraction	0.0614	0.0323	0.0108
Transport	0.491	0.00753	0.00281
Manufacture	2.25	0.00538	0.0000
Total to Construction Site	**2.80**	**0.0452**	**0.0136**

Fiberglass batt insulation

The fiberglass batt insulation embodied LCI was obtained from existing LCI studies. There are discrepancies among different resources regarding the embodied energy and carbon of fiberglass batt production (Matthews, 2011). As a result, the LCI incorporates an existing inventory study by Athena Sustainable Materials Institute & Norris, (1999), but considers a broader ranges by other studies in the sensitivity analysis to account for the limited transparency of those resources. For the Athena study, the production of R-19 fiberglass includes raw materials extraction and refining (mainly quartz sand and cullet), transportation to the plant and processing of the batt. Inputs and outputs for each of these individual stages were not provided in the referenced study. The production and transportation of 1 m^2 of fiberglass batt requires 60.5 MJ.

Table 44: Fiberglass batt energy use by operation

By Operation	Production	Transportation	Total to Construction Site
MJ/m^2 wall	60.0	0.455	60.5

Table 45: Fiberglass batt energy use by fuel type

By Operation	Coal	Natural gas	Oil	Electricity	Total to Construction Site
MJ/m^2 wall	0.720	3.69	0.422	55.6	60.5

Table 46: Air emissions per 1 m^2 fiberglass batt

kg/1 m^2	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NOx	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Production	15.3	0.00141	0.0584	0.00963	0.00687	0.0346	0.000514
Transportation	0.0321	1.52×10^{-5}	0.000218	1.05×10^{-5}	3.86×10^{-5}	0.000168	3.92×10^{-6}
Total to Construction Site	**15.3**	**0.00143**	**0.0586**	**0.00964**	**0.00691**	**0.0348**	**0.000518**

Rigid insulation – extruded polystyrene

The extruded polystyrene LCI was obtained from an existing study on envelope LCA by Athena (Athena, 1999). This LCA study breaks life cycle inventory into the following production stages: production and transportation of the polymer, sheet forming, thermo-forming (molding sheets into desired shapes), and packaging. Overall, the production and transportation of 1 m^2 51 mm (2 in.) thick rigid polystyrene insulation requires 265 MJ.

Table 47: Rigid insulation energy use by operation

By Operation	Production	Transportation	Total to Construction Site
MJ/m² wall	265	0.0865	265

Table 48: Rigid insulation energy use by fuel type

By Operation	Coal	Natural gas	Oil	Total to Construction Site
MJ/m² wall	26.4	121	117	265

Table 49: Air emissions per 1 m² extruded polystyrene rigid insulation

kg/1 m²	Carbon Dioxide, CO_2	Sulfur Dioxide, SO_2	Nitrous Oxides, NOx	Volatile Organic Compounds, VOC	Methane, CH_4	Carbon Monoxide, CO	Total Particulate Matter, TPM
Production	9.97	0.0816	0.0371	0.000235	0.0272	0.0207	0.00608
Transportation	0.00611	2.89×10^{-6}	4.15×10^{-5}	2.00×10^{-6}	7.34×10^{-6}	3.19×10^{-5}	7.45×10^{-7}
Total to Construction Site	**9.98**	**0.0816**	**0.0371**	**0.000237**	**0.0272**	**0.0207**	**0.00608**

4.4.3 Cob embodied LCI results

The cob wall system incorporated two layers: a cob layer of 460 mm (18 in.) and a clay plaster of 25 mm (1 in.). For this LCI, the flow of substances was assessed by evaluating each of the mixture components separately: straw, clay-rich soil, sand, and water. Weight distributions were calculated for the wall dry components: straw, sand, clay-rich soil, and clay plaster.

Table 50 shows the weight distribution of these components for a 1 m³ (35 ft³) cob mix, calculated using the volume distribution as recorded in a previous study on cob properties (Rizza and Bottgar, 2015). An approximate 24% water content was considered (Pullen and Scholz, 2011), and a drying losses ratio of 20% (Christoforou et al., 2016). The overall bulk density of the mixture is therefore 1462 kg/m³, corresponding with previous tests that showed 1400-1600 kg/m³ bulk density range for cob (Miccoli et al., 2014; Pullen and Scholz, 2011; Rizza and Bottgar, 2015).

Table 50: Bulk density, volume distribution, and weight per componenet for a m³ cob mix. Values retrieved from [a](IRC, 2015b) [b](SImetric, 2016) [c](USDA, 1998) [d](Rizza and Bottgar, 2015)

Component	(A) Bulk Density (kg/m³ component)	(B) Volume Distribution (%)	(C)=(A)*(B) Weight (kg/m³ mix)	(D)=(C)*0.457 Weight per 1 m² wall	(E)=(C)/(C_{total}) Weight distribution (%)
Straw	110[a]	20	22	10	2
Sand	1,600[b]	40	640	292	52
Clay-rich soil	1,400[c]	40	560	256	46
Total	-	100	(C_{total}) = 1,222	558	100

The results of the cob LCI illustrate the main fuel use and emissions outputs throughout the production and delivery of cob. Specifically, the cob LCI results show that cob production uses oil as its primary fuel resource, probably due to heavy duty quarry machinery and heavy material transportation. Sand and soil are shown to represent the majority of energy input. In contrast to its relatively low weight percentage in the mixture, straw results its high fuel demand values, due to its production phase that requires machinery, field preparations, pesticides, and fertilizers.

Table 51: The embodied inventory fuel demand for 1 m² cob (units are in MJ_{eq} unless listed otherwise)

Component	Unit per Functional Unit	Coal	Natural gas	Oil	Others	Total to Gate
Straw	0.61 bales (10.1 kg)	7.00	7.00	7.23	0.0403	15.5
Sand	292 kg	6.01	3.06	18.1	0.795	28.0
Soil	256 kg	0.297	2.77	22.4	4.53 (electricity)	30.0
Clay Plaster	28.1 kg	1.14	2.57	8.02	0.000	11.73
Water	185 kg	0.545	0.274	0.145	0.119	1.08
Total Cob Wall	1 m²	15.0	15.7	55.9	5.48	86.3

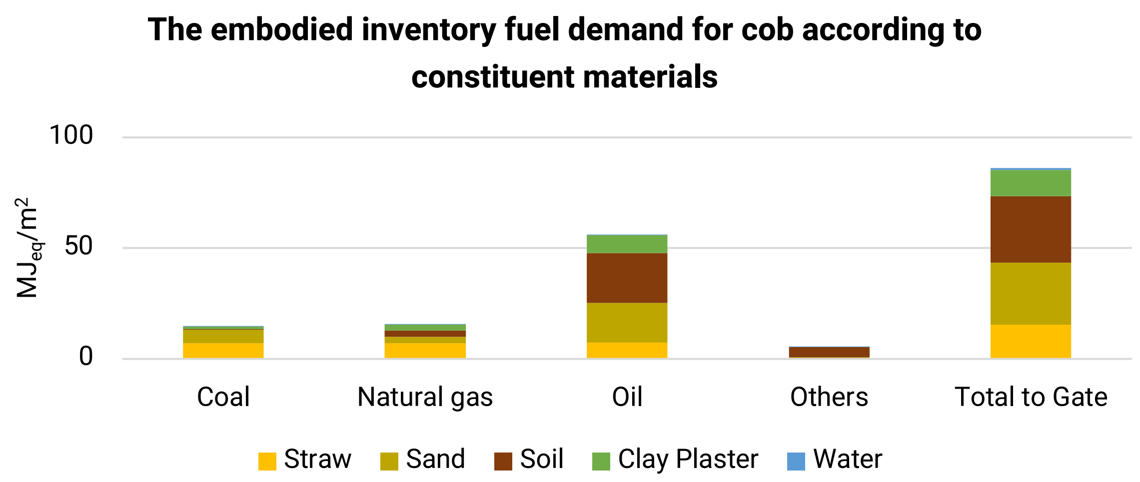


Figure 83: The embodied inventory fuel demand for 1 m² cob, for each constituent material

In terms of the embodied emissions, the results show that the straw is responsible for the majority of airborne Sulphur (SO_2), methane (CH_4), and nitrous oxides (NOx). This might be due to its energy inputs as a biomass, which require various chemicals for the treatment of the soil and crop, such as pesticides, herbicides, insecticides, fungicides, and fertilizers (Börjesson and Gustavsson, 2000; Offin, 2010).

Table 52: The embodied inventory emisions for 1 m^2 cob (units are in kg)

Component	CO2	SO2	NOx	VOC	CH4	CO	TPM
Straw	0.522	0.00367	0.00712	1.49×10^{-5}	0.00216	0.000429	0.000248
Sand	1.23	0.000836	0.0105	0.000275	0.00117	0.00669	0.000643
Soil	1.80	0.00156	0.00958	0.00264	0.00106	0.00996	0.0000898
Clay Plaster	0.428	0.000410	0.00304	6.59×10^{-5}	0.000392	0.00233	0.000397
Water	0.077	0.000319	0.000186	5.68×10^{-8}	4.24×10^{-11}	5.49×10^{-5}	0.000292
Total Cob Wall	4.06	**0.00679**	**0.0304**	**0.00300**	**0.00479**	**0.0195**	**0.00167**

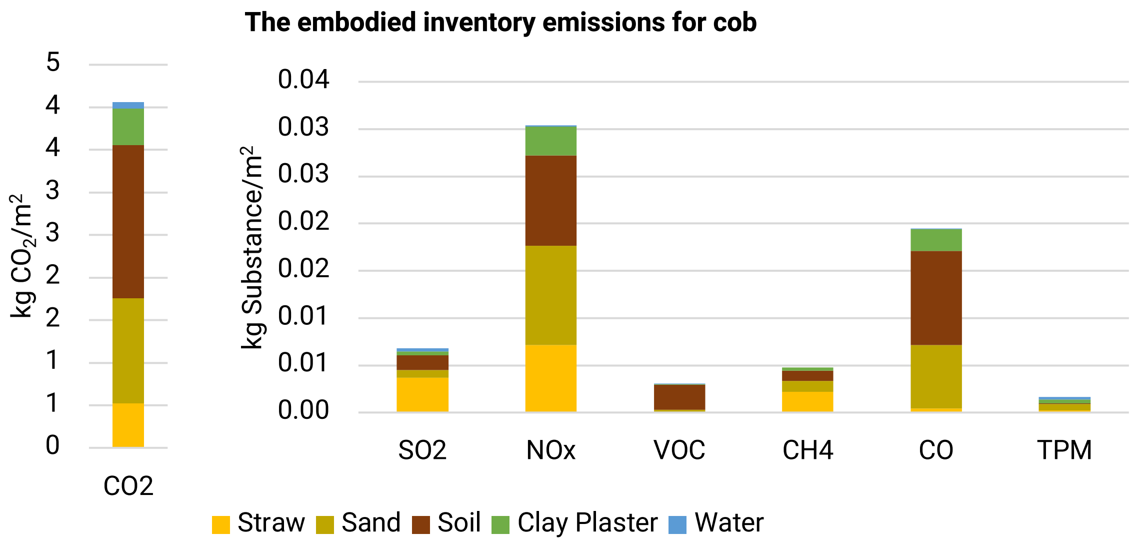


Figure 84: The embodied inventory emissions for cob, for each contituent material

The input-output LCI for cob is presented in Table 53 and can be replicated in future studies that account for the US geographical context.

Table 53: Data inventory for the production of a 1 m^2 of cob, 460 mm average thickness

Inputs		Outputs	
		Product (cob mixture) (kg)	735
Raw materials		Product (plaster mixture) (kg)	36.9
Straw (kg)	10.1	Mixing spoil (cob and plaster mixture) (kg)	77.2
Sand (kg)	292	Drying losses (kg)	154
Clay-rich soil (kg)	256	Dried cob wall with clay plaster skim (kg)	617
Clay plaster (kg)	28.1	Cob wall (m^2)	1.00
Water (for on-site mixing) (kg)	185	**Emissions**	
Water (from the off-site production of the constituent materials) (kg)	685		
		Inorganic emissions to air (kg)	
		Carbon monoxide (CO)	0.0195
Energy		Carbon dioxide (CO_2)	4.06
Coal (kg)	0.527	Nitrogen oxides (NO_x)	0.0304
Natural gas (m^3)	0.409	Sulphur dioxide (SO_2)	0.00647
Crude oil (kg)	1.22	Methane (CH_4)	0.00479
Electricity (kWh)	1.26		
Others (MJ_{eq})	0.954	**Particle to air (kg)**	
		Dust ($PM_{2.5-10}$)	0.217
		Dust ($PM_{<2.5}$)	0.000728
		VOCs	0.00300

4.4.4 Light straw clay embodied LCI results

The light straw clay mixture requires mainly straw (85%), and clay-rich soil slip (soil with water). The mixture is achieved by mixing the straw and coating it with clay slip such that there is no more than 5% uncoated straw (IRC, 2015a). The clay slip is made by mixing water with clay in a 3:2 water to clay ratio (Piltingsrud and Design Coalition, 2004). Therefore, the dry light straw clay mixture (only straw and clay-rich soil) includes 93% straw and 7% clay-rich soil. Lastly, the light straw clay mixture is tamped lightly into a lightweight timber frame. It is assumed that 2 x 4 studs are used, placed 400 mm (16 in.) on each face of the wall. Therefore, for a functional unit of 1 m^2 wall, 5 lumber studs of 1m length each will be required.

Table 54: Bulk density, volume distribution, and weight per componenet for a m^3 light straw clay dry mix. Values retrieved from [a](IRC, 2015b) [b](USDA, 1998)

Component	(A) Bulk Density (kg/m^3 component)	(B) Volume Distribution4 (%)	(C)=(A)*(B) Weight (kg/m^3 mix)	(D)=(C)*0.305 Weight per 1 m^2 wall	(E)=(C)/(C_{total}) Weight distribution (%)
Straw	110[a]	85	93	33	39
Clay-rich soil	1,400[b]	6	210	26	30
Water	1,000	9	90	27	31
Total	-	100	(C_{total}) = 393	86	100

The results of the light straw clay LCI illustrates the use of natural gas and oil as the main fuel resources for the production of the assembly. Lumber and straw are responsible for the majority of the fuel demand.

Table 55: The embodied inventory fuel demand for 1 m² light straw clay (MJ_{eq} unless listed otherwise)

Component	Unit per Functional Unit	Coal	Natural gas	Oil	Others	Total to Gate
Straw	2 bales (33 kg straw)	4.27	22.7	23.5	0.131	50.4
Soil	25.6 kg	0.0301	0.280	2.27	0.458	3.04
Clay Plaster	28.1 kg	1.14	2.57	8.02	0.000	11.7
Dimensional Lumber	0.02 m^3	4.51	14.9	6.17		25.6
Water (for light straw clay mixture and clay plaster)	72.9 kg	0.215	0.108	0.0571	0.0467	0.427
Total Light Clay Wall		10.2	40.6	40.0	26.2	65.6

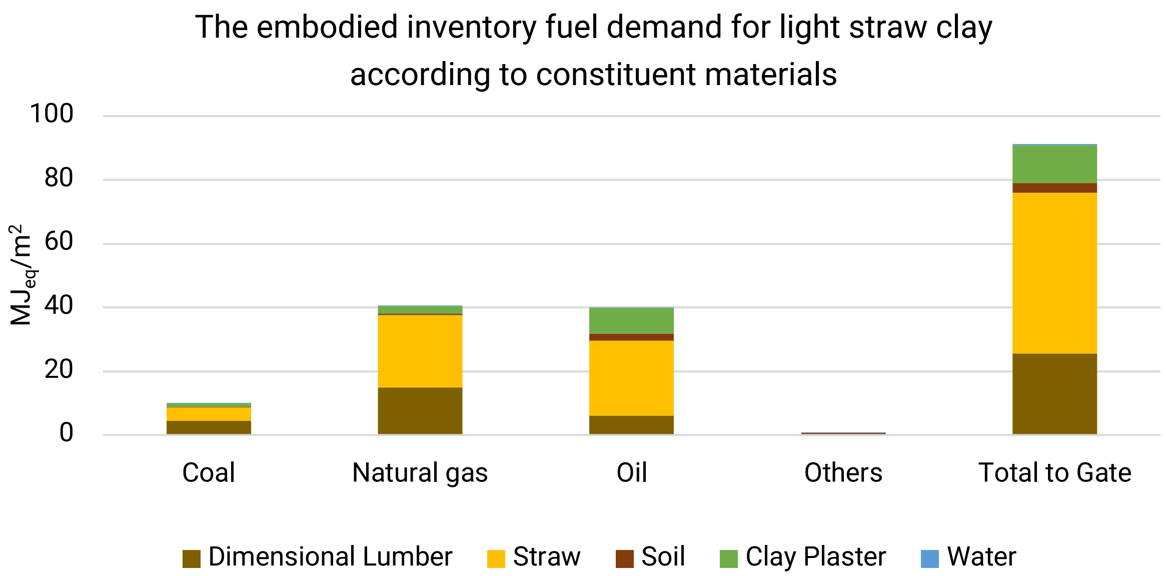


Figure 85: The embodied inventory fuel demand for light straw clay, for each contituent material

In terms of the embodied emissions, the inventory results show that the straw is responsible for majority of airborne Carbon Dioxide (CO_2), Sulphur (SO_2), nitrous oxides (NOx), and methane (CH_4), followed by the dimensional lumber.

Table 56: The embodied inventory emisions for 1 m² light straw clay (kg)

Component	CO2	SO2	NOx	VOC	CH4	CO	TPM
Straw	1.70	0.0119	0.0231	0.0000484	0.00700	0.00139	0.000804
Soil	0.182	0.000158	0.000970	0.000268	0.000108	0.00101	0.00000909
Clay Plaster	0.428	0.000410	0.00304	0.0000659	0.000392	0.00233	0.00040
Dimensional Lumber	1.95	0.0128	0.0108	0.00202	0.00647	0.00426	0.0137
Water	0.0303	0.000126	0.0000732	2.24E-08	1.67E-11	0.0000216	0.000115
Total Light Clay Wall	**4.29**	**0.0254**	**0.0380**	**0.00241**	**0.0140**	**0.00902**	**0.0151**

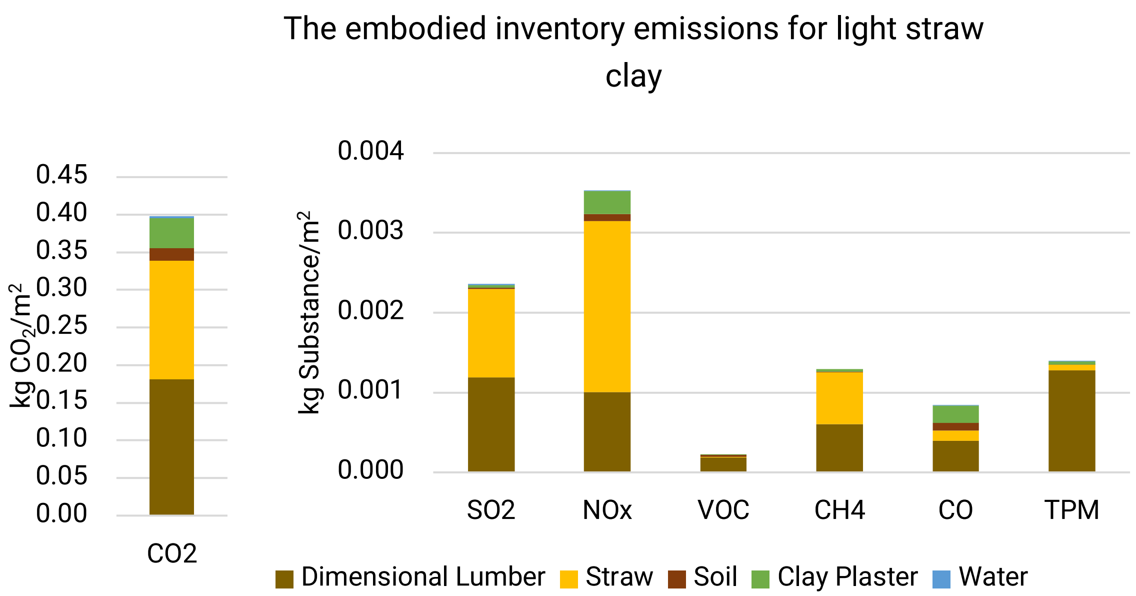


Figure 86: The embodied inventory emissions for light straw clay, for each contituent material

The input-output LCI for light straw clay is presented in Table 57 and can be replicated in future studies that account for the US geographical context.

Table 57: Data inventory for the production of a 1 m^2 of light straw clay 300 mm thick

Inputs		Outputs	
		Product (light straw clay wet mixture) (kg)	125
Raw materials		Product (plaster mixture) (kg)	36.9
Straw (kg)	33	Mixing spoil (light straw clay and plaster mixture) (kg)	16.8
Clay-rich soil (kg)	26	Drying losses (kg)	73
Clay plaster (kg)	28	Light straw clay wall (m^2)	1.00
Dimensional lumber (m^3)	0.019		
Water (for on-site mixing) (kg)	73	**Emissions**	
Water (from the off-site production of the constituent materials) (kg)	817.5*		
		Inorganic emissions to air (kg)	
		Carbon monoxide (CO)	0.00689
Energy		Carbon dioxide (CO_2)	3.31
Coal (kg)	0.420	Nitrogen oxides (NO_x)	0.0326
Natural gas (m^3)	1.06	Sulphur dioxide (SO_2)	0.0190
Crude oil (kg)	0.741	Methane (CH_4)	0.0107
Electricity (kWh)	0.127		
Others (MJ_{eq})	0.173	*Particle to air (kg)*	
		Dust ($PM_{2.5\text{-}10}$)	0.0407
		Dust ($PM_{<2.5}$)	0.00570
		VOCs	0.00140

*Water for lumber production is mainly used in the process for wetting logs when they are stored prior to sawing. This varied from zero to 350 kg. The high variability arises because not all mills sprinkle logs to control decay processes (Puettmann et al., 2013)

4.4.5 Rammed earth embodied LCI results

The rammed earth mixture requires mainly sand and clay-rich soil, with some gravel (20%). It does not incorporate fibers and requires very little water for mixing (8%). Rammed earth mixture is tamped within forms, achieving a higher density than the density of the dump mixture. The rammed earth wall is tamped into forms, a process that incur in increased density that can vary significantly, depending on workmanship and manual vs. mechanical construction practices, as seen in Table 3. The compression requires more raw material than the uncompressed mixture density. Loose density is given in Table 58 and an assumed compression ratio of 1.2 is applied, redulting in a final rammed earth wall density of 1,500 kg/m^3.

Table 58: Bulk density, volume distribution, and weight per componenet for a m^3 rammed earth mix.

Component	(A) Density (kg/m^3 component)	(B) Volume Distribution (%)	(C)=(A)*(B)*1.2 Weight (kg/m^3 mix)	(D)=(C)*0.457 Weight per 1 m^2 wall	(E)=(C)/(C_{total}) Weight distribution (%)
Gravel	1,250	20	300	137	20
Sand	1,353	40	640	292	43
Clay-rich soil	1,167	40	560	256	37
Total		100	(C_{total}) = 1,500	685	100

The results of the rammed earth LCI illustrate the heavy use of heavy materials transportation. For similar reasons, the main emissions from rammed earth production are carbon dioxide (CO2), nitrous oxides (NOx), and carbon monoxide (CO), that are associated with diesel-operated truck transportation.

Table 59: The embodied inventory fuel demand for 1 m^2 rammed earth (MJ$_{eq}$ unless listed otherwise)

Component	Unit per Functional Unit	Coal	Natural gas	Oil	Others	Total to Gate
Gravel	137 kg	2.82	1.44	8.49	0.373	13.1
Sand	292 kg	6.01	3.06	18.1	0.795	28.0
Soil	256 kg	0.297	2.77	22.4	4.525	30.0
Water	54.8 kg	0.162	0.0812	0.0429	0.0351	0.321
Total Rammed Earth	1 m^2	**9.28**	**7.35**	**49.1**	**5.73**	**71.1**

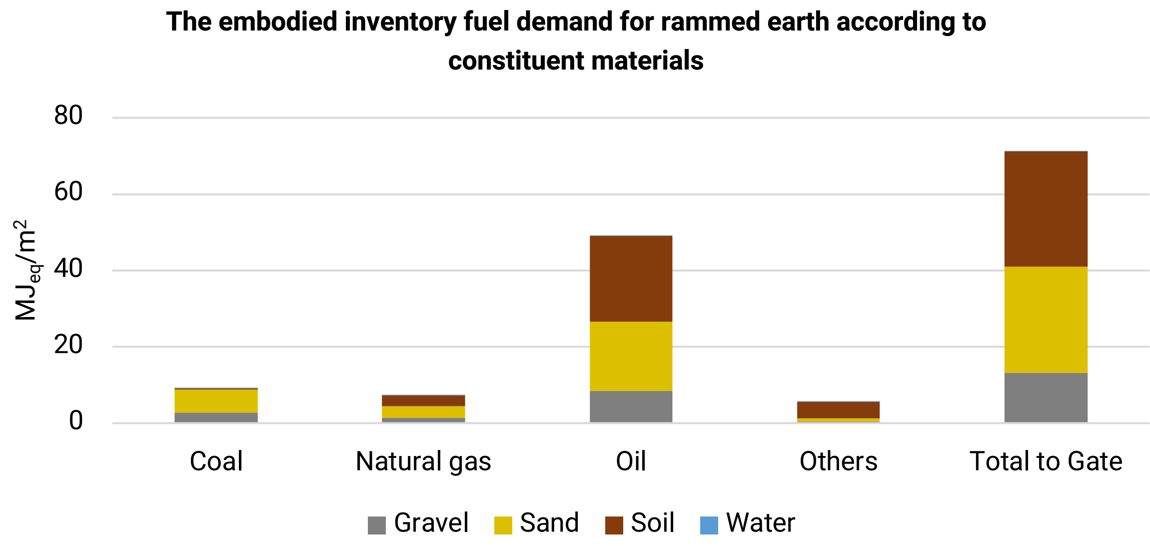


Figure 87: The embodied inventory fuel demand for rammed earth, for each contituent material

Table 60: The embodied inventory emisions for 1 m² rammed earth (kg)

Component	CO2	SO2	NOx	VOC	CH4	CO	TPM
Gravel	0.579	0.579	0.000392	0.00492	0.000129	0.000550	0.00314
Sand	1.235	1.235	0.000836	0.0105	0.000275	0.00117	0.00669
Soil	1.799	1.799	0.00156	0.00958	0.00264	0.00106	0.00996
Water	0.0228	0.0228	9.45×10^{-5}	5.51×10^{-5}	1.68×10^{-8}	1.26×10^{-11}	1.63×10^{-5}
Total Rammed Earth Wall	3.64	**3.64**	**0.00288**	**0.0251**	**0.00304**	**0.00279**	**0.0198**

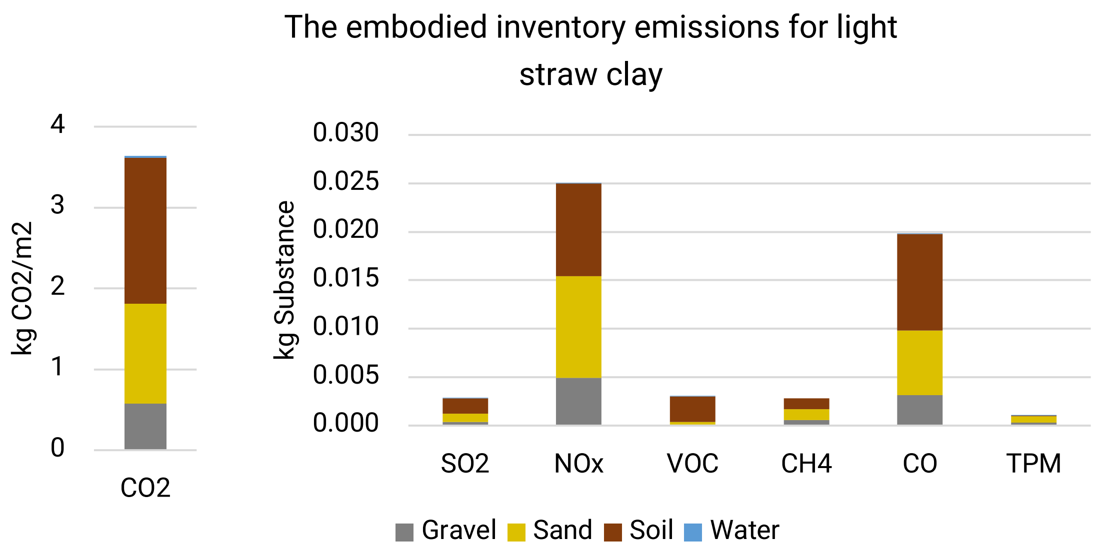


Figure 88: The embodied inventory emissions for rammed earth, for each contituent material

Inputs		Outputs	
Raw materials		Product (light straw clay wet mixture) (kg)	740
		10% Mixing spoil (rammed earth mixture) (kg)	74.0
		Drying losses (kg)	53.0
Gravel (kg)	137	Dried rammed earth wall (kg)	687
Sand (kg)	292	Dried rammed earth wall (m^2)	1.00
Clay-rich soil (kg)	256		
Water (for on-site mixing) (kg)	54.8	**Emissions**	
Water (from the off-site production of the constituent materials) (kg)	607	Carbon monoxide (CO)	0.0169
Energy		Carbon dioxide (CO_2)	3.09
Coal (kg)	0.53	Nitrogen oxides (NO_x)	0.0205
Natural gas (m^3)	0.19	Sulphur dioxide (SO_2)	0.00243
Crude oil (kg)	1.07	Methane (CH_4)	0.00229
Electricity (kWh)	1.26	**Particle to air (kg)**	
Others (MJ_{eq})	1.2	Dust ($PM_{2.5\text{-}10}$)	0.240

Table 61: Data inventory for the production of a 1 m^2 of rammed earth wall 460 mm thick

4.4.6 Comparative embodied LCI results

Figure 88 shows the comparative fuel consumption inventory and Figure 90 the emissions inventory. The comparative LCI results illustrate the use of nonrenewable energy by the conventional assemblies. Specifically, for the wood assembly, electricity is relatively high due to the fiberglass insulation production. Additionally, for the CMU wall assemblies, other types of fuel sources are high due to the use of liquified petroleum gas, middle distillates, and petroleum coke.

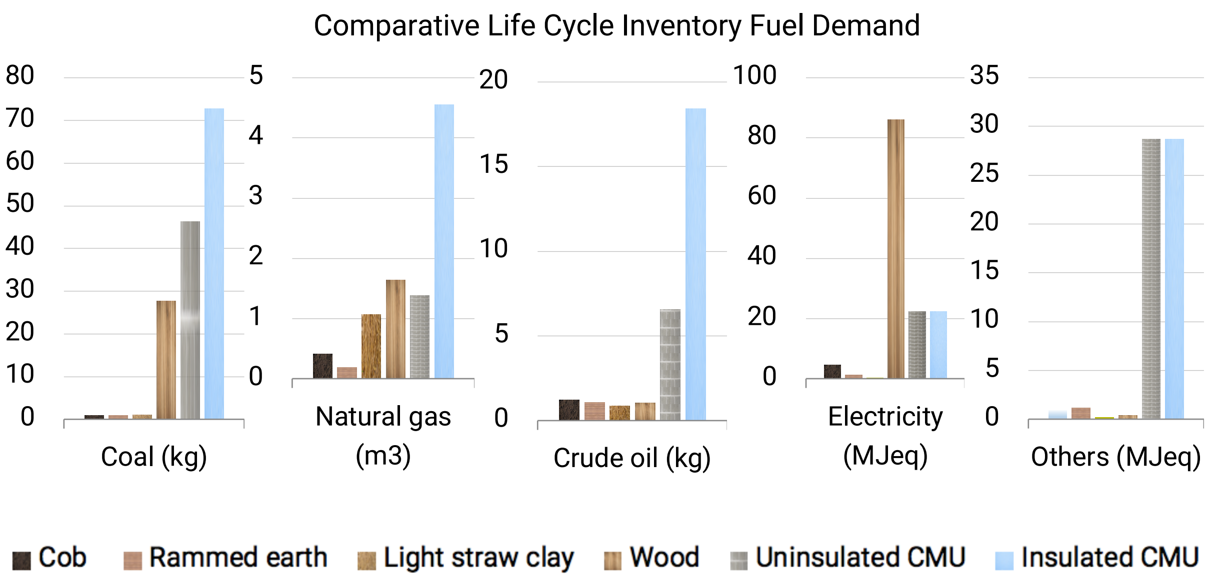


Figure 89: Inventory fuel comparison among the different wall systems, per m^2 wall

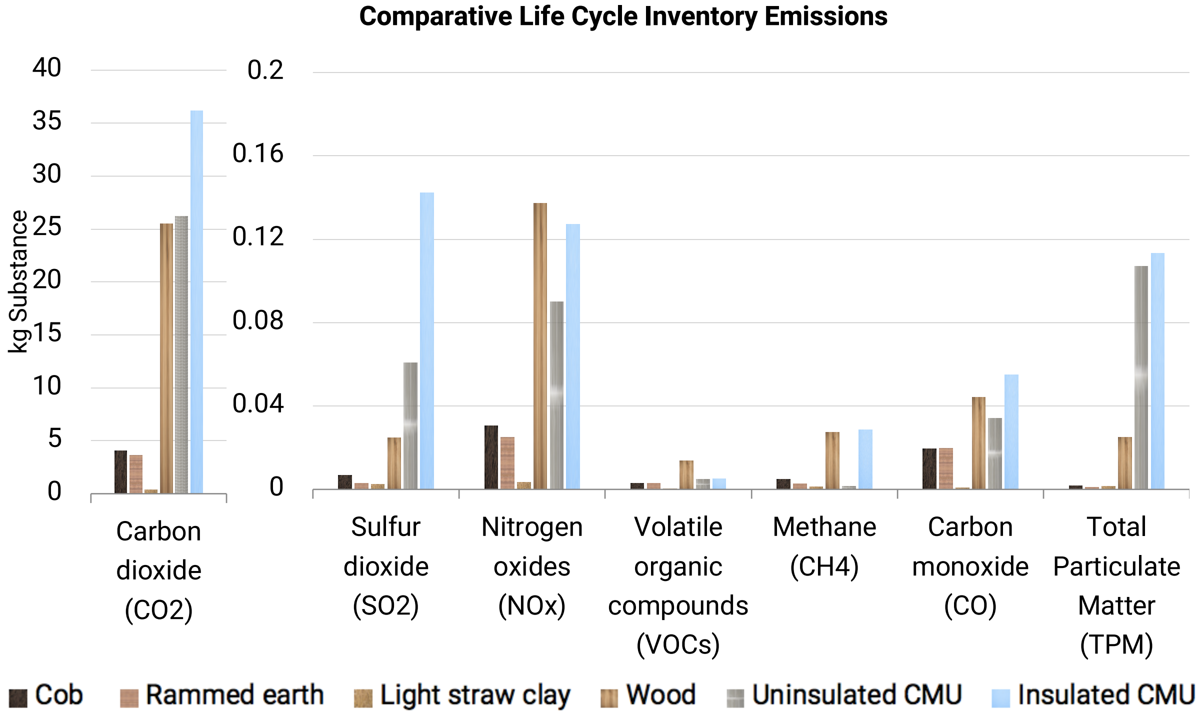


Figure 90: Inventory emisisons comparison among the different wall systems, per m² wall

4.5 Stage 3 – Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA), the third stage of the LCA, was conducted in terms of the impact categories (the environmental impact "indicators") as established in the methodology section. The LCIA is presented for each wall assembly according to each building stage. Following the embodied impacts assessment, a "whole house" LCIA that includes the operational stage is presented.

4.5.1 Global climate change potential

Figure 91 shows the results for the global climate change (also known as Global Warming Potential, GWP) in terms of kilograms of carbon dioxide equivalent emissions for 1 m² of each wall system. The results indicate that an external wall made from uninsulated rammed earth has the lowest global climate change potential, with the majority of the impact being attributed to the sand and clay-rich soil content.

The wall with the highest global climate change potential in shown to be the insulated CMU, following by the lightweight wood frame. For the CMU wall, the main component that contributes to the global climate change potential is the cement manufacturing for the CMU blocks. Additionally, the insulated CMU wall secondary source of global climate change impacts is the rigid insulation that requires the processing of polystyrene resins. These impacts could be reduced by using Compressed Earth Bricks

(CEBs), with or without stabilization of 2-5% cement, as well as natural insulation alternatives, such as a semi-rigid hemp fiber insulation sheet. For the lightweight wood frame, the fiberglass production, and mainly the quartz sand and cullet processing, contribute the most to the global climate change impacts. Similarly, For the lightweight wood frame, these impacts could be significantly reduced by using natural insulation alternative such as straw infill, wool, or cellulose.

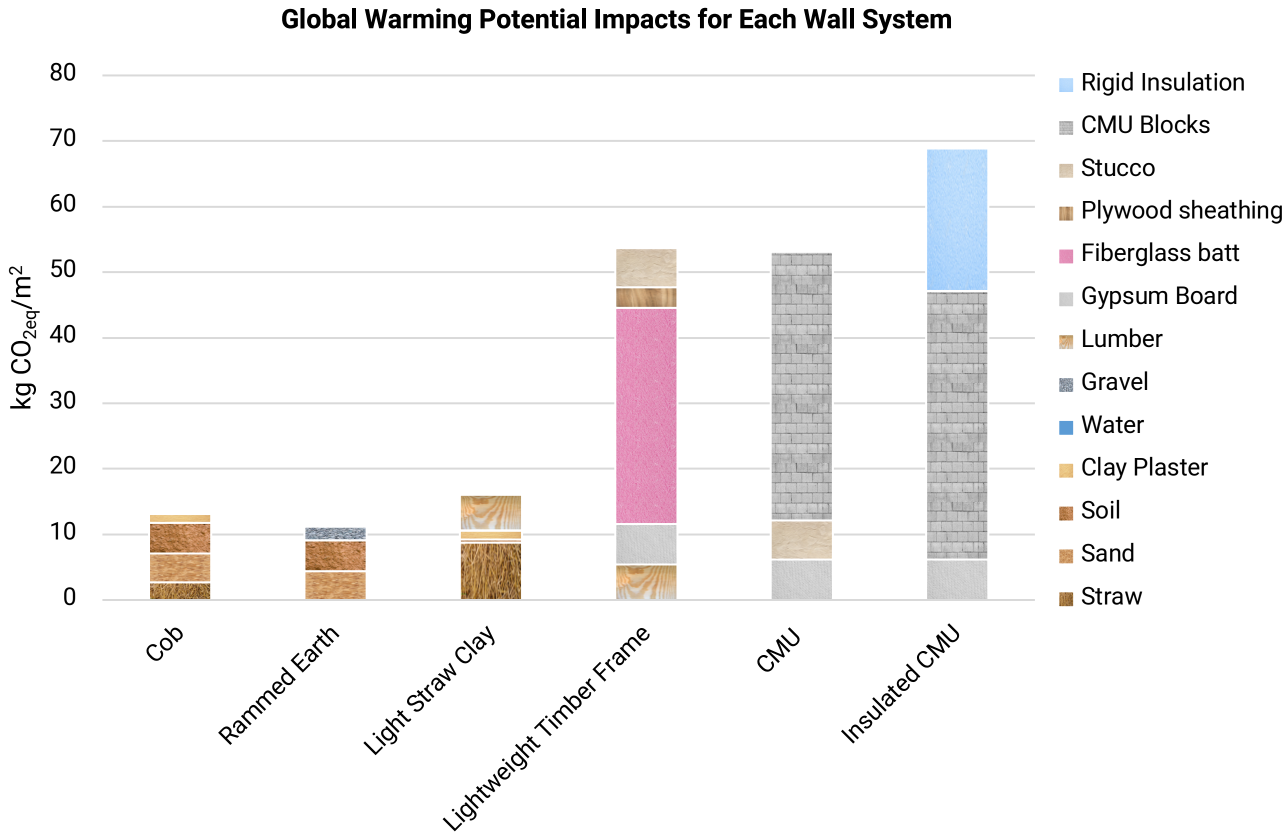


Figure 91: Global climate change impacts for each wall system

4.5.2 Energy demand

Figure 92 shows the results for the Embodied Energy (EE) demand in terms of MJ_{eq} for 1 m^2 of each wall system. The energy demand results profile is similar to that of the global climate change impacts with the exception of insulated CMU, which shows relatively greater embodied energy demand. This is due to the use of natural gas in the production of the rigid insulation, which results in lower source impacts.

The results indicate that, for each constituent material, processing and transportation demand more energy than other processes (extraction of raw materials, forestry operations, and transportation across short distances such as from quarry to plant). As for the apparent discrepancy of fiberglass data (as further revealed by Matthews, 2011), it might be that the results of this stage produced values that are lower than the actual for this impact category.

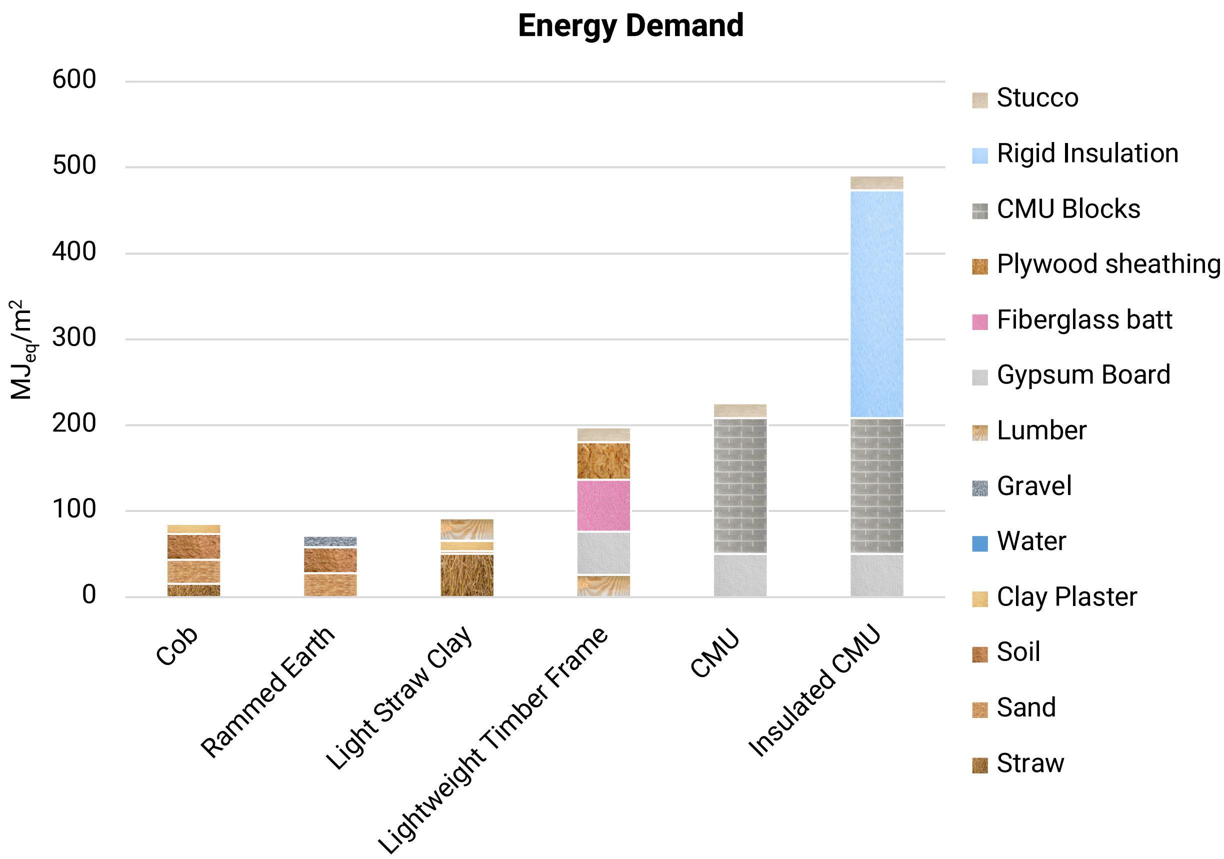


Figure 92: Energy demand for each wall system

4.5.3 Air acidification

Figure 93 shows the results for air acidification in terms of kilograms of Sulphur dioxide equivalent emissions for 1 m² of each wall system, taking into account the substance inventories specified in Table 12. Processes that involve fossil fuel burning and agriculture activities are the primary source to this impact category. Specifically, fossil fuels emit air pollution in the form of sulfur dioxide (SO_2) and nitrogen oxides (NOx), while agricultural activities are the primary source of ammonia released to the atmosphere, which in turn lead to acidic deposition of sulfuric and nitric acids.

The results indicate that external walls made from rammed earth and cob have the lowest air acidification potential, due to their minimally processed geological components coupled with the absence of biological constituent materials.

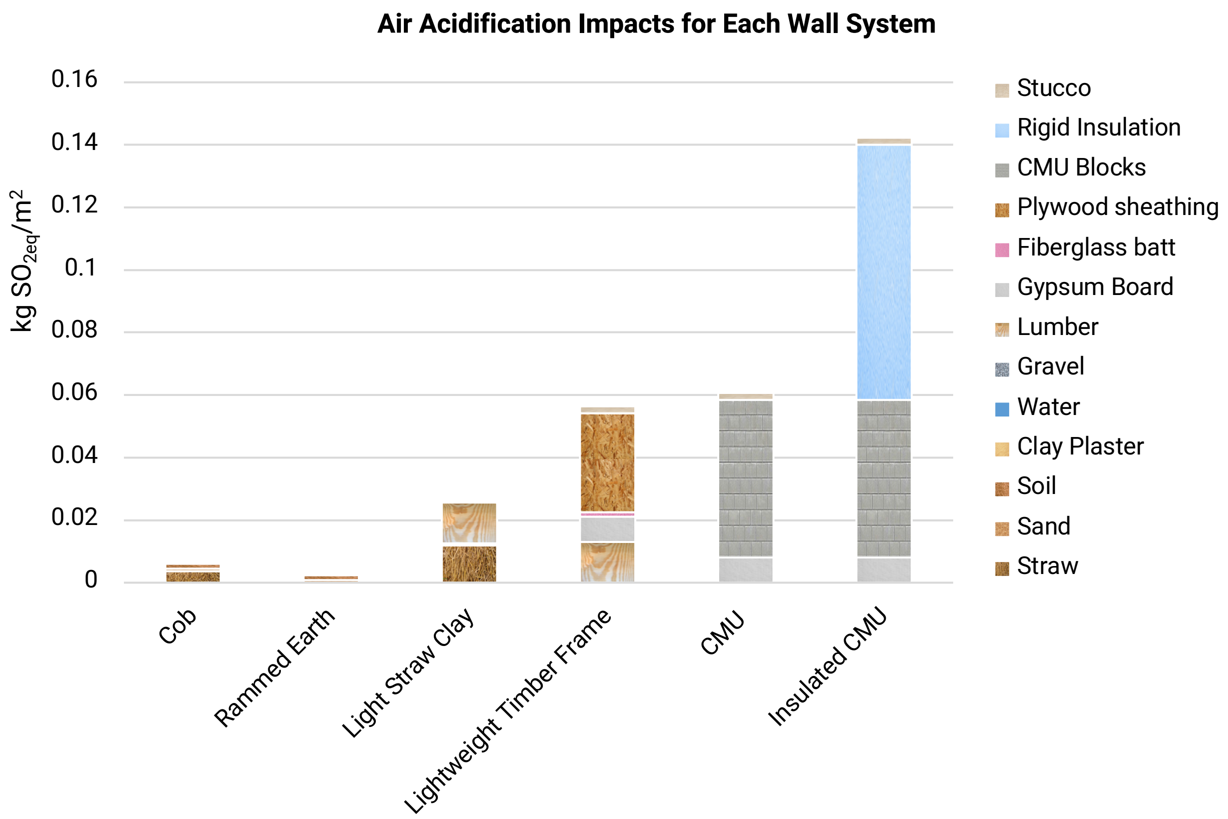


Figure 93: Global climate change impacts for each wall system

4.5.4 Human health air particulate

Figure 94 shows the results for Human Health (HH) air particulate in terms of Total Particulate Matter (TPM) 2.5 equivalent pollution for 1 m^2 of each wall system, taking into account the substance inventories specified in Table 12. Processes that involve smoke and fires, such as from fossil fuel burning, are the primary source to this impact category.

The results indicate that external walls made from geological materials (soil, sand, and gravel), such as the rammed earth and cob have the lowest HH air particulate pollution potential, due to their minimal processing.

The wall with the greatest particulate pollution is shown to be the insulated CMU. The main component that contributes to the CMU wall HH air particulate pollution potential are the CMU blocks. The amounts of pollutant (as well as other emissions) associated with the cement production for the CMU blocks are primarily a function of the cement content in the block. Further emissions are generated from quarry haul-road distances and unpaved road particulate emissions. The particulate matter of cement dust, incorporated in the LCI in this dissertation, often escapes in the transfer of cement to the silo, which is usually vented to a fabric filter ("sock") (Nisbet et al., 2002). As this is a problem that might occur also with higher demand and production rates of earthen materials, fugitive sources that include the transfer of sand and aggregate should be addressed, including truck loading, mixer loading, vehicle traffic, and wind erosion from sand and aggregate storage piles. The amount of fugitive emissions generated during the transfer of geological materials highly depends on the moisture content of these materials stockpiles. Therefore, this problem could be addressed by using water sprays, enclosures, hoods, or curtains to enclose soil, sand, and aggregate piles.

Lastly, for the timber, production that includes kiln drying requires electricity, diesel, and wood fuel, that emit TPM particles. In addition to the particle pollution, the process of wood drying also emits VOCs that are not represented in this impact category (Puettmann et al., 2013).

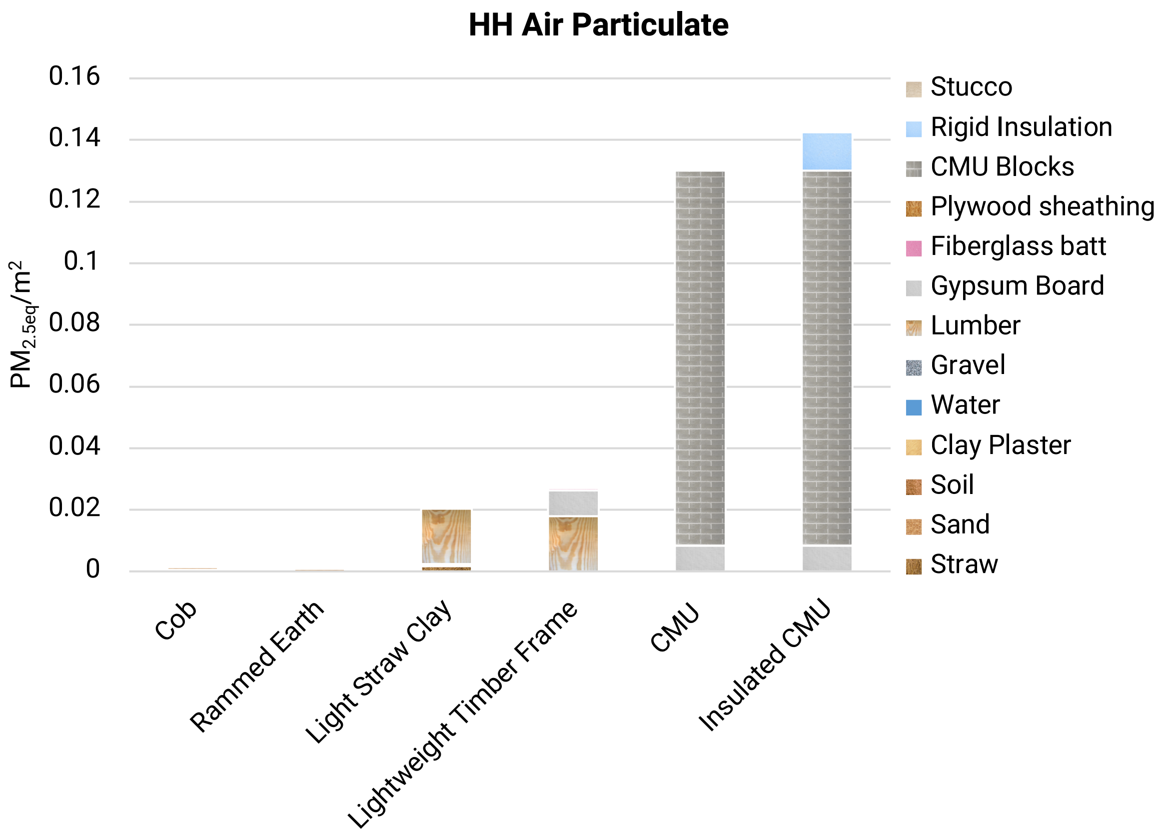


Figure 94: HH air particulate impacts for each wall system

4.5.5 Impact comparison overview

The comparison of the embodied environmental impacts among all six wall systems is shown in Figure 96 and Table 62. The results show that the earthen wall systems exhibit significantly lower environmental impacts than the wood frame and CMU wall systems for all impact categories.

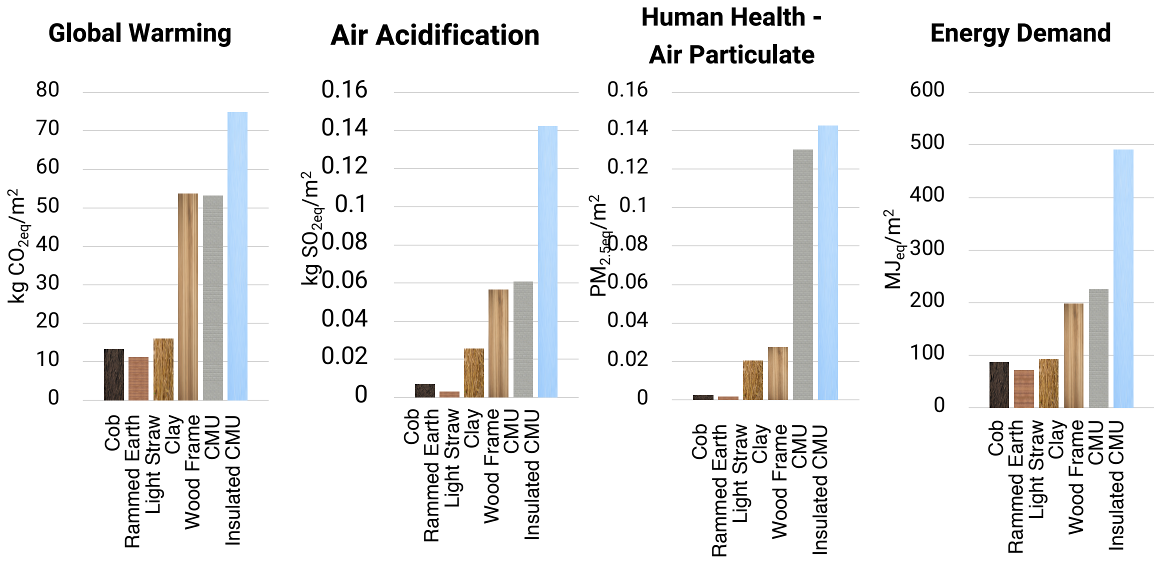


Figure 95: Environmental impacts comparison overview for each wall system

In terms of the overall impact category assessment, the study found that:

- Biological materials (fibers and lumber) increase the wall energy demand and emissions due to the growth and production stages that require herbicides, pesticides, fertilizers, and farm machinery. In addition to these requirements, biological materials require other chemicals, water use, and land use, which were not directly assessed as an individual impact category in this LCA study but do influence the incorporated system processes' emissions and energy demand.
- The harmful environmental effects of the wall assemblies increase by using synthetic insulation materials, especially due to the processing of raw materials and use of kiln heaters, combustion boilers, and other heavy plant manufacturing processes. These impacts might be reduced by using insulation products with recycled content or by using minimally processed insulation materials such as fibers (e.g., straw, hemp), wool, and cellulose.
- Cement manufacturing increases wall energy demand and emissions. Whereas compressed earth blocks may replace concrete, it should be noted that particulate pollution impacts might be a shared problem for earth-based and cement-based materials, because it depends on the scale of manufacturing. To this end, the expansion of earth-based materials manufacturing should be addressed by sealing the soil and sand piles.

Table 62: LCIA restuls for the constituent materials of each wall assembly

Assembly	Component	Stage	Impact Categories: Global Warming [kg CO2eq]	Acidification Air [kg SO2eq]	HH Particulate Air [PM10eq]	Energy Demand [MJeq]
Cob	Straw	Production	2.59	0.00362	0.000499	13.4
		Harvesting	0.0238	3.36×10^{-5}	2.41×10^{-5}	1.7920
		Baling	0.0000	8.41×10^{-12}	6.61×10^{-12}	0.0000
		Transportation	0.0874	1.37×10^{-5}	5.22×10^{-6}	0.4092
	Sand	Production	1.83	0.000439	0.000691	16.1
		Transportation	2.57	0.000398	0.000152	11.9
	Soil Clay-rich soil	Production	2.43	0.00121	7.63×10^{-5}	19.6
		Transportation	2.25	0.000348	0.000133	10.4
	Clay Plaster	Production	0.727	0.000314	0.000477	8.88
		Transportation	0.616	9.54×10^{-5}	3.64×10^{-5}	2.86
	Water		0.132	0.000319	0.00378	1.08
	Total Cob Wall	Total to Site	13.2	0.00679	0.00247	86.4
Rammed Earth	Gravel	Production	0.857	0.000206	0.000324	7.53
		Transportation	1.20	0.000186	7.12×10^{-5}	5.58
	Sand	Production	1.83	0.000439	0.000691	16.1
		Transportation	2.57	0.000398	0.00152	11.9
	Soil	Production	2.43	0.00121	7.63×10^{-5}	19.6
		Transportation	2.25	0.000348	0.000133	10.4
	Water		0.0392	9.45×10^{-5}	0.000112	0.321
	Total Rammed earth Wall	Total to Site	11.2	0.00288	0.00156	71.4
Light Straw Clay	Straw	Production	8.39	0.0117	0.00162	43.4
		Harvesting	0.0774	0.000109	7.83×10^{-5}	5.82
		Baling	2.33×10^{-8}	2.73×10^{-11}	2.15×10^{-11}	2.19×10^{-6}
		Transportation	0.284	4.44×10^{-5}	1.69×10^{-5}	1.33
	Soil	Production	0.246	0.000123	7.73×10^{-6}	1.99
		Transportation	0.228	3.52×10^{-5}	1.35×10^{-5}	1.06
	Lumber	Forestry Operations	1.10	0.000112	0.000124	2.43
		Wood Production	4.22	0.0129	0.0178	23.1
		Transportation	0.0937	1.45×10^{-5}	5.54×10^{-6}	0.435
	Clay plaster	Production	0.727	0.000314	0.000477	8.88
		Transportation	0.616	9.54×10^{-5}	3.64×10^{-5}	2.86

Assembly	Component	Stage	Global Warming [kg CO2eq]	Acidification Air [kg SO2eq]	HH Particulate Air [PM10eq]	Energy Demand [MJeq]
			Impact Categories			
	Water	Production and transportation	0.0521	0.000126	0.000149	0.427
	Total Light Straw Clay Wall	Total to Site	16.0	0.0256	0.0203	91.8
Lightweight Wood Frame	Gypsum Board	Gypsum Extraction	0.0591	1.94×10^{-5}	0.00570	0.266
		Raw Materials Transportation	3.05	0.00201	0.000124	10.5
		Manufacturing	2.79	0.00596	0.00251	38.6
		Transportation	0.2669	8.73×10^{-5}	5.47×10^{-6}	0.856
	Dimensional Lumber	Forestry Operations	1.10	0.000112	0.000124	2.43
		Wood Production	4.22	0.0129	0.0178	23.1
		Transportation	0.0937	1.45×10^{-5}	5.54×10^{-6}	0.000
	Fiberglass	Production	32.9	0.00141	0.000730	60.0
		Transportation	0.098	1.52×10^{-5}	5.80×10^{-6}	0.455
	Plywood sheathing	Extraction	0.330	0.0226	0.000233	1.94
		Transport	0.561	0.00527	5.44×10^{-5}	6.46
		Manufacture	2.25	0.00377	3.89×10^{-5}	35.3
	Stucco	Raw Materials Extraction	0.152	4.97×10^{-5}	0.00261	0.487
		Raw Materials Transportation	0.0271	7.47×10^{-5}	4.57×10^{-6}	0.182
		Processing	5.51	0.00200	0.00258	15.7
		Transportation	0.272	8.90×10^{-5}	5.58×10^{-6}	0.873
	Total Wood Wall	Total to Site	53.7	0.0564	0.0325	197
CMU	CMU Blocks	Cement Manufacturing	33.0	0.0389	0.0630	105
		Aggregate Production	1.47	0.000646	0.0446	11.0
		Raw Materials Transportation	3.16	0.00129	0.00151	11.9
		Concrete Plant Operation	1.81	0.00814	0.0126	24.2
		Concrete Block Curing	1.52	0.00142	8.69×10^{-5}	6.33
	Gypsum Board	Gypsum Extraction	0.0591	1.94×10^{-5}	0.00570	0.266
		Raw Materials Transportation	3.05	0.00201	0.000124	10.5
		Manufacturing	2.79	0.00596	0.00251	38.6
		Transportation	0.267	8.73×10^{-5}	5.47×10^{-6}	0.856
	Stucco	Raw Materials Extraction	0.152	4.97×10^{-5}	0.00261	0.487

			Impact Categories			
Assembly	**Component**	**Stage**	**Global Warming [kg CO2eq]**	**Acidification Air [kg SO2eq]**	**HH Particulate Air [PM10eq]**	**Energy Demand [MJeq]**
		Raw Materials Transportation	0.027	7.47×10^{-5}	4.57×10^{-6}	0.182
		Processing	5.51	0.00200	0.00258	15.7
		Transportation	0.272	8.90×10^{-5}	5.58×10^{-6}	0.873
	Rigid Insulation	Production	21.7	0.0816	0.0125	265
		Transportation	0.0187	2.89×10^{-6}	1.10×10^{-6}	0.0865
	Total CMU wall		53.1	0.0607	0.135	226
	Total insulated CMU wall		74.8	0.142	0.148	491

In summary, the environmental impacts of the external walls that have been assessed in this LCA study vary considerably and show the environmental urgency of earthen construction. Specifically, earthen assemblies are shown to reduce embodied energy demand by 62-68%, climate change potential by 83-86%, air acidification by 58-95%, and particulate pollution by 84-99%.

4.6 Stage 4 - interpretation of the results

The presented environmental impact assessment includes embodied energy demand, global climate change, air acidification, and Human Health (HH) particulate pollution impacts for six different wall assemblies. For the earthen wall assemblies, cob, rammed earth, and light straw clay are assessed. For the conventional wall assemblies, lightweight wood frame, Concrete Masonry Units (CMU), and insulated CMU are assessed.

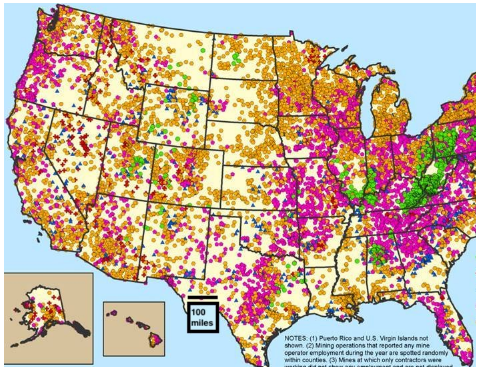
When considering only the embodied impacts, the earthen assemblies exhibit a reduction in impacts that result in the lowest of all the environmental impacts. In terms of the embodied energy demand and global climate change impacts, rammed earth showed the least harmful environmental impacts, with the highest impacts for the insulated CMU, that could be reduced by utilizing CBEs. For the air acidification and HH particulate pollution impacts, the results indicate that rammed earth and cob have the lowest harmful environmental impacts, due to their use of minimally processed geological components (soil, sand, and gravel) and their absence of biological constituent materials (such as fibers and wood).

4.6.1 Sensitivity analysis

For a more detailed comparison, a sensitivity study was conducted to demonstrate the effect of all the various assumptions included in this LCA study. The sensitivity study accounts for cob, which represents an "average" between the rammed earth and light straw clay assemblies due to its inclusion of both geological and biological materials. The analysis was conducted using the @Risk software and uses a model that resides in excel (Palisade, 2009).

Table 63 details the tested assumptions about each of the constituent materials. Using triangular input distributions and modeled over 1000 iterations, the sensitivity analysis illustrates the effects of transportation distances, wheat grain and straw market prices, average wall thickness, amount of clay-rich soil required, straw density, and average wheat yield at field. The transportation distances for the clay-rich soil, sand, and straw ranged between 16-80 km, according to interviews with experts (Ben-alon et al., 2017). The transportation distance of the clay plaster ranged between 0-100 km, reflecting the possible application of plaster made from the on-site cob mixture. Likewise, the required clay-rich soil ranged between 0-560 kg in order to account for the scenario of available clay-rich soil on site. Lastly, other outputs ranges were varied by $\pm 10\%$.

Table 63: Sensitivity analysis input parameters and their range values

Input Parameter	Minimum Value	Value Assumed in the study	Max Value	Notes / References
Acquired Clay-Rich Soil (kg)	0	256	560	Acquired clay-rich soil is soil that is purchased from a quarry. Alternatively, clay-rich soil can be used as the byproduct soil of the foundation excavation (Reeves et al., 2006). The acquired clay-rich soil requires excavation, and transportation, that are avoided when using on-site soil.
Average Wall Thickness (m)	0.300	0.460	0.610	Wall thickness is a function of the required wall strength, as well as the mix of materials, workmanship, etc. To achieve thinner sections, various techniques should be studied, including the standardized quality control and development of on-site testing for the earthen building mixture.
Straw Density (kg/m³)	99	110	121	As opposed to existing earthen building codes, strawbale construction codes require specific measurements for the density of a construction grade bale (Most strawbale codes in the US have chosen to use a minimum density of 110 kg/m³ (7 pcf). (IRC, 2015b). However, without proper testing of the bales, due to lack of standardized instructions, earthen building might utilize bales with lower densities. Values were assumed to range between +/-10%.
Straw Transportation Distance (km)	16	35	80	The study assumes that soil, sand, and gravel are extracted from local quarries, which as can be seen in Figure 96 , are abundant in the US.
Clay-Rich Soil / Sand Transportation Distance (km)	16	20	80	 Figure 96: Active sand & gravel (in yellow), and stone (in pink) mining quarries in the US (CDC, 2010)
Clay Plaster Transportation Distance (km)	0	50	100	The minimum value reflects the possible application of plaster made from the on-site cob mixture. Other values were assumed to correspond with plaster distribution centers in the US (e.g., Americal Clay, 2017)
Straw Price per Bale ($/bale)	5.49	6.10	6.71	Assuming a market value change of +/- 10%
What Price per Bushel ($/bushel)	7.16	7.96	8.76	Assuming a market value change of +/- 10%
Straw Yield (bale/hectare)	14.7	16.4	18.0	Assuming a yield that varies across +/- 10%

The results of the sensitivity analysis are presented in Figure 96-Figure 98 for each assumption so that it could be understood in isolation. The results of the sensitivity analysis show that the inputs with the greatest influence on the cob LCIA are the average wall thickness, the amount of acquired clay-rich soil, as well as the transportation distances of constituent materials. Other modeled factors have markedly less effect on overall results.

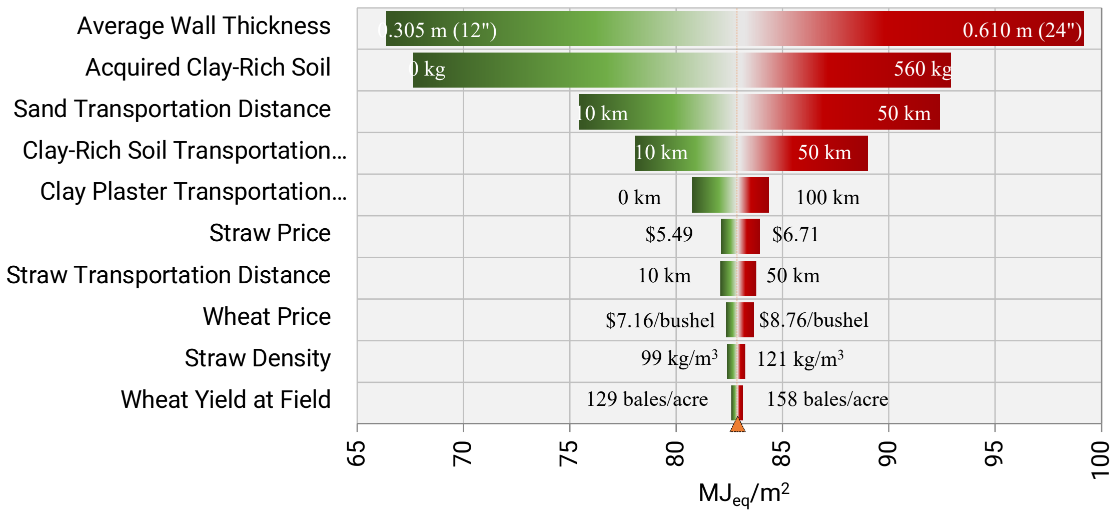


Figure 97: Sensitivity analysis of the energy demand of cob production, ranked by the input effect on output mean

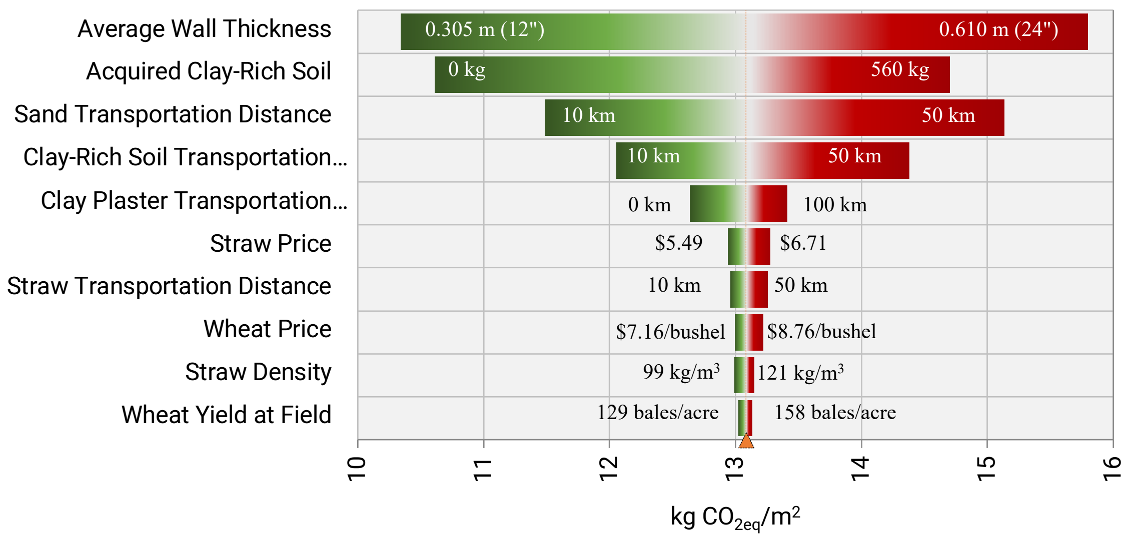
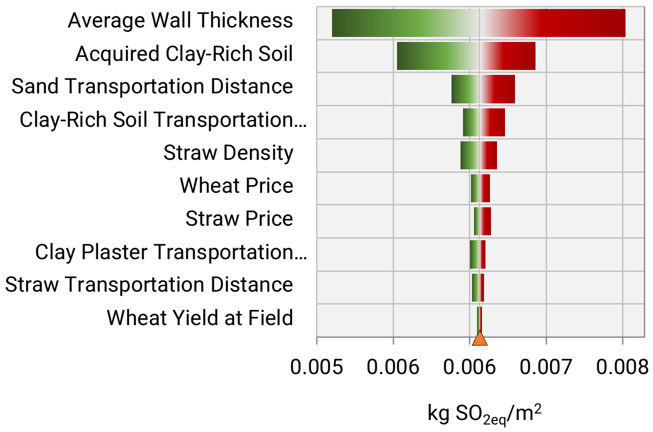


Figure 98: Sensitivity analysis of the global climate change impacts of cob production, ranked by the input effect on output mean



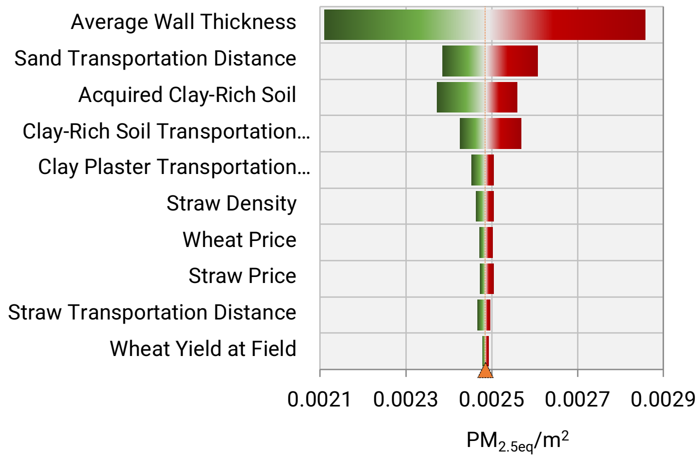


Figure 99: Sensitivity analysis results of the air acidification (left) and HH air particulate (right) impacts of cob production, ranked by the input effect on output mean

The high dependence of the environmental impacts of cob on the amount of acquired clay-rich soil demonstrates the benefits of using on-site subsoil, which can be made available from foundation excavation, or from nearby excavation projects. This scenario adds the benefit of avoiding the transportation or re-grading impacts of otherwise unused excavated soils. For example, the sensitivity analysis shows that use of on-site clay soil may reduce energy requirements from 83 MJ_{eq}/m^2 to 67 MJ_{eq}/m^2. Lastly, the effects of transportation distances on the results indicate that the environmental benefits of cob are highly dependent on the local availability of its constituent materials, especially the sand and clay-rich soil that are highest in weight.

The effect of the wall thickness on the environmental impacts of cob may encourage research and field efforts towards an optimal mixture that could provide a wall thickness that is minimal as possible. Increasing the R-value of cob might also allow a smaller thickness.

4.6.2 Limitations

This LCA study includes various limitations. The comparison with data from various LCI databases and resources introduces discrepancies due to inconsistent scope of the LCI data in terms of geographical context, year, and methodology of data acquisition. Although aiming for consistency in terms of LCI data parameters such as fuel types and air emissions, some parameters were available for certain materials while for others it was missing.

In addition, future analysis should include other types of wall systems and insulation materials, both conventional (e.g., rock wool and Polyurethane Foam) and eco-friendly (e.g., cellulose and light straw clay), as well as the application of CEBs instead of CMUs, and natural insulation rather than synthetic insulation. For instance, although not modeled in this dissertation, it has been shown that a 30% pumice addition increased the R-value of cob to R-0.63 K·m²/W per cm (R-0.9 ft²°Fh/Btu per inch) (Goodvin et al., 2011), achieving an average R-1.12 K·m²/W/cm (R-16.2 ft²°Fh/Btu) for the total cob wall.

Furthermore, the chosen functional unit of 1 m^2 wall used for the embodied impacts study is limited because it does not represent other building geometry considerations that vary among wall systems, such as amount and size of openings, required footing size, presence of bond beams, etc.

While this part of the analysis has focused on the embodied impacts only, the next chapter investigates the operational impacts of the assemblies by developing a dynamic complete-structure thermal simulation. In addition to including other types assemblies, such as insulated rammed earth, the next chapter expands the results to a typical residential house.

5 Technical Gap: Earthen Building Operative Thermal and Environmental Performance

This section investigates the thermal performance and the consequent operational environmental impacts of earthen and conventional wall assemblies introduced in Chapter4. The thermal performance analysis involves computer simulation models using EnergyPlus and DesignBuilder software to compare the earthen and conventional wall assemblies for different climates. Then, the thermal simulation results are used to evaluate the environmental impacts of the operational phase for each wall assembly in terms of energy demand, global climate change, air acidification, and air particulate pollution.

5.1 Critical review of thermal and environmental studies of earthen construction

Thermal modeling is a scientific method to simulate indoor comfort conditions and operational energy demand that arise from a wide range of variables including climate conditions, building envelope construction, and use of heating, cooling, and ventilation systems. Thermal modeling software use sophisticated heat flow algorithms and physical properties to calculate a building's theoretical thermal performance, thereby enabling a critical assessment of potential energy efficiency over the building's operational phase.

Thermal modeling of earthen building materials and methods have been receiving increasing attention in the past decade. Various studies illustrate the ability of earthen materials to passively regulate indoor environments due to their thermal mass (Beccali et al., 2017; Chel & Tiwari, 2009; Heathcote, 2011; Kuil, 2012). Many of these studies focus on the thermal properties of earthen materials (e.g., Heathcote, 2008; Piltingsrud & Design Coalition, 2004) or hygroscopic and humidity buffering capacity (e.g., Cagnon et al., 2014; Labat et al., 2016; McGregor et al., 2016; Touré et al., 2017). Only a few existing studies explore the effect of thermal performance on the operational environmental impacts of earthen construction, do be further discussed.

Studies on the operational environmental impacts of earthen construction were shown to be heavily influenced by the climate and weather context, occupants' activities, and especially the physical properties of the building assemblies. Hernandez & Kenny (2010) identifies the significance of building energy performance and occupants' preferences for life cycle energy use, and the added benefit of natural ventilation as a means of reducing space conditioning in marine climates.

The approach of integrated thermal dynamic performance and LCA has only been briefly addressed in the earthen construction literature. Rodrigues & Freire (2014) identifies that integrating life-cycle assessment and thermal dynamic simulation provides "more robust and representative results by considering a more realistic use of the building and avoiding overestimating energy needs". This integration of thermal dynamic modeling in LCA studies was shown to be significant for the assessment of trades-offs between embodied and operational energy (Rodrigues and Freire, 2014). Lastly, integration between LCA and thermal dynamic simulation was shown to be a critical tool for assessing solutions for both new and retrofitted buildings (Peuportier et al., 2013; Thiers and Peuportier, 2012).

The approach of integrated thermal dynamic performance and LCA has only been briefly addressed in the earthen construction literature. Previous research can only be considered a first step towards a more profound understanding of earthen materials' indoor environment and environmental benefits.

This research is a first step towards a more profound understanding of earthen materials' indoor environment and environmental benefits. More detailed studies are critically needed to compare the range of earthen construction methods for more environmental outcomes. Allinson & Hall (2010) used thermal simulations to provide energy demand recommendations for stabilized rammed earth (SRE). Specifically, the study focused on hygrothermal properties of SRE to assess energy savings due to reduction in humidification and dehumidification requirements. The results of this study show that SRE walls significantly reduced the amplitude of relative humidity fluctuations during both summer and winter in the UK, maintaining a relative humidity between 50-60% in unconditioned space, as oppose to painted plasterboard that fluxed between 40-85%. As a result, SRE was shown to reduce up to 62% of energy demand in buildings (located in UK) due to humidification and dehumidification in a conditioned building with 18-20 Co and 40-50% RH set points.

Chel et al. (2009) measured passive adobe houses and simulated in Matlab to show energy reductions in different climates. The results show that annual heating and cooling energy were reduced by up to 1,480 kWh/year and 1,813 kWh/year respectively, leading to 5.2 CO_2 ton/year emissions reductions for subtropical bordering semi-arid climates (New Delhi, India). For other climates, energy reductions were shown to be up to 7,280 kWh/year for heating in cool winter (Srinagar, India), and 2,770 kWh/year for cooling in humid summer (Mumbai, India).

These studies are significant because they integrate LCA and thermal modeling, however, they are also limited in scope. Each study addressed one particular earthen assembly, and none of the studies perform an overarching life cycle impact assessment. There is a critical need to expand energy and emissions inventories, and translate these inventories into environmental impact assessments for earthen construction approaches for use by decision makers and stakeholders. Indeed, a comparative assessment of different earthen assemblies and conventional assemblies should be completed in order to identify promising hybrid solutions that integrate both embodied and operational energies. This chapter quantifies the thermal performance of earthen assemblies compared to conventional assemblies, and consequent operational environmental impacts, using dynamic thermal and operational energy simulations with rich environmental input including climate, weather, thermal, and hygrothermal characteristics

5.2 Objectives and methodology of the operational thermal and environmental performance analysis

This dissertation offers in depth analysis of the operational performance of four earthen assemblies compared to three conventional assemblies, to quantify their operational environmental impacts. Seven assemblies were studied: insulated rammed earth, uninsulated rammed earth, cob, light straw clay, insulated wood frame, insulated concrete masonry units (CMU), and uninsulated CMU (still prevalent around the world).

The study was conducted for six cities in the US context. Warm-hot dry climates were represented by Tucson, Arizona (ASHRAE climate zone 2B), El Paso, Texas (3B), and Albuquerque, New-Mexico (4B). In addition, due to the abundance of historical earthen building in temperate climates (Watson and McCabe, 2011), additional mixed and temperate climates were investigated, represented by Los Angeles, California (3C), Portland, Oregon (4C), and Denver, Colorado (5B). Figure 100 show the location and climate of each city, and Table 64 provides geoclimatic information in detail.

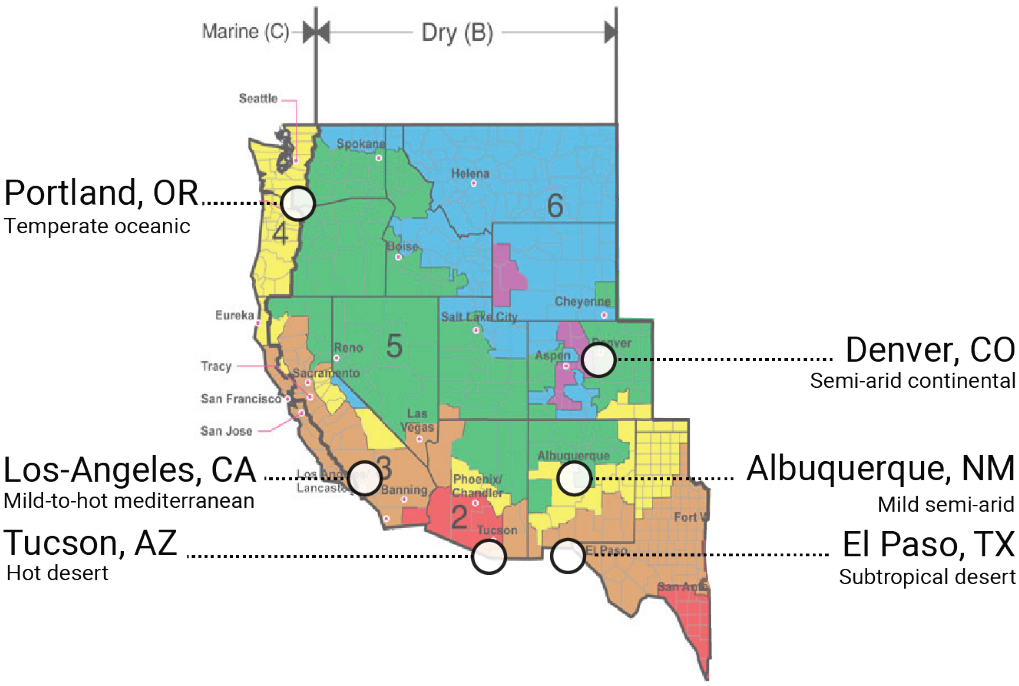


Figure 100: The six locations that were chosen to represent warm-hot and mixed climates

The six cities were chosen mainly due to their climates and, when possible, their association with earthen buildings in terms of availability of building codes and earthen building projects. For instance, Tucson resides in Pima County, in which the Pima Earthen Building Code is available (Pima County

Development Services, 2013), and Portland is home to the Cob Cottage Company, US cob building pioneers (Evans et al., 2002).

EnergyPlus version 9.2.0 (US Department of Energy, 2019) and DesignBuilder version 6.1.3 (DesignBuilder, 2019) were used to model the thermal performance of the earthen assemblies. The heating and cooling load results were then used to conduct the environmental LCA using US-LCI database (NREL, 2012). Information synthesized from the performance matrix (Section 2.5) was used for the earthen assemblies' thermal input parameters. In addition, hygrothermal properties were adopted from an existing study that synthesized the Combined Heat And Moisture Finite Element (HAMT) properties for EnergyPlus (Rempel and Rempel, 2016).

As depicted in Figure 101, the operational thermal and environmental study incorporates a methodology that begins with setting the knowledge base from literature (using the Table 3 from Section 2.5) gaining familiarity with the simulation tools, conducting simple tests for validation, and then testing more complex scenarios such as hybrid assemblies and a full-scale residential model. Accordingly, the study was divided into two steps:

Step 1: Operational Thermal Analysis - This analysis fine tuned and validated the thermal simulation model for the different wall assemblies, incorporating a simulated experimental chamber in both passive and active states in order to isolate and investigate the heat gains and losses through the walls. This analysis further investigated the thermal performance of the earthen assemblies, while taking into account hybrid assemblies and structure composition.

Step 2: Environmental Impacts Assessment - This assessment simulated heating and cooling energy requirements for the different wall assemblies to provide a comparative analysis of the heating and cooling loads and their subsequent environmental impacts for dynamic versus static simulation mode. This assessment used findings from the Step 1 calibration processes to re-evaluate the thermal and environmental performance of earthen construction for different climates.

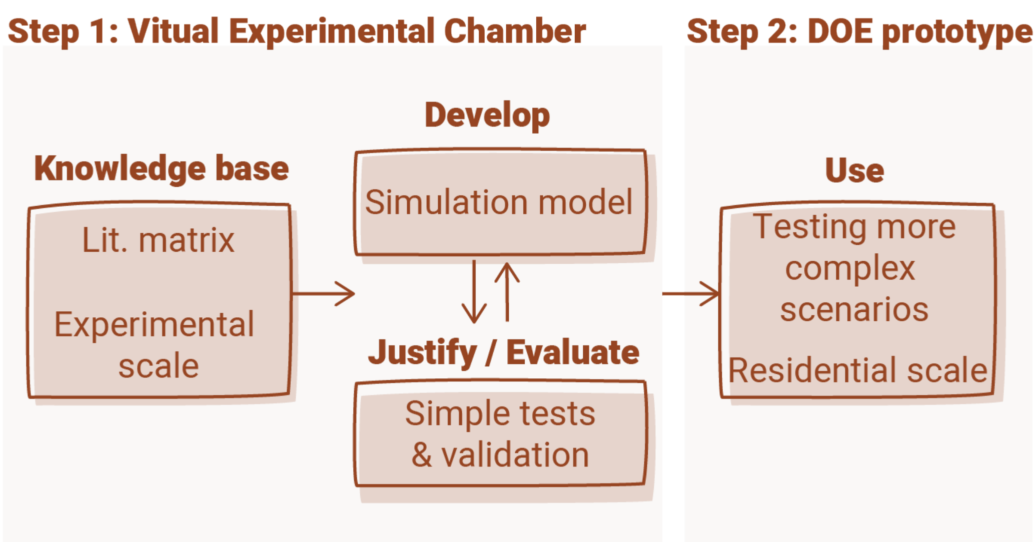


Figure 101: The model of the passive chamber used in the first study

5.3 Step 1: operational thermal analysis of earthen vs. conventional assemblies

The chamber validation study was designed to examine the thermal performance of an experimental chamber following an alteration of external wall construction. The effect of glazing layout, roof, and other construction details were minimized in order to isolate the effects of wall performance. The main output parameter tested was the wall interior surface temperature, which is a proxy for the comfort level provided by the wall type.

5.3.1 Model design and parameters

Site parameters

The study used Typical Meteorological Year version 3 (TMY3) (Wilcox and Marion, 2008), which represents 30 year climate data, for each of the tested cities. Intended for thermal simulations in the US context, the TMY3 data sets hold hourly values of thermal data such as temperature, humidity, solar radiation, wind speed and precipitation for each location. Table 64 details the default "template" data as provided by DesignBuilder for each city.

Table 64: DesignBuilder geographical site parameters for each of the tested cities

	Tucson, AZ	El Paso, TX	Albuquerque, NM	Los—Angeles, CA	Portland, OR	Denver, CO
ASHRAE climate zone	2B	3B	4B	3C	4C	5B
Koppen classification	BWh	BSk	BSk	Csb	Cfb	BSk
heating degree days, HDD	741°C 1,333°F	1,413°C 2,543°F	1881°C 2,378 °F	766°C 1,379°F	2.444°C 4,400°F	2922°C 5259°F
cooling degree days, CDD	1,945°C 3,501°F	1,252°C 2,254°F	717°C 1,290°F	496°C 893°F	217°C 390°F	370°C 666°F
Latitude (degrees)	32.1 N	31.8 N	35.0 N	33.9 N	45.6 N	39.8 N
Longitude (degrees)	-111 W	-107 W	-107 W	-118 W	-123 W	-105 W
Elevation above sea level (m)	779	1194	1620	99	33	1655

Structure Parameters and Occupancy

The simulation of a livable test chamber constructed with the seven wall assemblies supports the calculation of interior air and surface temperature for representative winter and summer periods when the building is operating without conditioning (passively), as well as calculation of the annual heating and cooling loads when the building is running actively to indoor comfort standards. The layout of the test chamber was determined according to existing studies that investigate wall heat transfer using experimental chambers (Heathcote, 2002; Peng & Wu, 2008). Figure 102 illustrates the experimental chamber nominal dimensions, which are set to 4 x 4 m in plan and 3.2 m in height. The thermal envelope internal area is 14 m^2 having an internal volume of 44.4 m^3. Each of the four walls has 2% glazed area, assumed to be a double-glazed assembly to reduce heat transfer. The square structure is aligned such that the four walls face the cardinal points of the compass.

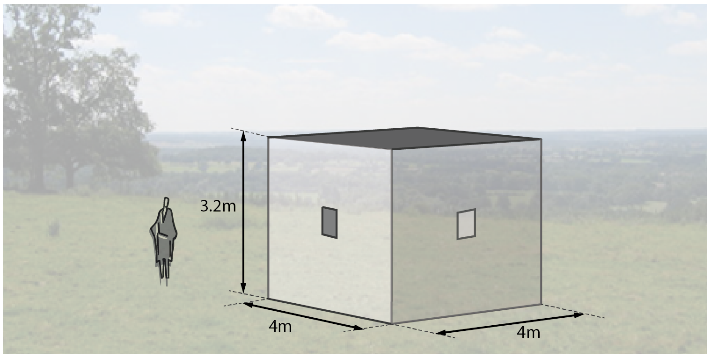


Figure 102: The model of the passive chamber used in the first study

The construction assemblies of the chamber, apart from the walls, were chosen according to energy code standard templates, as shown in Table 65. These chosen templates represent common heavyweight construction components that ensure minimal heat gains and losses through surfaces that are not the walls.

Table 65: Construction assemblies description, thickness, and U-Values

Component	Chosen assembly	Description	Thickness m (inch)	U value W/m^2·K (R-value °F·ft^2·hr/Btu)
Floor	IECC-2000 Ground Floor, Heavyweight	Insulated 100mm thick concrete with timber flooring	0.150 (5.90)	0.350 (16.2)
Roof	Flat Roof – Energy Code Standard - Heavyweight	Insulated and asphalt-protected 100mm thick concrete	0.180 (7.09)	0.486 (11.7)
Glazing	Double Ref Clear 6mm/6mm Air	Double glazed, 6mm clear, 6 mm air, 6 mm clear	0.016 (0.629)	2.83 (1.99)

For the purpose of generating heat gains, it was assumed that the chamber is occupied by one person for 24 hours per day, every day. The occupant's metabolic activity was chosen to be reading / seated activities and clothing was assumed to be generic. The model infiltration was set at a constant rate of 0.300 Air Changes per Hour (ACH). For the passive state, mechanical conditioning systems were turned off completely, including heating, cooling, and ventilation. For the active state, heating and cooling systems were available 24 hours per day, every day. The heating set point temperature was 20°C (68°F) for winter and 24.4°C (76°F) for summer, as recommended by ASHRAE (2017). For the night ventilation state, operation control was set to begin at a minimum indoor temperature of 22°C (71.6°F), as long as the outdoor temperature was between 20°C (68°F) and 27.8°C (82°F) (Madres, 2012).

Wall types and materials properties

The same wall systems as described in Chapter 4 are used here. Table 66 and Table 67 detail the construction layers and wall properties for the seven tested wall types, based on their constituent layers and thicknesses. The tables also show the ranking of different wall assemblies according to their insulation and thermal mass performance.

Table 66: Wall type description and performance

Wall type	Abbreviation	Layer description from outside to inside	Overall thickness m (inch)	U-value W/m·K (R-value °F·ft²·hr/Btu)		Internal heat capacity kJ/m²K (Btu/ft²°F)	
				Value	Rank	Value	Rank
Rammed Earth Insulated	IRE	203mm (8”) rammed earth, 51mm (2”) extruded polystyrene, 203mm (8”) rammed earth	0.457 (18)	0.449 (12.7)	4	254 (44.8)	1 best
Rammed Earth Uninsulated	RE	457mm (18”) rammed earth	0.457 (18)	1.24 (4.60)	7 poorest	254 (44.8)	2
Cob	COB	25mm (1”) cob plaster, 457mm (18”) cob wall	0.483 (19)	0.851 (6.70)	5	151 (26.6)	3
Light Straw Clay	LSC	25mm (1”) cob plaster, 305mm (12”) light straw clay, 25mm (1”) cob plaster	0.356 (14)	0.256 (22.2)	1 best	65.2 (11.5)	4
Insulated Wood Frame	IWF	13mm (0.5”) stucco, 13mm (0.5”) plywood sheathing, 100mm (3.5”) R-19 fiberglass batt, 2x4 wood, 13mm (0.5”) gypsum board	0.140 (5.5)	0.386 (14.7)	2	8.53 (1.51)	7 poorest
Concrete Masonry Units Uninsulated	CMU	13mm (0.5”) stucco, 203mm (8”) concrete masonry unit block, 25mm (1”) wood furring, 13mm (0.5”) gypsum board	0.254 (10)	1.13 (5.00)	6	11.7 (2.06)	6
Concrete Masonry Units Insulated	ICMU	13mm (0.5”) stucco, 203mm (8”) concrete masonry unit block, 51mm (2”) extruded polystyrene, 25mm (1”) wood furring, 13mm (0.5”) gypsum board	0.305 (12)	0.410 (13.85)	3	11.7 (2.06)	5

Table 67: Insulation and thermal mass assembly rating. Insulation rating is shown by U-value W/m·K (R-value °F·ft²·hr/Btu) and thermal mass by internal heat capacity kJ/m²K (Btu/ft²°F)

Insulation rating						
1	2	3	4	5	6	7
LSC	IWF	ICMU	IRE	COB	CMU	RE
0.256 (22.2)	0.386 (14.7)	0.410 (13.85)	0.449 (12.7)	0.851 (6.70)	1.13 (5.00)	1.24 (4.60)
Thermal Mass Rating						
1	2	3	4	5	6	7
IRE	RE	COB	LSC	ICMU	CMU	IWF
254 (44.8)	254 (44.8)	151 (26.6)	65.2 (11.5)	11.7 (2.06)	11.7 (2.06)	8.53 (1.51)

Performance specifications for the rammed earth, cob, and light straw clay, shown in Table 68, were drawn from simulation data by Rempel et al. (2016), as well as reference literature summarized in the performance synthesis matrix in Section 2.5. For the conventional materials, default thermal settings were used from the DesignBuilder database.Hydrothermal building material parameters are given in Table 68.

Table 68: Building materials parameters

Material type	Conductivity W/mK (Btu/hr-ft-°F)	Specific heat capacity J/kgK (kBtu/lb-F°)	Density kg/m³ (lb/ft³)	Thermal Resistance m²·K/W (F°··hr/Btu)	Vapor resistivity (MNs/gm)
Rammed Earth	0.721 (0.417)	1,260 (0.301)	2,013 (126)		70
Cob	0.480 (0.278)	1,022 (0.244)	1,478 (92.3)		50
Light Straw Clay	0.0840 (0.0484)	900 (0.215)	400 (25.0)		50
Extruded Polystyrene	0.0340 (0.0197)	1,400 (0.334)	30 (1.87)		600
Stucco	1.35 (0.780)	840 (0.201)	1,858 (116)		150

Material type	Conductivity W/mK (Btu/hr-ft-°F)	Specific heat capacity J/kgK (kBtu/lb-F°)	Density kg/m³ (lb/ft³)	Thermal Resistance m²·K/W (F°··hr/Btu)	Vapor resistivity (MNs/gm)
Concrete Masonry Unit Block	0.403 (0.233)	850 (0.203)	1,280 (79.9)		60
Wood Furring (modeled as air gap)				0.180 (1.02)	1
Gypsum Board	0.650 (0.376)	840 (0.201)	1,100 (68.7)		30
Plywood	0.120 (0.0694)	1,210 (0.289)	540 (33.7)		250
R-19 fiberglass batt	0.0465 (0.0269)	840 (0.201)	10.5 (0.655)		150
2x4 wood				0.102 (0.579)	150

The simulations were conducted for each external wall type for each location, according to Table 65. The parameter chosen to illustrate the wall performance for the passive chamber state was the internal surface temperature of the walls. The data was plotted for the east facing wall, although all four walls were considered in the analysis. The east facing wall may be most representative of the time lag impacts moderate exposure to solar gains.

Each analysis is run using the appropriate TMY3 record. In the following sections, simulation results are shown for two-week periods in winter (January) and summer (July). Using EnergyPlus, the analysis begins with a set of hard-coded initial conditions. "Warmup day" time steps are applied to bring the system to an appropriate initial condition for meaningful analysis to begin. Twenty-five warmup days are applied which are not included in the reported data.

5.3.2 Passive and active chamber results for each climate

For the majority of cases studied, the results show that **the integration of mass and insulation** perform best, providing more comfortable and stable indoor temperatures in a passive state, and lower heating and cooling loads in an active HVAC state. The following subsections outline the main findings for each tested climate location.

Hot desert climates (Tucson, AZ)

For Tucson, AZ, earthen assemblies show thermal buffering capabilities and significant time lag as opposed to the conventional assemblies. Figure 103 and Figure 104 depict the inside surface temperatures for each wall assembly alternative, in winter and summer, respectively. Each figure shows a typical two-week portion of the year-long TMY3 record. Figure 105 provides a closer look of a 24h period from Figure 5, showing an approximate 6h time lag for the light straw clay, with a daily fluctuation of no more than 1.5 °C.

The insulated wood frame wall achieves the warmest temperatures in winter and the coolest temperatures in summer in the chamber's passive state, however with the greatest temperature fluctuations for both winter and summer due to its low mass (mean fluctuations of 5.5°C and 4°C, respectively). The insulated CMU wall, with higher heat capacity, provides less temperature fluctuations both winter and summer, compared to the insulated wood frame, but still greater fluctuations than earthen assemblies.

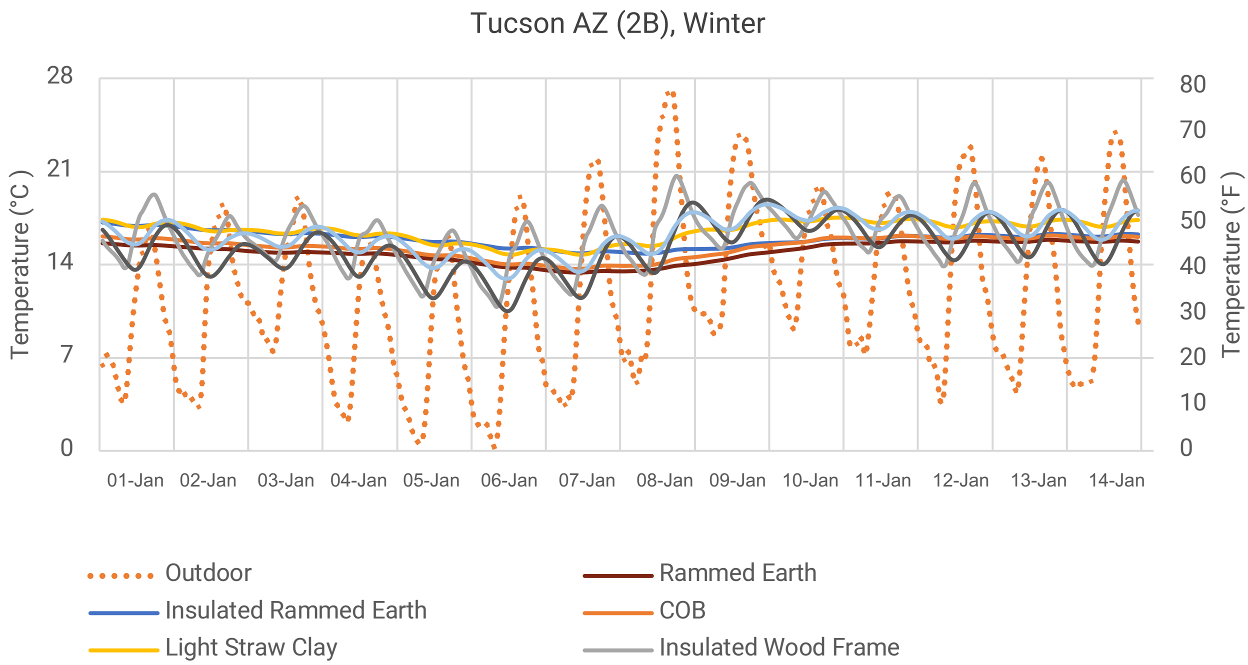


Figure 103: Tucson winter inside surface temperature for each wall alternative (east facing wall)

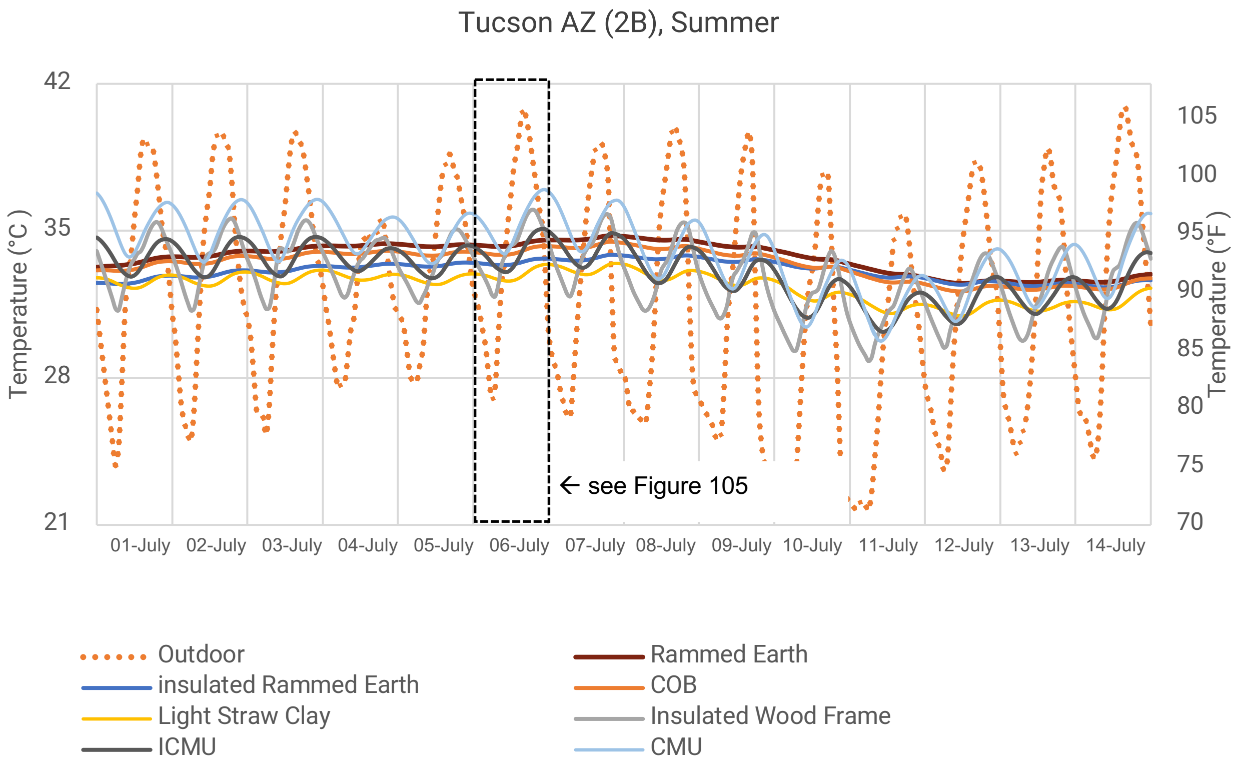


Figure 104: Tucson summer inside surface temperature for each wall alternative (east facing wall). Detailed results of July 6th are shown in Figure 105.

Figure 105 provides a closer look of a 24h period, showing an approximate 6h time lag for the light straw clay, with a daily fluctuation of no more than 1.5 $^{\circ}$C compared to wood.

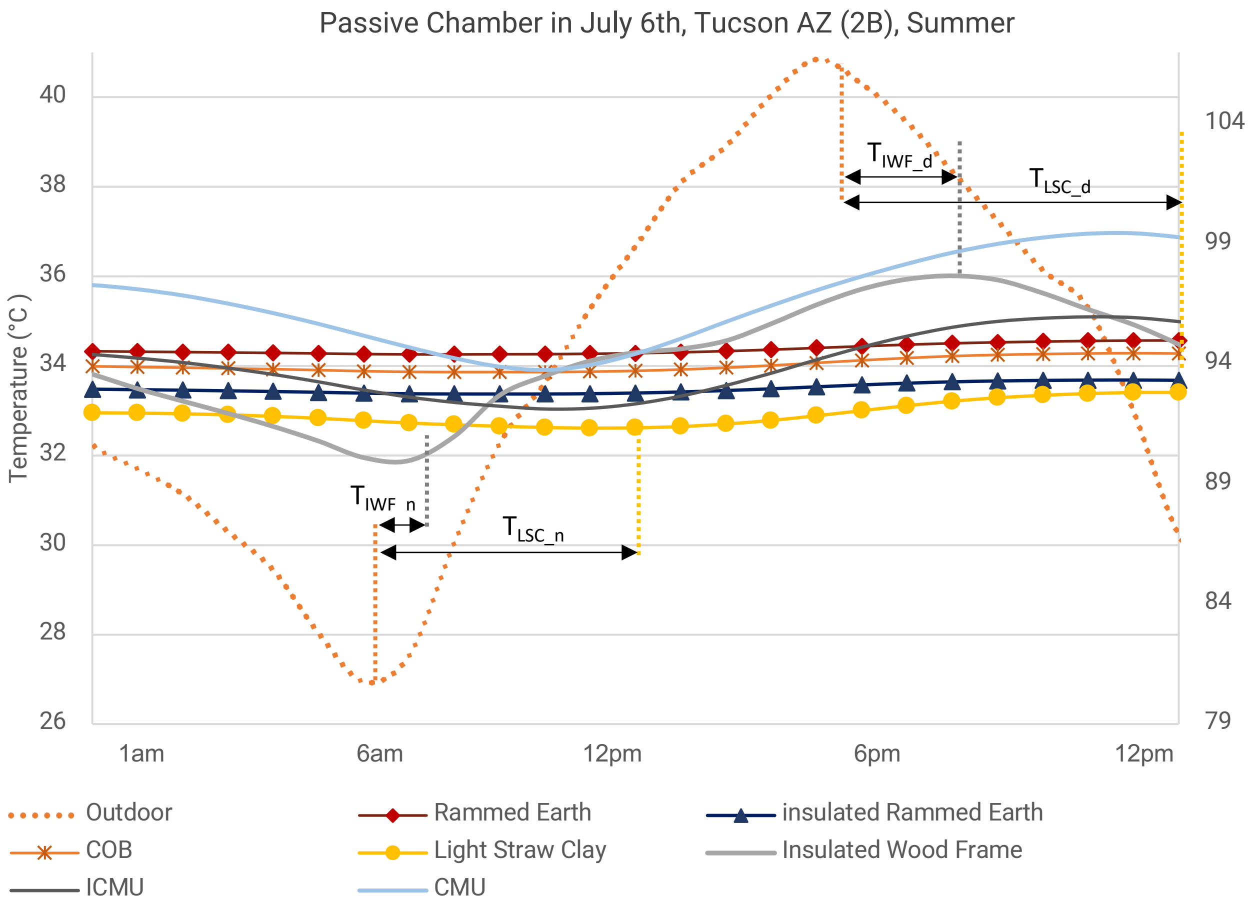


Figure 105: Spotlight on passive chamber internal wall temperature during one 24h summer day (east facing wall). T_{IWF_n}, T_{LSC_n}, T_{IWF_d}, and T_{LSC_d} are the the time lag if the insulated wood frame and light straw clay, for night and day, respectively.

Each two-week record is summarized in Table 69.. Among the earthen assemblies, the light straw clay wall achieves the best performance; it both regulates the indoor temperature and provides the best average comfort levels for each season.

Table 69: Mean interior surface temperature for two weeks during winter (Figure 4) and summer (Figure 5), Tucson, AZ in °C (green highlights best performance)

	OUTDOOR	RE	IRE	COB	LSC	IWF	CMU	ICMU
Winter (Jan 1-15)								
East wall	11.75	14.9	15.9	15.3	16.5	16.2	15.3	16.3
North wall		14.4	15.7	15.0	16.4	16.0	14.9	16.1
West wall		14.9	15.9	15.3	16.5	16.2	15.3	16.2
South wall		15.8	16.4	15.9	16.7	16.5	16.2	16.6
Summer (July 1-15)								
East wall	31.7	33.8	33.1	33.4	32.4	32.9	34.1	33.0
North wall		33.4	32.9	33.2	32.3	32.8	33.7	32.9
West wall		33.6	33.0	33.3	32.3	32.9	33.9	33.0
South wall		33.4	32.9	33.2	32.3	32.8	33.7	32.9

The chamber study also allows the effect of night ventilation to be tested, examining the free cooling through reduction in temperature that is possible for the earthen wall assemblies. As shown in Figure 106 and Figure 107, night ventilation provided the most significant cooling effect for the light straw clay and insulated rammed earth assemblies. The most significant reductions are achieved for hours with very high temperatures (>30°C, 86°F) as opposed to warm temperatures (>24.4°C, 76°F). The reductions in hours with very high temperatures were shown to be 71% for insulated rammed earth, 65% for light straw clay, 39% for cob, and 31% for uninsulated rammed earth., while conventional assemblies received very little benefit.

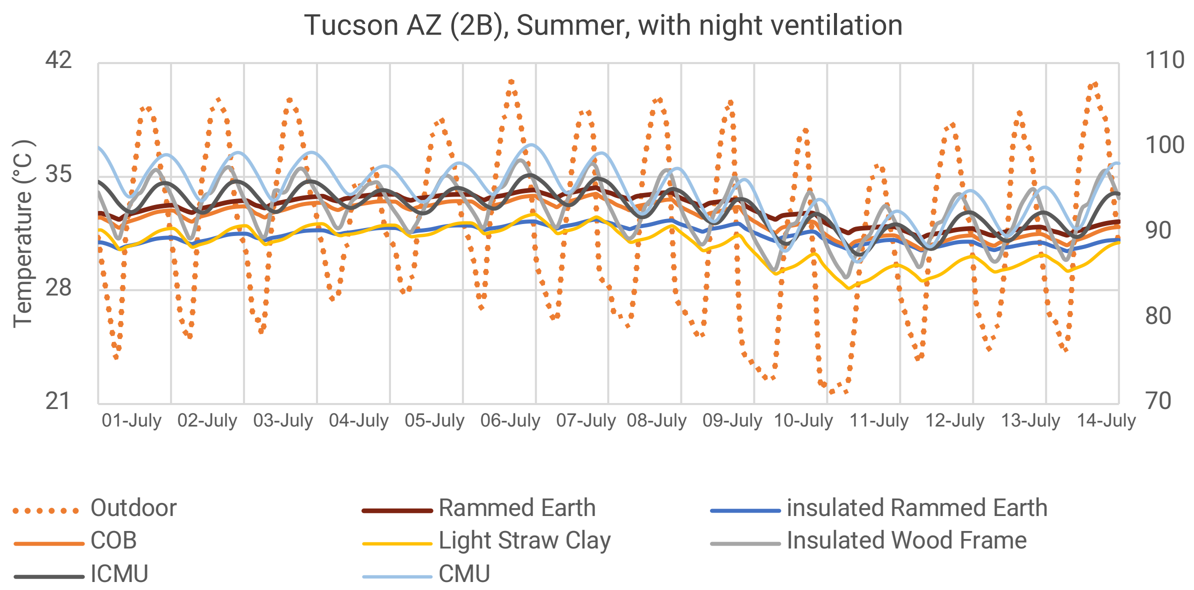


Figure 106: Tucson summer with night ventilation, inside surface temperature for each wall alternative (east facing wall)

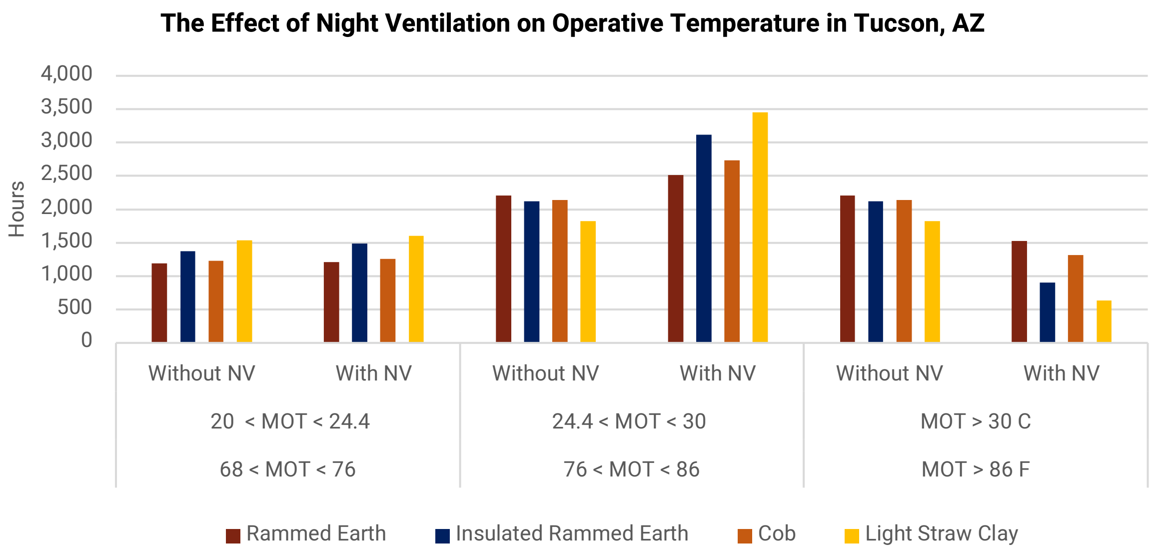


Figure 107: Simulated chamber with night ventilation on high temperature hours for Tucson, year long

Subtropical desert climates (El Paso, TX)

For El Paso, TX, insulated rammed earth provided the most constant warm temperature in winter, whereas light straw clay maintained the coolest temperatures in the summer. With a dry climate, hot summers and short cold winters, El Paso is shown to benefit from different insulated thermal mass constructions, depending on the season and orientation of the wall. As shown in Figure 108 and Table 70, the insulated rammed earth provided steady state temperatures above 15.3°C (59.6°F) in winter, constantly maintaining a higher temperature than the average outdoor temperature (8.6°C, 47.5°F). For summer, Figure 109 and Table 70 show that light straw clay and insulated rammed earth perform slightly better, interchangeably: light straw clay for east and west walls, and insulated rammed earth for north and south walls.

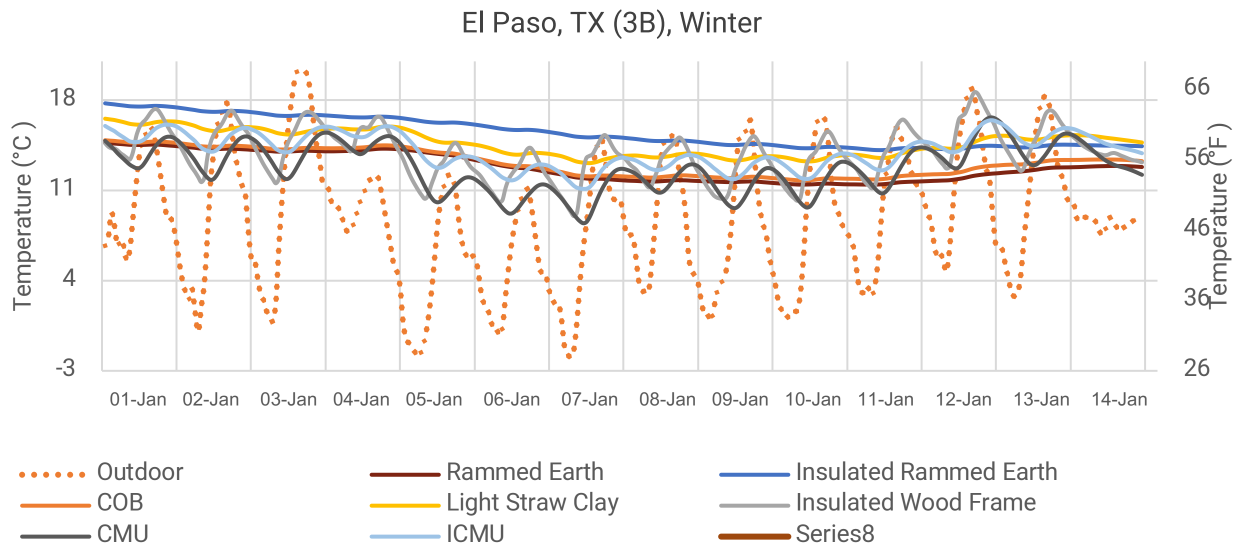


Figure 108: El Paso winter inside surface temperature for each wall alternative (east facing wall)

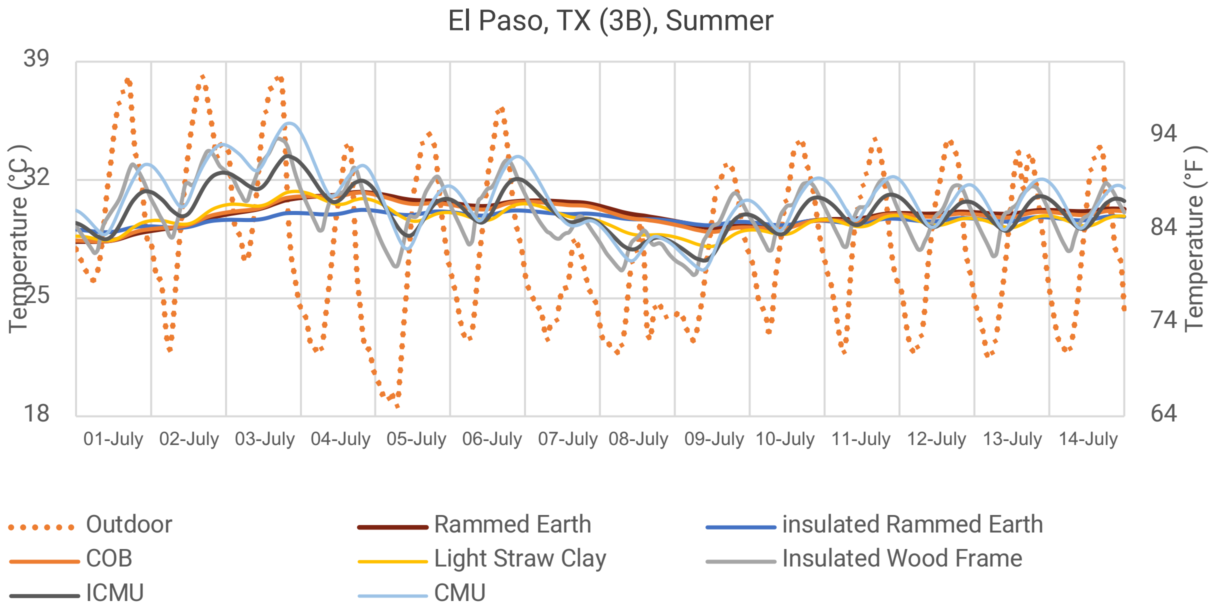


Figure 109: El Paso summer inside surface temperature for each wall alternative (east facing wall)

Table 70: Mean inside surface temperature for two weeks during winter and summer, El Paso, TX , in °C (green highlights best performance)

	OUTDOOR	RE	IRE	COB	LSC	IWF	CMU	ICMU
Winter (Jan 1-15)								
East wall	8.65	12.8	15.5	13.1	14.6	13.9	12.7	14.1
North wall		12.4	15.3	12.8	14.6	13.8	12.3	13.9
West wall		12.8	15.5	13.1	14.6	13.9	12.7	14.0
South wall		13.6	15.8	13.7	14.8	14.2	13.5	14.3
Summer (July 1-15)								
East wall	28.1	30.0	29.7	29.9	29.6	30.1	30.8	30.2
North wall		29.6	29.5	29.6	29.5	30.0	30.3	30.0
West wall		29.9	29.6	29.8	29.6	30.1	30.6	30.1
South wall		29.6	29.5	29.6	29.5	30.0	30.3	30.0

Mild semi-arid climates (Albuquerque, NM)

In Albuquerque, the two-week winter passive performance of insulated rammed earth performed best, similar to El Paso. Albuquerque, with a dry and mild semi-arid climate, has high diurnal temperature range, leading to a significant average 15°C (27°F) outdoor temperature fluctuations during the wintertime. Figure 110 shows that the earthen assemblies provide a steady state indoor passive environment, with less than 1°C (1.8°F) fluctuations, as opposed to the insulated wood frame that showed a mean 4.8°C (8.6°F) temperature difference per day. Indoor heat fluctuations greater than 3°C (5.4°F) lead to increased occupant discomfort and complaints of drafts (Melikov et al., 1997). The earthen assemblies reduce temperature fluctuations also in summer, as shown in Figure 111. Significantly, Table 71 shows that different earthen assemblies perform best for each wall orientation for managing summer overheating: uninsulated rammed earth for the west wall, insulated rammed earth for the south wall, and light straw clay for the east and west walls.

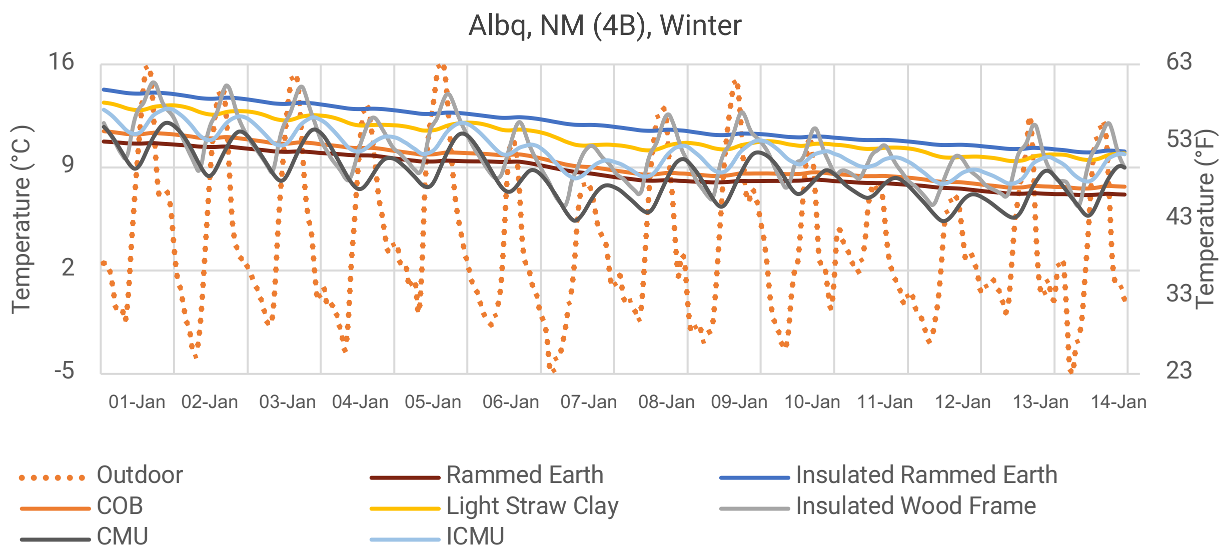


Figure 110: Winter inside surface temperature for each wall alternative (east facing wall) for Albuqueque, NM

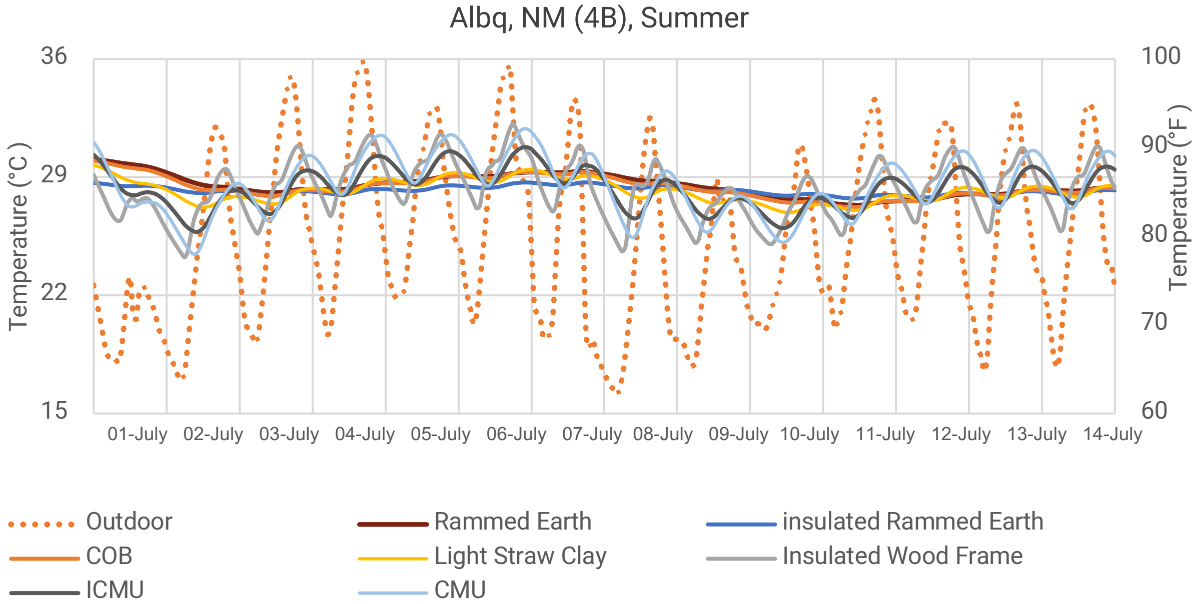


Figure 111: Summer inside surface temperature for each wall alternative (east facing wall) for Albuqueque, NM.

Insulated rammed earth provided a mean of 3°C (6°F) warmer indoor temperatures in winter during passive conditioning as opposed to the uninsulated rammed earth, as shown in Table 71, and 3-4°C (6-7°F) warmer conditions in winter than conventional insulated construction in passive mode, a critical contribution to resiliency if the power goes out.

Table 71: Mean inside surface temperature for two weeks during winter and summer, Albuqueque, NM, in °C (green highlights best performance)

	OUTDOOR	RE	IRE	COB	LSC	IWF	CMU	ICMU
Winter (Jan 1-15)								
East wall	3.91	8.78	11.9	9.29	11.1	10.0	8.38	10.1
North wall		8.35	11.8	8.99	11.0	9.87	7.95	9.95
West wall		8.70	11.9	9.23	11.1	9.99	8.31	10.1
South wall		9.52	12.2	9.79	11.3	10.3	9.12	10.4
Summer (July 1-15)								
East wall	25.2	28.4	28.2	28.4	28.2	28.2	28.5	28.3
North wall		28.0	28.0	28.1	28.1	28.1	28.0	28.2
West wall		28.2	28.1	28.2	28.1	28.1	28.2	28.2
South wall		28.1	28.1	28.1	28.1	28.1	28.1	28.2

Mild-to-hot Mediterranean climates (Los Angeles, CA)

The results for the mild climate in Los-Angeles, CA, illustrate that for the two-week periods shown, rammed earth is preferable for summer and insulated rammed earth is preferable for winter, as shown in Figure 112 and Figure 113.

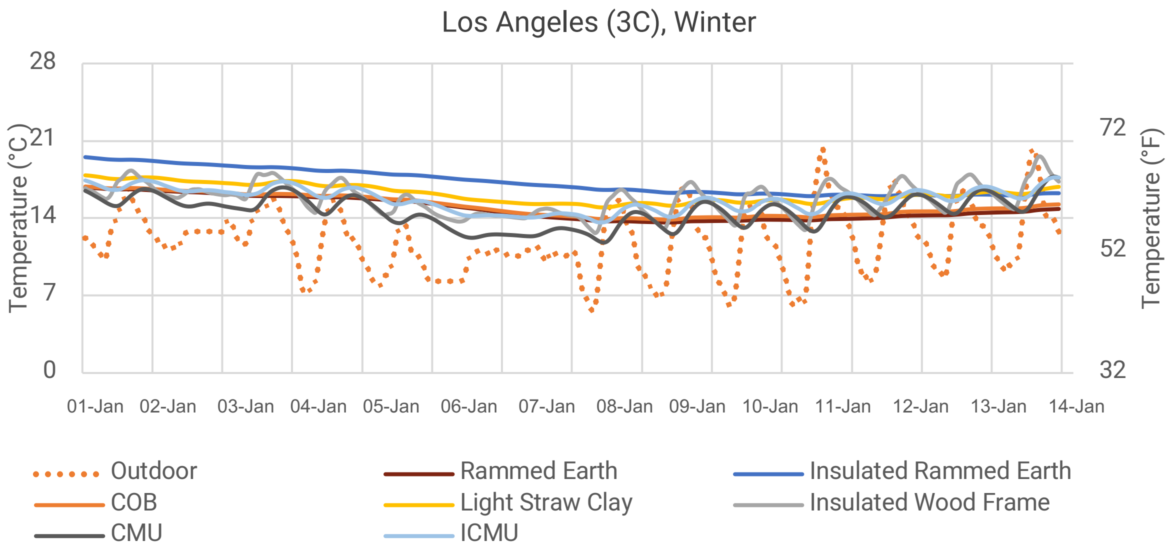


Figure 112: Summer inside surface temperature for each wall alternative (east facing wall) for Los-Angeles, CA

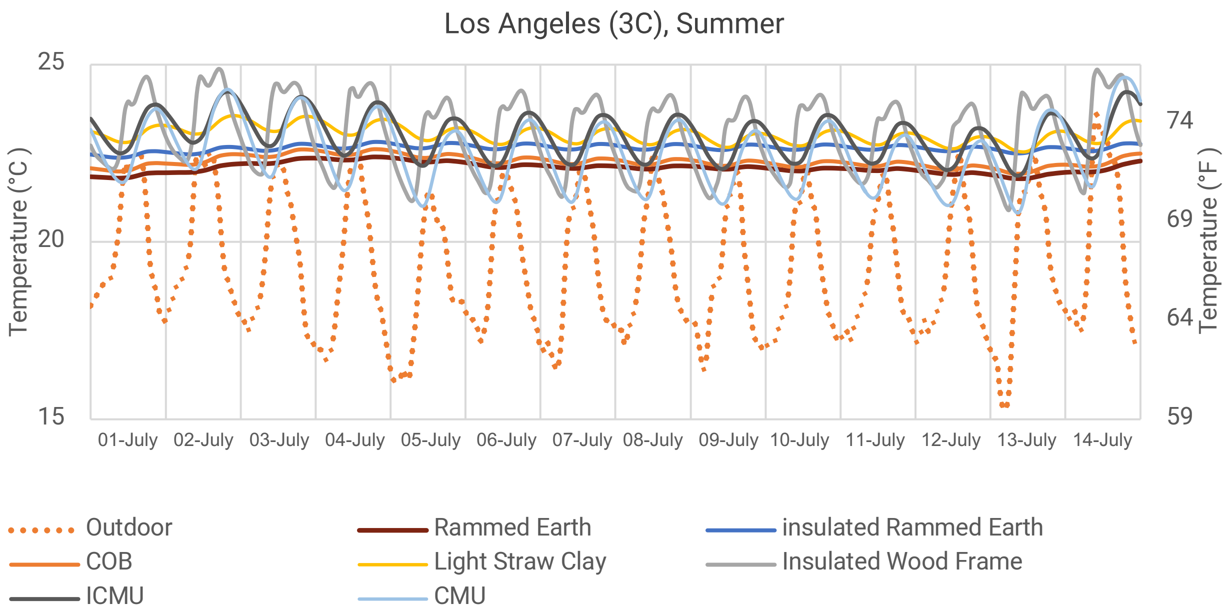


Figure 113: Summer inside surface temperature for each wall alternative (east facing wall) for Los-Angeles, CA

The benefits of insulated rammed earth for indoor comfort in winter is evident in Table 72, and the slight benefit of non insulated rammed earth for indoor comfort in summer is also shown, although designing for variable insulation of a rammed earth building could be challenging.

Table 72: Mean inside surface temperature for two weeks during winter and summer, Los Angeles, CA, in °C (green highlights best performance)

	OUTDOOR	RE	IRE	COB	LSC	IWF	CMU	ICMU
Winter (Jan 1-15)								
East wall	11.9	14.8	17.2	15.1	16.2	15.7	14.6	15.7
North wall		14.6	17.2	14.9	16.2	15.7	14.4	15.6
West wall		14.8	17.2	15.0	16.2	15.7	14.5	15.7
South wall		15.3	17.4	15.4	16.3	15.9	15.1	15.9
Summer (July 1-15)								
East wall	19.3	22.1	22.6	22.3	23.0	23.0	22.5	23.0
North wall		21.9	22.6	22.1	23.0	22.9	22.3	22.9
West wall		22.1	22.7	22.3	23.0	23.0	22.5	23.0
South wall		21.9	22.6	22.1	23.0	22.9	22.3	22.9

Temperate oceanic climates (Portland, OR)

With a mixed climate (warm days and cold nights), thermal performance in Portland is optimized with different assemblies for each season. Shown in Figure 114, light straw clay performed best in Portland winter when relying on passive conditioning alone. In this figure, earthen assemblies are shown to "surf" (i.e., rely on the natural flows of temperature, sun, and wind, to bring comfort without dependency on non-renewable energy (Loftness, 2013)) over the cold night into the first half of the warmer day as is particularly evident January 01-03 (Figure 15). Similar behavior is seen in the cool nights of the summer shown in Figure 115 (especially July 06-08).

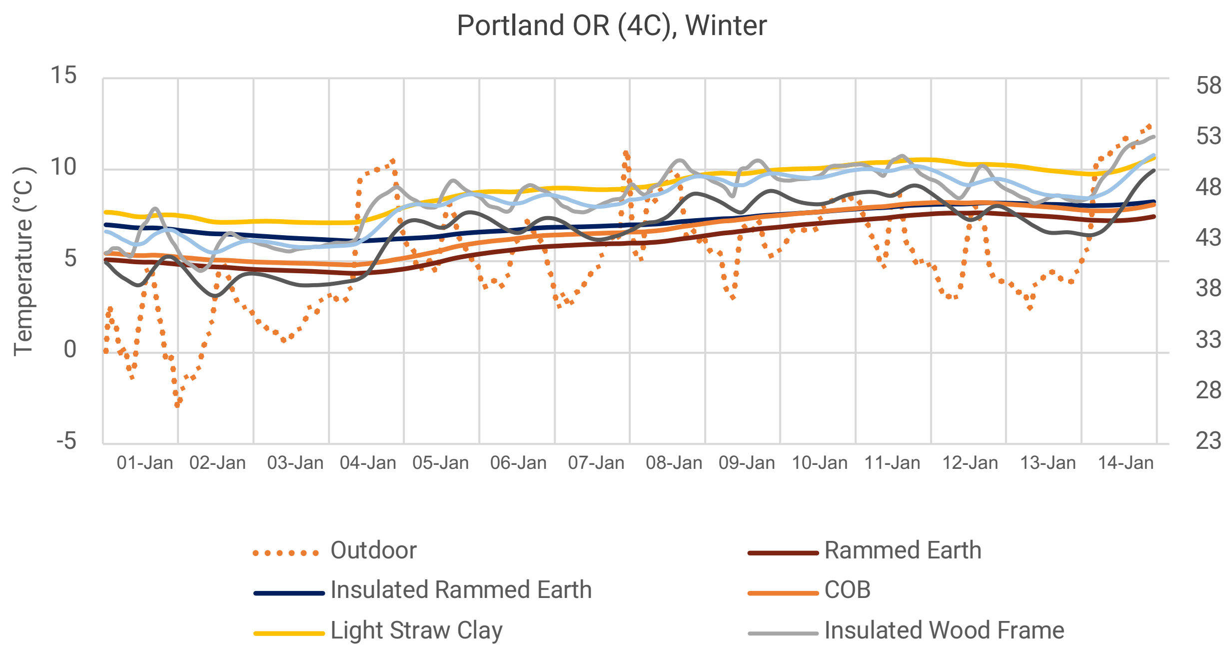


Figure 114: Portland winter inside surface temperature for each wall alternative (east facing wall)

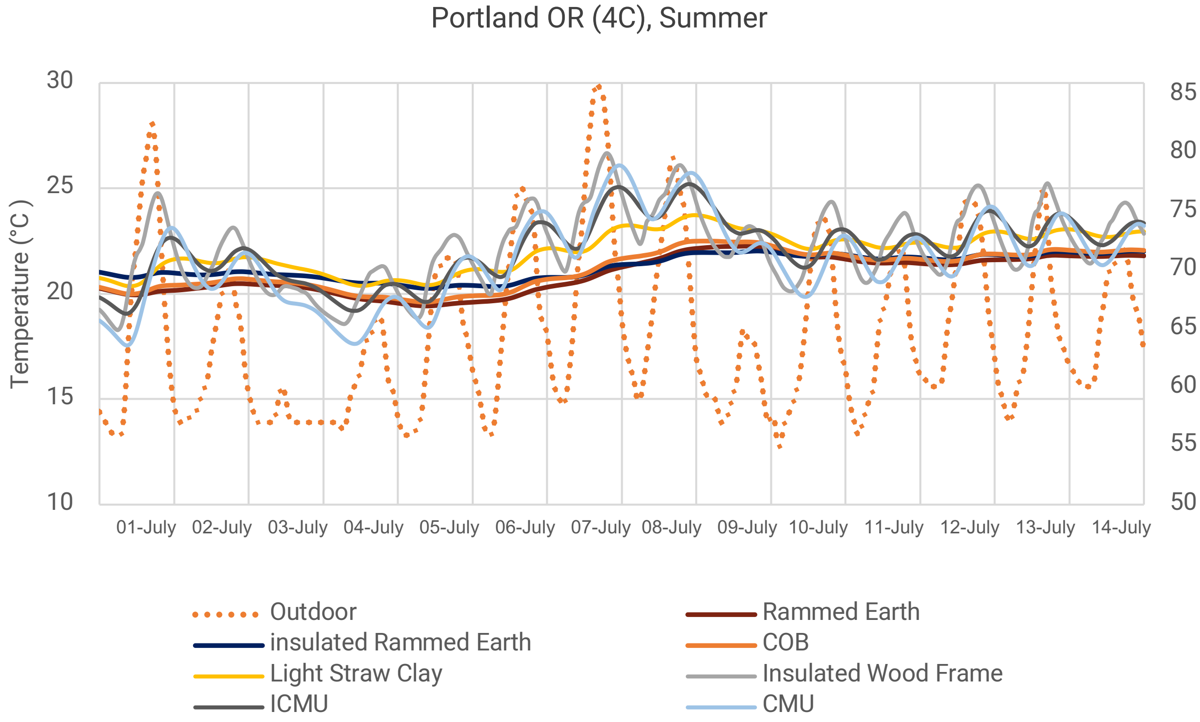


Figure 115: Portland summer inside surface temperature for each wall alternative (east facing wall)

The reduced heating loads the earthen assemblies evident in Table 73, and the slight benefit of non insulated earthen assemblies in for indoor comfort in both winter and summer is also shown, allowing reduced equipment cycling.

Table 73: Mean inside surface temperature for two weeks during winter and summer, Portland, OR (green highlights best performance)

	OUTDOOR	RE	IRE	COB	LSC	IWF	CMU	ICMU
Winter (Jan 1-15)								
East wall	5.22	6.04	7.16	6.60	8.97	8.38	6.68	8.24
North wall		7.47	7.10	6.17	8.44	8.35	6.60	8.20
West wall		7.53	7.15	6.24	8.45	8.37	6.66	8.23
South wall		7.73	7.33	6.49	8.52	8.44	6.88	8.32
Summer (July 1-15)								
East wall	18.1	20.9	21.3	21.1	22.0	22.2	21.7	22.1
North wall		21.3	21.2	20.8	22.0	22.1	21.4	22.0
West wall		21.4	21.3	21.0	22.1	22.2	21.6	22.1
South wall		21.3	21.2	21.0	22.1	22.2	21.6	22.1

An additional analysis was performed for a hybrid natural-materials option, in which light straw clay is used for the east, north, and south walls, and rammed earth for the west wall. Evening solar radiation on west wall with mass contributes to heating during the cold night hours. Figure 116 and Figure 117 depict the indoor air temperatures for both the hybrid and mono construction alternatives. The hybrid assembly of 3/4 light straw clay and 1/4 rammed earth in Portland Oregon results in warmer indoor temperatures in winter than only rammed earth, and cooler indoor temperatures in summer than only light straw clay, thus providing an optimized performance that over the course of a year outperforms the choice of only one assembly.

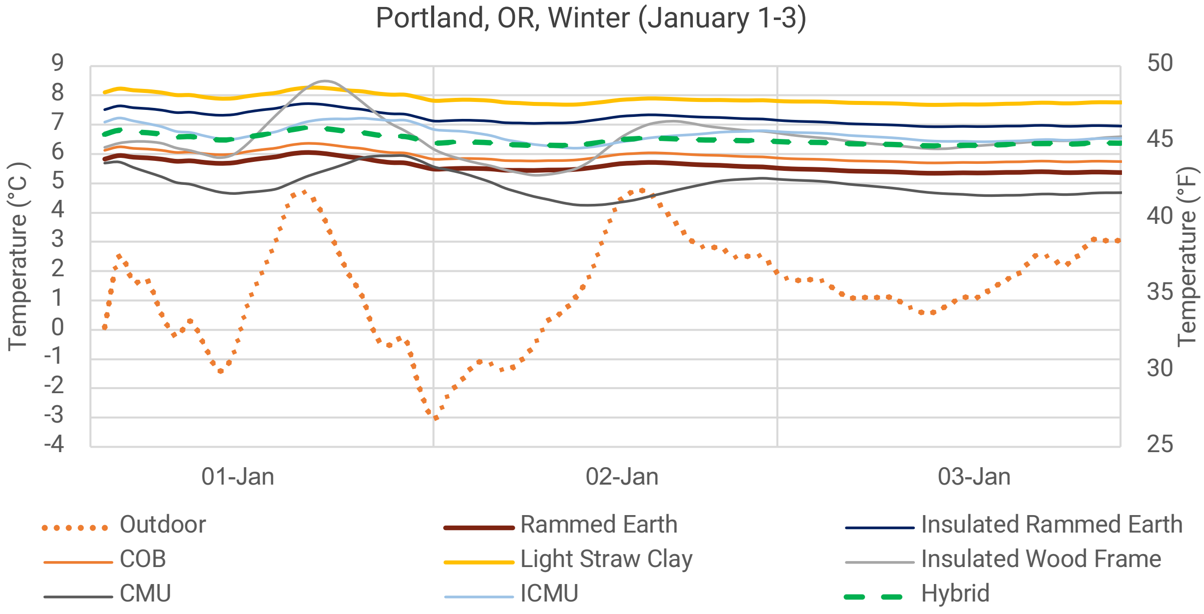


Figure 116: Portland winter indoor air temperature for the hybrid light straw clay and rammed earth chamber as opposed to the mono-constructed chamber alternatives

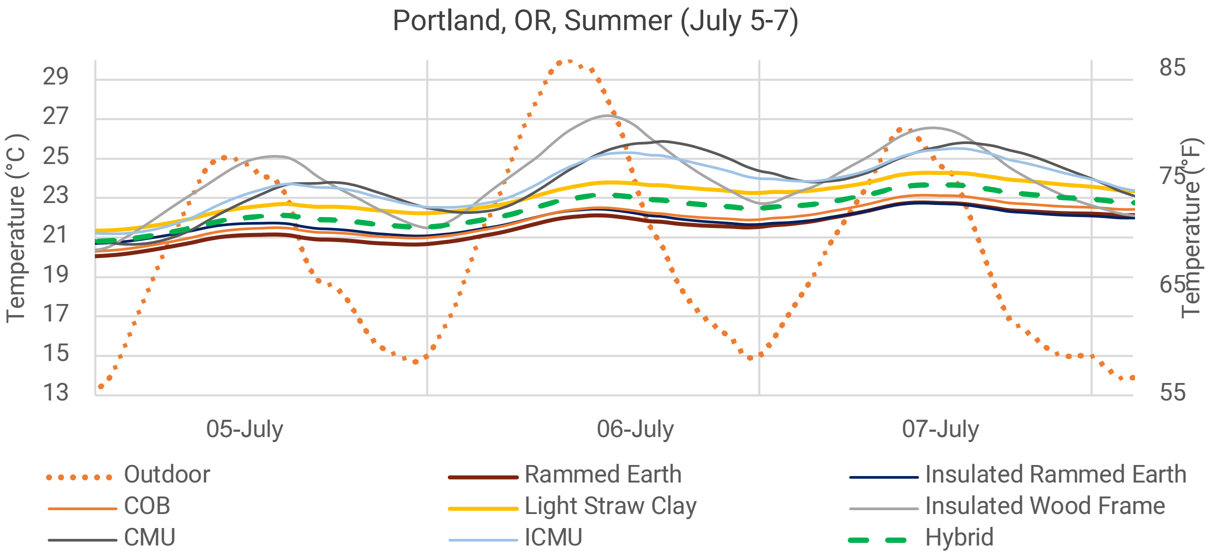


Figure 117: Portland summer indoor air temperature for the hybrid light straw clay and rammed earth chamber as opposed to the mono-constructed chamber alternatives

Continental semi-arid climates (Denver, CO)

Denver's continental semi-arid climate is characterized by cold winters and hot summers. Similar to Portland, the best comfort results were obtained with light straw clay during winter, and insulated rammed earth during summer. While outside winter temperature dropped below -15°C (5°F), all of the earthen assemblies did not fall below the freezing point in the passive conditioning mode, unlike traditional assemblies of insulated wood frame and uninsulated CMU. However, the temperature fluctuations of the insulated wood frame and CMU also resulted in warmer temperatures during the passively conditioned day, whereas the rammed earth and cob assemblies remain steadily colder.

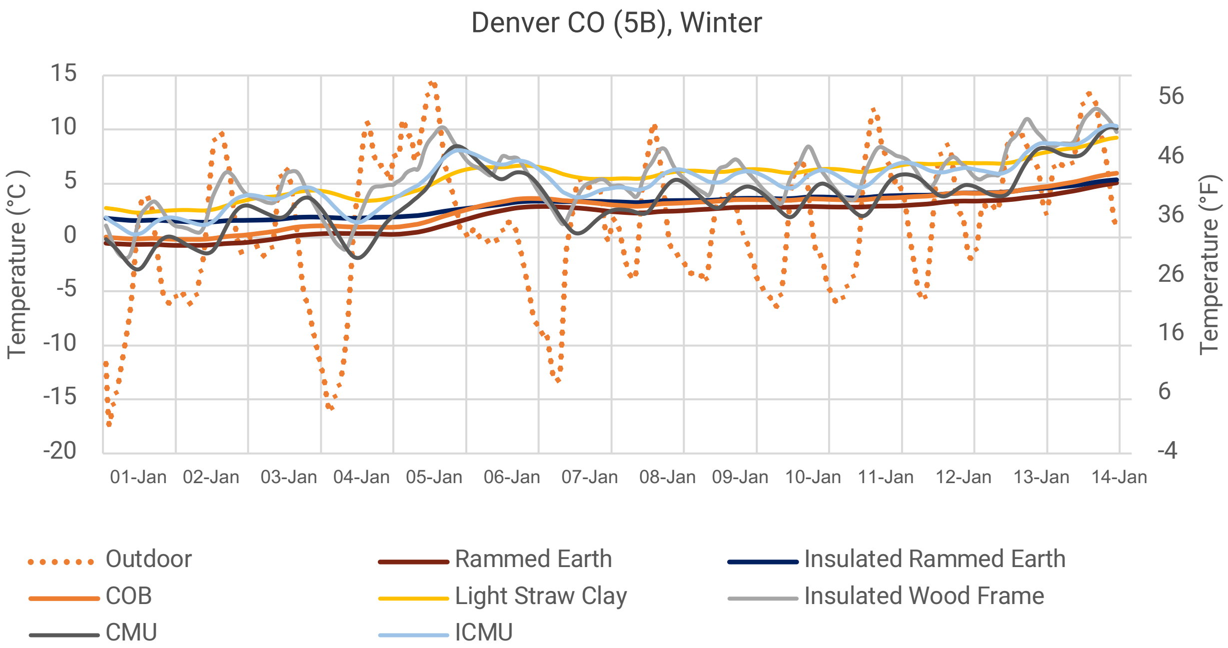


Figure 118: Denver winter inside surface temperature for each wall alternative (east facing wall)

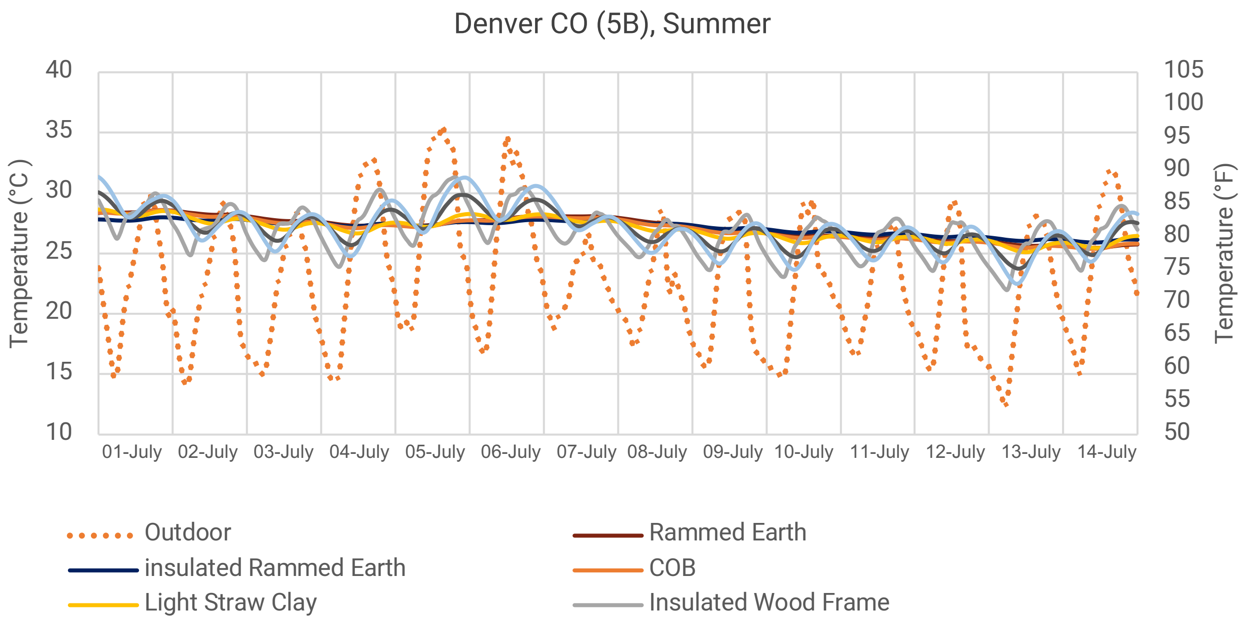


Figure 119: Denver summer inside surface temperature for each wall alternative (east facing wall)

The benefits of light straw clay during winter is shown in Table 74. While rammed earth provided the best comfort leves during the two-week test, it achieves higher mean inside surface temperatures during the months of summer, as opposed to the conventional assemblies, illustrating the need for hybrid assembies in continental climates in which winters are cold and summers are hot.

Table 74: Mean inside surface temperature for two weeks during winter and summer, Denver, CO (green highlights best performance)

	OUTDOOR	RE	IRE	COB	LSC	IWF	CMU	ICMU
Winter (Jan 1-15)								
East wall	1.14	1.93	3.06	2.63	5.50	5.40	3.45	5.13
North wall		1.66	2.91	2.44	5.44	5.30	3.17	5.02
West wall		1.88	3.03	2.60	5.49	5.38	3.41	5.12
South wall		2.46	3.35	3.00	5.61	5.58	4.01	5.34
Summer (July 1-15)								
East wall	22.7	27.1	27.1	27.0	27.0	26.8	27.0	27.0
North wall		26.6	26.9	26.7	26.9	26.6	26.4	26.8
West wall		26.9	27.0	26.8	26.9	26.7	26.7	26.9
South wall		26.8	26.9	26.8	26.9	26.7	26.6	26.8

5.3.1 Thermal analysis results overview and discussion

Comparative thermal results overview

The comparative performance of the four earthen and three conventional chamber simulations for six climates is shown in

Table 75 with mean air and wall radiant temperature results for two-week winter and summer TMY3 periods operating in a passive mode.. Radiant temperatures reflect the mass influence on the operative temp and thus on the heating and cooling systems operation. The results for the passive chamber study – which is critical to comfort, resiliency and operational energy – can be summarized as follows:

- For a hot desert 2B climate represented by Tucson, AZ, light straw clay results in the most comfortable temperature levels in both winter and summer when the house is passively conditioned.
- For a desert 3B climate represented by El Paso, TX, insulated rammed earth perform best in winter, and all the earthen assemblies perform similarly well for summer when the house is passively conditioned.
- For a mild semi-arid 4B climate represented by Albuquerque, NM, insulated rammed earth perform best in winter and the different walls perform equally well in summer when the house is passively conditioned.
- For a Mediterranean 3C climate represented by Los Angeles, CA, insulated rammed earth performs best in winter, and rammed earth and cob are optimal for summer when the house is passively conditioned.
- For a temperate oceanic 4C climate represented by Portland, OR, insulated rammed earth and wood frame are preferable for winter and rammed earth for summer when the house is passively conditioned.
- For a continental 5B climate represented by Denver, CO, light straw clay and insulated wood frame provide the warmest indoor temperature whereas conventional mass and wood assemblies provide equal comfort in summer when the house is passively conditioned.

Overall, light straw clay, with U = 0.256 W/m·K (R = 22.2 $^{\circ}$F·ft^2·hr/Btu) and internal heat capacity of 65.2 kJ/m^{2}K (11.5 Btu/ft^2°F), perform better than other assemblies for extreme weather conditions: hot Tucson summer, cold Portland or Denver winter. However, for milder climate conditions, insulated rammed earth performed best, with its lower conductivity and higher mass capacity (U = 0.449 W/m·K, R = 12.7 $^{\circ}$F·ft^2·hr/Btu and internal heat capacity of 254 kJ/m^{2}K, 44.8 Btu/ft^2°F). For very mild climate conditions, when outdoor thermal conditions provide good comfort levels, such as in Los Angeles and Portland summer, rammed earth and cob with their high conductivity and high thermal capacity perform the best.

Table 75: Mean inside surface temperature for two weeks during winter and summer, for all climates, in degrees °C. (darker green signifies better performance)

			Outdoor	RE	IRE	COB	LSC	IWF	CMU	ICMU
Tucson, AZ	Winter (Jan 1-15)	Air	11.7	15.7	16.5	16.0	17.0	16.7	16.0	16.8
		Radiant		15.0	16.0	15.4	16.5	16.2	15.4	16.3
		Operative		15.3	16.3	15.7	16.7	16.5	15.7	16.5
	Summer (July 1-15)	Air	31.7	33.4	32.8	33.1	32.2	32.7	33.7	32.8
		Radiant		33.5	33.1	33.3	32.5	32.9	33.8	33.0
		Operative		33.5	33.0	33.2	32.4	32.8	33.7	32.9
El Paso, TX	Winter (Jan 1-15)	Air	8.65	13.6	16.0	13.9	15.2	14.5	13.5	14.6
		Radiant		13.0	15.5	13.3	14.7	14.0	12.9	14.1
		Operative		13.3	15.7	13.6	14.9	14.2	13.2	14.3
	Summer (July 1-15)	Air	28.1	30.0	29.9	30.0	29.9	30.3	30.7	30.3
		Radiant		29.7	29.5	29.7	29.5	29.9	30.4	30.0
		Operative		29.9	29.7	29.8	29.7	30.1	30.5	30.1
Albuquerque, NM	Winter (Jan 1-15)	Air	3.91	9.55	12.4	10.0	11.6	10.6	9.16	10.7
		Radiant		8.99	12.0	9.46	11.2	10.1	8.61	10.2
		Operative		9.27	12.2	9.74	11.4	10.4	8.89	10.5
	Summer (July 1-15)	Air	25.2	28.1	28.0	28.1	28.1	28.1	28.2	28.2
		Radiant		28.5	28.4	28.5	28.4	28.4	28.5	28.5
		Operative		28.3	28.2	28.3	28.2	28.2	28.3	28.3
Los Angeles, CA	Winter (Jan 1-15)	Air	11.9	15.6	17.7	15.8	16.8	16.3	16.8	163
		Radiant		15.0	17.2	15.1	16.2	15.7	16.2	15.7
		Operative		15.3	17.5	15.5	16.5	16.0	16.5	16.0
	Summer (July 1-15)	Air	19.3	22.6	23.1	22.8	23.4	23.4	23.4	23.4
		Radiant		22.0	22.6	22.2	23.0	22.9	23.0	22.9
		Operative		22.3	22.9	22.5	23.2	23.2	23.2	23.2
Portland, OR	Winter (Jan 1-15)	Air	5.22	6.99	8.01	7.48	9.64	9.03	7.52	8.92
		Radiant		6.27	7.33	6.78	9.02	8.43	6.84	8.30
		Operative		6.63	7.67	7.13	9.33	8.73	7.18	8.61
	Summer (July 1-15)	Air	18.1	21.5	21.8	21.7	22.5	22.6	22.0	22.5
		Radiant		20.9	21.3	21.1	22.0	22.1	21.6	22.1
		Operative		21.2	21.5	21.4	22.2	22.3	21.8	22.3
Denver, CO	Winter (Jan 1-15)	Air	1.14	2.94	3.98	3.58	6.19	6.03	4.29	5.80
		Radiant		2.25	3.32	2.90	5.59	5.48	3.65	5.23
		Operative		2.60	3.65	3.24	5.89	5.75	3.97	5.51
	Summer (July 1-15)	Air	22.7	27.1	27.3	27.1	27.2	27.0	27.0	27.1
		Radiant		26.8	26.9	26.8	26.9	26.7	26.7	26.8
		Operative		27.0	27.1	27.0	27.0	26.9	26.8	27.0

Comparative energy results

The chamber study also supported comparative energy analysis of the single zone building in active mode. Figure 120 and Figure 121 show the monthly and total heating and cooling loads for the chamber, relative to each assembly in the six locations. In five climates, the heating loads are shown to be more dominant than cooling loads, and the relative impacts of the seven wall constructions are critical. Only in Tucson, with its very hot summers, are the cooling loads higher than the heating loads. This result corresponds well with measured residential heating and cooling loads for US households for each climate type (US EIA, 2018).

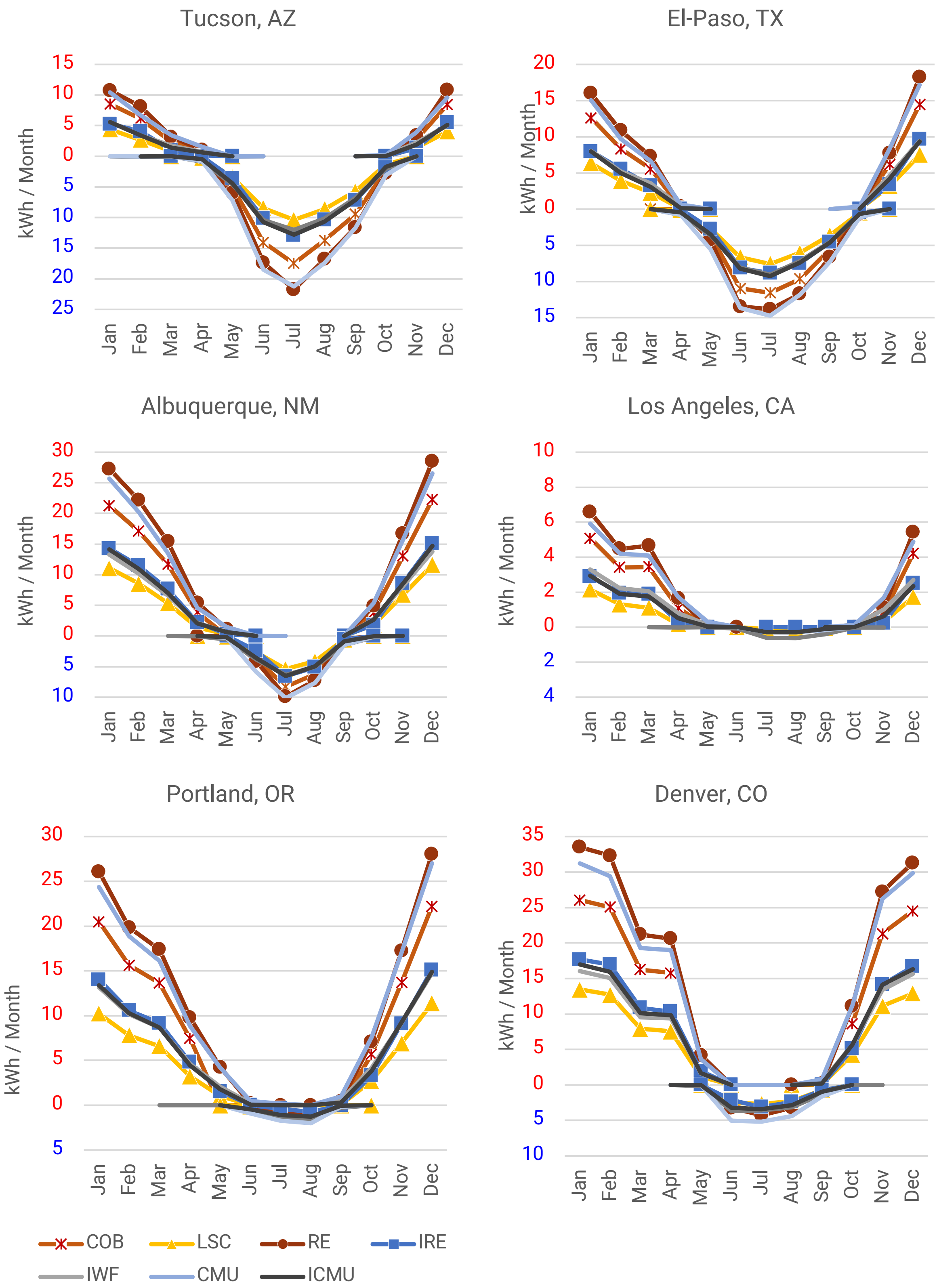


Figure 120: Chamber heating and cooling per month, for each wall assembly in each location

The following charts reveal that insulation is critical for lowering annual energy loads in all climates except Mediterranean climate represented by Los Angeles, CA (first set of three bars are uninsulated assemblies of concrete masonry, rammed earth and cob). Among the insulated choices, light straw clay outperforms all other choices by 18-54%, 19-55%, and 26-61% in Tucson, AZ, El Paso, TX, and Portland, OR, respectively, followed by the insulated rammed earth that outperforms the conventional choices by 4-45%. However, some hybrid solutions of LSC and IRE might offer even better performance as previously mentioned.

Figure 121: Chamber annual heating and cooling loads for each wall assembly in each location

Table 76 details the results of the chamber in its active state, with heating and cooling systems on. The annual mean load results for the chamber show that the light straw clay outperforms the other assemblies in the majority of instances. Insulated rammed earth is shown to result in the least heating loads for Portland's winter and cooling loads for Denver's summer. It is only in the mildest conditions that the complete suite of earthen assemblies performs best. This is evident for Los Angeles summer cooling loads, although due to its mild climate, the overall loads for this location are lower and less significant compared to other locations.

Table 76: Mean annual heating and cooling loads in kWh/m^2 floor/year, U-value is given in W/m·K, R-value is given in °F·ft^2·hr/Btu, **c** represents internal heat capacity in kJ/m^{2}K, green signifies best performance and red signifies poorest performance)

	RE U-1.24 R-4.60 c=254	IRE U-0.448 R-12.7 c=254	COB U-0.851 R-6.70 c=151	LSC U-0.256 R-22.2 c=65.2	IWF U-0.386 R-14.7 c=11.4	CMU U-1.13 R-5 c=11.7	ICMU U-0.410 R-13.85 c=8.53
Heating							
AZ	2.66	1.24	2.07	0.98	1.36	2.57	1.30
TX	4.32	2.14	3.38	1.66	2.25	4.14	2.12
NM	8.64	4.38	6.65	3.34	4.11	8.07	4.32
CA	1.71	0.701	1.29	0.484	0.886	1.64	0.721
OR	7.06	3.57	9.29	4.84	4.83	9.00	4.77
CO	13.0	6.69	9.86	5.08	6.19	12.2	6.49
Cooling							
AZ	5.46	3.29	4.44	2.72	3.35	5.71	3.43
TX	3.62	2.31	3.01	1.94	2.44	3.92	2.44
NM	1.56	1.05	1.34	0.93	1.26	1.83	1.17
CA	0	0.00107	0	0.0164	0.126	0.0534	0.0484
OR	0.114	0.119	0.118	0.0807	0.306	0.340	0.206
CO	0.84	0.599	0.757	0.581	0.843	1.16	0.750
Annual (heating + cooling)							
AZ	8.12	4.52	6.51	3.70	4.71	8.28	4.73
TX	7.94	4.44	6.39	3.61	4.69	8.06	4.56
NM	10.2	5.43	7.99	4.27	5.36	9.91	5.49
CA	1.71	0.700	1.29	0.500	1.01	1.69	0.771
OR	9.43	4.95	7.17	3.65	5.14	9.31	4.98
CO	13.8	7.29	10.6	5.66	7.04	13.4	7.24

Combining heating and cooling loads,

Table 77 shows that insulated mass (both earthen and conventional) reduce energy loads 3%-32%, as compared to insulation only (the insulated wood frame). For all climates, light straw clay is shown to have the lowest yearly loads, saving 21-35% over ICMU, and 19-50% over IWF. In addition, the insulated mass wall alternatives (light straw clay and insulated rammed earth) reduce 8-40% energy loads over conventional insulated wood frame, and 10-22% over conventional insulated CMU. Lastly, the uninsulated earthen assemblies (cob and rammed earth) reduce 9-12% energy loads over the uninsulated CMU.

Table 77: Mean annual heating and cooling loads in kWh/year (Green signifies best performance and red signifies poorest performance)

	Mean values					Energy Reduction			
Location	Insulated mass mean (LSC, IRE, ICMU)	Insulated earthen mean (LSC, IRE)	Uninsulated mass (RE, COB, CMU)	Uninsulated earthen mass (COB, RE)	IWF	Insulated earthen vs IWF	Insulated earthen vs CMU	Insulated earthen vs ICMU	Uninsulated earth vs CMU
AZ	60.4	57.5	107	102	4.71	13%	50%	13%	12%
TX	58.8	56.3	104	100	4.69	14%	50%	12%	11%
NM	70.9	67.9	131	128	5.36	10%	51%	12%	8%
CA	9.22	8.41	21.9	21.1	1.01	40%	65%	22%	11%
OR	63.4	60.2	121	116	5.14	16%	54%	14%	11%
CO	94.2	90.7	176	171	7.04	8%	51%	10%	9%

5.4 Step 2: environmental impacts assessment

The main goal of Step 2 was to provide a comparative analysis of the heating and cooling loads and their subsequent environmental impacts in terms of energy demand and air-borne emissions. The virtual chamber from Step 1 is used for this step, and then expanded to a full residential construction Section 5.5.

A full year heat balance was simulated for the chamber walls in each climate. Figure 122 illustrates the heat gains and losses of the insulated wood frame wall and other contributing building and occupancy components in Tucson AZ.

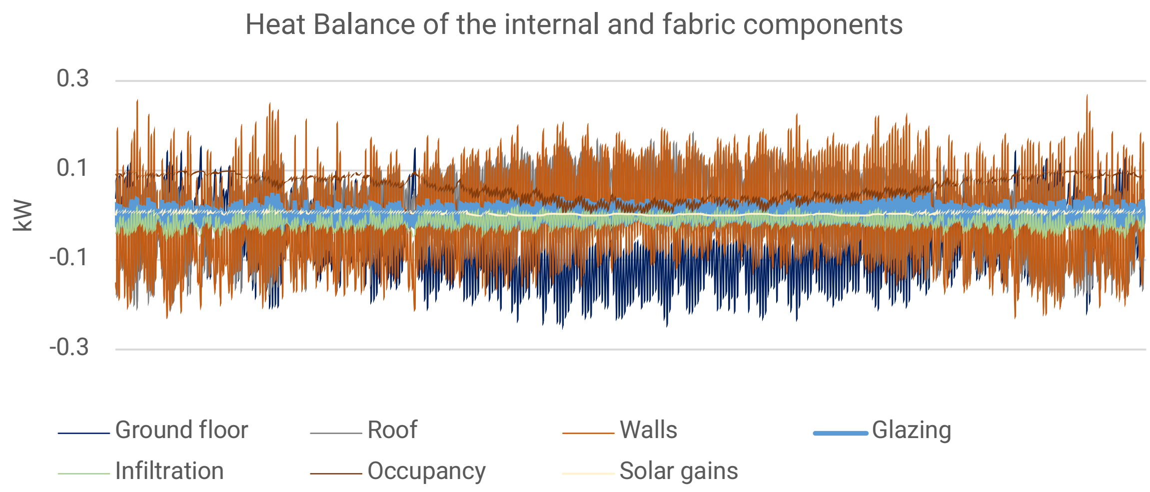


Figure 122: Breakdown of the internal and fabric heat gains and losses for rammed earth for Tucson, AZ

The heat gains and losses from the different wall assemblies in each climate are detailed in Table 78, showing that the walls contribute to gains and losses in colder climates such as in Portland and Denver more than in warmer climates.

Table 78: Heat gains and losses from walls, % from total

	COB	LSC	RE	IRE	IWF	CMU	ICMU
Tucson, AZ	0.455	0.207	0.505	0.301	0.296	0.526	0.300
El Paso, TX	0.447	0.204	0.486	0.273	0.275	0.502	0.293
Albuquerque, NM	0.514	0.246	0.646	0.305	0.289	0.513	0.316
Los Angeles, CA	0.306	0.155	0.286	0.174	0.142	0.255	0.136
Portland, OR	0.514	0.262	0.551	0.326	0.281	0.488	0.307
Denver, CO	0.564	0.289	0.617	0.393	0.364	0.590	0.375

5.4.1 Converting heating and cooling loads to environmental impacts

The energy loads for each chamber were used to estimate the operational environmental impacts from a life cycle perspective. The contribution of the walls to the overall heat gains and losses, shown in Table 78, was then used in order to isolate the impacts of the walls. Thus, all the results calculated in the analyses were scaled by the wall contribution to the overall gains and losses to arrive at the portion of heating and cooling loads that are attributable to the wall construction.

The overall heating and cooling loads that are attributable to the wall construction supports the calculation of the heating and cooling loads to arrive at the total *site* and *source* heating and cooling energy use.

Site energy consumption results

Figure 123 and Figure 124 illustrate the transfer from annual heating and cooling loads to annual energy use, using the coefficients described in the previous section. The site energy for 1 m² floor was obtained by dividing the overall site energy by the chamber floor area. Similarly, the site energy for 1 m² wall was obtained by dividing the total site energy by the relative gains and losses share of the walls (Table 78) and the chamber wall area. Similar to the chamber, the results for 1 m² floor and wall show that the insulated mass assemblies perform better than the uninsulated mass or the insulation alone.

Additionally, an average Annual Fuel Utilization Efficiency (AFUE) of 80% was used for the gas furnace and Energy Efficiency Ratio (EER) of 9.5 for the cooling system, for a Coefficient of Performance (CoP) of 2.78, as recommended by the Department of Energy (2018).

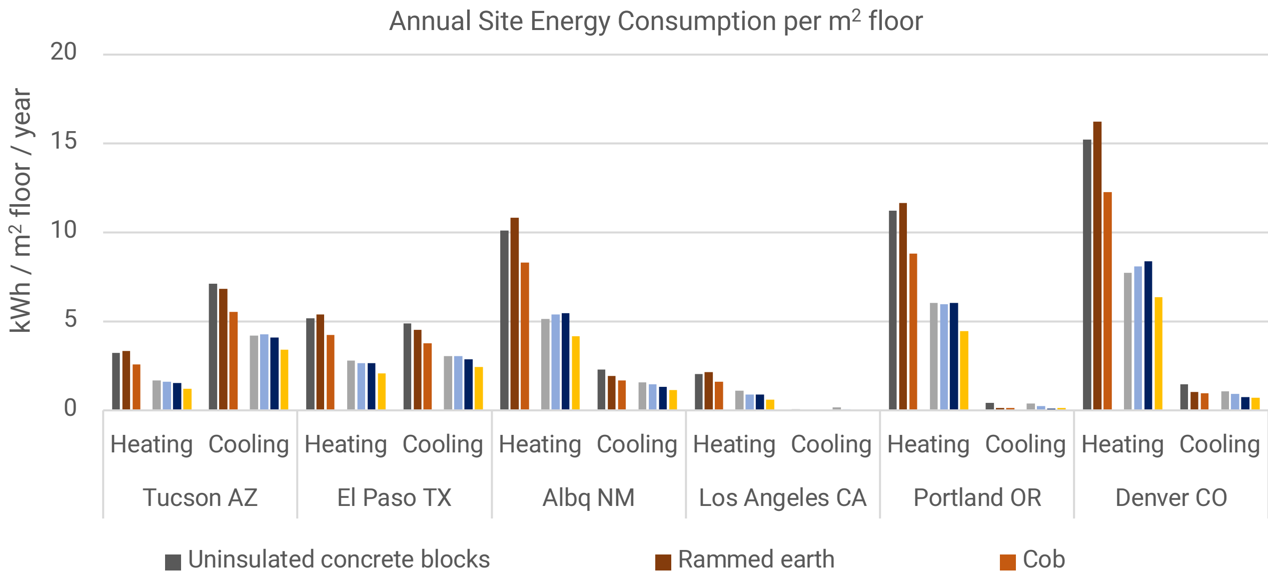


Figure 123: Site heating and cooling loads for each 1 m² wall assembly in each location, normalized according to the wall heat balance

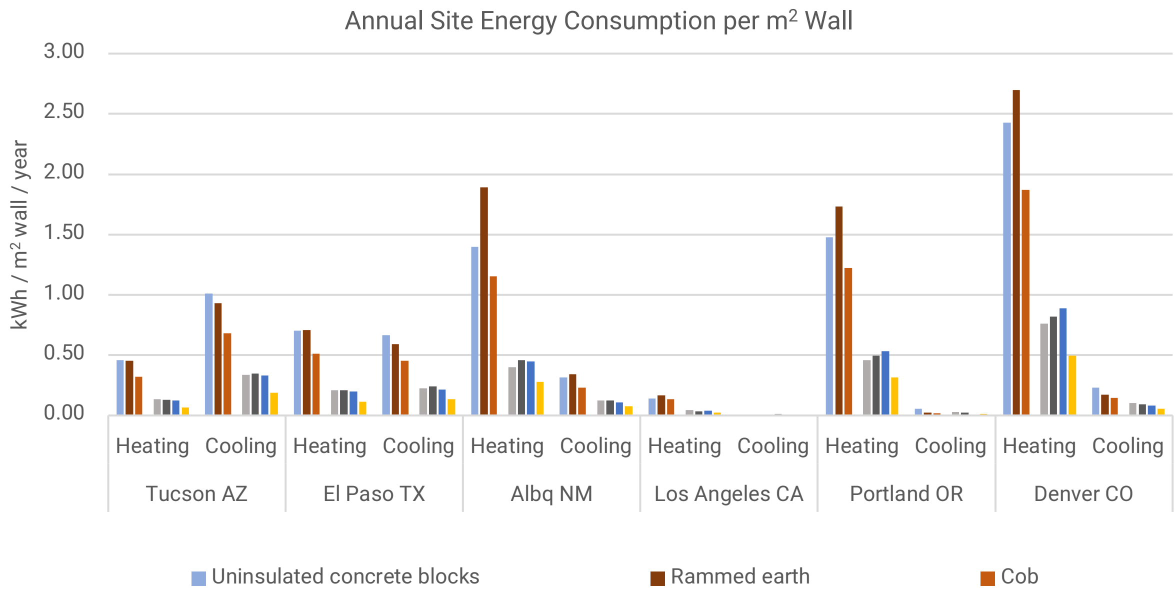


Figure 124: Site heating and cooling loads for each 1 m² wall assembly in each location, normalized according to the wall heat balance

From *site* to *source* energy

Site energy can be delivered to a building using primary and/or secondary energy. Primary energy is the raw fuel that is burned to create heat and electricity. Secondary energy is created from the raw fuel, such as electricity purchased from the grid. As a result, the *site* heating and cooling energy use are not directly comparable because the heating energy represents primary energy (natural gas) whereas the cooling energy represents secondary energy (electricity).

Site energy however does not reflect the energy and environmental cost of generating and delivering the fuel or electricity to the residential unit, a process that has significant energy waste and environmental consequence. EPA has shifted the Energy Star designation to *Source Energy* that includes the primary energy and transmission costs (EPA, 2019) by using average site to source ratios. The site-to-source energy conversion in this section is made using the environmental Life Cycle Inventories (LCI) factors rather than the EPA site to source ratios in order to generate impact results that account for the inventory fuels and emissions.

Inventory fuels and emissions were selected from the US-LCI database according to their relevance to the US Southwest geographical context. The Western Electricity Coordinating Council (WECC) process was used for electricity sources and substances outputs. For natural gas, a US-LCI system process that includes a combination of trucks, diesel powered rail, and pipeline transport was used. Figure 125 depicts the difference between electricity and natural gas production inventories, normalized by the greater value, showing that the inventory fuels and emissions for electricity are much greater for electricity. For instance, 8.91×10^{-4} kg Methane will be emitted during the process of delivering 1 kWh of electricity at grid as opposed to 1.36×10^{-3} for delivering 1 kWh natural gas. In other words, 1 kWh natural gas will emit 0.65 the amount of Methane over 1 kWh of electricity at grid.

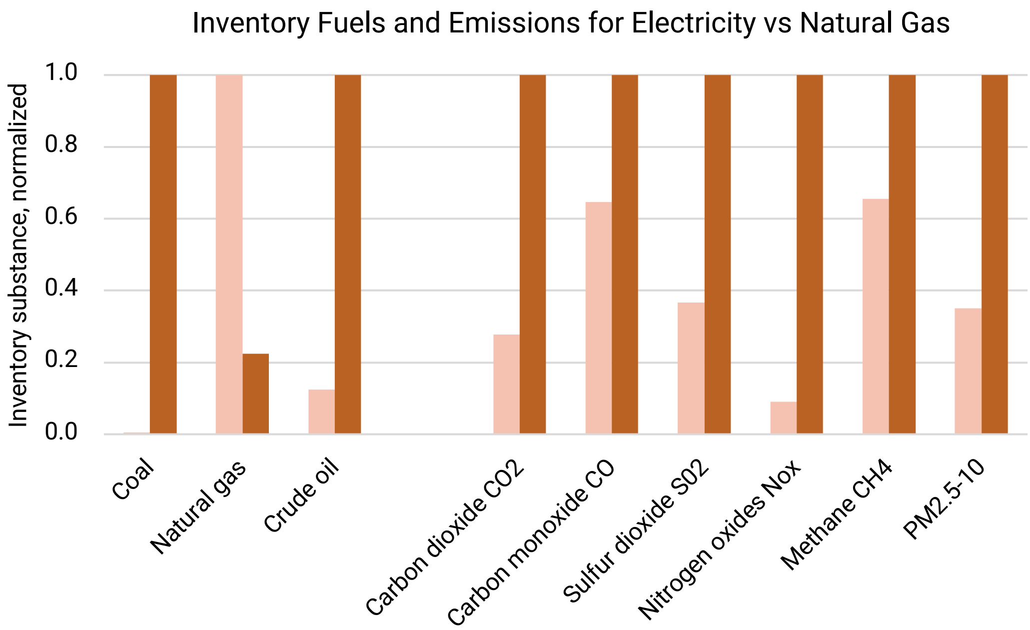


Figure 125: Inventory fuels and emissions of 1 kWh natural gas vs 1 kWh electricity at grid

The site-to-source conversion for energy use is shown in Table 79, resulting in a mean 1:3 site-to-source ratio, which correspond with the ratios provided by (EPA, 2019).

Table 79: Mean annual *site* and *source* energy use in kWh/ m² floor / year

		RE	IRE	COB	LSC	IWF	CMU	ICMU
Tucson AZ	Site	10.2	5.65	8.14	4.62	5.88	10.3	5.91
	Source	25.9	14.5	32.4	17.7	18.6	32.9	18.6
El Paso TX	Site	9.93	5.55	7.99	4.50	5.86	10.1	5.70
	Source	26.7	15.4	33.1	18.9	19.9	33.9	19.5
Albq NM	Site	12.8	6.78	10.0	5.34	6.70	12.4	6.86
	Source	37.3	19.7	48.0	25.1	24.6	46.0	25.3
Los Angeles CA	Site	2.14	0.88	1.62	0.63	1.26	2.12	0.97
	Source	6.33	2.43	8.38	3.43	4.77	8.21	3.72
Portland OR	Site	11.8	6.14	8.96	4.61	6.42	11.6	6.22
	Source	34.9	17.9	46.0	23.9	24.7	45.1	24.1
Denver CO	Site	17.3	9.12	13.2	7.08	8.80	16.7	9.05
	Source	50.8	26.9	66.4	34.9	33.3	63.8	34.4

Comparative environmental life cycle impacts assessment

The analysis in the subsequent sections account for a 1 m² wall (rather than 1 m² floor), corresponding with the LCA functional unit, as defined in Chapter 4. The environmental impact assessment was conducted using TRACI impact factors of global climate change, air acidification, and human health particulate pollution, as well as CED for energy demand (Bare, 2012; Rolf Frischknecht et al., 2015), as described in Section 4.2 for the embodied LCA. These life cycle values per year were then multiplied by 50 in order to model the life cycle impacts of the structure's anticipated life span.

Figure 126 to Figure 129 show the environmental Life Cycle Impact Assessment (LCIA) results using the heating and cooling energy use as the Life Cycle Inventory (LCI). Whereas the load-to-energy-use conversion reduced the values for cooling, the life cycle analysis, which accounts for source values, increased the impacts of cooling. Even more so, the global climate change and air acidification impacts are shown to be increased for the cooling requirements (which use electrical systems), due to the significant use of fossil fuels and emissions of Greenhouse Gasses (GHG) as part of the production of electricity.

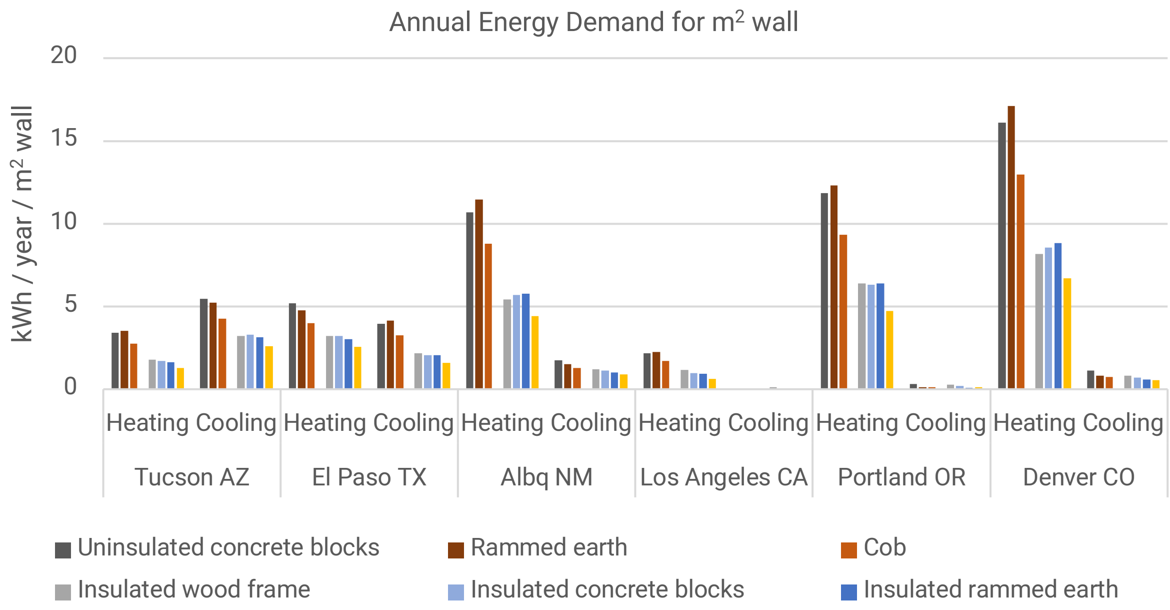


Figure 126: Annual source heating and cooling energy demand impacts for each assembly in each location

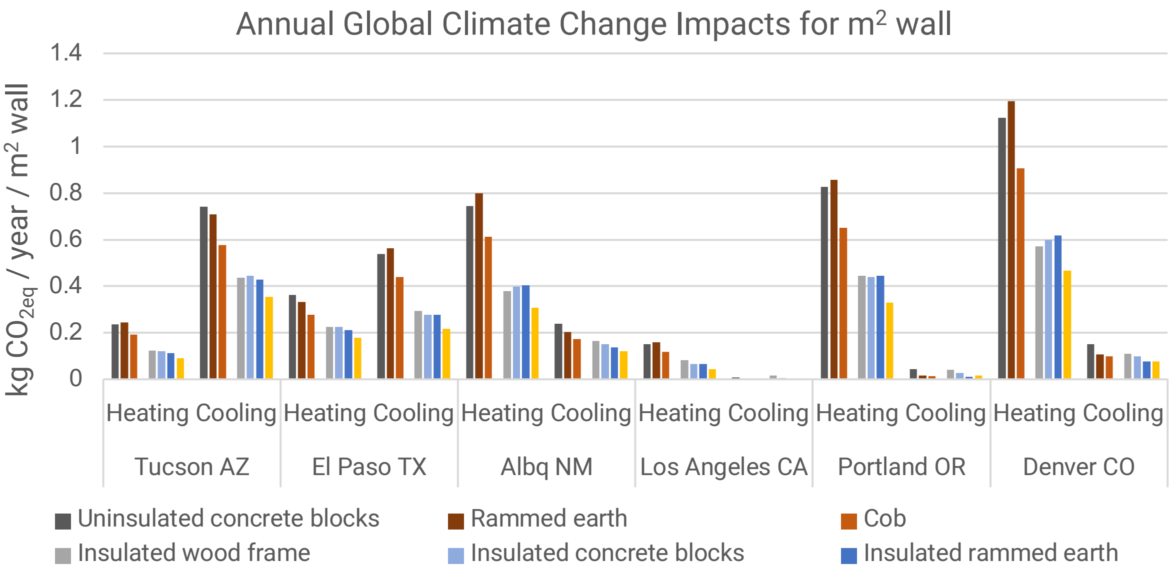


Figure 127: Annual global climate change impacts for each assembly in each location

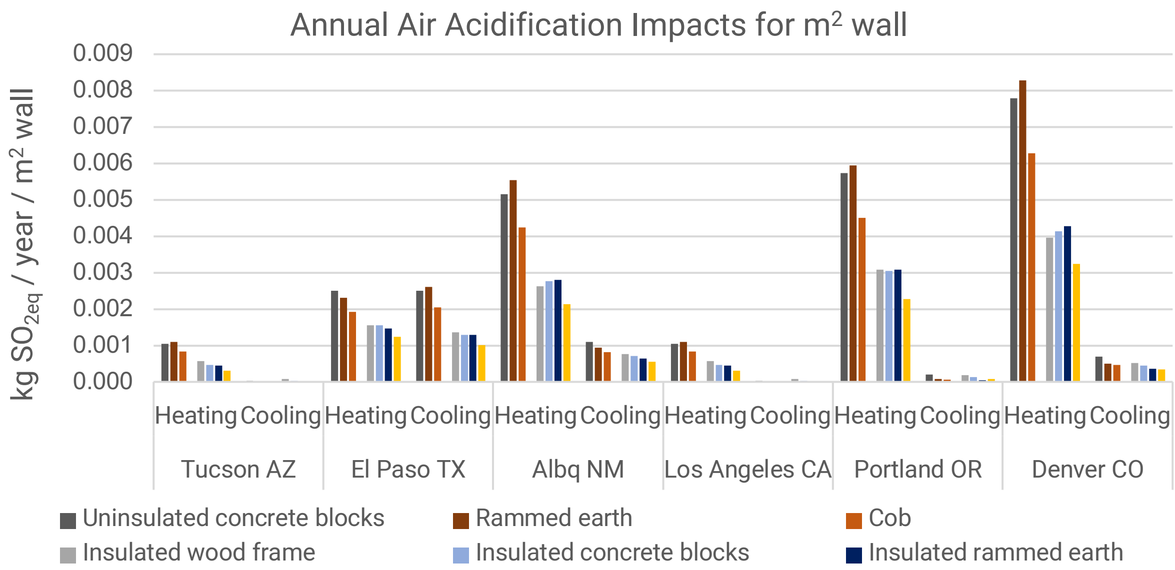


Figure 128: Annual air acidification impacts for each assembly in each location

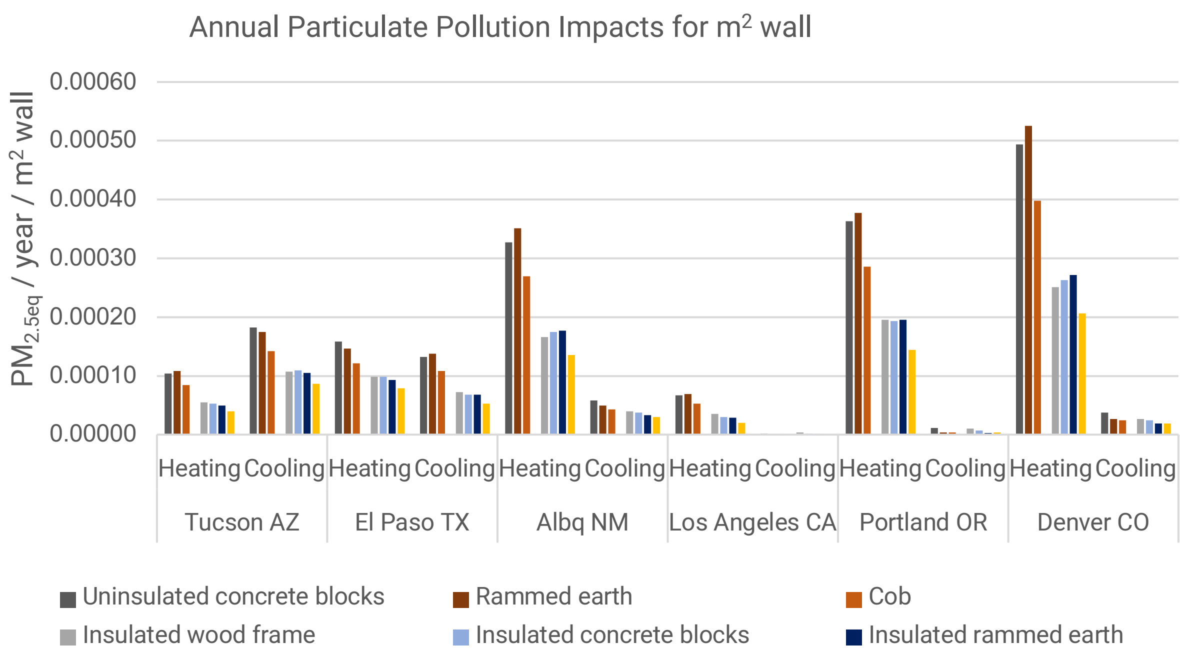


Figure 129: Annual Human Health (HH) Air Particulate impacts for each assembly in each location

5.4.2 Combining embodied and operational life cycle impacts analysis

Ongoing investments for Maintenance

The energy and environmental costs of maintaining homes of different construction materials must also be factored into the operational energy and environmental footprint calculations. Maintenance requirements for different wall assemblies include many uncertainties because they are highly dependent on various aspects such as the design details, original construction quality, quality of the materials and products, climate and weathering, as well as occupant's behavior. In addition, the significance of the maintenance impacts is highly dependent on the life cycle assessment

For earthen assemblies, maintenance requirements may be substantially reduced or avoided altogether depending upon design features that reduce erosion, such as wide roof overhang that keeps rain off the walls (Walker et al., 2005). Similarly, appropriate materials selection may also avoid the need for frequent maintenance. In this dissertation, earthen wall constructions were designed to provide a fully natural alternative with no added cement for stabilization. While existing studies reveal maintenance reductions for stabilized earth (Bui et al., 2009), increased maintenance may be required for unstabilized earthen walls in comparison to conventional assemblies.

Due to lack of maintenance records regarding various wall assemblies and the likelihood that the significance of the impacts of maintenance would be relatively low (Monteiro and Freire, 2012), the maintenance impacts in this dissertation are limited to exterior finish replacement. The following aspects were considered:

- The cob and light straw clay are assumed to be re-plastered every 10 years.
- The rammed earth assembly is assumed to require repairs using the original soil mix in the sum of a 25 mm (1 inch) plaster coat, every 10 years.
- The stucco rendering of the conventional assemblies was assumed to be renewed every 20 years.

Over a 50-year operational life, the environmental impacts of these maintenance tasks would still support earthen construction, as shown in Table 80 for two render types.

Table 80: Environmental impacts for the incroporated external rendering materials

		Energy Demand [kWh_{eq}]	Global Warming [kg CO_{2eq}]	Acidification Air [kg SO_{2eq}]	HH Particulate Air [$PM_{2.5eq}$]
Clay Plaster	Production	2.47	0.727	0.000314	0.000477
	Transportation	0.794	0.616	0.0000954	0.0000364
	Total	**3.26**	**1.34**	**0.000409**	**0.000513**
Portland-Cement Stucco	Materials Extraction	0.135	0.152	0.0000497	0.00261
	Materials Transportation	0.0506	0.0270	0.0000747	0.00000457
	Processing	4.36	5.51	0.00200	0.00258
	Transportation	0.243	0.272	0.0000890	0.00000558
	Total	**4.79**	**5.96**	**0.00221**	**0.00520**

These maintenance related energy and environmental costs were added to the energy use in 50 years of residency and their environmental costs to create the total operational impacts for each of the earthen and conventional assemblies, as show in Table 81.

Table 81: The environmental impacts for the wall assemblies for a 50-year lifecycle.

	Earthen Assemblies (COB, LSC, IRE, RE)	Conventional Assemblies (IWF, ICMU, CMU)
Energy Demand [MJeq]	58.7	43.1
Global Warming [kg CO2eq]	6.72	14.9
Acidification Air [kg SO2eq]	0.00205	0.00553
HH Particulate Air [PM10eq]	0.00257	0.0130

Comparing and combining embodied and operational impacts

The operational life cycle impacts for space heating, cooling, and maintenance for a 50-year building life summarized in this chapter were compared to the embodied life cycle impacts developed in Section 4.5.

The combined environmental impacts, shown in

Figure 130-

Figure 133, illustrate the environmental urgency of using earthen building materials and methods in mainstream construction in the full range of arid or semi-arid climates. It is also important to note that the energy impacts of the embodied calculations can dominate insulated concrete masonry, and play a significant role in other conventional construction, even with 50 years of operational energy use. For all climates except the mildest, light straw clay is shown to achieve the best performance with the least energy use and environmental impacts. Light straw reduces 40-60% energy demand as opposed to conventional assemblies for the hot desert climates of Tucson, AZ, and El Paso, TX, 36-56% in the semi-arid climate of Albuquerque, NM, 57-75% in the Mediterranean Los Angeles, CA, 41-58% in temperate Portland, OR, and 33-51% in cold Denver, CO.

The insulated rammed earth is shown to reduces 32-52% energy demand as opposed to conventional assemblies for the hot desert climates of Tucson, AZ, 31-54% in El Paso, TX, 24-48% in the semi-arid climate of Albuquerque, NM, 53-74% in the Mediterranean Los Angeles, CA, 27-49% in temperate Portland, OR, and 18-41% in cold Denver, CO.

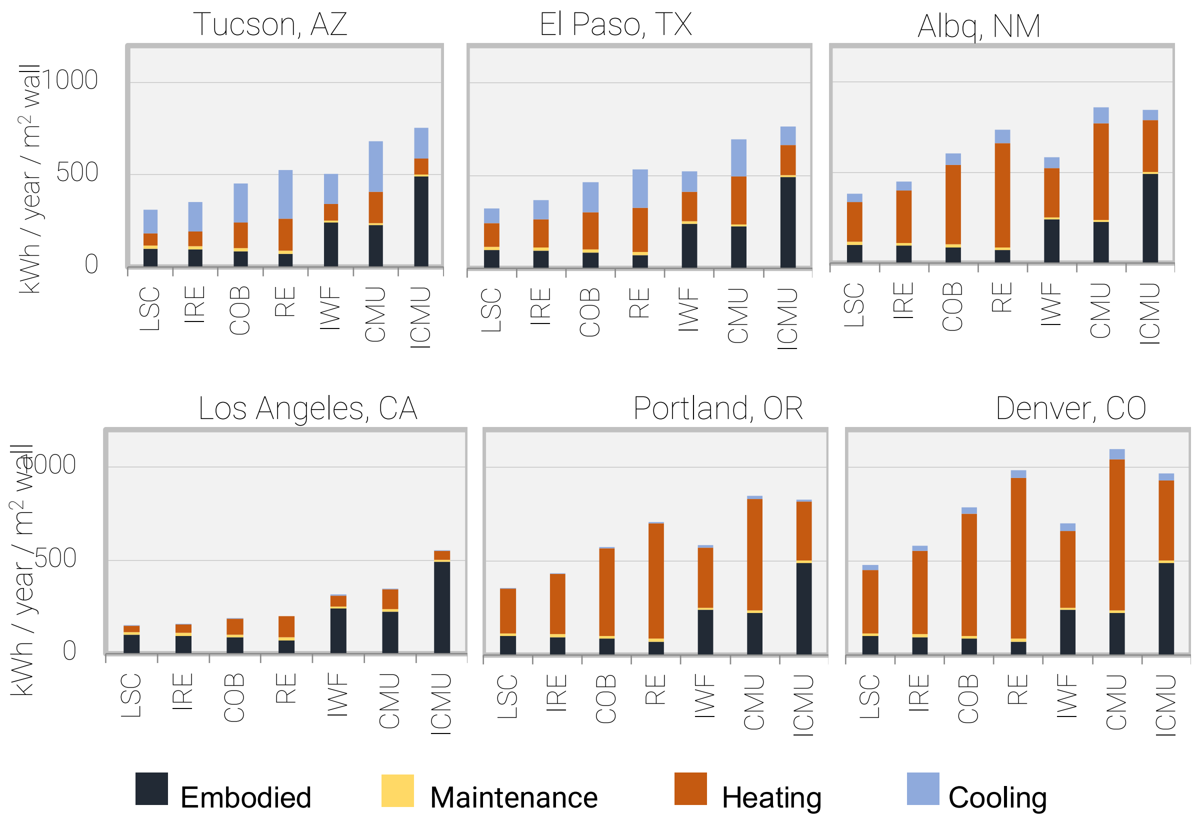


Figure 130: Embodied and operational (heating and cooling) energy demand impacts for each wall alternative in each climate

Earthen assemblies also demonstrate a dramatic reduction in global climate change impacts when accounting for both embodied and operational values. In this case, the environmental impacts of the embodied energy dominate in all conventional construction, even with 50 years of operational energy use.

- The overall **climate change impact reductions** (measured in CO_{2eq}), achieved by implementing earthen assemblies, range between 21-79%, with the highest reductions for Los Angeles, CA and Portland, OR.
- The reductions in **air acidification** impacts (measured in SO_{2eq}), are shown to be the most significant in Tucson, AZ, due to the need for cooling.
- The overall human **health particulate pollution impacts reductions** (measured in $PM_{2.eq}$), achieved by implementing earthen assemblies for earthen assemblies, range between 48-97%.

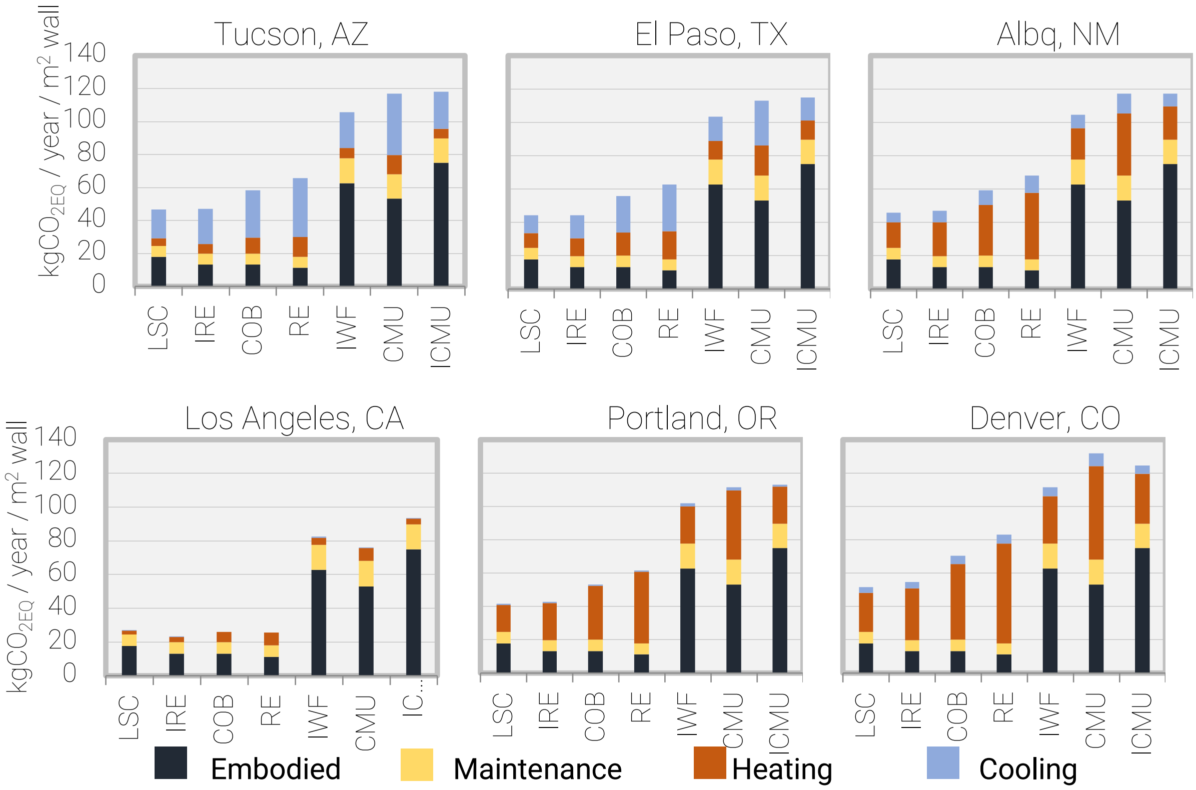


Figure 131: Embodied and operational (heating and cooling) global climate change impacts for each wall alternative in each climate

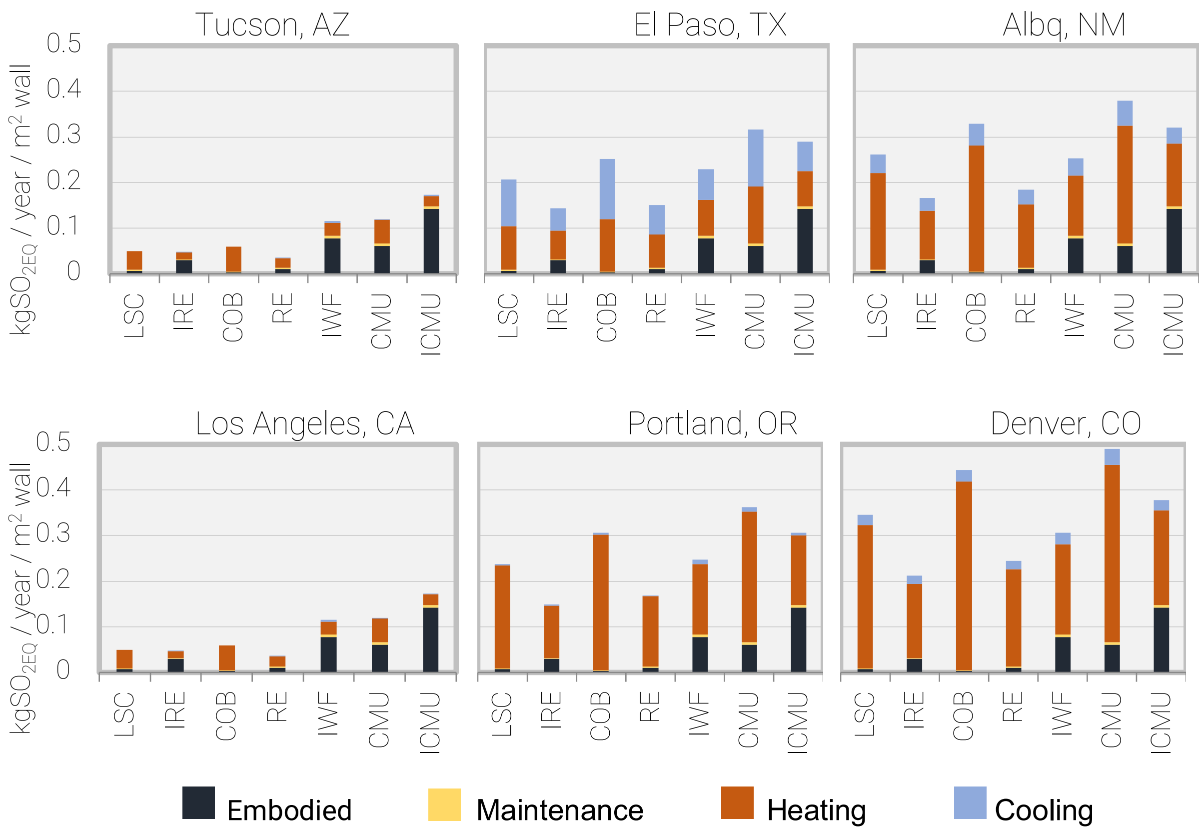


Figure 132: Embodied and operational (heating and cooling) air acidification impacts for each wall alternative in each climate

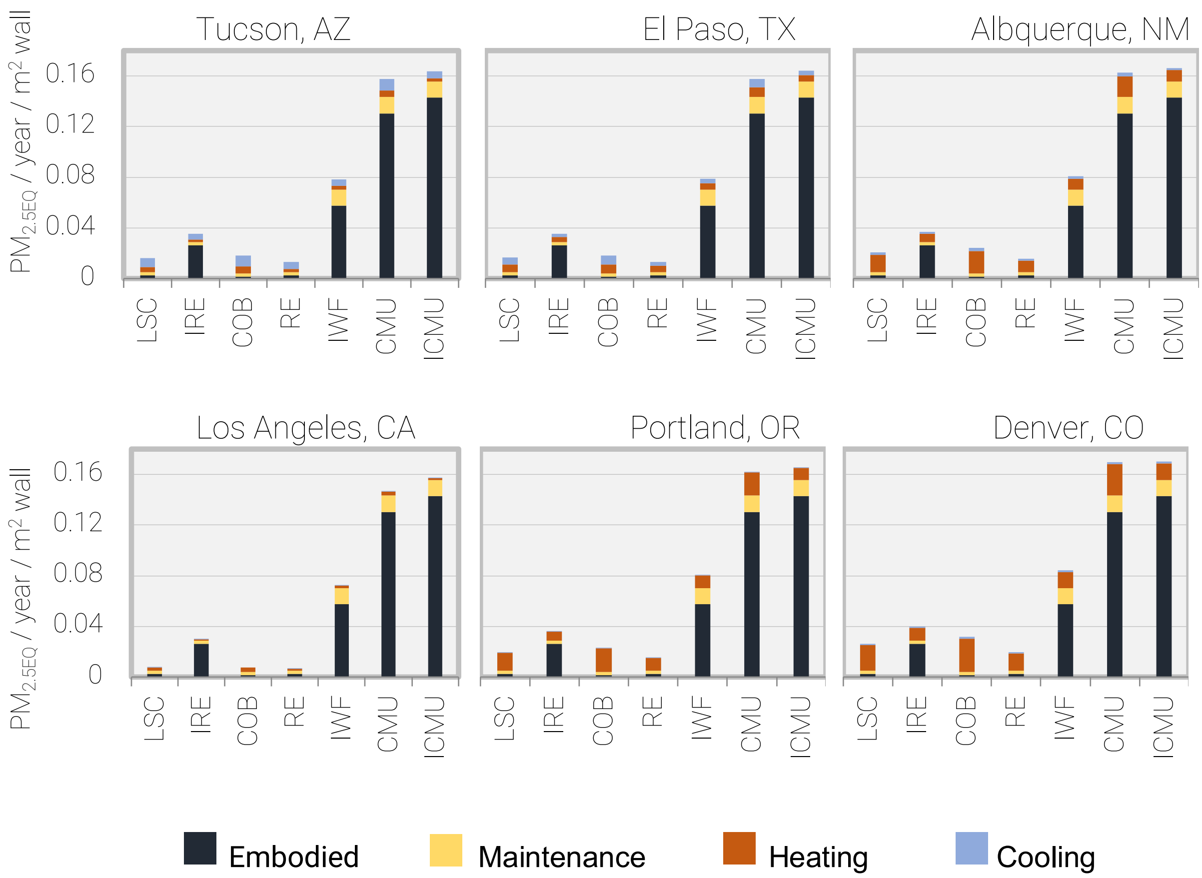


Figure 133: Embodied and operational (heating and cooling) HH air particulate impacts for each wall alternative in each climate

5.5 Implications for a full residential structure configuration

Shifting from a chamber study to a full residential structure configuration is critical to finalize residential energy savings by climate and to complete environmental impact assessments given those energy demands and airborne emissions.

While the chamber is too small to be a realistic estimate of a multi room but skin dominated residence, the results of the simulation may be used to provide a solid basis for comparison among the wall assemblies. The comparative results of the virtual chamber are used to expand the conclusions to a full-scale residential structure. In order to validate the expansion of the virtual experimental to a full-scale 230 m^2 (2,500 ft^2) residential structure, an expansion based on a floor area (from 14 m^2 to 230 m^2) was conducted, showing good correspondence with the US EIA (2018) field data, as shown in Figure 125 for insulated wood frame construction.

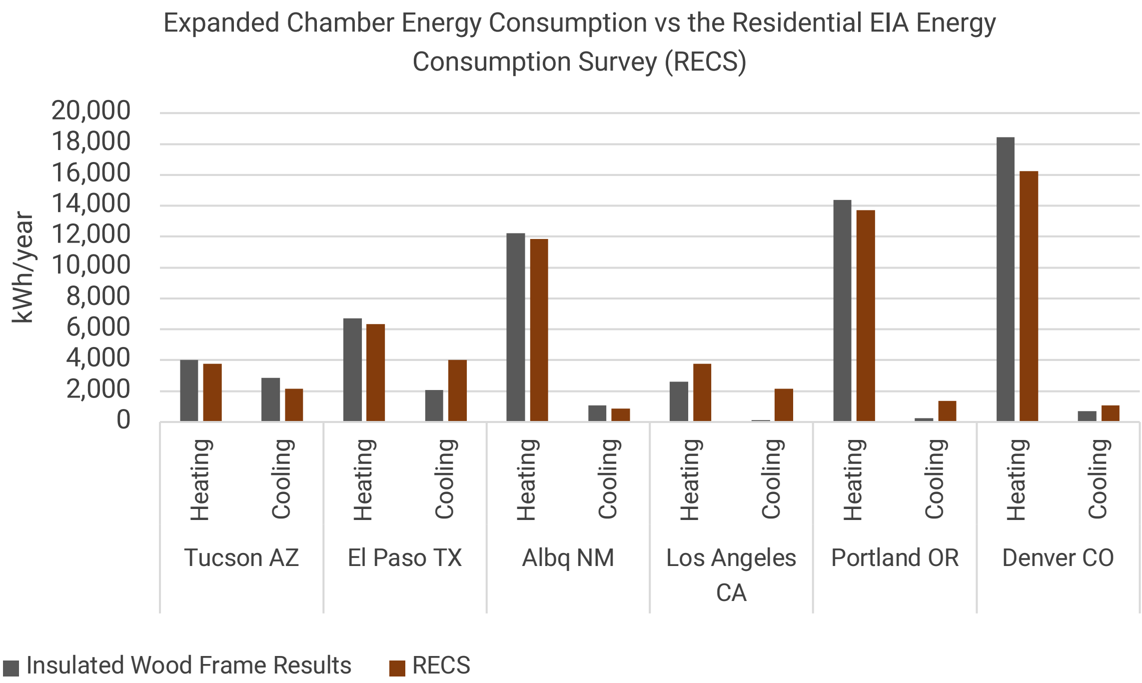


Figure 134: Expanded chamber energy consumption vs RECS

The enclosure impacts reductions for an entire year for a residential structure were calculated based on data from the field, as reported in (US EIA, 2018), which indicate that space heating and cooling consume an annual total of 1,370,000 GWh (4,676 trillion Btu) for the residential sector. Overall, space heating and cooling account for 51% of the total energy consumption per household, as shown in Table 82

Table 82: Annul household site end-use consumption in the US according to end-use (US EIA, 2018)

	Total	Space heating	Space cooling	Water heating	Refrigerators	Other
All homes (GWh)	2,671,050	1,156,165	214,235	511,409	88,801	700,440
All homes (Trillion Btu)	9,114	3,945	731	1,745	303	2,390

	Total	Space heating	Space cooling	Water heating	Refrigerators	Other
Average per household (Million Btu)	77.1	35.3	7.1	14.8	2.6	20.2
Average per household (kWh)	22,596	10,345	2,081	4,337	762	5,920
% from total	100%	43%	8%	19%	3%	26%
% Heating and cooling from total: 51%						

The walls contribution for the heating and cooling loads were analyzed for each wall alternative for each climate, as shown in Table 78. Using the relative contribution of the walls to the structure energy consumption, the reductions obtained from using light straw clay and rammed earth were assessed, as detailed in Table 83.

Table 83: Site energy use in kWh/m² wall/year, according to the relative contribution of each wall alternative for each climate

		IWF	IRE		LSC	
			Site energy use	Reduction from IWF	Site energy use	Reduction from IWF
Tucson AZ	Heating	0.135	0.125	-7%	0.068	-50%
	Cooling	0.335	0.334	-0%	0.190	-43%
El Paso TX	Heating	0.209	0.197	-6%	0.114	-45%
	Cooling	0.226	0.212	-6%	0.134	-41%
Albuquerque, NM	Heating	0.401	0.450	12%	0.278	-31%
	Cooling	0.122	0.108	-12%	0.077	-37%
Los Angeles CA	Heating	0.0423	0.0411	-3%	0.0253	-40%
	Cooling	0.0127	0.000112	-99%	0.00115	-91%
Portland OR	Heating	0.458	0.532	16%	0.316	-31%
	Cooling	0.0290	0.00889	-69%	0.0105	-64%
Denver CO	Heating	0.761	0.888	17%	0.495	-35%
	Cooling	0.104	0.0794	-23%	0.0566	-45%

The possible reductions for light straw clay and insulated rammed earth assemblies were interpreted using the simulated site energy reductions, shown in Table 83, Table 84, and the field data (US EIA, 2018). Table 84 depict the potential reductions that can be achieved in the US total site energy consumption by implementing earthen assemblies. The results show that implementing insulated rammed earth can save up to 890,000 kWh in annual consumption per household when applied in hot desert climate. Implementing light straw clay can reduce up to approximately 780,000 kWh/year in annual consumption per household when applied in arid climates, 1,114,000 kWh/year when applied in Mediterranean climates, 560,000 kWh/year when applied in temperate climates, and 590,000 when applied in continental climates.

Table 84: The potential energy reductions for implementing light straw clay and insulated rammed earth walls, according to the annul household site end-use consumption in the US as obtained from (US EIA, 2018),

	RECS Climate data (US EIA, 2018)	Space Heating (Kwh)	Space Cooling (Kwh)	Total (Kwh)	Energy saving (%)	Energy saving (kWh)	Energy saving (MBtu)
Hot Desert 2B	Mixed-dry / Hot-dry	4,015	4,425	8,440			
LSC		1,991	2,511	4,502	47%	778,096	2655
IRE		3,719	4,412	8,131	4%	63,428	216
Desert 3B	Mixed-dry / Hot-dry	4,015	4,425	8,440			
LSC		2,194	2,618	4,812	43%	716,954	2446
IRE		3,779	4,149	7,929	6%	107,615	367
Semi-Arid 3C	Mixed-dry / Hot-dry	4,015	4,425	8,440			
LSC		2,784	2,781	5,565	34%	568,108	1938
IRE		4,516	3,902	8,418	0%	4,393	15
Mediterranean 4B	Mixed-dry / Hot-dry	4,015	4,425	8,440			
LSC		2,402	401	2,803	67%	1,113,753	3800
IRE		3,903	39	3,942	53%	888,770	3033
Temperate 4C	Marine	6,067	440	6,506			
LSC		4,180	158	4,338	33%	555,652	1896
IRE		7,038	135	7,173	-10%	(170,889)	-583
Continental 5B	Very cold / cold	15,562	879	16,441			
LSC		10,135	480	10,615	35%	590,972	2016
IRE		18,156	673	18,829	-15%	(242,197)	-826

Limitations

While the chamber is too small to be a realistic estimate of a multi-room but skin dominated residence, the following assumptions are made when expanding the results to a full-scale structure:

- The chamber simulation model included one occupant and a resting activity. However, the full residential structure includes four occupants, performing various tasks. It is therefore assumed that the linear expansion accounts for the change in occupancy heat gains, taking into account additional occupants and more heat-generating tasks.
- The interior thermal mass and its buffering effects were assumed to increase linearly. Similarly, increased glazing contribution was assumed to be linear.
- The residential structure has an increased perimeter, which effects infiltration. The contribution of the increased infiltration was assumed to be negligible as opposed to the walls, as shown in Figure 122.
- Furthermore, expanding a chamber into a full-scale structure may impose other inaccuracies for dimensional analyses, as scaling by one parameter requires different scaling for others. For instance, building shape may also affects results. Square or circular shapes have equal exposure to all four cardinal points, whereas rectangular would not.

5.6 Conclusions and discussion

In-depth calculations of the operational thermal performance of four earthen assemblies, compared to three conventional assemblies reveals startling differences in energy and environmental impacts. Seven assemblies were studied with varying insulation and heat capacity capabilities -insulated and uninsulated rammed earth, cob, and light straw clay as well as wood frame and insulated and uninsulated concrete masonry units. The study was conducted for six cities in the US context: Tucson, AZ (hot desert); El Paso, Texas (subtropical desert); Albuquerque, NM (mild semi-arid) Los Angeles, CA (mild Mediterranean, Portland, OR (temperate oceanic), and Denver, CO (continental semi-arid).

Using a virtual experimental chamber in both passive and active states, TMY simulations revealed that rammed earth and cob assemblies reduced temperature fluctuations to less than 1°C (1.8°F) along with a providing 6-10 hrs of valuable time-lag displacing daytime heat until evening when outdoor temperatures have dropped. Conventional assemblies showed significantly more fluctuation and shorter lags. Overall, the light straw clay, with the insulation and moderate internal heat capacity was shown to perform better than other assemblies for multiple climates including hot arid 2B (represented by Tucson, AZ), and temperate 4B (represented by Portland, OR), and continental 5B (represented by Denver, CO). For milder climate conditions, insulated rammed earth, with the highest heat capacity and moderate insulation, performed best. The uninsulated mass assemblies were shown to be preferable only for very mild climate conditions, when the outdoor thermal conditions provide comfortable temperature levels, such as in Los Angeles and Portland summer.

Using the virtual chamber model to calculate annual site and source energy demand, comparative energy and environmental impacts were completed. The results show that while the load-to-energy-use conversion reduced the values for cooling, the life cycle analysis, which accounts for source values, increased the impacts of cooling. Even more so, the global climate change and air acidification impacts are shown to be increased for the cooling requirements (which use electrical systems), due to the significant use of fossil fuels and emissions of Greenhouse Gasses (GHG) as part of the production of electricity.

Combining these operational energy and environmental impacts with the embodied environmental impacts illustrate the environmental urgency of using earthen building materials and methods in mainstream construction in the full range of arid or semi-arid climates. The combined embodied and operational results revealed that the energy impacts of the embodied calculations can dominate insulated concrete masonry, and play a significant role other conventional construction, even with 50 years of operational energy use. For all climates except the mildest, light straw clay is shown to achieve the best performance with the least energy use and environmental impacts, reducing 40-60% energy demand as opposed to conventional assemblies for the hot desert climates, 36-56% in semi-arid climates, 57-75% in Mediterranean climates, 41-58% in temperate climates, and 33-51% in continental climates.

The results also reveal a dramatic reduction in global climate change impacts when accounting for both embodied and operational values. Earthen assemblies were shown to outperform conventional assemblies, reducing the overall **climate change impact reductions** by 21-79%, **air acidification** impacts by 34-80% for 2B,3B, and 3C climates, **health particulate pollution impacts reductions** by 48-97%.

Furthermore, the potential energy savings by climate was assessed using field data, showing that insulated rammed earth can reduce up to 890,000 kWh in annual consumption per household when applied in hot desert climate. Furthermore, Implementing light straw clay can reduce approximately 817,000 kWh/year in annual consumption per household when applied in hot desert climates, 840,000 kWh/year when applied in Mediterranean climates, 191,000 kWh/year when applied in temperate climates, and 512,000 when applied in continental climates.

Recommendations for future research

While this study is limited to the effect of temperature mean range and minimal temperature fluctuations, the indoor thermal performance of each wall system is affected by many parameters that are not included in this dissertation, such as relative humidity levels, diurnal temp. cycles, wind speed and direction, etc. Additionally, the simulation results are dependent on the various assumptions and other factors aside from the wall construction. For example, changes in the roof construction and glazing area will result in changes to the results. Additionally, the model does not consider self-shading by the roof; yet some of these wall systems require this for durability constraints that arise from rain-driven erosion.

Future research should expand this dissertation by analyzing the thermal, as well as the hygrothermal, properties for each wall assembly. Indoor relative humidity buffering should be taken into account in the analysis, as well as the environmental impacts of humidifying and dehumidifying systems. Furthermore, future study should examine loads and impact improvements in terms of enhanced hybrid assemblies and insulation location. Strategies to help reduce heating and cooling loads should be examined, for instance, by reducing how often the heating and cooling system operates or allowing the temperature to drift to a lower (heating mode) or higher (cooling mode) temperatures (also known as setback temperatures). Lastly, future predicted TMY climate data should be explored to investigate future resiliency in the face of climate change.

6 Regulatory Gap: Earthen Building Policy Repair Analysis

6.1 The status of earthen building policies, codes and standards

A limited number of studies examine the status and efficiency of earthen codes and standards in specific regions. These studies mainly focus on codes and standards in Germany (Schroeder, 2016), New-Zealand (Tenorio et al., 2006; Walker & Morris, 1998), and the United Kingdom (S. Goodhew and Griffiths, 2005). One of the few existing studies that focuses on North America, by Swan et al. (2011), reviews the allowable dimensions, connections between building elements, engineering properties, and tests required by main North America earthen codes and standards. Swan et al. suggests that earthen codes and standards in North America are inadequate due to their two-story limitation, as well as their lack of instructions for seismic regions. In addition, the authors emphasize that earthen building codes and standards are not widely accepted by the engineering community. Swan et al. identify critical research needs that have led to the present dissertation: (1) a comprehensive study to characterize earthen structural performance and mechanical properties, including long-term durability; (2) a theoretical study to allow the adoption of earthen building in building codes and standards; and (3) a life-cycle analysis of earthen building materials.

Few studies include a critical review of earthen building policy from a broader, global perspective. Niroumand et al. (2017) investigates the effect of earthen building policy on the development of earthen architecture worldwide. The authors used a survey to assess the value of national earthen building guidelines among architects that are members of the International Council on Monuments and Sites (ICOMOS) in six countries: USA, UK, Australia, Iran, India, and Malaysia. The results of this study demonstrate that while most of the respondents were not aware of their national earthen building norms, they did indicate that earthen building norms are extremely important for their nation. These results might demonstrate that although important, existing earthen building norms are neglected in the surveyed countries. However, these results might also be a consequence of the study surveying only architects rather than a range of building professionals including engineers and contractors. Additionally limitations in the building type with a focus on historical monuments restoration rather than contemporary earthen construction; the national norms described in this work address the latter.

Two studies offer a critical review of earthen building code metrics from a broader, global perspective. King (2006) presented a review of 12 codes and standards from around the world, quantifying materials, prescriptive requirements, and engineering design requirements, concluding that the documents exhibit a “striking range of styles, detail, clarity, and intent”. One of the main findings of King is the disagreement among the different earthen building regulatory documents in terms of cement stabilization and reinforcement techniques. In another study, 23 earthen building codes and standards from 19 countries were analyzed according to three aspects: soil classification, compressive strength, and wall thickness requirements (Schroeder 2012). Schroeder concludes that international normative terminology for earthen building is still lacking and should be developed as an essential prerequisite for the development of earthen building normative codes and standards and for the establishment of earthen building in the contemporary building industry.

These studies indicate a critical need for the investigation into the cross-regional solutions and improvements that could be obtained by comparing existing codes and standards from around the world, as well as effectiveness in sponsoring an increase in modern earthen architecture. To address this need, this section investigates the strengths and weaknesses in existing earthen building codes and standards, as well as develop recommendations for a more comprehensive and uniform international building code.

6.2 Toward a comprehensive distillation of earthen building codes and standards from around the world

A large number of earthen building codes, standards and guidelines have been developed around the world over the last few decades. This section reviews a selection of the leading earthen codes and standards, as well as maps the different earthen building codes and standards climatically, with an emphasis on dry warm and dry cold climates. Table 85 presents a review of the dominant codes and standards from around the world, as well as their main features.

Table 85: Overview of earthen building codes and standards from around the world (King, 2006; Schroeder, 2012)

#	Abbreviation	Country	Name	Year	Type	Description	Source	Language	Compliance Type
1	ASTM	USA	American Society of Testing and Materials E2392-05, Standard Guide for Design of Earthen Wall Building Systems.	2005	Standard	A 6-page general document describing different earthen building systems. The document primarily aims to re-introduce these materials to the modern building practice and provides context of their sustainability gains and energy efficiency. Relates to adobe, stabilized adobe, compressed block, rammed earth, and cob.	(ASTM E2392-M10, 2010)	English	Non-mandatory
2	AZ	USA	Pima, Arizona Uniform Administrative Code Amendment for Earthen Material and Straw Bale Structures	1997	Code	Prescriptive code for earthen structures in low seismic context area. Contains some general parts and some very specific parts. Relates to adobe, stabilized earth, compressed blocks, rammed earth, and puddled earth. Contains 15 pages.	(Pima County Development Services, 2013)	English	Mandatory
4	CA	USA	California Historical Building Code	2001	Code	This code contains prescriptive guidelines and retrofit design criteria for adobe, stone masonry, and other historic structures, for a highly seismic risk context. Relates to adobe only. Contains 3 pages.	(CBSB, 2016)	English	Mandatory
5	IBC	USA	International Building Code	2000	Code	Prescriptive guidelines and minimum strengths for adobe structures. Relates to adobe, and stabilized adobe. Contains 3 pages.	(ICC, 2015)	English	Mandatory
6	NM	USA	New Mexico Earthen Building Materials Code	2004	Code	Prescriptive guidelines for adobe, compressed earth block, and rammed earth, for moderate high seismic risk context. Contains 30 pages.	(New Mexico Regulation & Licensing Department and NMAC, 2015)	English	Mandatory
7	APP R	USA	ICC Appendix R: Light Straw Clay Construction	2015	Code	Prescriptive guidelines for light straw clay, including structural, thermal, and construction instructions	(IRC, 2015a)	English	Mandatory
8	AUST	Australia	The Australian Earth Building Handbook	2002	Standard	This is a highly detailed and well-illustrated 152-page standard. Relates to adobe, stabilized adobe, compressed block, rammed earth, and cob.	(P. Walker and Standards Australia, 2001)	English	Non-mandatory
9	ABNT	Brazil		1984-1996		standards for the production of cement-stabilized earth blocks and rammed earth	(NBR 8491-92, 10832-36, 12023-25, 13553-55: Standards for Earthen Building, 1996)	Portuguese	NA
10	China	China			Standard	Simple guidelines for lime-stabilized earth and unstabilized earth blocks. Contains 3 pages.		Chinese	NA
11	ICONTEC	Colombia	Colombian Institute of Technical Standards and Certification ICONTEC NTC 5324: Stabilized Cement Earthen Blocks for walls and divisions. Definitions, Specification, and Testing Methods.	2004		standard for the production of cement-stabilized earth blocks	(ICONTEC, 2004)	Spanish	Mandatory
12	ACU	Ecuador			Standard	Detailed standard in Spanish, for both cultural and common building practices of earthen buildings, for high seismic risk context.		Spanish	NA

#	Abbreviation	Country	Name	Year	Type	Description	Source	Language	Compliance Type
13	AFNOR: XP P13-901	France	AFNOR: XP P13-901: Compressed Earth Blocks for Walls and Partitions: Definitions—Specifications—Test Methods—Delivery Acceptance Conditions.	2001	Standard	Regulations for building with earth blocks have been introduced by the building supervisory authorities	(AFNOR, 2001)	French	Mandatory
14	DIN	Germany	DIN 18945: Earth Blocks, DIN 18946 Earth Masonry mortar, DIN 18947 Earth Plasters	1970's	Standard		(NABau, 2013)	German	Mandatory
15	IND	India	Indian Standard, Improving Earthquake Resistance of Earthen Buildings - Guidelines	1993	Standard	Prescriptive guidelines for adobe, cob, rammed earth, and Assam (wattle and daub), for low to high seismic risk context. Accounts for unstabilized earthen materials. Contains 12 pages.	(Improving Earthquake Resistance of Earthen Buildings – Guidelines, 1993; Bureau of Indian Standards, 1998; Standards, 2013)	English	Mostly non-mandatory, few sections include mandatory language
16	KEBS	Kenya	Kenya Bureau of Standards KEBS: Specifications for Stabilized Soil Blocks. KS02- 1070:1993	1999	Standard	Standard for the production of cement-stabilized earth blocks. Contains 19 pages.	(KEBS (Kenya Bureau of Standards), 1999)	English	NA
17	PCH	Kyrgyzstan	PCH-2-87: Building of low-storied houses with stabilized rammed earth	1988	Norm		(State Building Committee of the Republic of Kyrgyzstan, 1988)	Russian	NA
18	MOR	Morocco	Royaume du Maroc: Regulation of para-seismic of earthen constructions.	2012	Technical Regulation	A technical regulation that accounts for earthquake-resistant building with earth. Three ministries were involved in the development of the text. In addition to binding guidelines for building material properties and design, the document also contains recommendations and comments.	(Royaume du Maroc, 2001)	French	Non-mandatory
19	NZS	New Zealand	NZS97: Engineering Design of Earth Buildings, NZS98: Materials and Workmanship for Earth Building, NZS99: Earth Buildings not Requiring Specific Design	1998	Standard	NZS97: Methodology for engineering design principles of earthen structures, based on testing of earthen buildings and on historical building practice. NZS98: Highly detailed and well-illustrated guidelines for material selection, stabilization, testing and quality control (in both field and laboratory). Contains 81 pages NZS99: Highly detailed and well-illustrated prescriptive guidelines for adobe, stabilized adobe, compressed earth block, rammed earth, cob, and poured earth, for moderate to high seismic risk context. Contains 121 pages	(NZS 4299: Earth Buildings Not Requiring Specific Design, 1998; NZS 4297: Engineering Design of Earth Buildings, 1998; NZS 4298: Materials and Workmanship For Earth	English	Mandatory

#	Abbreviation	Country	Name	Year	Type	Description	Source	Language	Compliance Type
							Buildings, 1998)		
20	NEP	Nepal	Nepal National Building Code, Mandatory Rules of Thumb, Load Bearing Masonry	1995	Code	Prescriptive guidelines for stone masonry with cement and/or earthen mortars, for high seismic risk areas. Contains 22 pages.	(Nepal Ministry of Physical Planning and Works, 1993)	English	Mandatory
21	NBC 10.23	Nigeria	National Building Code (NBC), Section 10.23	2006	Code	Section 10.23 accounts for structures made of sun-dried earth blocks (adobes), rammed earth, and cement-stabilized earth blocks.	(Federal Republic of Nigeria, 2006)	English	Mandatory
22	PERU	Peru	National Building Standards, Technical Building Standard NTEE.080	2000	Standard	Prescriptive guidelines for adobe structures, and some engineering guidelines addressed to areas of both moderate and high seismic risk. It was developed by a team of representatives from architecture and engineering organizations as well as universities and the building industry and has been confirmed by the responsible standardization organization as a national building standard.	(National Building Standards of Peru, 2000)	Spanish, English	Mandatory
23	UNE 41410	Spain	The Spanish Association of Normalization and Certification AENOR: Compressed Earthen Blocks for Walls and Partitions. Definitions, specifications, and testing methods. UNE 41410	2008	Standard	Normative document for earthen blocks and building rammed earth structures. The first published standard that adhere to the EU 305/2011 harmonized marketing conditions.	(AENOR, 2008)	Spanish	Mandatory
24	SLS 1382	Sri Lanka	Sri Lanka Standard SLS 1382: Specification for Compressed Stabilized Earth Blocks. Part 1: Requirements; Part 2: Test methods; Part 3: Guidelines on production, design and construction.	2009	Standard	After the 2006 tsunami disaster, a building standard draft for construction with stabilized earth blocks was developed and officially introduced.	(Sri Lanka Standard Institution, 2009)	English	Mandatory
25	D 0111	Switzerland	"Regeln zum Bauen mit Lehm" ("Regulations for Building with Earth")	1994	Guidelines	Developed by the Swiss Society of Engineers and Architects (SIA). Include completed examples and technical details (D 0112)	(SIA, 1991)	German	NA
26	NT 21.33 & 21.35	Tunisia	National Institute of Normalization and Industrial Property INNOPRI. NT 21.33 - Blocks of Compression — Specification Techniques. NT 21.35 - Earthen Blocks - Definition, classification, and design.	1996	Standard	Standards for the production of CEB, published by the national Tunisian standardization organization INNOPRI	(INNOPRI, 1996, 1998)	French	NA
27	TSE	Turkey	Turkish Standard Institution TSE (1995–1997): TS 537 (1985) - Cement Treated Adobe Bricks TM 2514 (1997) - Adobe Blocks and Production Methods TM 2515 (1985) - Adobe Buildings and Construction Methods	1997	Standard		(TSE, 1985, 1997)	Turkish	NA
28	SAZS 724:2001	Zimbabwe	The Zimbabwe Standard Code of Practice for Rammed Earth Structures	2012	Standard	Standard Code of Practice for Rammed Earth Structures. Was introduced as a regional standard SADCSTAN/TCI SC5-001 in the countries of the Southern African Development Community (SADC)	(Standards Association of Zimbabwe, 2001)	English	NA

Given the geographic and cultural diversity in this comprehensive list, it should be evident that a level of policy analysis would be invaluable for extracting strengths towards the development of a complete international earthen building code. The following subsections analyze the field situation, as indicated by in-depth interviewees, as well as review of dominant codes, identifying strategies to writing earthen standards that could lead to structures that are both affordable and safe.

6.3 Earthen building policy analysis methodology

Policy analysis can be defined as a systematic evaluation of how effectively a policy addresses specific problems and people's needs, and achieves its goals (Kirst-Ashman, 2016). In the context of earthen building policy, a policy repair analysis should address regulatory barriers to earthen building materials and methods and their implementation by assessing strengths and weaknesses of existing earthen building codes and standards, as well as by developing recommendations for enhancement in the context of the USA International Codes.

Policy analysis can employ various methods and is characterized as a *skilled art of argument that cannot be done following rational model steps* (Patton et al., 1993). Policy analysis can be carried out before or after a policy has been implemented. Generally, the following categories can be used to describe the main policy analysis methods:

1. *Descriptive policy analysis for existing policy (Patton et al., 1993)*
    - Retrospective policy analysis – describes and interprets existing policies
    - Evaluation policy analysis – examines whether the aims of existing policy were met

2. *Anticipatory policy analysis types for proposed policy (Kirst-Ashman, 2016)*
    - Predictive policy analysis – predicts results from adopting policy alternatives
    - Prescriptive policy – develops recommendations for a positive change in existing policy.

In order to achieve the aims of the policy analysis, a hybrid approach between both models will be used, starting with evaluation of existing policy documents and continuing with recommendations for a positive change in existing codes and, finally, development of complete and comprehensive international earthen building codes. The steps of the study are:

1. *Verify, define, and detail the challenges* – in this step, the impact of the regulatory gap and its extent are determined according to its influence on experts and homeowners, as identified in the Survey conducted (Chapter xx), and In-depth Interviews reported in Section xx.
2. *Analyze alternative policies criteria* – this step incorporates the identification of exemplary existing policy documents where the challenges are met, or in which an acceptable recommendation is developed.

Evaluation criteria include user-friendliness of the building code/standard, utility (to what extent the code can be utilized for a certain earthen materials), as well as familiarity among building officials.

3. *Establish recommendations for positive changes* – in this step, amendments that could attain the evaluation criteria are developed for an International earthen building code.

The analysis in this chapter is organized according to the identified challenges and proposed solutions. Figure 135depicts the structure of the policy analysis.

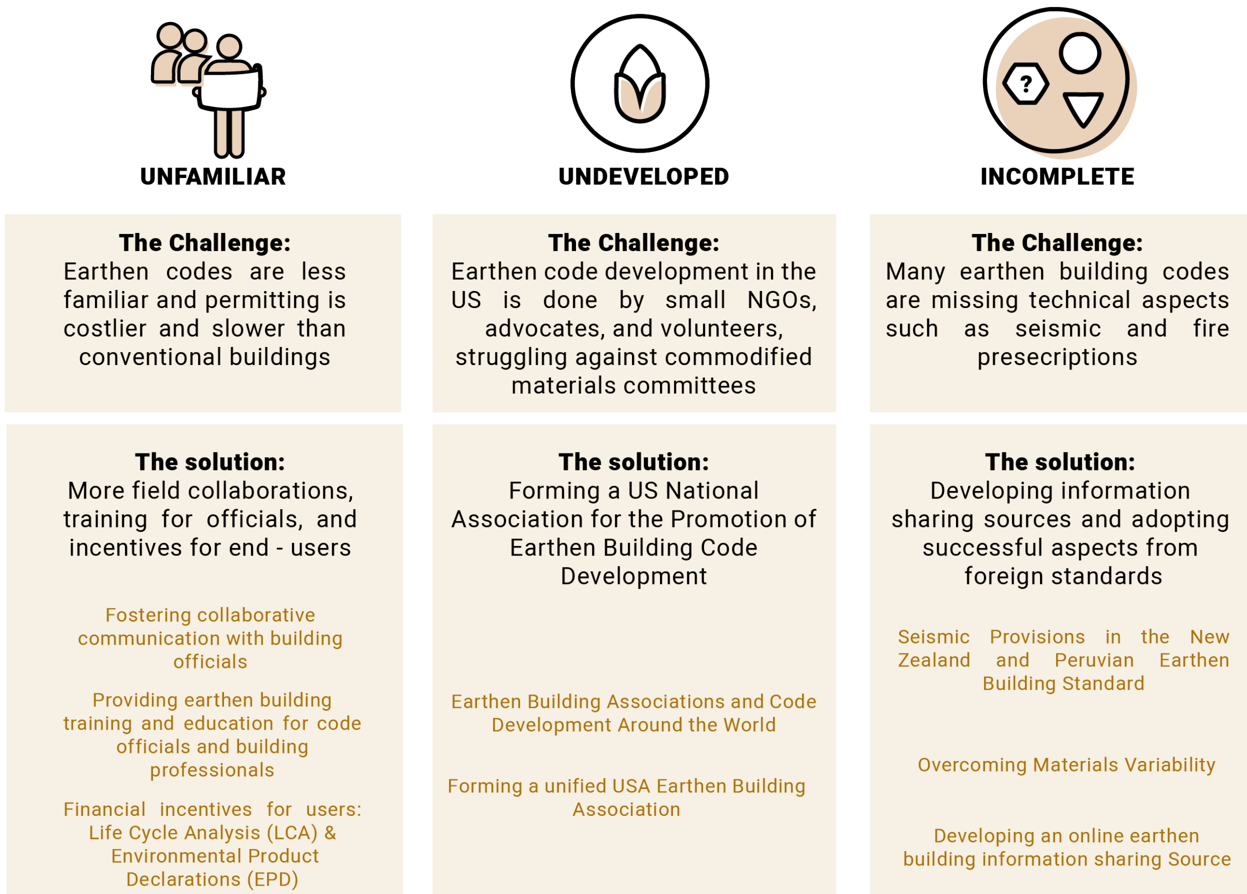


Figure 135: Policy analysis overview, addressing the main problems of arthen building regulations and suggesting strategies for improvements

6.4 Earthen building regulation is unfamiliar to building officials and requires more education and training

6.4.1 The challenge: earthen codes are less familiar and permitting is costlier and slower than conventional buildings

In chapter 3, the experts' perception survey results suggest that even within the earthen building community, building codes are often unfamiliar or not applied. As shown in Figure 61, 24% (n=18) of surveyed experts indicated that they are not familiar with any building codes for earthen construction. Additionally, of the experts who use building codes, 27% (n=15) had been applying conventional material codes to their earthen building projects. The remaining experts reported to be predominantly using the earthen codes from Germany (16%) (Dachverband Lehm, 2008), New-Zealand (13%) (NZS 4297: Engineering Design of Earth Buildings, 1998; NZS 4298: Materials and Workmanship For Earth Buildings, 1998; NZS 4299: Earth Buildings Not Requiring Specific Design, 1998), New-Mexico (9%) (New Mexico Regulation & Licensing Department and NMAC, 2015), India (7%) (BIS 1993) or Peru (5%) (NBSP 2000).

Of the predominantly used earthen codes and standards, only a few represent code-compliant and comprehensive options. Detailed in Table 86, the Indian earthen building codes, for instance include many instances of non-mandatory language with requirements that might be open to the interpretation of the user.

Table 86: Overview of the predominantly used earthen building codes and standards

	Materials and systems	Plasters and renders	Limits of application	Pages	Unique Features and comments
German DIN and Lehmbau Regeln	Rammed earth, adobe, CEB, light clay, timber-framed earth infill, cob, clay panels.	Includes the DIN 18947 for specification of earthen plasters	NA	Lehmbau Regeln: 120 pages, DIN 18945: 24 pages	Includes instructions for LCA
New-Zealand Standards 4297,4298,4299	Adobe, stabilized adobe, CEB, rammed earth, poured earth, cob, earth floors, wattle and daub	Plaster tests are defined in Appendix L (Surface Coating), with detailed instructions on preparation, properties, and application.	Walls up to 6.5 m (21 feet) high	238	Includes extensive requirements for seismic loading.
New-Mexico 12.7.4 Earthen Building Code	Adobe, stabilized adobe, burned adobe, rammed earth, "Terrón" (dried cut sod)	Earth plaster allowed; cement plaster can be applied over unstabilized earthen walls with metal wire mesh.	1-2 story dwellings	37	Short, self-contained and comprehensive building code rather than a standard cited from within an existing building code

	Materials and systems	Plasters and renders	Limits of application	Pages	Unique Features and comments
Indian Earthen Building Standards	Adobe, cob, rammed earth and Assam (wattle and daub) without any stabilizers	Mud plaster recommended as part of water protection regimen. Plaster should include additions of cow dung, bitumen, or kerosene in wet areas.	1-2 story dwellings	12	Recommendations given throughout high risk areas, often with open ended requirements
Peruvian Adobe Norms E-080	Adobe, stabilized adobe	Stabilized earthen mortar allowed with wire mesh.	1-2 story dwellings	49	Seismic provisions are designed by rational method based on elastic behavior

Regardless of their existence, according to the surveyed experts, building officials are not familiar with earthen building codes, resulting in a costlier and slower permitting process than is the case for conventional materials having established design standards. Specifically, the German Earth Building Regulations are rated as the least familiar among building officials, followed by the NZS, as shown in Figure 136.

Experts have identified that earthen building codes are generally representative of the various earthen techniques in a user-friendly manner, with highest ratings given to the NZS (NZS 4299: Earth Buildings Not Requiring Specific Design, 1998; NZS 4297: Engineering Design of Earth Buildings, 1998; NZS 4298: Materials and Workmanship For Earth Buildings, 1998). However, experts also indicated that using earthen building codes/standards results in a costlier and longer permitting process compared to conventional building projects, with the greatest impact stemming from the use US-based earthen codes/standards, specifically the NM code (New Mexico Regulation & Licensing Department and NMAC, 2015). This observation may be less a function of the code documents and more a reflection of the permitting environment in the United States. Furthermore, this might be a result of an inherent bias against such construction that is often used in traditional Native American structures.

The representation of the different materials and systems by the predominantly used earthen building codes/standards is further analyzed in Figure 136, showing that New Zealand standards include various types of earthen construction, whereas the USA codes focus mainly on adobe. This likely reflects the rich vernacular heritage of adobe in USA – implying experience and acceptance – whereas New Zealand has little history of earth construction and is therefore “clean slate” open to alternatives

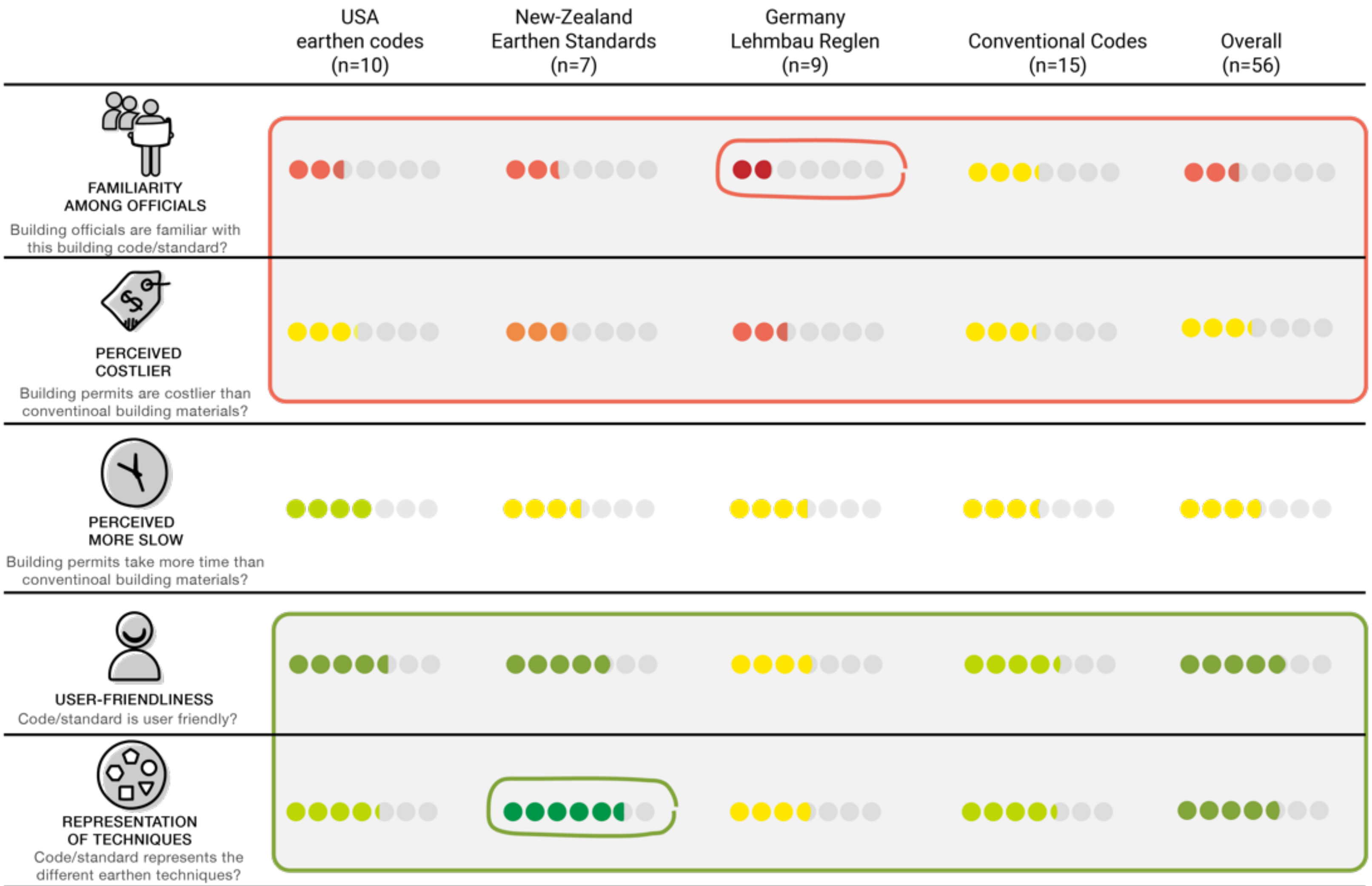


Figure 136: Earthen building codes/standards problems, as rated by surveyed experts, color-coded with red being most problematic.

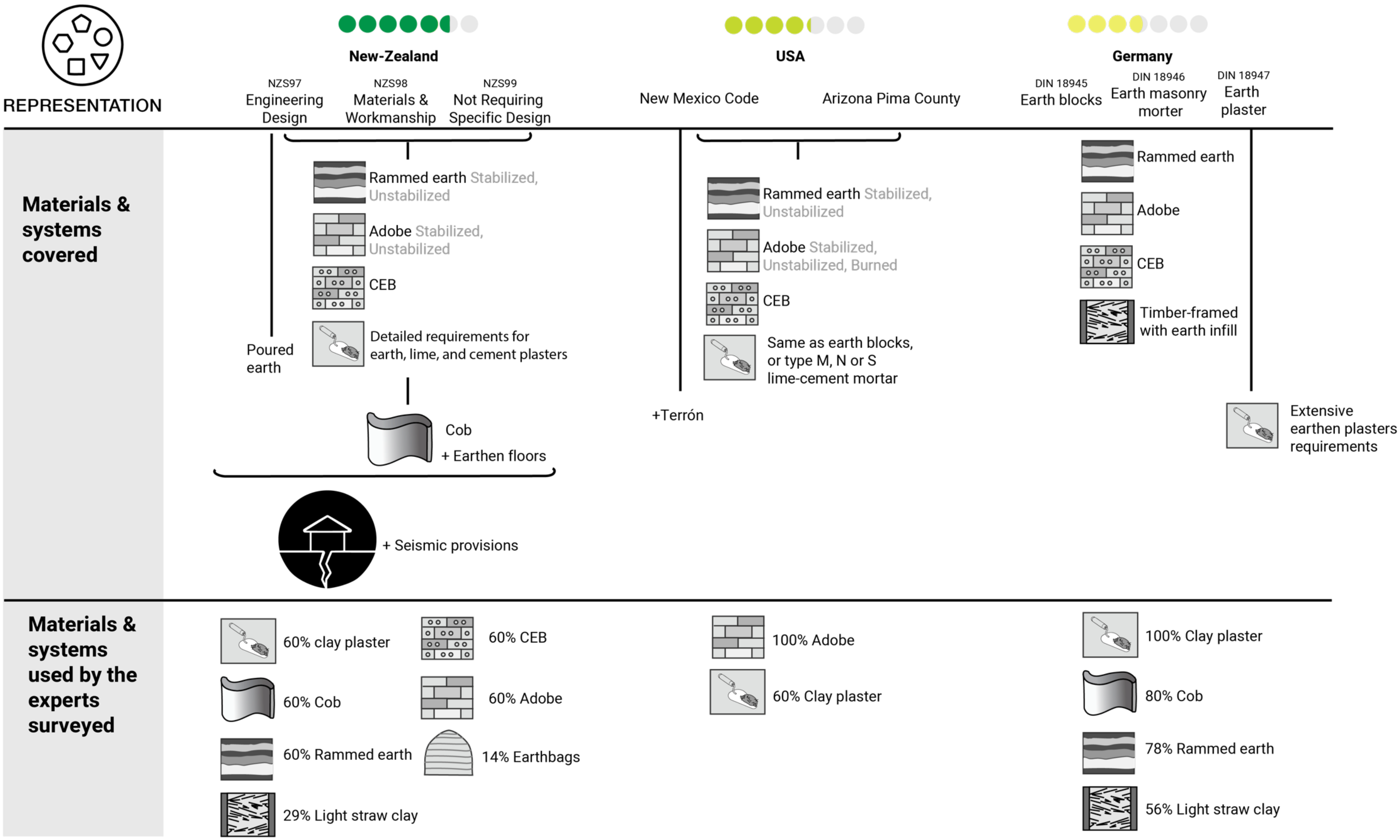


Figure 137: Represetation of the differenr earthen materials and systems by the arthen building codes/standards predominantly used

Of the experts who use earthen building codes, 43% (n=15) reported using codes different from their geographical locations (i.e., implying the adoption of 'foreign' codes). Shown in Figure 139, For the German Earth Building Regulations, 78% (n=7) are local users from Europe, although none are from Germany. Only half of the expert users of the NZS are located in New-Zealand. The potential unfamiliarity of earthen codes among building officials might be a result of the unavailability of the German building regulation in other languages, as well as the remoteness of New-Zealand.

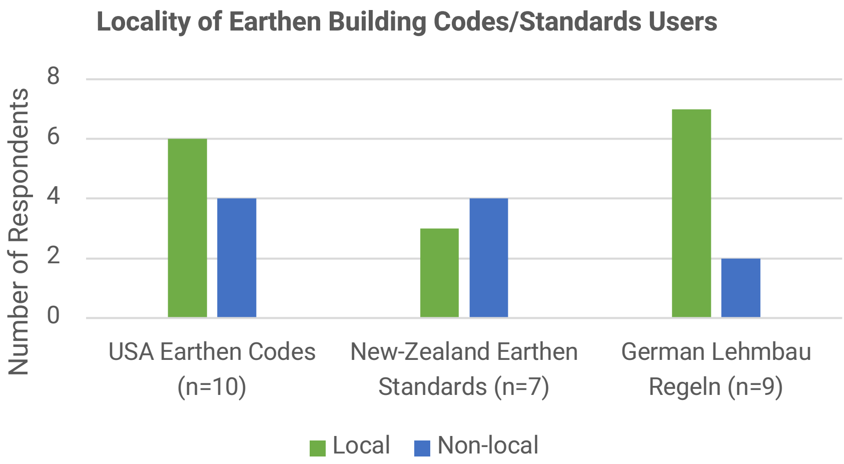


Figure 138: Earthen building codes/standards users locality

The in-depth interviews shed additional light on the unfamiliarity of earthen codes. The challenge, from a building permitting professional standpoint, was building official inexperience in using the codes and not being able to predict the behavior of the earthen materials:

> "[The barrier] from a building permit standpoint, with a permit official not having any idea how to look at an earthen material and know where in their experience and their knowledge of the building codes does this fall... So being able to provide them enough information so they know even how to think about it." [Architect from PA and MD, USA]

Significantly, some earthen codes were found to be confusing for building professionals. For instance, the 2015 Adobe Section in the IBC requires the application of cement-stabilized mortar to unstabilized adobe, which is known to promote erosion. Additionally, the 2015 IBC Adobe Section was minimal in scope and directed professionals to TMS 402 (Masonry Standards Joint Committee, 2008). As one of the interviewed architects, who helped making corrections for the 2019 IBC, testified:

> "Structural engineers mostly don't know how to use it [the adobe section in the IBC]. The guidance in the code is really bizarre. It tells you that you can do it, but it's not very realistic. It's called: 'Empirical Design for Adobe Masonry', but then it kicks you to TMS 402, which is this reference standard for design masonry structures; [a] very technical manual. Once you get in there, [adobe] is never mentioned again. ... It's like,

OK, you want to design with adobe, just use this reference manual that never once uses the term adobe, and that's super confusing"

Finally, unfamiliarity with earthen building regulations was affecting permitting procedures, leading to clients balking at the use of earthen materials:

> "The third [barrier] would be finding clients who are willing to go through the process, given what the process is now. Finding people who are willing [and] financially able to support it... There is some fanciful desire, and then there's the reality" [Architect from CA, USA]

6.4.2 Suggested solution: more field collaborations, training for professionals and officials, and incentives for users

Fostering collaborative communication with building officials

Positive communication with the building officials was stated to be crucial for projects success. For instance, one of the interviewed architects recommends bridging the gap:

> "My goal with a permit official is to create a collaborative relationship with them, not an adversarial one... If you can step into their shoes and say: 'where are they coming from?', then you have a way to communicate. And so, my goal is to be in their shoes... and if I can understand where they're coming from, then I can best give them what they need [in terms of materials testing]"

Specifically, one element of collaborations is understanding the perspectives of building officials who do not want to take personal responsibility for missing elements of the codes (such as fire rating for different earthen methods). Experts repeatedly mentioned the need to justify earthen materials using external sources and even to find ways to overcome missing sections of the code. As one of the interviewees, a licensed architect mentioned, one solution for using cob, which is omitted from any of the USA-based codes, was to mark it as a "sculptural adobe":

> "Letting you do something that's just different from the intention of the building code - that requires the permit official to take a personal liability to grant that variance, which is huge. Especially if it's something structural. Whereas, if you're demonstrating that you're meeting the intention of the code for insulation, for fire safety, for durability, etc. and by handing them the ASTM test, they don't have to stress at all about approving it because you just handed them their argument for why they approved it. It's the intent of the code. Done. Check. It just makes their life easier. So [for cob] I say, OK, apply it like you apply Adobe. So I write in my drawings: 'Cob (Sculptural Adobe)'".

While these strategies offer effective arguments and informal solutions, a more formal solution should come in the form a comprehensive earthen building code that includes the technical justifications available relative to each of the earthen techniques. A comprehensive earthen building code would allow effective streamlining between users and building officials.

Providing earthen building training and education for code officials and building professionals

One key to overcoming unfamiliarity with earthen building codes is providing education and hands-on training. For instance, workshops for permit officials about earthen materials helped make the permitting process easier, as one of the interviewed architects mentioned:

> "I was asked by the State of Maryland to go to their annual meeting of all of their permit official representatives... and I got a whole day with them to talk about straw bale and cob and adobe and rubble trench foundations and living roofs... And now in Maryland, it is so easy to get a building permit for natural buildings, partly because of that... Oh my gosh, if every state did something like that."

This effective way to disseminate information could be modified into an interactive online workshop with thereby addressing budgetary constraints of other states. Fostering earthen building education can enhance familiarity among building officials, but it should also be introduced in the of education of building professionals. This is imperative since both building professionals and permit officials discourage clients from implementing natural building materials, as stated by one of the interviewed architects:

> "I just had an email today from someone who has been trying to build a straw bale home in Colorado, a very responsible thing to do, and they have been going around in circles with their permit official and their engineer, around and around until they just wear this person out and they decide not to pursue it. ... if architects and engineers have [nonconventional construction] as part of their education, then they know how [to properly support] someone ... who comes to them."

Modules for training professionals on earthen construction should include theory, field awareness, and practical experience modules, while partnering with local academic institutes, vocational universities, trades-oriented colleges, and sustainable construction and products firms. As illustrated in Figure 4, programs should draw from existing inspiring projects while being exposed to current research work.

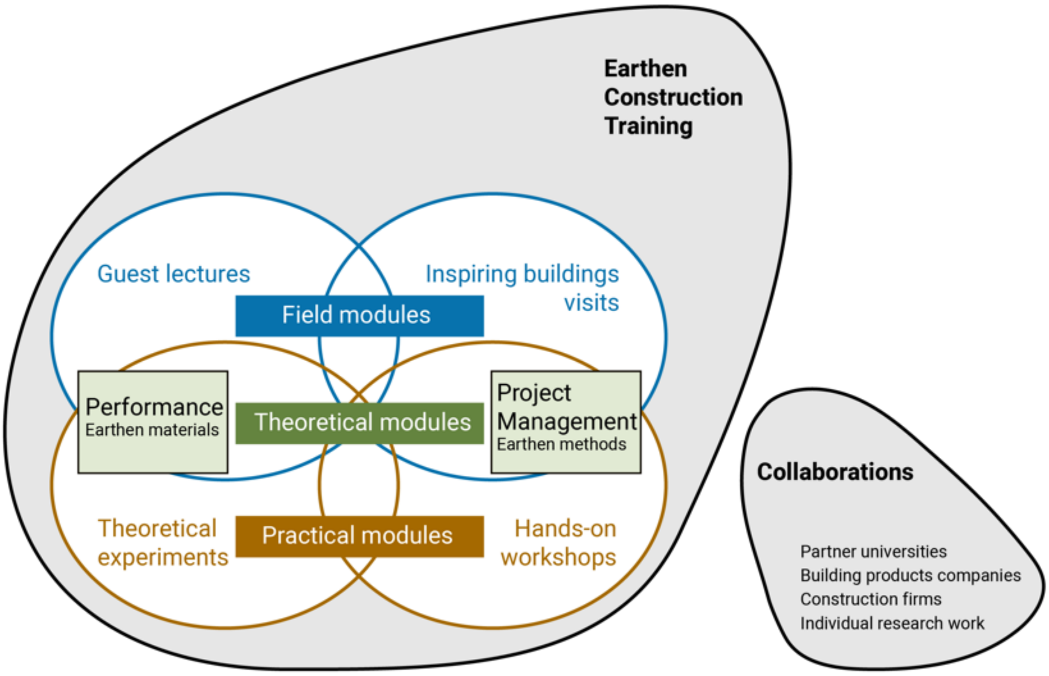


Figure 139: Earthen construction training modules, Image by Ben-Alon, according to (ETH, 2017)

An example of such an approach is the Grounded Materials training at ETH Zurich. As shown in Figure 5, this program aims to train specialists on the effective use of earth and bio-based materials in a 5-week module for projects managers, building contractors, and members of the City Technical Services.

ETH zürich

CAS / MAS «GROUNDED MATERIALS» ETH Zürich 2019

Construction industry is consuming a tremendous amount of resources and is responsible for more than half of the greenhouse gas emissions and the waste released from our societies. Alternative solutions out of earth and bio-based materials are emerging all over the world. The TERRA Award and FIBRA Award have attracted a lot of attention by putting the light on these materials and their use in contemporary architecture. Earth and bio-based materials are everywhere available in sufficient quantity. However, they are not widespread in the construction sector due to lack of information from decision makers and lack of competence from practitioners. The education program "Grounded materials" aims to give them tools and methods to use earth and bio-based materials with efficiency and creativity in order to contribute to the necessary ecological and social transition in the construction sector. It combines a CAS for the management of projects with non-conventional materials and a MAS to go deeper in the construction with earth or with straw, reed, bamboo...

Objectives

- Participate to the necessary ecological and social transition in the construction sector.
- Answer a growing demand for specialists on earth or/and bio-based construction.
- Train specialists able to conduct complex projects using earth and bio-based materials with realistic and affordable solutions.
- Offer a practical experience on real projects (new construction or renovation of a heritage site).

Target Audience

MAS «BUILDING WITH GROUNDED MATERIALS»
Architects, engineers...
20-25 students from Switzerland and all over the world
60 credits, 30 weeks (1 semester with theoretical lectures and practical exercises + 1 semester Master work)

CAS «MANAGING A PROJECT WITH GROUNDED MATERIALS»
Project managers, members of city technical services, building contractors...
10-15 Students from Switzerland and abroad
12 credits, 5 weeks distributed over 1 semester (theoretical blocks and practical modules + individual analyse of a project)

Pedagogical Program

The program is organised in 3 theoretical blocks completed by 4 modules with more practical aspects, open to the MAS and CAS students and sometimes to a wider public.

The **3 main blocks** are based on **theoretical knowledge.**
- The blocks **Building with earth** and **Building with bio-based materials** explain in detail how to use those ecological and local materials: structural design, technological design, building physics...
- The block **Managing a project with grounded materials** explains how to achieve a project with non-conventional materials in the Western world as well as in emerging and developing countries: environmental aspects (footprint, carbon storage...), regulations (hygrothermal, fire resistance, seismic safety...), evaluation of the costs, social aspects (communication, empowerment of the population, training of craftsmen...).

The **4 complementary modules** are concerning more **practical issues.**
- The **2 «Inspiration modules»** propose all along the semester 6 **inpuls lectures** from well-known specialists (Wang Shu, Anna Heringer, Simón Veléz...) open to a large audience for public awareness as well as the **visit of inspiring buildings** and discussion with stakeholders involved in their realisation.
- The **2 «Practical modules»** gather **real-life experiences** that can prepare the students to apply their knowledge. They include **hands-on workshops** to understand the materials and **technical experiments** to test the different ways of building with earth and bio-based materials.

The **MAS work** can deal with theoretical or practical issues. Students can work on an **individual research project** or participate with partner universities or companies to a **Design Build project** or to the **renovation of a heritage site.**

Figure 5: The 2019 Grounded Materials training Brochoure, ETH Zurich

Financial incentives for earthen materials based on life cycle analysis and environmental product declarations (EPD)

While some states provide financial incentives to homeowners and builders based on operational energy savings, current research is focused on identifying the full life cycle of environmental impacts. The next generation of incentive calculations should account for embodied and operational carbon for possible emissions trading (Bojarski et al., 2009). One of the experts interviewed suggested showing the real environmental cost of using cement versus clay:

> "What will really propel earthen building is if we ever get a brand. Putting a price on carbon. ... If we put a price on carbon, then suddenly cement is a lot more expensive than it was. And people will be looking for other ways to build other kinds of concrete or clay-based concrete - clay is everywhere. How cheap and great. That's the whole appeal of so-called natural building"

Earthen building materials are locally sourced and readily available, which also makes them more affordable. Nonetheless, the lack of clear code allowances and professional education has created a need for incentivizing earthen construction to accelerate its application with carbon, health and job benefits. Building techniques must be evaluated according to the health and safety of all the people involved with the buildings during the entire building life cycle, including communities and the larger population. According to Woolley (2006), the development of earthen building codes and regulations should be accompanied by financial incentives, in order to give rise to real-estate investment.

The advantages of earthen construction are the result of combining embodied energy, human and environmental health gains with operational energy – the principle of comprehensive LCA calculations. According to Schroeder (2018), earthen building codes should include specific steps to develop Environmental Product Declarations (EPD) based on an LCA methodology. As a prominent example, the German DIN 18945-48 Earthen Standards includes procedure guides to evaluating the EPD of earthen building components and products for the use of certificate awards and rating systems such as LEED. Based on DIN EN ISO 14040, the DIN 'Appendix: CO_2 Equivalent' is hereby translated to English (by the author):

Appendix A.2 CO_2-equivalent characteristic value

The following are the product category rules for earthen bricks, according to DIN EN 15804 [Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products]

For earthen bricks, the CO_2 equivalent characteristic value can be determined and specified as following:

A.2.1 Calculation

The CO_2 equivalent value for earthen bricks shall be calculated using eco-balances, kilograms of CO_2 are given for tonnes of earthen bricks. For the eco balance, DIN EN ISO 14040 shall be used. Preparation of Environmental Product Declarations (EPD) should be in accordance with DIN EN ISO 14025 as well as DIN EN 15804.

An environmental declaration for earthen bricks shall be obtained using the balance sheet that is provided in DIN EN ISO 14040. The calculation of the CO_2 equivalent values requires a balance sheet according to DIN EN ISO 14040. Furthermore, the environmental declaration may contain additional relevant information modules from all stages of the life cycle beyond what is specified in the balance sheet.

The balance sheet shall include the consumption of resources, including renewable and non-renewable energy resources as well as emissions in air, water and soil. The CO_2 equivalent characteristic shall be used as an indicator of the performance analysis of the resource consumption calculated in the balance sheet over the entire life cycle of earthen bricks.

A.2.1.1 Raw materials and cut-off criteria

The earthen bricks raw materials shall be declared by percent (%) by mass. According to their mass fraction, each raw material is to be included in the calculation of the CO_2 equivalent characteristic value if it makes up > 1% of the total mass of the earthen bricks or contributes > 1% to the primary energy demand to make the bricks.

A.2.1.2 System boundaries of life cycle analysis

The earthen bricks shall have defined system boundaries. The system boundaries are determined using the life cycle analysis method. The life cycle analysis includes the extraction and transport of the raw materials, the production into a ready-to-use material, the usage phase, and the disposal phase.

a) Raw material extraction
When the construction clay is used from excavated soil, it shall be considered as a secondary raw material. The fuel consumption for the removal of the clay layers in the soil excavation should be included in the calculation of the CO_2 equivalent. Any mineral supplements shall be included parameters in accordance with their known, declared or verifiable calculated CO_2 equivalent values. Plant additives shall be considered as CO_2 neutral and are not to be included in the calculation of the CO_2 equivalent.

b) Transportation
The raw materials transportation energy depends on the distance in kilometers between the source of the material and the production site. The mode of transport should be specified. The energy consumption should be calculated or plausibly estimated and calculated per tonne of materials transported. The consumption is calculated in the unit of the respective energy source. The CO_2 equivalent is then calculated.

c) Production
The energy for the electricity used in the production and for the drying of the blocks should be recorded. Electricity consumption shall be recorded in kWh / t. The CO_2 equivalent characteristic value is calculated from this. The thermal energy for drying should be recorded in the unit of the respective energy source. The CO_2 equivalent value is then calculated. The proportion of regenerative energy should not be included in the calculation of the CO_2 equivalent values for the drying.

d) Use phase
Earth bricks with natural raw materials declared according to A.2.1.1 can be beneficial for the environmental and occupants' health during the use phase. Earth bricks do not emit volatile organic compounds (VOCs) that are harmful to the environment or human health. Further evidence is provided in accordance with DIN EN ISO 16000-9. The dynamic humidity absorption of clay bricks during the use phase can have an impact on the indoor environment and on the necessary air exchange rates, reducing energy consumption.

e) Disposal
Earth bricks are completely recycled without further treatment. The disposal of earth bricks is CO_2 neutral and is not included in the calculation of the CO_2 equivalent parameters.

A.2.2 Specification of the result

The CO_2 equivalent characteristic value is to be stated in the product data sheet according to Section 11 in the following form:
The CO_2 equivalent characteristic value result is: ______kg / t

Similar to the DIN standards, future development of earthen building codes and standards should include procedures for declaration of product environmental features and consider aspects of LCA for sustainable building. Furthermore, due to the geographic-specific dependency of LCA, future building regulations should provide local inventory data and be linked to environmental assessment tools such as embodied carbon calculators that provide regional-specific estimations.

The next generation of financial incentives for carbon savings and human health in the residential and commercial building sector should combine embodied, operational and end of life LCA calculations, with an increase in environmental product declarations (EPD) for construction material and assembly choices.

6.5 Earthen building regulation is under-developed and requires organizational effort

6.5.1 The challenge: earthen code development in the US is currently pursued by advocates, volunteers, and small NGOs, competing against commodified materials committees

Despite their numerous environmental benefits, earthen building materials and methods are typically non-commodified systems (i.e., have no formal industry representation) and therefore lack financial support for expert representation in regulatory committees (Eisenberg & Persram, 2009). Specifically, one interviewed earthen building policy advocate testified:

> "[code hearings are] really heavy politics in a way that I didn't really expect. You go into the meeting and you think... everything is just going to be evaluated on its basic terms based on the language of the proposal. But in fact, what happens is that if you want to get something done there, there are all these different stakeholders from FEMA, to representatives of each of the insurance industries, SEAOC and these engineering societies. And pretty much if you want to succeed, you need to make sure that you don't have opposition from any of them, or at least that everyone stays quiet in their seats"

Realistically, building codes are influenced by financial market forces, not only by scientific and technical justification. Additionally, each stakeholder will have different concerns and different expertise, reconfirming the need to be able to communicate earthen building performance to the full range of professionals. Indeed, the impediment of entrenched interests between earthen materials advocates and conventional commodified materials organizations is shown to act as a strong challenge, as mentioned by one of experts interviewed:

> "ASTM, like other code writing organizations [sic; ASTM is not a code-writing organization – ASTM writes standards and specifications], is to all appearances agnostic, non-profit, consensus-based and almost entirely run by volunteers. What's not to like? But though that is all true, it takes a lot of money and time to show up at the, at least, twice a year meetings around North America, read through and comment on drafts, and just in general have a noticeable effect on standards development. The result is that deep pockets almost always dominate code development — and they don't like the looks of you, kid.

National standard-writing organisations with limited resources and volunteer committees have little incentive to address technology that is often considered marginal. While earthen building materials remain rare, there is little support and often no perceived need for standards.

The organized presence of earthen building advocacy is imperative for the enhancement of earthen building codes, and thus, implementation. In some cases, earthen building advocacy was shown to be crucial against commodified organizations who posed threats to current earthen codes. For instance, in 2016, an Earth Builders Guild representative (one of the experts interviewed) was on his way to a code hearing to propose a simple change to the IBC Adobe section. However, as he arrived in the morning, he discovered that his amendment was in a direct conflict with the Masonry Society proposed change to eliminate adobe from the code entirely:

> "We made this code proposal to change the portion of the IBC that disallowed earthen mortars on unstabilized adobe bricks.... and I had heard that there was this proposed change by the Masonry Society.... we were not paying a whole lot of attention. I showed up in Louisville, and I'm going through all of the proposed actions in my hotel room at 6:00 am in the morning... and I'm like, oh my God, they actually want to take adobe out of the entire section. Get it out of the IBC and put it into the IRC... Apparently, they thought that no one is using adobe for commercial construction. But this would be a big deal. Even more perilous was that there were two proposals: their proposal to adding it to the IRC and their proposal to delete it from the IBC were in two separate proposals so we were faced with the potential that the proposal to add it to the IRC could be declined and the proposal to remove it from the IBC could have been accepted and then it just would have vanished entirely... We ended [spending] three crazy days trying to reconstruct this thing, wandering around just talking to all of these different folks, getting them on our side. Ultimately, we scuttled their proposal because we pushed back so hard there. But that was not our first intention [when arriving to the code hearing].

Competing stakeholders can have a large impact on the building codes. Whereas serving on a code committee requires commitment to the entire process, time and money are required to allow adequate earthen building advocacy. Expert time and organizational resources are critically needed for earthen building code development to ensure balanced decision making in the face of commercial industry (commodity) stakeholders, as further outlined in the next section.

6.5.2 The solution: forming a US National Association for the promotion of earthen building and code development

Earthen building associations and earthen code development around the world

The success of previous earthen building standards from around the world is highly dependent on the nature of their respective code development processes. Ironically, the development of codes, which can support field practice, requires a mature practice community, paraphrasing Mottram (2017): "…*to be able to write a consensus standard, the stakeholder community requires mature practice from which lessons can be learned. To reach this level of practice, standards are required in order to overcome inherent reluctance and cost barriers to adoption of the structural material*".

One way to overcome this paradox is to have experts organise in a way that can produce valuable exchange of experience and technical documentation. Specifically, for the USA, a national organization that could broadly and vigorously promote and preserve earth building architecture is missing. Such national organizations dedicated to the production of earthen codes and standards exist in many other countries, including the Earth Building Association of New Zealand (EBANZ), Earth Building Association of Australia, France CRAterre (the International Center for Earthen Architecture), Dachverband Lehm e.V. (the German Association for Building with Earth), and PROTerre in Latin America.

In addition, advancing an earthen building standardization process will also need to the 'inertia' of code precedent and legacy, as mentioned by one of the interviewed earthen building policy advocates:

> [Ben-Alon: "And how is it that adobe construction is mentioned in the IBC but not in the IRC?"]
>
> Arch4: "I believe that's a legacy of when it was in the Uniform Building Code. So the IRC is a more recent development. Basically, if you look back at the genealogy, it's got an immediate predecessor in the UBC [Uniform Building Code]... The IRC was created right about that same time as [the transition from UBC to IBC] to sort of simplify things for residential construction."

Earthen construction standards development must take place within the existing framework. Collaborations between a national technical association and governmental organizations, as seen in other countries, has been shown to provide the financial and motivational frameworks. For instance, in the case of the NZS, the EBANZ first developed a set of guidelines in 1991, with the participation of local engineers and architects. Thereafter, the larger New Zealand Standards (NZS) took responsibility for the standard and joined together with Standard Australia (SA) in 1993 to develop a joint earthen standard with an enlarged committee (Walker and Morris 1998). The collaboration was discontinued in 1997 mainly due to differences in seismic requirements, yet the exchange of information and expertise was invaluable. One year later, NZS published the New Zealand earth building standards (NZS 4297, NZS 4298, NZS 4299) which comply with the New Zealand Building Code. Simultaneously, SA developed *The Australian Earth Building Handbook* (HB-195 2002) and the Earth Building Association of Australia (EBAA) developed the *Building with Earth Bricks and Rammed Earth in Australia* (EBAA 1997). The hybrid approach combining expert organizations and standard bodies' in the development of New Zealand and Australian construction guidance for earthen material is summarised in Figure 140. The over fifty-year time frame and decades-long development process is also noted – standards development is a generational endeavour requiring both 'champions' and continuity (institutional memory).

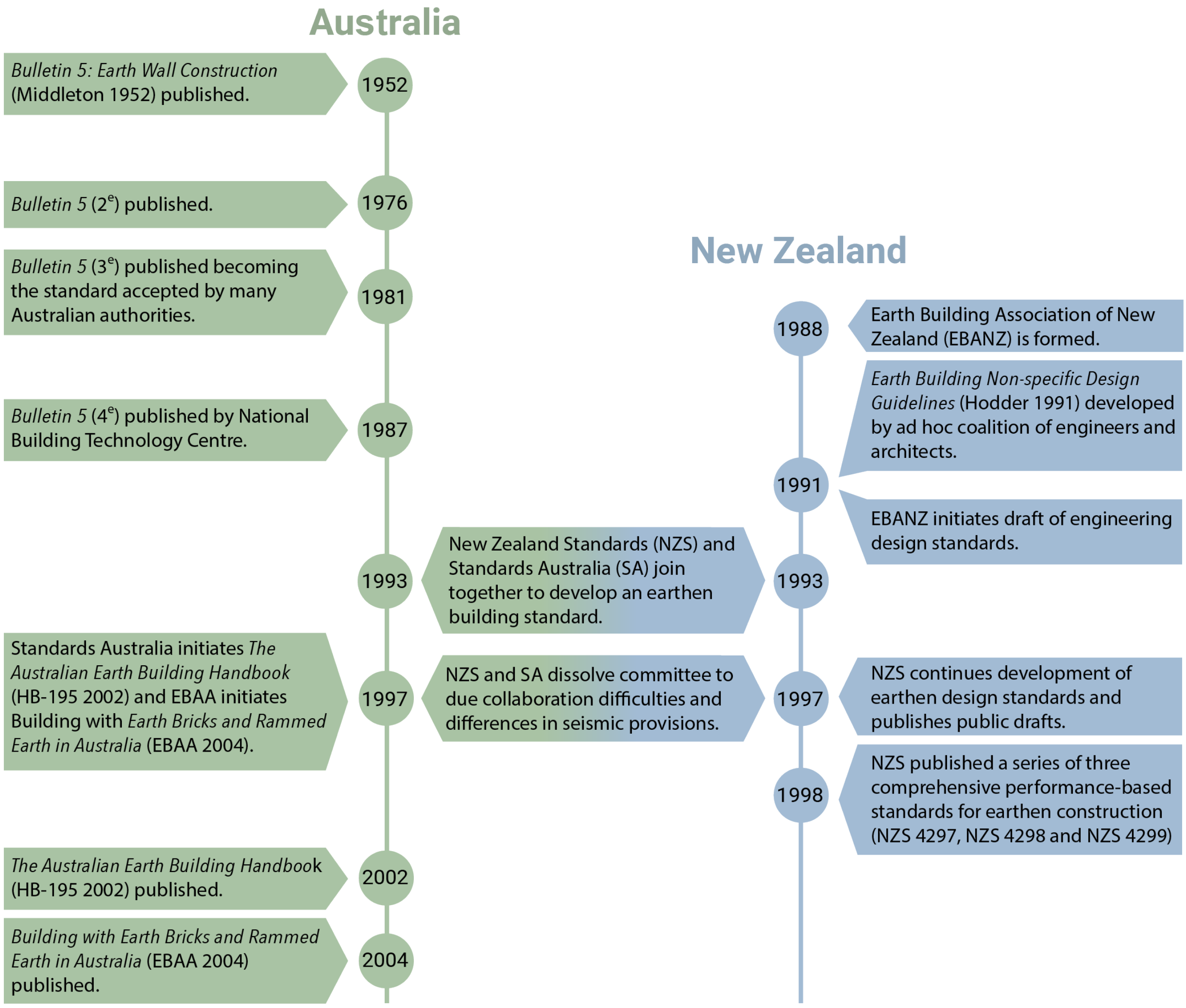


Figure 140: Timeline of NZS and Australia Earth Building Standards development process.

Similarly, the development of the German earthen building codes also illustrates the power of collaboration between an expert organization and governmental commissions in developing earthen construction standards. Shown in Figure 141, the timeline of the German DIN development included various collaborations and funding resources. In 1995, the German Association for Building with Earth (DVL) was invited (with five years of funding) by the German "Construction Standardization" expert commission to re-examine the earth building standards, which had been withdrawn in 1971. This decision was made due to the considerable rise in the number of earth building activities, both for restoration as well as new construction work (Schroeder, 2016). DVL served as a professional organization in a project group formed by representatives of ARGEBAU (The German construction, housing, and settlements ministries) and the German Institute of Construction Technology (DIBt–Deutsches Institut für Bautechnik).

Funded by the German Federal Environmental Foundation over the next few years, DVL formed its own project group consisting of experienced specialists and developed the Lehmbau Regeln, a technical building regulation for building with earth. The publication of the Lehmbau Regeln in 1999 closed a 30-year gap in the assessment of earth building construction by German building authorities. This also resulted in a significant improvement in legal certainty for earthen building in Germany and removed the complex process of "case-by-case approval". This change has also led to the increased earthen building product development within Germany's building industry since the mid-1990s (Schroeder, 2016).

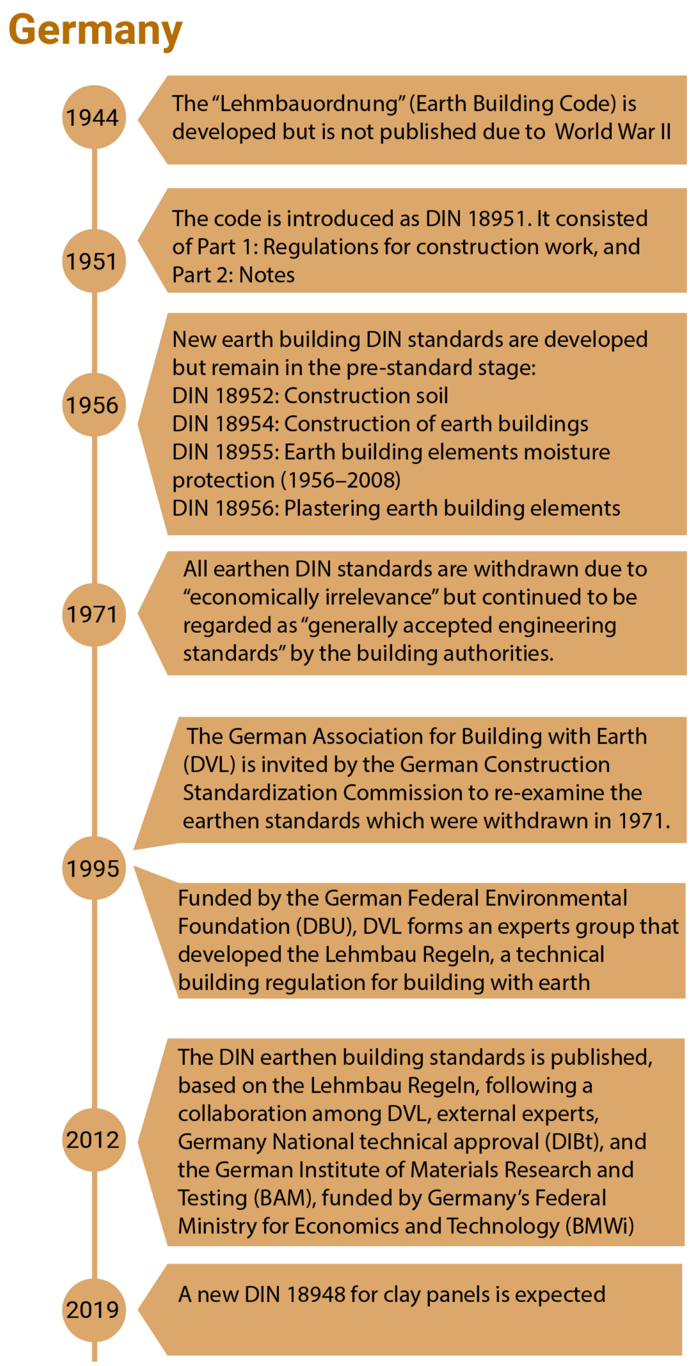


Figure 141: Timeline of Germany Earthen Building Standards development process

The Lehmbau Regeln consist of three parts: Chapter 2: construction soil; Chapter 3: earth building materials; and, Chapter 4: earth building elements. Overall, the Lehmbau Regeln accounts for various loadbearing and infill wall techniques, including CEBs, rammed earth, cob, earthen infills, light straw clay, clay panels, dry-stacked earth walls, sprayed earth walls, earthen ceilings, and earthen plasters, as illustrated in Figure 136.

In 2013 the DIN earthen standards (NABau, 2013) were published following a collaboration led by DVL, external experts, as well as representatives of the DIBt and the German Institute of Materials Research and Testing (BAM). As part of a three-year research project called "StandardLehm" (Earth Standard), which was funded by Germany's Federal Ministry for Economics and Technology (BMWi), BAM carried out numerous tests on earthen building materials and building elements (Schroeder, 2016).

The development process examples of Australia, New Zealand, and Germany illustrate the role of experts and government collaborations in the successful delivery of comprehensive earthen building regulations. Earthen standards development must involve expert stakeholders while ensuring the necessary resources for their participation and engagement in the process. While current earthen construction regulations are mainly developed in a bottom-up approach by advocates with little funding, it is crucial that a collaborative future be planned among governmental and regulatory organizations, practitioners (e.g., researchers and experts), and a unified earthen building professional organization.

Forming a unified USA earthen building association

Table 87 summarizes six leading proponents of earth building in the United States as of this writing. Each organization has a unique focus, yet all have a shared vision to promote the use of earthen construction. Thus, a unified umbrella organization could lead efforts that would benefit all organizations.

Table 87: Summary of current USA-based earthen organizations

Organization	Mission	Website
Cornerstones Community Partnerships	Dedicated to preserving the architectural heritage and cultural traditions of New Mexico and the greater Southwest, using a hands-on approach to teach and reinforce these methods to both adults and youth.	https://www.cstones.org
The Earthbuilders' Guild (TEG)	Represent and promote the earthen construction industry of New Mexico to the interested public, clarify misconceptions about Adobe, Compressed Earth Blocks, and Rammed Earth and act as a volunteer, qualified interface with officials when building codes that may affect its members are written, adopted or modified.	https://theearthbuildersguild.com
Adobe in Action (AIA) / Earth USA	Support owner builders with the planning and construction of their adobe homes. Promote adobe home building and ownership through education and student-based field support.	https://www.adobeinaction.org/
Earthen Construction Initiative (ECI)	Aims to advance and promote earthen construction with the vision of having earthen construction as an established mainstream building technology	https://www.earthenci.org/
Natural Building Alliance (NBA)	Committed to expanding and sharing knowledge, experience, and techniques for sustainable building. Promote quality building practices and serve as a resource for building professionals and homeowners.	https://natural-building-alliance.org/
Cob Research Institute (CRI)	The mission of the Cob Research Institute is to make cob legally accessible to all who wish to build with it. Dedicated to the scientific study of cob's material properties and standard development.	https://www.cobcode.org

Four primary tasks are identified that could directly lead to growing the industry for both practitioners and general public awareness. Description of these tasks are shown in Figure 142 and described below:

1. *Earthen Building Education and Training*

   This task includes education, training, marketing, and branding to move the industry forward by sharing knowledge and information with design and construction professionals, as well as code officials and building departments. The effort should both promote and provide education and training for earthen building techniques, including technical data and resources for products support and guidance.

2. *Code Development and Research*

   This task includes identifying language for performance and prescriptive codes based on national and international expertise with climate specific standards. The task also would identify research needs and promote the development of university research and education centers, seeking funding sources to serve code development and industry advancements.

3. *Environmental Product Declaration (EPD) and Life Cycle Assessment (LCA)*

   This task includes setting guidelines and promoting the development of EPD's for earthen materials and assemblies. EPDs are independently verified and registered documents that communicate transparent and comparable information about the life-cycle environmental impact of products.

4. *Online Library*

   This task includes curating and disseminating the plethora of research papers, books, and technical testing on earthen construction to create a platform of shared knowledge. The library would provide a single source for international reference documents and identify where additional research may be needed.

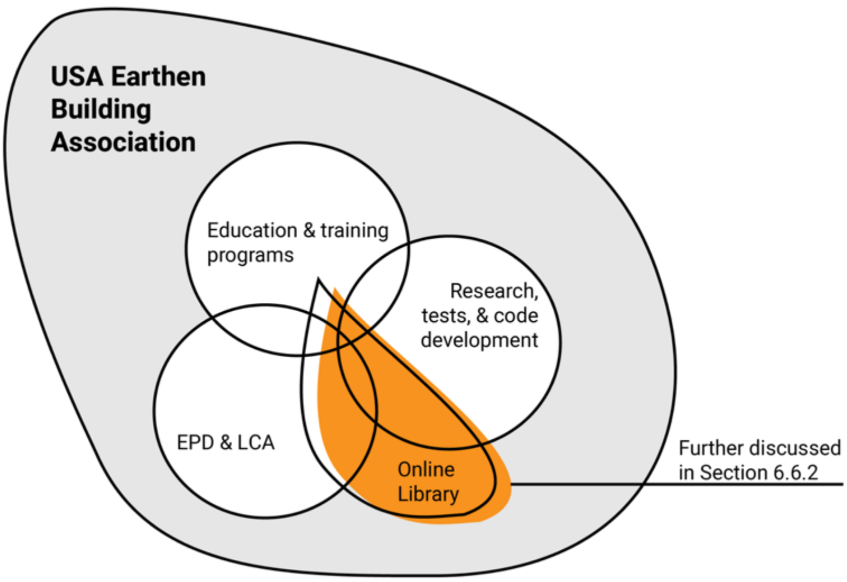


Figure 142: A propsed USA Earthen Building Association organizational scheme

6.6 Earthen building regulations are incomplete and require more technical data and communication

6.6.1 The challenge: many earthen building codes are missing technical aspects such as fire and seismic specifications

Experience from previous generations that is well preserved and dutifully transmitted within a community can be the basis of an informal, non-codified "standard" (Harries et al., 2019). For example, bamboo design standards consider "old and pure tradition[al]" practice as being "equivalent to code" in very specific scenarios (ISO 22156, 2004). However, the development of sound 'engineering judgement' is required for continuous improvement in the field and for maintenance of standards worldwide. For this reason, standard development for earthen materials must begin with synthesis of the existing engineering data, as well as documentation and enhancement of local practices. Such synthesis requires consistent test procedures for material test studies, as well as proper documentation and interpretation of results.

To date, researchers studying earthen materials have adopted a variety of different established and ad hoc test methods – some for concrete materials, others for masonry units, and even others for masonry assemblies – and their attendant test geometries. These result in a considerable range of reported data that cannot be directly compared. In some cases, test method selection results in a bias in reported properties. For example, it has been shown that different studies report the compression modulus of cob material with variations of an order of magnitude depending on the test method used (Section 2.5).

Notably, for the USA earthen codes, technical considerations such as fire safety and seismic considerations are critically missing.

Fire Safety

The absence of fire safety rating tests for cob led to the failure to approve cob provisions at the 2019 IRC Hearing (Cob Research Institute, 2019a). Additionally, earthen construction practitioners are required to repeatedly justify cob's non-combustibility, as mentioned by the following experts interviewed:

> "I've had questions, for example, from a fire marshal, who said ... "you need to show me that data on the fire rating for a clay wall." ... we had this conversation about whether you can light the dirt on fire in your yard, [he agreed], and I said - that's the wall. ... I was just trying to put it in a context that he has complete understanding of the material. So that's number one barrier."

The fire behavior of clay-based materials has been previously studied, as shown in Table 88, and is reported in various earthen building standards. One efficient way to provide fire classification can be shown in the German Earthen Standards, in which an explicit combustability class is given for earthen materials, according to their fiber content. The following excerpt is translated by the author from the German DIN 18945:

SECTION 9.8. FIRE BEHAVIOR

The fire behavior of earthen blocks is determined by testing according to DIN 4102-1 or DIN EN 13501-1 on samples cut from the adobe.

Clay blocks without organic additives or fibers can be classified according to DIN 4102-4 without any testing as building material class A1 (non-combustible).

Clay blocks that have no more than 1.0% mass fraction of homogeneously distributed organic components can be classified according to DIN 4102-4 without further testing in building material class A1.

As detailed in Table 88, fire-resistance ratings that provide the duration for which a passive fire protection system can withstand a fire is shown for various earthen construction techniques.

Table 88: Summary of fire testing for clay materials

Material	Rating (hrs) / Test duration (hrs)	Load Bearing	Hose Stream	Thickness m (in.)	Standard	Source
Compressed Earth Block	2.0 / 2.4	Y	Pass	0.25 (10)	ASTM E119	(Urban Earth, 2013)
Compressed Earth Block	2.0 / 2.4	Y	Not done	0.25 (10)	ISO 834 (similar to ASTM E119)	(Buson et al., 2012)
Compressed Earth Block	2.0 / 4.1	N	Not done	0.15 (6)	EN 1363-1 with ISO 834 time-temp curve to 120 min.	(Buson et al., 2012)
Rammed Earth Block	3.6 / 7.3	Y	Not done	0.15 (6)	AS 1530-1975 (based on ISO 834)	(CSIRO, 1976)
Adobe Block	4.0 / 4.9	Y	Not done	0.25 (10)	AS 1530-1975 (based on ISO 834)	(Department of Transportation and Construction Australia, 1982)

By using fire-resistance rating, earthen building standards are able to provide a comparable measure for clay-based materials following standard fire tests. The following excerpt, from Section 5.5.1 on Fire Resistance from the NZS 4297 (1998a) indicates a two-hour rating for all three conditions addressed in the NZ Building Code: structural adequacy/integrity/insulation (i.e., 120/120/120):

5.1.1. FIRE RESISTANCE

The fire resistance of earth construction shall be taken as 120/120/120 for a wall thickness of 150 mm unless proved greater than that by testing in accordance with NZS/AS 1530.

Similarly, Section 4.6 on Fire Resistance Level from the Australian Earth Building Handbook, HB195-2002 (Walker et al., 2001) states:

> 4.6 FIRE RESISTANCE LEVEL
> In the absence of specific test data, the general fire resistance level (FRL) of earth walls satisfying the minimum thickness requirements outlined in Clause 4.3.4 [external walling – 200 mm, internal walling – 125 mm] may be taken as not greater than 120/120/120, or 90/90/90 where wall thickness is less than 200 mm. For other walls or an FRL in excess of those specified above, the specific proposed construction should normally be tested in accordance with AS 1530.4.

The three numbers in the FRL represent the fire rating for structural adequacy/integrity/insulation. In other words, the time for a 200 mm (8") earthen wall to maintain load-carrying capacity, maintain its integrity, and before heat increase on the unheated side of the wall exceeds accepted limits meets the standard for a 2-hour fire resistance rating.

Despite the existence of these various testing and fire-resistance justification, there is still a gap in the field and experts continue to be challenged to find fire justifications, as one of the experts interviewed attested:

> "I have not seen actual fire testing, which is kind of silly that you would do fire testing on clay materials, that it would burn. There is that information for straw bale and it would be really useful to be able to attach [this kind of information] to earthen building plans. Smoke development, fire rating, and even though it is completely intuitively logical what the results are going to be, it would be helpful to be able to attach those because there's often just questions."

In conclusion, there is a need to record, share, and publish existing information, as well as provide the argument for a fire rating and fire behavior in USA earthen building codes. Additionally, as shown in Table 88, only one test included and passed a hose stream test following the fire-resistance test.

Finally, it must be acknowledged that fire ratings are for systems. There is a need for clear prescriptive guidance for floor and roof systems associated with earthen construction that ensure the natural fire-resistance of earth materials can be realized in a building.

Seismic Design

Seismic design can be a significant concern for earthen structures due to their relatively large mass and typically low structural period (high natural frequency). Seismic design provisions for earthen construction are required, especially for regions of higher seismicity. Despite extensive research on seismic design enhancements for earthen construction (e.g., Blondet & Aguilar, 2007; Tolles et al., 2002; Walker et al., 1998), regional design guidelines are still missing to allow successful permitting of earthen structures in seismic areas, as mentioned by one engineer interviewed:

> "When you talk about adobe in California, it has some definite negative connotations.... in the seismic country... Which I think are a little bit misleading. Obviously, there are safe and effective ways to do seismic adobe that's been proven by

> [researchers in] Peru. But the popular opinion maybe hasn't caught up with technology and research."

Additionally, experts interviewed mentioned that applying seismic design principles from a strength approach, which increases the structural strength to resist lateral forces, can result in requiring larger concrete bond beams and the addition of reinforcement. However, these additions might not work well with the earthen materials (e.g., steel reinforcing bar does not bond well with earthen materials; concrete frame and earthen infill have dissimilar stiffness and are not likely to be designed to work in tandem). One of the engineers interviewed suggested:

> "Publications of standards in English that addresses seismic performance that are research based is really important ... we've had shake table testing done here that was part of the Getty Seismic Adobe Project, but that was really just how existing structures behave in earthquakes. But I think research that evaluates how some of these stability approaches [rather than the strength approaches] could be used in new construction in our construction environment. I think will be super helpful."

One solution might be adopting seismic design principles from a stability approach, as done by (Blondet and Aguilar, 2007) and adopted in the Peruvian Earthen Building Standards. Nonetheless, the NZS uses the strength approach and is used by professionals worldwide. The relative values of the strength and stability approaches should be investigated.

6.6.2 The proposed solution: developing information sharing internationally and adopting successful criteria from foreign standards

Build on Seismic Provisions in the New Zealand and Peruvian Earthen Building Standards

While seismic design principles in earthen standards are context-specific given regional seismic factors, coefficients and design paradigms, some design principles should be universal when developing new codes. Currently, the NZS provides the most comprehensive guide for building with earth in seismic regions. In addition, novel approaches for using earth in seismic regions have been developed in Peru (Torrealva et al., 2006; Vargas et al., 2006), and implemented in the Peruvian earthen building standards.

The seismic provisions in the NZS 4297 include instructions on the application of seismic zones, general design principles and construction requirements for members under seismic loading, flexure and shear design requirements, reinforcement and anchorage details, and foundations design.

Particularly, the NZS is designed in a user-friendly manner, providing both prescriptive requirements and commentary supporting these clauses. Shown in Figure 143, the structure of the standard includes various elements that can assist the end-user's understanding and application of the standard; external references are given by their full title, instructions are given in both text and visual representation, and commentary accompanies the instructions. Overall, 53 comments are provided throughout the NZS 4297 document, including reasoning background, rationale, calculation examples, and recommendations.

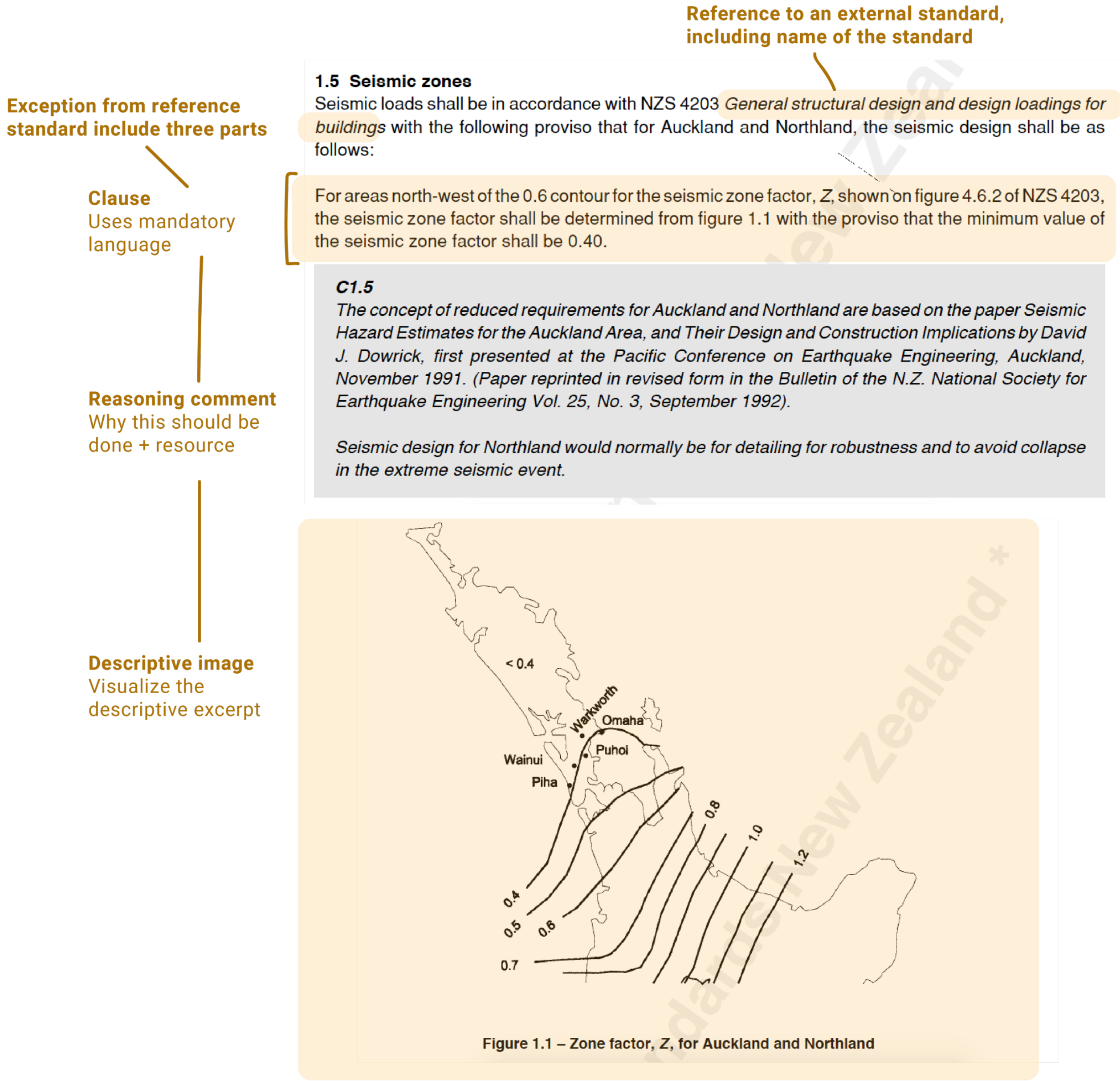
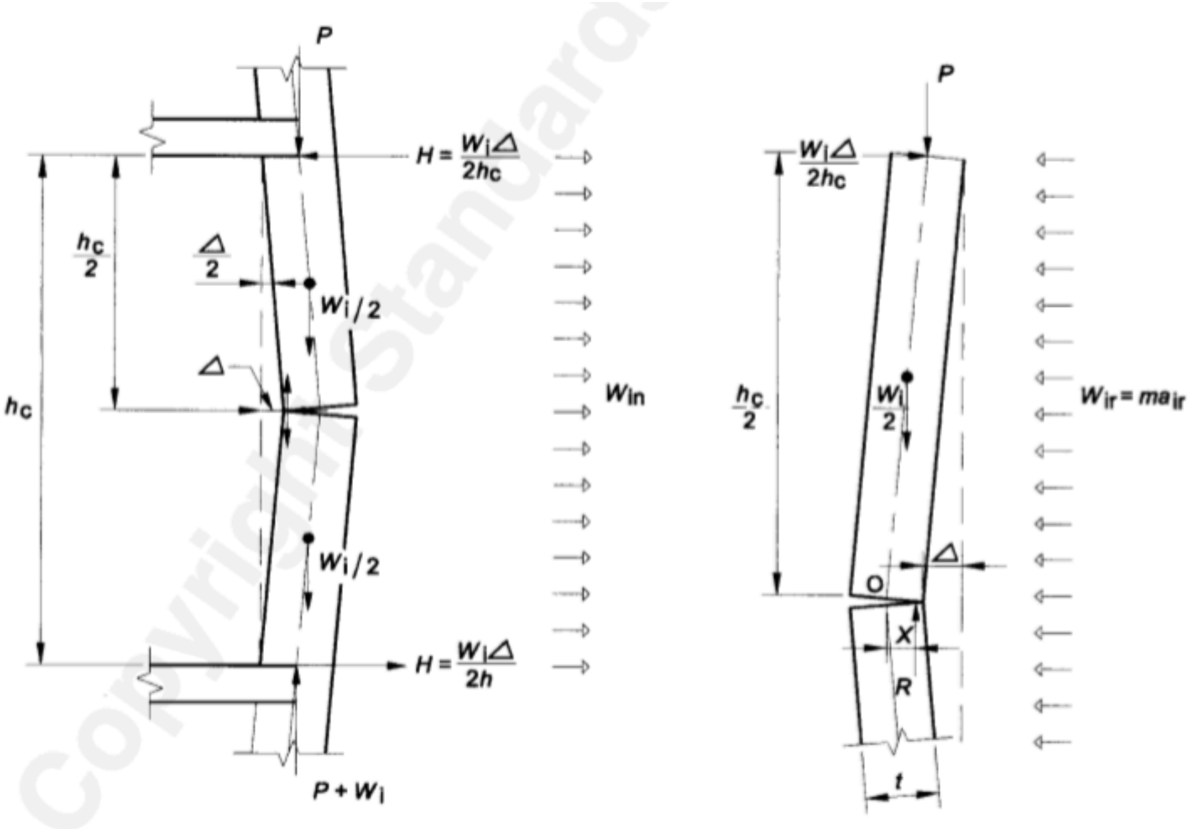


Figure 143: General application of seismic zones (NZS, 1998a, Section 1.5)

In order to facilitate usability, the NZS also provide calculation examples, including notation, calculation procedure steps, and comments for interpretation. For instance, an additional NZS appendix provides a detailed method for determining the seismic resistance of unreinforced earthen walls. For example, as shown in Figure 144, the NZS appendix clarifies all forces and reactions associated with the rigid-body mechanics simplification of out-of-plane wall behavior.



(A) FORCES ON FACE-LOADED WALL INCLUDING LATERAL REACTIONS

(B) MOMENT EQUILIBRIUM FOR FACE-LOADED WALL

Figure 144: Summary of loads, forces, and actions on unreinforced earth wall (NZS, 1998a, Appendix B)

Additional prescriptive requirements for members designed for seismic loads are given, including slenderness limits adjusted for reinforced members according to the earthquake zone factors, and reinforcement. For reinforced earthen members, NZS 4297 provides steel reinforcement, geomesh reinforcement, and anchorage requirements. Figure 145 illustrates a prescriptive requirement for vertical reinforcing including required anchorage details to the bond beam.

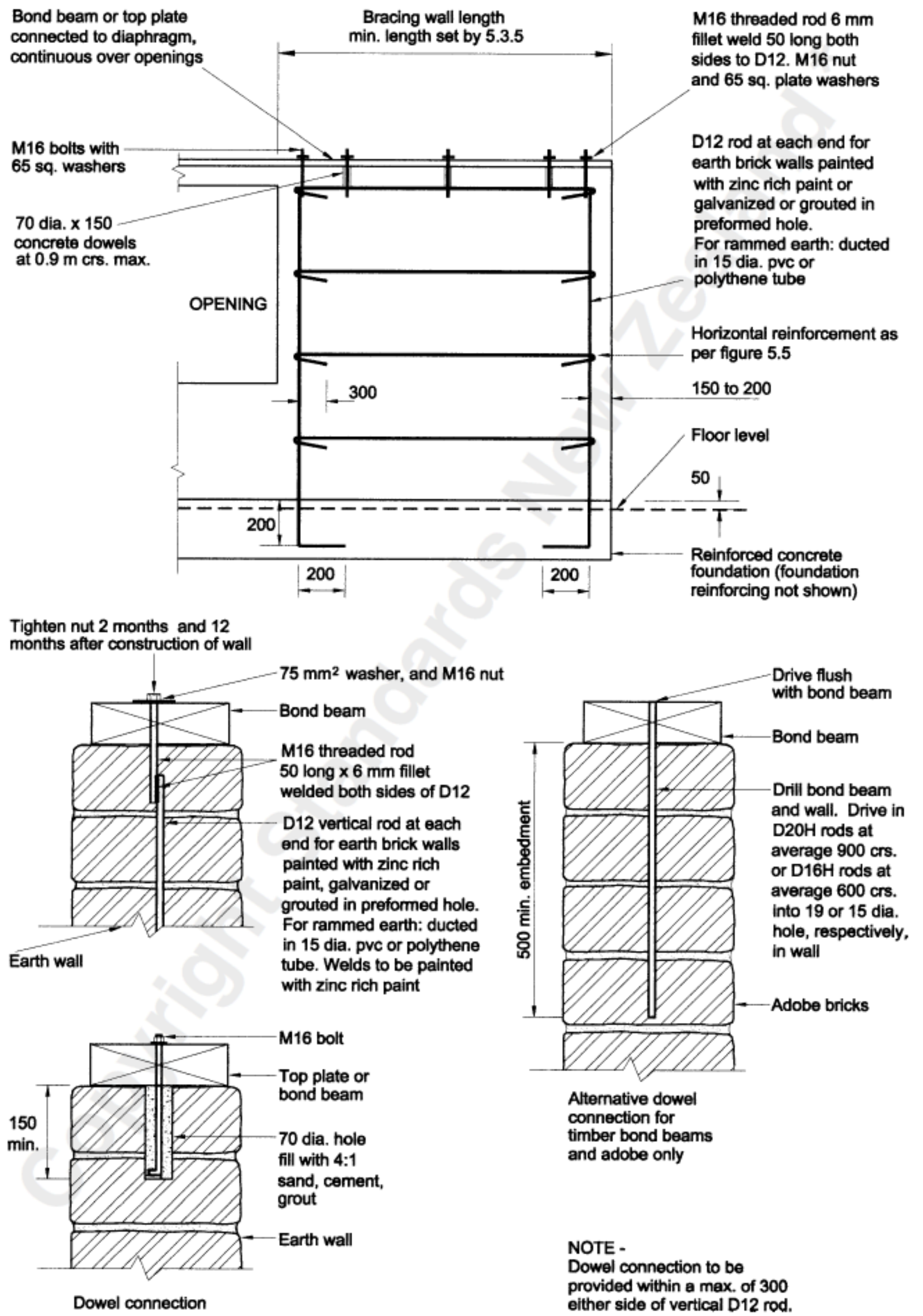


Figure 145: Reinforcing and dowels for reinfoced and partially reinforced earth walls (NZS, 1998c, Section 5.7)

As opposed to the strength approach taken in NZS, the Peruvian Earthen Building Standard uses the stability approach with vertical and surface reinforcement options using rods and pins, polymer mesh (geomesh), as well as natural materials such as bamboo and flattened sugar cane fibers as shown in Figure

146 to Figure 148. These strategies were evaluated using dynamic shake table testing, showing that the geomesh confined the earthen walls, significantly reducing wall displacement and improving ductility for seismic energy dissipation, as compared to the steel reinforced alternatives (Torrealva et al., 2006; Webster, 2012).

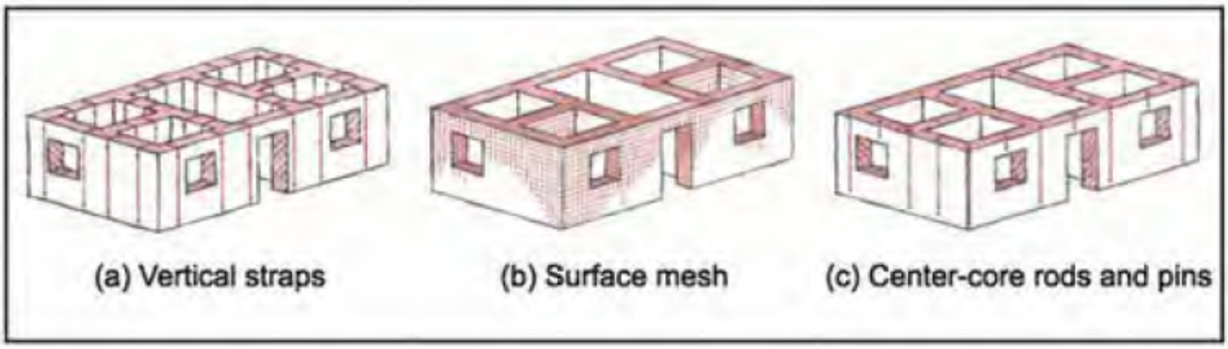
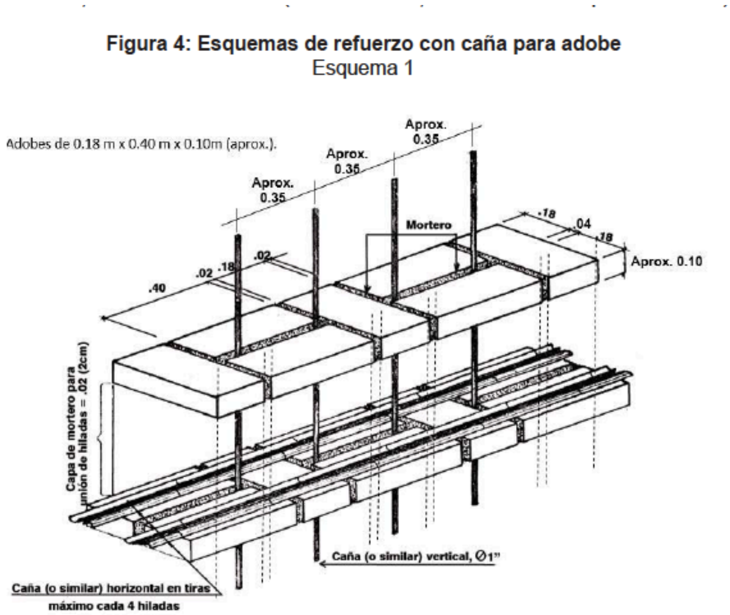


Figure 146: Overturning stabilization using simple and effective seismic retrofit techniques, as suggested by (Webster, 2012)



"Note: It is recommended to place horizontal rod reinforcements (or similar) every four courses in the lower third of the height of the wall (be the building of 1 or 2 floors), every three rows in the central third and every two rows in the upper third. At the maximum, every four courses."

Figure 147: Rod reinforcement for adobe (National Building Standards of Peru, 2000, section 6.10)

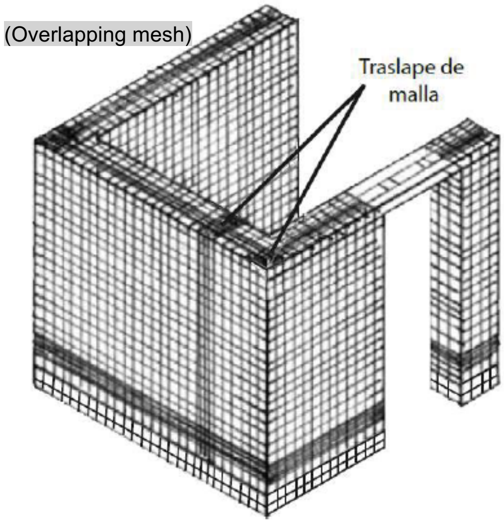


Figure 148: Geomesh reinforcement placement scheme (National Building Standards of Peru, 2000, section 6.10)

Address Regional Material and Assembly Variability through Classification

One of the main challenges to the emergence of earthen materials standards is the high variability of material characteristics and reliance on local construction methods. Earthen materials are often locally sourced and processed or mixed on site. Regional variations are also evident in the construction processes used (e.g., working mixes, drying time) and the required performance of the building outcome (e.g., structural, thermal, durability). To illustrate these variations, Pullen & Scholz, (2011) completed an experimental study of cob technical performance, collecting specimens from local builders, revealing a substantial variation in the plasticity index results (indicated by a high coefficient of variation) among the different mixtures. In terms of building standards, this high variability reduces characteristic strength values resulting in inefficient utilization of the material. This, in turn, could potentially lead to unrealistic required building element dimensional requirements and increased environmental and monetary costs. Furthermore, due to their variability, and in order to verify their code compliance and desired performance, natural materials often require more frequent field tests. Emphasis on local determination of properties can, in many cases, mitigate these issues but at the expense of more testing.

The challenge of material variation can be addressed by various strategies. Wood is an example of a natural building material with large variability for which both prescriptive and performance standards have been developed. While the number of wood species is great, the main strategy used in timber standardization is to group species according to their structural properties and appearances, prescribing uniform grade-use data for each group. Similar to timber codes and standards, such a homogenization approach should be developed by grouping different species or 'classes' of clay materials to ensure adherence with format and objectives of conventional standards, as illustrated in Figure 149 and Figure 150

Figure 149: Homogenized soil classification, assessed in accordance with Australian Standard (MJM Consulting engineers, 2017)

Detailed classification within a soil textural triangle is another approach. For example, Figure 151 shows acceptable soil textural limits for stabilized and unstabilized rammed earth applications.

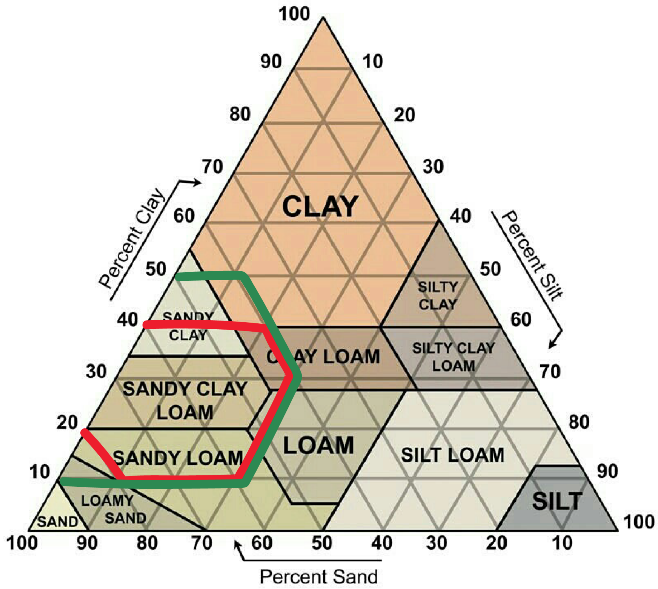


Figure 150: Classification of soil suitable for stabilised (green) and unstabilised (red) rammed earth (after NZS 1998)

The challenge of high variability of technical data should be addressed by online resources as recommended by one of the experts interviewed:

> “Nobody knows what knowledge we have about earthen building; nobody has a sense of it ... that's very easily possible that somebody in India ten years ago did exactly that test and just nobody knows about it or somebody in China or somebody in Brazil did. The Brazilians do all sorts of cool stuff and nobody knows about ... Building an online library so it all can be in one place. So, if you want to know what we know about the compressive strength of cob or the acoustic qualities of rammed earth or

whatever it might be, you can just go to the library and search and find what's been done."

One prominent solution for addressing the challenge of the high variability of earthen construction would be to utilize the Materials Informatics approach, which uses multiscale material sampling to construct a robust and accurate database. By using artificial intelligence (AI) and deep learning models, Materials Informatics can be applied to process structure-property relationships of earthen materials and to discover correlations between a variety of characteristics and properties (Zheng and Nettleship, 2019).

Developing an online earthen building information sharing source

Technical data on natural and healthy building materials is scattered and disaggregated, often leaving conventional building materials the default for construction. There is, therefore, a need for an online open source that could disseminate earthen material data to building professionals. This (necessarily curated) "source" should provide an online open-sourced library, enabling the sharing of information that could open up the possibilities for building with earth. In addition, materials informatics data-driven approaches could be embedded in order to aggregate scattered patterns into robust and meaningful performance matrices.

The development of this kind of earthen building library source must include expertise for the identification, curation, and structuring of information for accessibility. The conceptual framework, as shown in Figure 151, should be built upon existing references to research papers, books, and technical documents, while providing aggregated performance data, as well as design and construction recommendations. In addition, the performance synthesis could be used by earthen building researchers in identifying where additional research may be needed

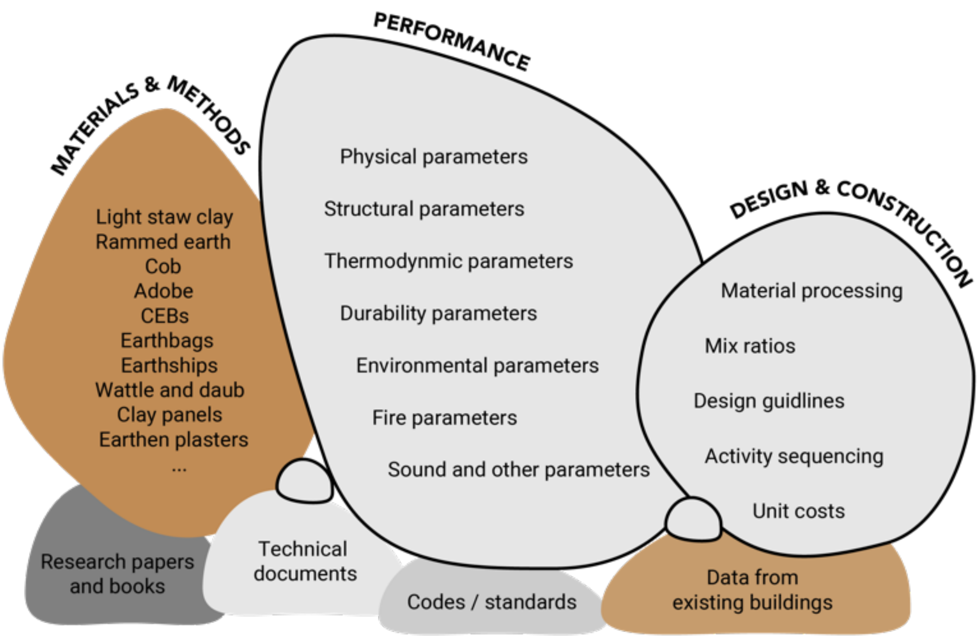


Figure 151: The conceptual framework of the earthen building library

Illustrated in Figure 152, the user interface of the earthen building source should be designed to meet the needs of the various building professions and end-users, from occupants and builders, to designers, product developers, and building officials. The library should facilitate activities beyond the use of performance data, such as uploading resources and building data points, learning about earthen building performance and benefits using online educational modules, rating earthen building products, and connecting with professional individuals and groups. Lastly, the earthen building library source should provide improved design and construction data for users, as well as promote training opportunities to foster knowledge and awareness of earthen materials and make them more marketable and accessible.

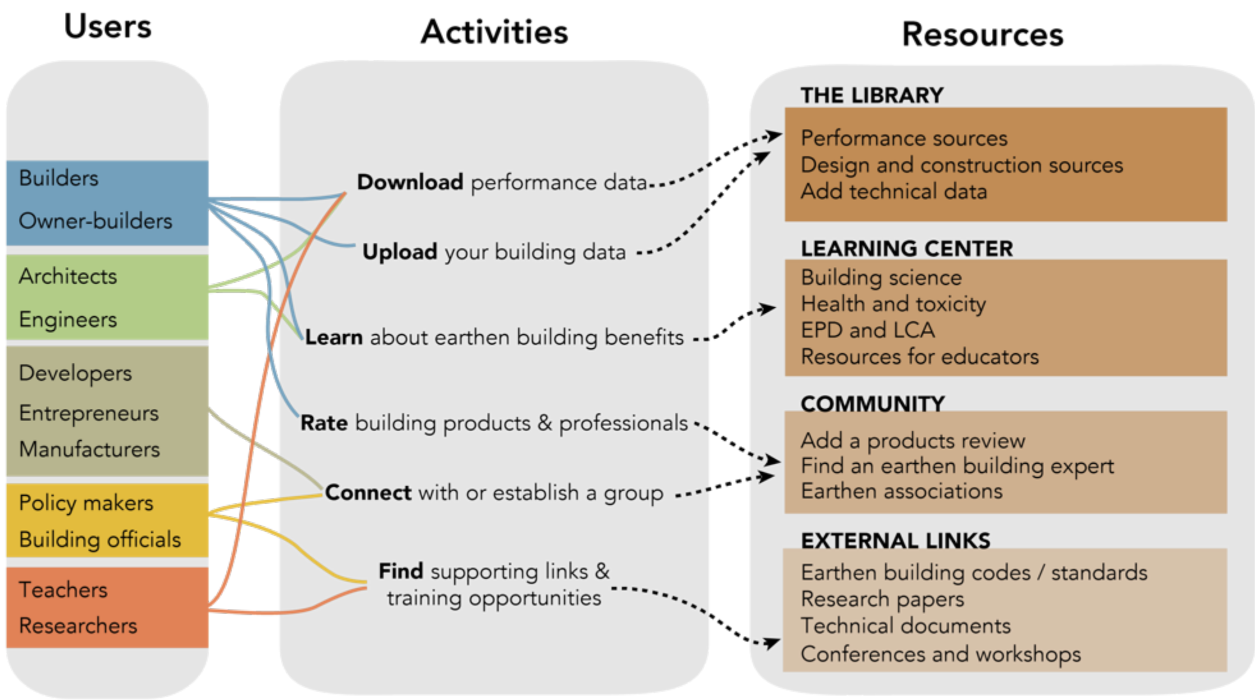


Figure 152: Structure of an online earthen building library

In order to manage large amounts of data, the library should integrate methods to mine and curate data from previously published information using data-driven approaches. Some of the long-term missions of the library should be to facilitate networking and collaborations between users, experts, manufacturers, and building officials, by allowing each user to share their experiences and review products and services.

6.7 Conclusions and discussion

The analysis of existing earthen codes and standards are few. Although significant, these studies do not include a critical investigation of the cross-regional solutions and improvements that could be obtained for the development of an international earthen building regulation with regional and local guidelines. This chapter investigates which improvements are required in existing earthen building codes and standards, as well as for future international earthen building standardization. The methodology of the policy analysis in this chapter includes a hybrid approach of existing policy evaluations and recommendations for a positive change in a future scenario.

By using the results of the survey analysis from Chapter 3, in-depth interviews from Chapter 2, and existing earthen building codes reviews, this chapter concludes with the following key challenges:

The expertise challenge:

Earthen building regulation is unfamiliar among building officials, resulting in a costlier and slower permitting process than convention buildings.

The code development challenge:

Earthen codes development in the US is currently pursued by advocates, volunteers, and small NGOs that are competing against commodified materials committees.

The technical challenge:

Many earthen building codes are incomplete and missing technical aspects, such as seismic and fire prescriptions.

Proposed solutions were drawn for each problem by analyzing the response of the interviewed experts as well as reviewing existing earthen building codes. The converged solutions form the following key recommendations:

When earthen codes are still missing, end users should use foreign documents and foster collaboration with officials

Where earthen building codes and standards are still missing, experts and end-users should provide officials with justification and documentation from existing resources to reduce "case-by-case" inefficiencies. Building officials take personal responsibility on variances, therefore, a collaborative communication with building officials should be fostered by inviting officials to existing job site and providing as much technical data as possible. As one of the interviewed architects mentioned:

> "My most recent [encounter with building officials] was unbelievably positive - the building inspector was at the job site and he was talking to the builder who was not sure how to make a railing that curves along the cob wall. And the inspector said: 'well, the clay is really strong. Can you just carve railings out of clay?' And that's what we did. There's five of them and he approved them all. So that was a really positive interaction, where he came to the job site so many times and he could feel how strong the wall is, and he had this transformation of trust"

Specifically, foreign standards and codes should be used by professionals to justify technical aspects in the absence of a local earthen building code. For instance, seismic guidelines from NZS 4297 and the Peruvian earthen building codes should be used for earthquake resistance design details and the list of existing fire tests from Table 88 should be compared to the material that requires permits for fire-resistance justification.

Additionally, overcoming unfamiliarity among building officials must include training and educational workshops for code officials and building professionals. These educational opportunities should be invited by local authorities and developed by professional earthen building organizations. Educational modules should include theory, field awareness, and practical experience, while partnering with vocational and trade-oriented universities, as well as construction firms.

Creating a USA National Institute for Earthen Building to foster earthen building education, innovation, and building codes

Successful earthen building regulations development processes from around the world illustrate the critical need for collaboration among governmental entities, practitioners, and a strong earthen building professional organization, in the development of future earthen regulations. Such a unified earthen building organization is still missing in the USA, where various organization with unique focus and narrow geographical interest exist. Such an umbrella organization promulgates a shared vision to promote the use of earthen construction and could lead efforts that would benefit all organizations.

This national institute/association should be a board-based, membership-oriented, non-profit association that vigorously promotes earthen building in the USA by providing educational leadership and knowledge as well as building networks and collaborations. This association will work with established associations and companies. Forming a unified USA earthen building institute or association should include four mission tasks: education and training development, research and code development, EPD and LCA development, and online library curation to synthesize performance data. Specifically, the online library should be developed to promote information sharing among the different earthen building stakeholders.

The organization's research and code development team should be dedicated to improving existing earthen building codes, as well as developing a proposal for an international comprehensive earthen building code that includes the various earthen building techniques in one place. Whereas serving on a code committee requires commitment to the entire process, fundraising efforts would have an imperative role in the success of this mission.

Developing an international comprehensive earthen building codes using existing examples and field data

The development of a comprehensive earthen building code (or a code-compliant standard) should follow a framework for reducing the complexity and measuring the quality of the code proposal. As outlined in Harries et al. (2019), the "purpose" of the code must first be identified to guide the drafting of the document at all stages. For instance, a very specific mission statement is included in the NZS:

> "The objective of this Standard is to provide for the structural and durability design of earth buildings. The Standard is intended to be approved as a means of compliance with clauses B1 and B2 of the New Zealand Building Code"

A more general specific example for the international earthen building code may *be to codify existing information and knowledge on earthen building in order to ensure structural safety and design integrity while providing means of compliance with building codes and supporting innovative design* (after Harries et al., 2019).

In developing a comprehensive earthen building standard, the language must be mandatory ("shall", rather than "should" or "may") to ensure possible reference from within building codes. Standard development might allow additional elements such as navigation flow charts, typical design cases, and construction guidelines schemes.

As the development of an earthen building code is a long and complex task, some immediate and simple changes to existing building codes for concrete might also be beneficial to promote stabilized earthen components that replace some content of cement with clay binder, as suggested by the interviewed structural engineer:

> "If I, as a structural engineer, am designing a building and I'm making a concrete wall, I can use some fly ash to replace some cement. I can use some slag. But I cannot make clay-based concrete and that is a little part of the code we could change and that would open up a door for sure."

The comprehensive earthen building code should not start with a "blank page", but rather should use existing USA and foreign earthen building codes and standards. Successful code examples, such as the Appendix R for light straw clay, should be used in its current state. Other code sections that were shown to be less user-friendly, such as the IRC adobe masonry chapter, should be improved. Additionally, Prescriptions for underrepresented techniques such as cob and earthbags should be written anew. Lastly, existing codes and standards as well as committee constitutions that prove successful should be used as exemplars to avoid excessive complexity that results from "re-inventing the wheel". These include the NZS seismic provisions and the German DIN inclusion of LCA within the code. Specifically, EPD and LCA should be used within the code to provide regulatory and financial incentives to users, as further reinforced by one of the interviewees, a building policy expert:

> "Doing an LCA makes a lot of sense because the next well-being hazard to billions of people everywhere is climate change. And the building code, under its current mission, should be extended to mitigate demonstratable harm that will come to people through the use of inappropriate construction materials that have high embodied energy and carbon content."

The usability of the proposed code must be based on the needs and expectations of earthen building users and must include a complete suite of earthen building techniques. Simplicity and understandability should be improved while mitigating inappropriate applications and allowing innovative successful solutions. For instance, simplicity and ease-of-use may be enhanced through integrating commentary and visual explanations throughout the clauses, as done extensively in the NZS. Particularly, prescriptive clauses should include the supporting reasoning behind the requirements to allow design changes and case-by-case modifications. Furthermore, various elements that can assist the end-user's understanding and application of the instructions must be included; external references should be clearly cited (an annotated bibliography can be useful), and calculation methods should include visual schemes.

Overcoming materials variability should be achieved by following existing highly variable natural materials predecessors such as wood. For instance, homogenization approaches from timber codes and standards use grouping of different species or 'classes' of materials. Similarly, for earth, different types of construction soils could be categorized utilizing Materials Informatics approaches and multiscale material sampling to create a robust database.

In summary, regulatory development processes are highly dependent on market and field forces, while also being reliant on adequate research. The analysis presented in this chapter contributes to the development of adequate earthen policy and could be used by policy makers and advocates in their endeavors to form an industry association and overcome organizational challenges in the advocacy of earthen materials. Specific recommendations for earthen building users and experts are drawn, including suggestions to advance permitting processes in the absence of a local earthen building code, motivation for forming a USA national organization for earthen building, as well as a pathway to develop an international comprehensive earthen building code.

7 Conclusions, Limitations and Future Research

7.1 Earthen Buildings are Critical for our Future

Building with earthen materials, with techniques including rammed-earth, adobe, cob, and compressed earth blocks (CEB), is a critical alternative to conventional construction materials because they are readily available, minimally processed, low-carbon, healthier, and biodegradable. In projects around the world, earthen materials have been shown to buffer indoor temperature and relative humidity due to their excellent thermal inertia properties coupled with their high hygrothermal performance. Despite their advantages, earthen materials have not been broadly implemented, primarily for technical, perceptual and policy reasons. First, technical data on earthen materials and assemblies varies significantly, making it challenging to quantify their true performance for different climates. Second, there is a broad and often negative perception that earthen materials are a "poor-man's material" and low-tech. Lastly, earthen materials are not comprehensively represented in building codes and standards. In light the benefits of earthen construction and in consideration of the challenges, this research was prompted to provide justification, demonstration, and code permission possibilities for earthen materials.

The objective of this dissertation was to develop perception-based, performance-based, and policy-based assessments that could be used by policy makers and give rise to a top-down implementation of earthen building materials and methods. To achieve this goal, the research incorporated the following critical steps:

1. Analyzing the factors that affect interest and barriers to using earthen building materials among experts and end-users using perception surveys and in-depth interviews.

2. Developing a cradle to grave environmental Life Cycle Assessment (LCA) to compare three different earthen building assemblies with the three common conventional building assemblies.

3. Analyzing existing policy barriers to formulate a policy repair analysis to support policy makers and earthen building advocates in the improvement of earthen building codes and standards.

7.2 Addressing the Perceptual gap: earthen building homeowners and experts' perception surveys results

In addition to a broad literature review, this dissertation identified the range of perceptions about earthen building through phone in-depth interviews and on-line surveys. The main goal was to identify the perceptual barriers that hold back earthen buildings' broader implementation and to ascertain possible solutions to these barriers.

Ten in-depth interviews were conducted to gain detailed insights and examples about earthen building barriers to field-implementation of earthen construction as well as explore the respondent's point of view about required research in the field. The main challenges were extracted and cited from each interview and analyzed according to their perceived causes and effects. Five major gaps were identified from the in-depth interviews: technical, perceptual, regulatory, implementation, and innovative gaps. Shown in Figure 45, each of these gaps were shown to entail specific barriers. For instance, the regulatory gap led to a barrier in obtaining building permits and insurance for earthen structures; the implementation gap led to lack of design and construction professionals; the innovation and technical gaps were shown to keep earthen construction in a traditional niche.

Following the in-depth interviews, 126 unique online survey responses were collected from earthen building experts and homeowners from around the world. The survey gathered information regarding a range of barriers to, and motivating factors for, the implementation of earthen materials, as well as design and performance aspects of earthen homes, from 74 experts, 35 homeowners (including 19 experts), and 36 potential homeowners.

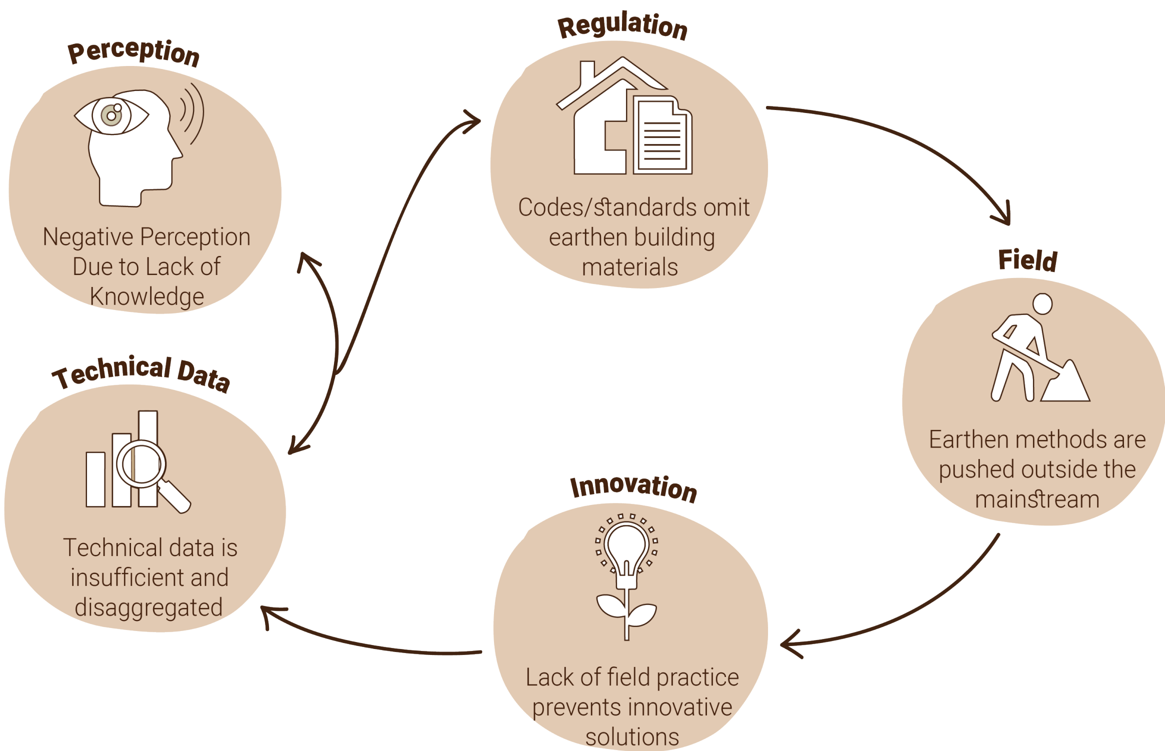


Figure 153: The cycle of key implementation gaps of earthen building materials

Barriers to and motivation for using earthen building materials

The results of the dissertation survey show that earthen construction is not pervasive because it is limited by aesthetic perception, technical knowledge, and policy limitations, with significant differences in priorities between experts, homeowners and potential homeowners.

For earthen building experts and potential homeowners, the most challenging barrier was shown to be obtaining building permits. For current homeowners, the most challenging barrier was shown to be labor intensity and maintenance, presumeably because they have already passed the hurdle of obtaining a building permit. Illustrated in Figure 1, Compressed Earth Bricks (CEBs) and rammed earth were shown to suffer most from a lack of design and/or construction professionals. Furthermore, light straw clay showed the best results for low maintenance, and adobe and clay plaster showed the best scores overall, with the fewest perceived barriers.

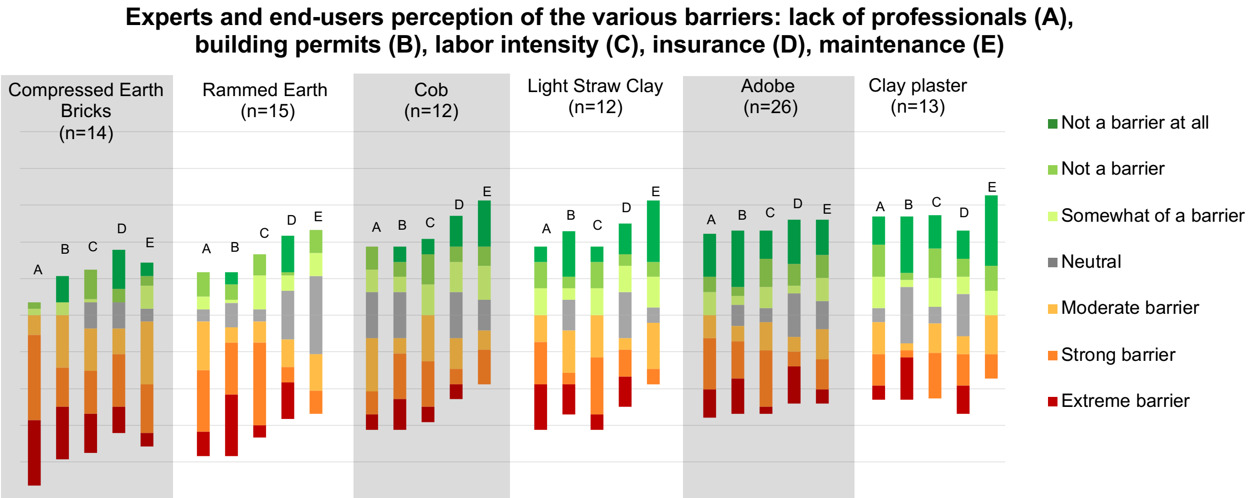


Figure 154: Experts and homeowners are mostly challenged by lack of professionals and building permits for compressed earth bricks

The dissertation survey included a visual preferability assessment of earthen structures among potential homeowners, revealing a ranking of earthen construction techniques. In brief, the potential homeowners surveyed prefer more rectilinear buildings, natural colors, and earthen materials in the interiors, rather than the more colorful and irregular options often typical of earthbag construction, for instance.

The main survey findings about earth building experience among experts that participated in the survey, including architects, structural engineers, builders, contractors, teachers, and researchers, revealed that the most experienced techniques were clay plaster, adobe, rammed earth, and cob, and mostly in residential projects.

Relative to building code-related questions, 24% of the experts reported using conventional building codes to permit their earthen projects, 14% used the German earthen building code, and 11% used the New Zealand earthen building standard series. . Of the experts who use building codes, 27% (n=15) had been applying conventional material codes to their earthen building projects. This finding might indicate that even within the earthen building community, earthen building codes are either unavailable or unfamiliar. It might also be that permitting authorities are unfamiliar with such codes and therefore require projects to be “fit” into existing code frameworks. As illustrated in Figure 62, experts also identified that using earthen building codes results in a costlier and longer permitting process compared to conventional building projects, with the greatest impact stemming from the use of US-based earthen codes.

Quality rating for different codes/standards, according to experts participants, in terms of representation (A), user-friendliness (B), cost to permit (C), time to permit (D), and familiarity among building officials (E)

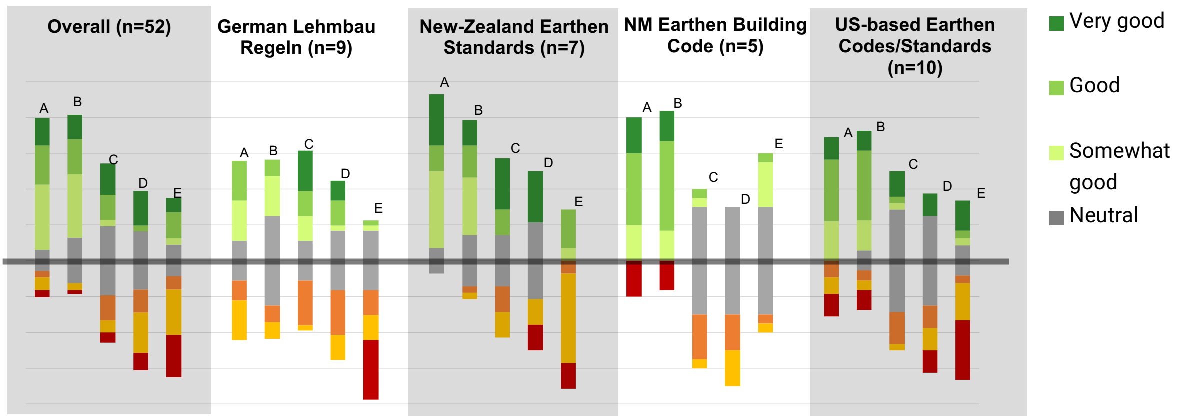


Figure 155: According to experts, earthen building codes/standards are not familiar among building officials, and result in a costlier and longer permitting process

Based on these results, the mission of overcoming the regulatory gap barrier may begin with drawing from the benefits that were voted for each existing earthen building code: New Zealand earthen standards were preferred for their representiveness of the various earthen techniques. The New Mexico code was found to be most user friendliness and familiar among code officials, presumeably because it is cited from within the IRC. Although being the least familiar to permit officials, the German Lehmbau Regeln was shown to provide the best permitting process that does not incur higher cost and delay.

Overall, the key survey findings indicate that in order to change negative perceptions among prospective homeowners and the design community, the quality and performance of earthen buildings must be promoted and building regulation hurdles should be overcome.

Increasing awareness about earthen building should be approached differently for each target group. For experts, who rated resource depletion and climate change as the most valuable factors for decision makers, environmental advantages should be enumerated to highlight the urgency of earthen construction. For homeowners and potential homeowners, health and indoor air quality advantages should be investigated and promoted, mainly for clay plaster that was shown to be used mostly by earthen homeowners (51% of homes) and found to be most attractive in the visual assessment for potential homeowners. For instance, future research about contaminant reduction and thermal comfort derived from clay plaster, should be catalyzed.

Surveyed earthen building homeowners: energy data and perceived comfort

Earthen building homeowners were asked about the performance of their earthen homes. Adobe was shown to be the most used earthen building techniques in the respondents' homes. Of the earthen homes, 55% reported to have no supplemental insulation, as shown in Figure 156. Insulation types, when reported, included 24% straw bales, 9% light straw clay, 6% blown cellulose, and 6% sheep's wool. None of the homeowners reported synthetic insulation in their home.

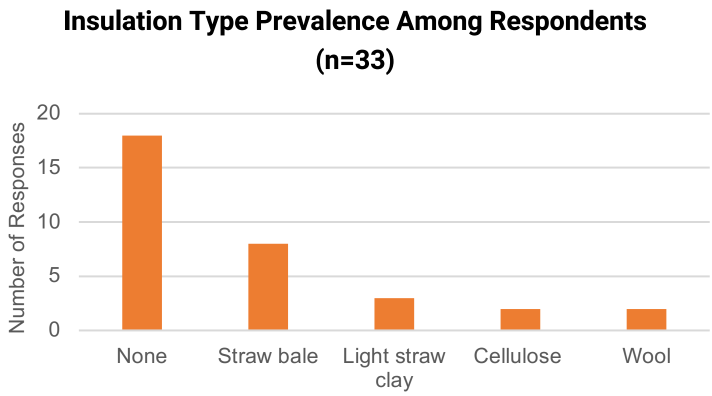


Figure 156: Homes are mostly uninsulated (55%), and no homes in the study contain synthetic insulation

75% of homeowners – residing in ASHRAE climates 2-6 – reported that their house has no cooling system. These results, shown in Figure 157, might indicate that earthen homes reduce the need for cooling, for all climate zones. A Few passive cooling systems – including shading and open windows – were indicated to be "activated" (manually) by the owners for several months per year. 51% of homeowners indicated using wood-burning stoves to provide heat in winter. Among the passive strategies employed, homeowners indicated using solar air heaters, earth air tubes for tempered ventilation, trombe walls, and sunlight.

The results of the perceived thermal comfort indicate that 94% of earthen homeowners are comfortable within their home during summer days, 91% during winter days, 89% during summer days, and 86% during winter nights. In terms of perceived humidity comfort, 52% occupants reported to be comfortable, 59% of which have uninsulated homes.

The existing homeowners survey results may be a key part of the solution to changing perception. The earthen homeowners' comfort and the energy performance of their earthen homes show that insulation over earthen walls may increase comfort levels, but only slightly. This last observation also showed that insulated earthen assemblies were more likely to be suitable for passive cooling. These results should be further studied to gain more insights for thermal performance and comfort guidelines for earthen structures.

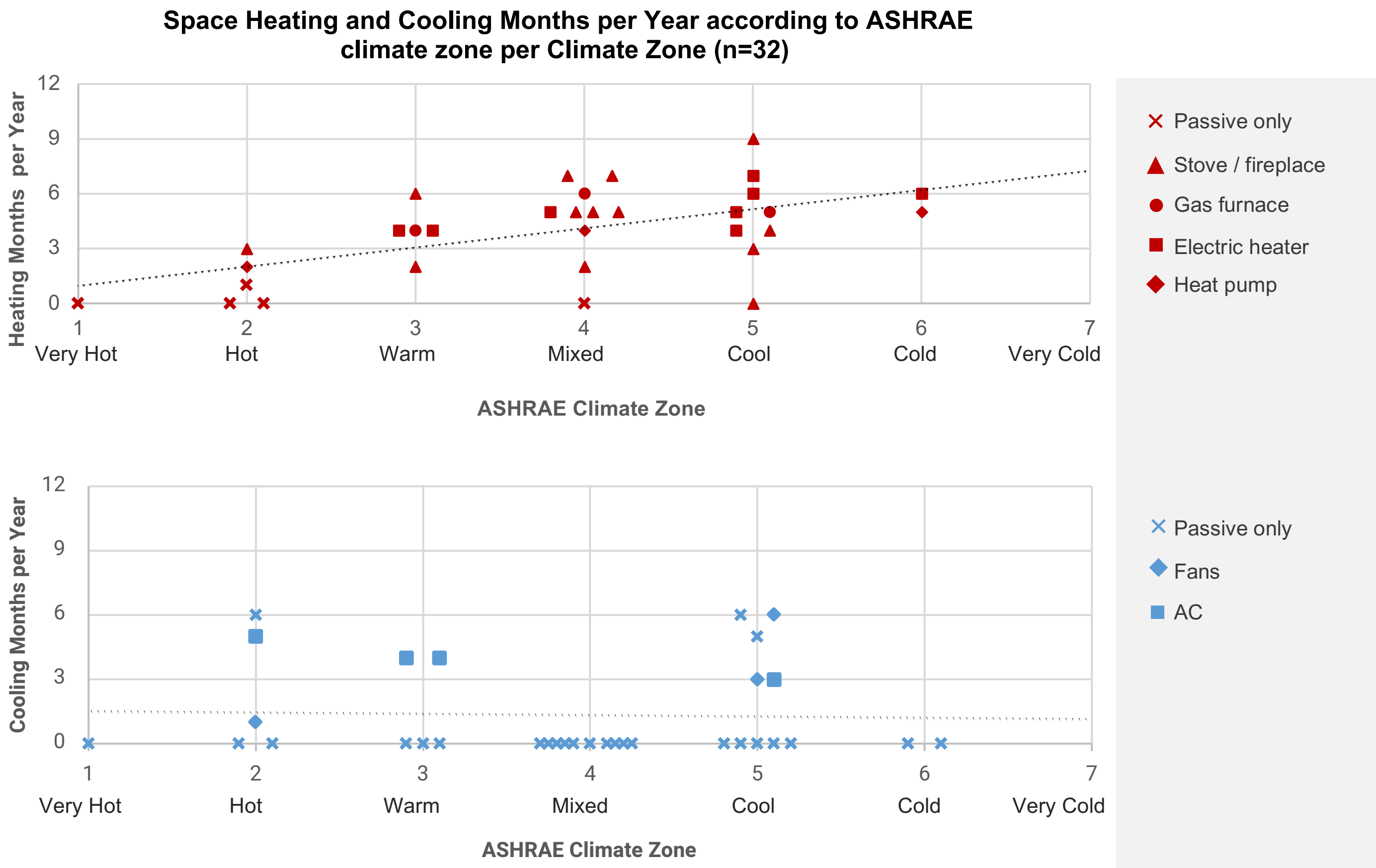


Figure 157: Earthen homes reduce the need for cooling, for all climates

7.2.1 Addressing the Technical gap: earthen building life cycle assessment results

This dissertation developed a Life Cycle Inventory and used Life Cycle Assessment to evaluate the embodied and operational environmental impacts of three earthen assemblies (rammed earth, cob, and light straw clay) and compared these to three conventional assemblies (wood frame and concrete masonry units (CMU) with and without insulation). A review of the literature and primary research were the basis of assumptions regarding the conventional assemblies. Literature and SimaPro LCA software were used to develop the LCI of the earthen assemblies, which is depicted in Figure 77.

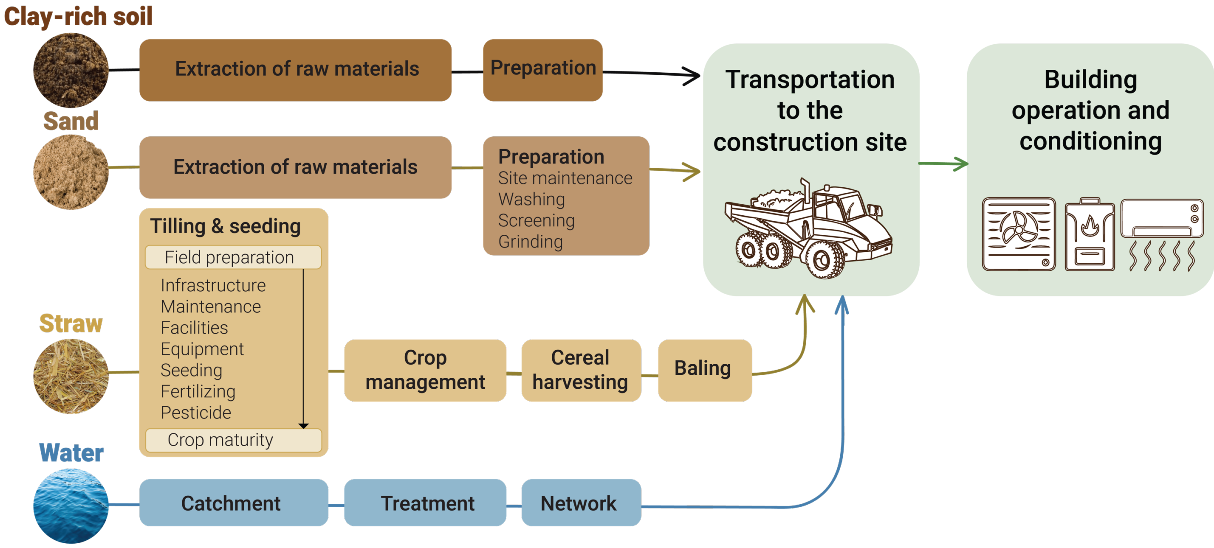


Figure 158: System boundaries of the developed earthen building LCI

The thermal performance of each assembly was assessed for the operational performance using dynamic simulations in EnergyPlus, thereby providing data to support assumptions regarding the heating and cooling loads for a 50-year lifespan. The impacts assessment accounted for energy demand, global climate change impacts, acidification of air, and human health particulate pollution.

The embodied LCA study results, shown in Figure 158, indicate that the environmental impacts of the eight external wall assemblies vary considerably and show the environmental urgency of earthen construction.

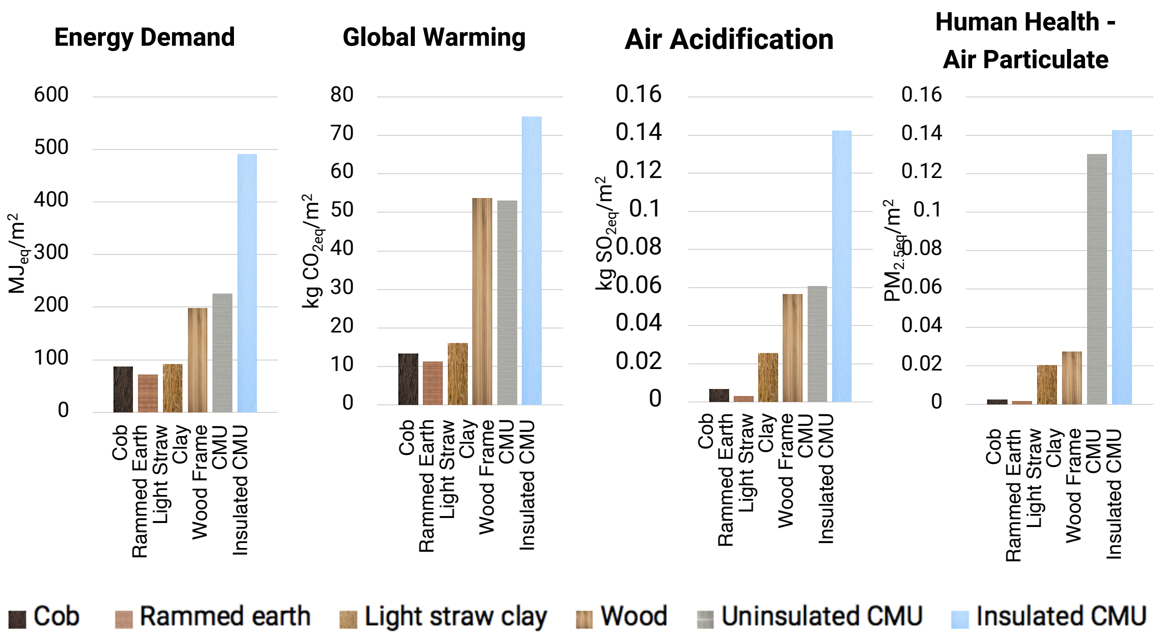


Figure 159: Environmental impacts comparison overview for each wall system, per m^2 wall

Significantly, earthen assemblies were shown to reduce embodied energy demand by 62-68%, embodied climate change potential by 83-86%, air acidification by 58-95%, and particulate pollution by 84-99%.

The greatest challenge for embodied LCA of earthen assemblies is the biological material content (fibers and lumber) which increase the wall energy demand and emissions through their growth and production stages that require herbicides, pesticides, fertilizers, and farm machinery. In addition to these requirements, biological materials require other chemicals, water use, and land use, which were not directly assessed as an individual impact category in this dissertation but do influence the incorporated system processes' emissions and energy demand.

The addition of any cement to the earthen assembly increases embodied energy demand and emissions. Whereas compressed earth blocks may replace concrete, it should be noted that particulate pollution impacts might be a shared problem for earth-based and cement-based materials, because these depend on the scale of manufacturing. To this end, the expansion of earth-based materials manufacturing should be addressed by covering the soil and sand piles.

The addition of synthetic insulation also has harmful embodied environmental effects for any of the wall assemblies, due to the processing of raw materials and use of kiln heaters, combustion boilers, and other manufacturing processes. These impacts might be reduced by using insulation products with recycled content or by using minimally processed insulation materials such as fibers (e.g., straw, hemp), wool, and cellulose.

The operational LCA study results indicate that earthen assemblies have a smaller footprint than conventional assemblies. The operational thermal performance of the earthen and conventional wall assemblies were analyzed for six US cities representative of hot and mild, arid and semi-arid climates: Tucson, AZ (hot desert); El Paso, Texas (subtropical desert); Albuquerque, NM (mild semi-arid) Los Angeles, CA (mild Mediterranean, Portland, OR (temperate oceanic), and Denver, CO (continental semi-arid).

Thermal simulations illustrate that rammed earth and cob assemblies result in temperature fluctuations of less than 1°C (1.8°F) along with a significant 6-10 (hrs) time-lag in passive operation, whereas conventional assemblies showed more fluctuation and a shorter lag. Overall, the light straw clay, providing both insulation and moderate internal heat capacity, was shown to perform better than other assemblies for extreme weather conditions, such as in the hot Tucson summer, and cold Portland and Denver winter. For milder climate conditions, insulated rammed earth, with the highest heat capacity and moderate insulation, performed best. The uninsulated mass assemblies were shown to be preferable only for very mild climate conditions, when the outdoor thermal conditions provide comfortable temperature levels, such as in Los Angeles.

The operational LCA results reveal that while the thermal energy use is dominated by heating loads, the environmental life cycle impact results are dominated by cooling loads. Significantly, when coupling the embodied and operational environmental impacts, as shown in Figure 160 and Figure 161, the earthen assemblies produce lower environmental impacts than the conventional assemblies.

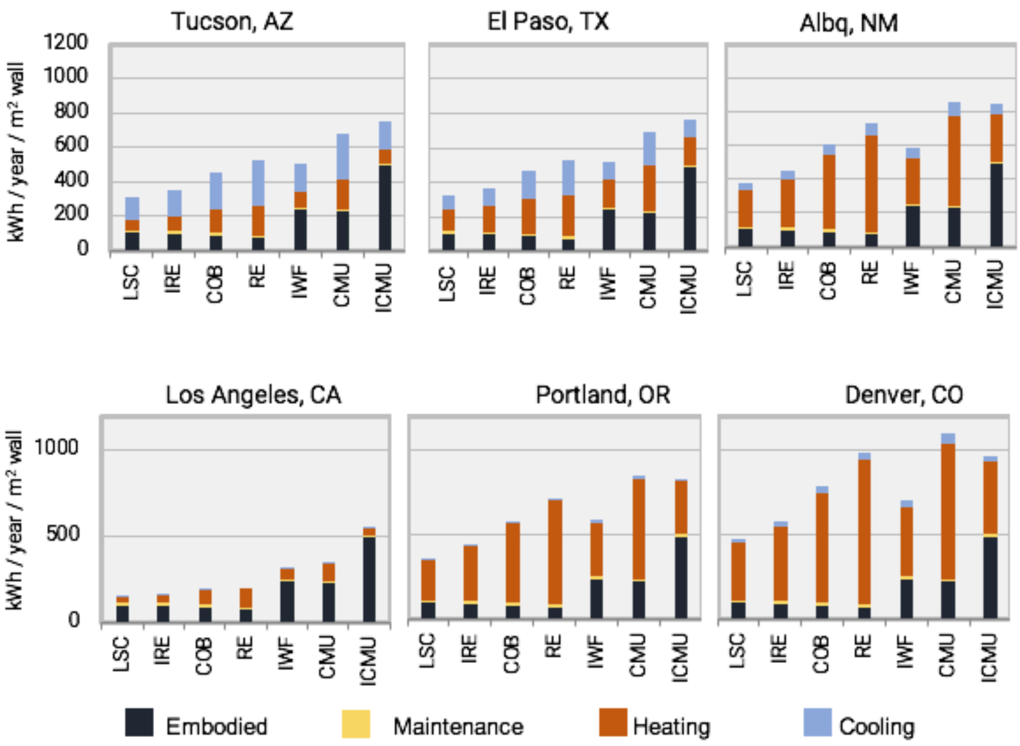


Figure 160: Embodied and operational (heating and cooling) energy demand per 1 m^2 wall impacts for each wall alternative in each climate

The reduced environmental impacts are shown to be more dramatic for emissions. This is due to the fact that embodied energy accounts for energy generation, whereas emissions result from energy generation and also from chemical reactions during materials processing and fugitive emissions during quarry operations. Overall, in terms of climate change impacts, earthen assemblies outperform conventional assemblies by 21-78%. Similarly, air acidification is reduced up to 78%, and particulate pollution up to 97%.

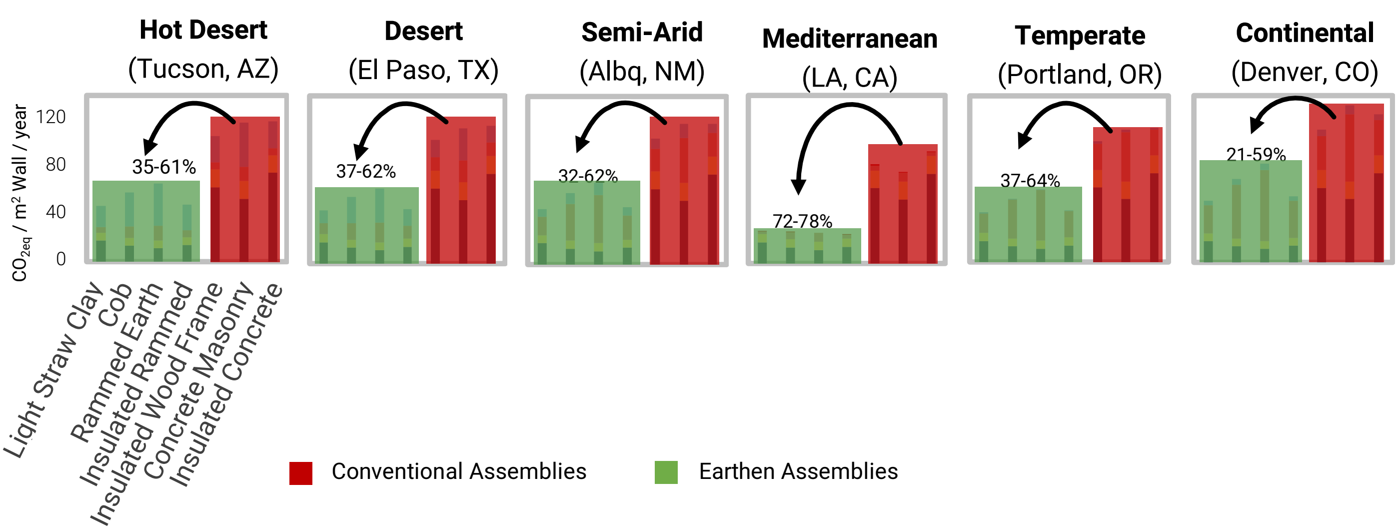


Figure 161: Embodied and operational (heating and cooling) global climate change impacts per 1 m^2 wall for each wall alternative in each climate

7.2.2 Addressing the regulatory gap: earthen building policy analysis results

A critical investigation of earthen building regulations worldwide was completed to support the development of cross-regional solutions and improvements for an international earthen building regulation. The analysis depicts the strengths and weaknesses of existing earthen building codes and standards using code and standard text analysis, experts' survey responses and in-depth interviews. Three critical earthen building regulatory challenges are identified – earthen building codes are unfamiliar, undeveloped, and incomplete, and a set of recommendations were generated, as summarized in Figure 162.

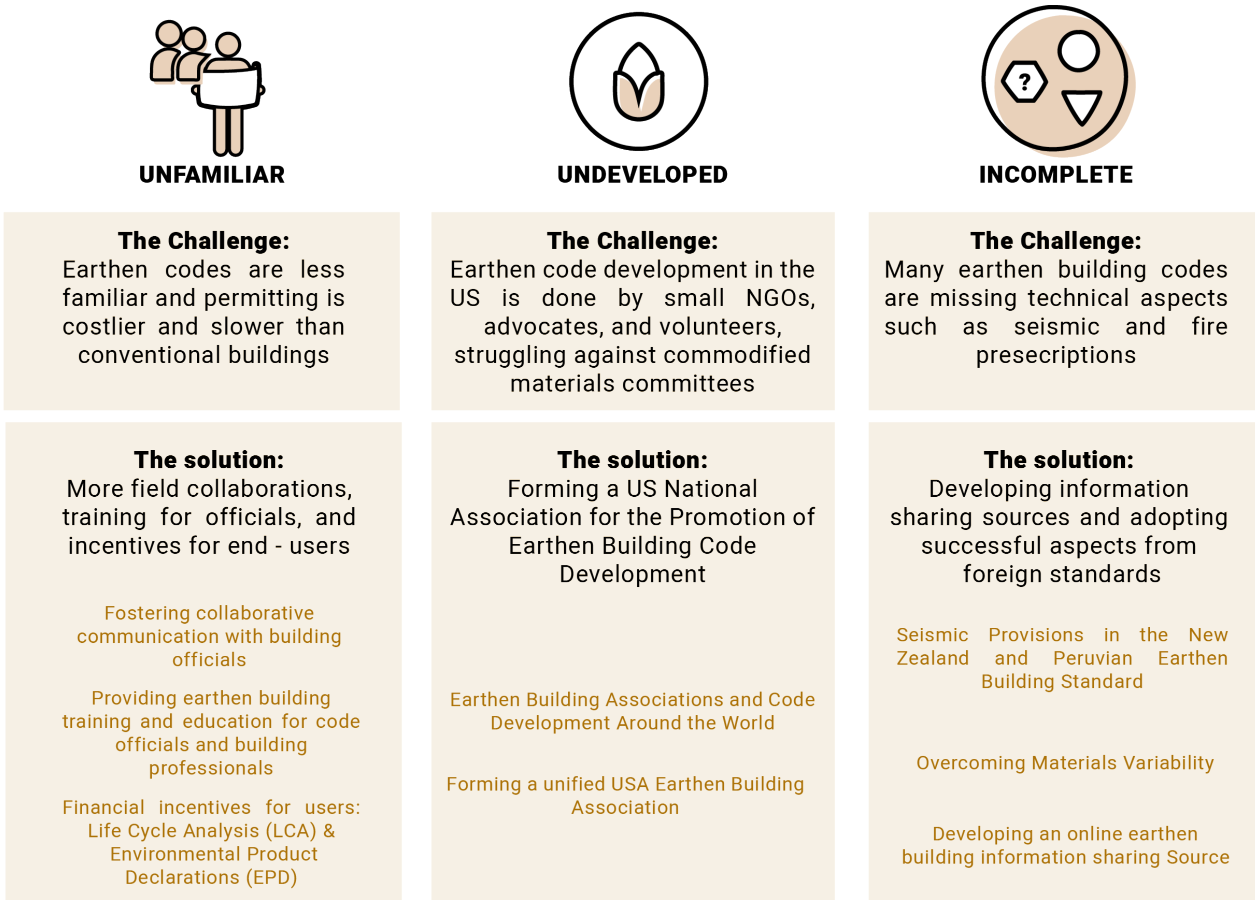


Figure 162: Policy analysis overview, addressing the main problems of arthen building regulations and suggesting strategies for improvements

The first challenge identified was that building officials are not familiar with earthen building regulations, resulting in a costlier and slower permitting process than conventional buildings. To overcome this problem, building officials should be provided with precedents, justifications and documentation from existing codes and standards (including international). Additionally, an earthen building training and education program for code officials and building professionals should be developed, as illustrated in Figure 139, and include theory, field awareness, and practical experience models. Lastly, financial incentives for users, integrating Life Cycle Analysis (LCA) and an inventory of materials and assemblies through Environmental Product Declarations (EPD), should be incorporated into earthen building regulations, such as in the German DIN standards.

The second challenge identified was that earthen code development in the US is currently pursued by advocates, volunteers, and small NGOs that are competing against commodified materials committees. As shown by successful earthen building regulations development processes from around the world, there is a critical need for collaboration among governmental entities, practitioners, and a strong earthen building professional organization, in the development of future earthen regulations. Additionally, forming a unified USA earthen building association would ensure critical mass for four strategic tasks: education and training development, research and code development, LCA with and EPD inventory, and online library, as depicted in Figure 164 and Figure 165.

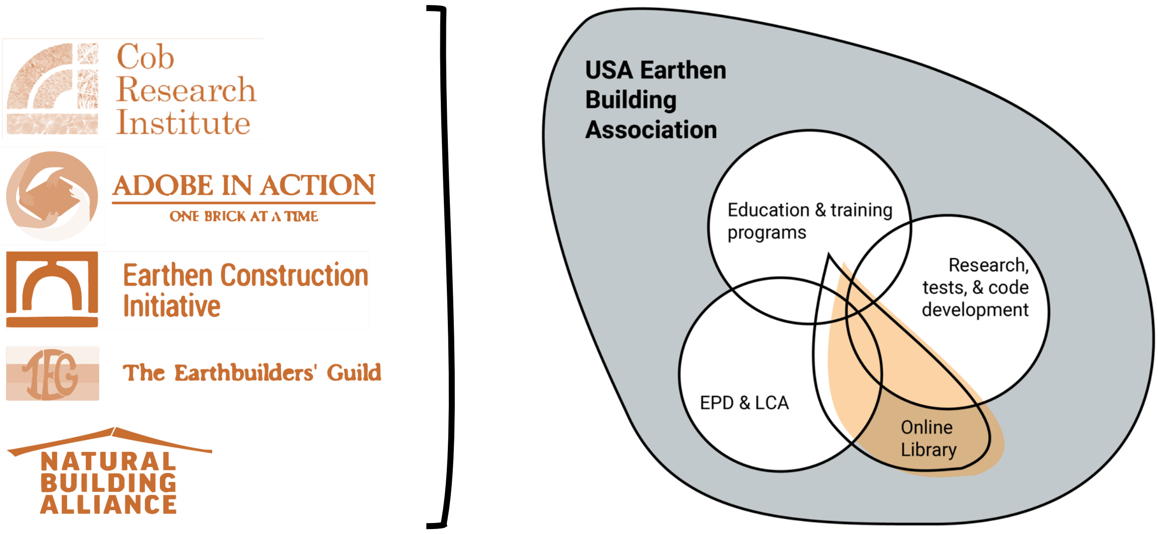


Figure 163: A propsed USA Earthen Building Association organizational scheme

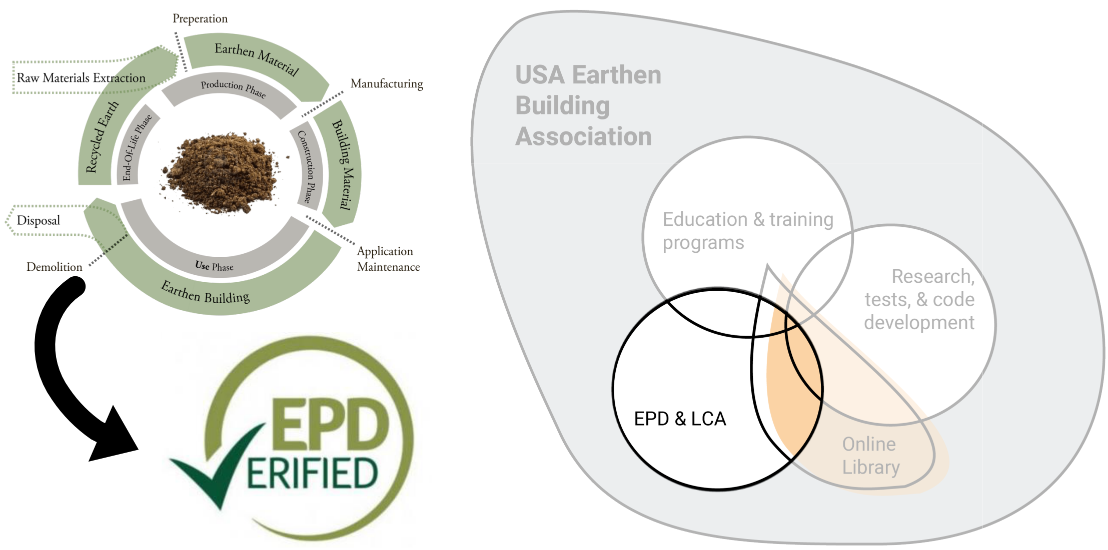


Figure 164: Promote Environmental Product Declarations (EPD) that use externally-reviewed LCA

The third challenge identified was that many earthen building codes are incomplete and missing technical details, such as seismic and fire provisions. As shown in Figure 163, this step strategically draws from the benefits of each of the existing earthen building policy documents, as voted by the experts surveyed.

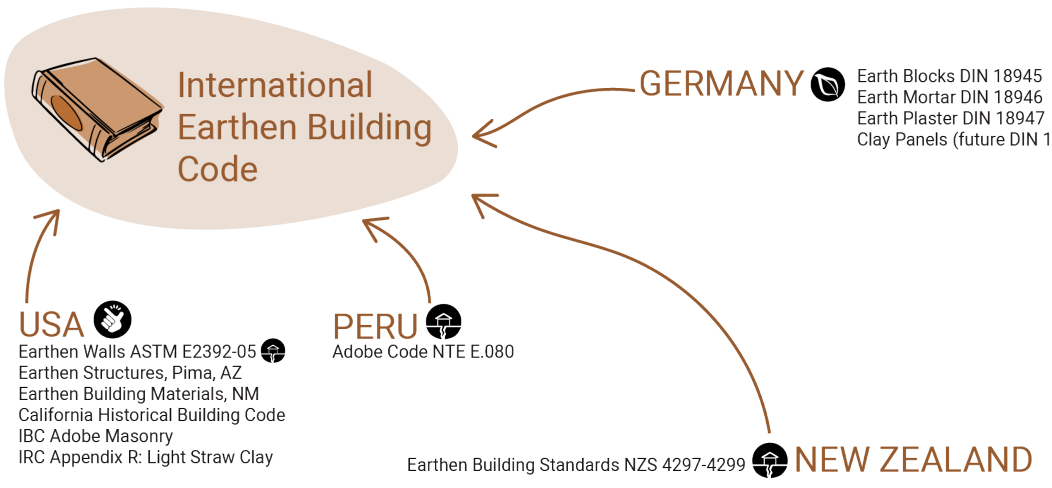


Figure 165: Formulating recommendations for a comprehensive earthen code, emerging from the existing available documents

In order to formulate a comprehensive earthen building code, future regulatory committees should incorporate successful elements from codes, standards and guidelines around the world, such as the earthen building seismic prescriptions of the New Zealand and Peruvian Standards and the LCA appendix from the German Earthen Codes. Overcoming materials variability should be achieved by following existing highly variable natural materials predecessors such as wood. Furthermore, developing an online earthen building information sharing source should be catalyzed, in order to provide a framework for information sharing among the different earthen building stakeholders. Shown in Figure 166, the earthen building information source should be built upon existing references to research papers, books, and technical documents, while providing aggregated performance data, as well as design and construction recommendations.

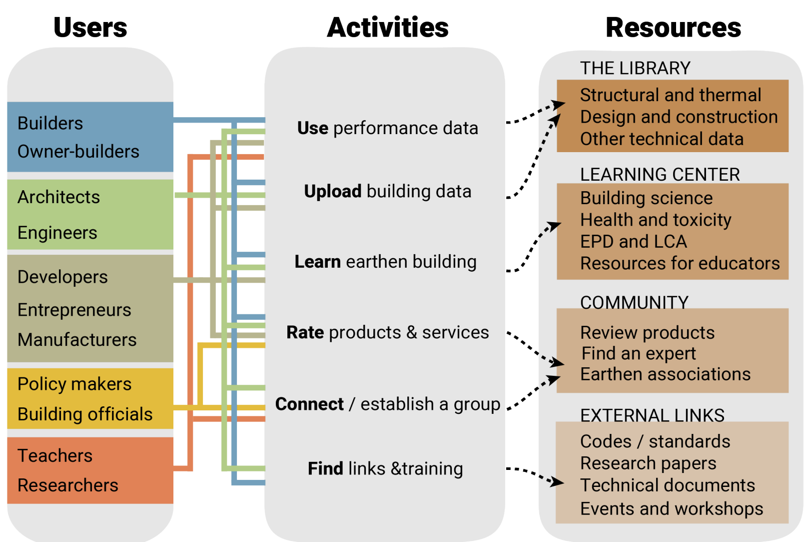


Figure 166: The conceptual framework of the earthen building library source

7.3 Limitations, Opportunities, and Future Research

Earthen building materials and methods are a critical future for sustainable architecture. The following key conclusions contribute critically needed environmental quantification and policy recommendations to catalyze the advancement of healthier and more environmentally sound commitments to earthen construction worldwide:

According to the perception surveys, environmental and indoor quality are critical for end-users and should be enumerated to transform negative perception and advance policy of earthen building.

According to the technical analysis, earthen assemblies exhibit drastically lower embodied impacts than conventional assemblies, offsetting a major part of the operational impacts over a 50-year lifespan. Considering embodied, operational heating and cooling, as well as maintenance phases, earthen assemblies can reduce up to 74% in energy demand, 79% climate change impacts, 80% air acidification, and up to 97% particulate pollution when compared to insulated wood frame and insulated CMU.

According to the policy analysis, comprehensive earthen codes should adopt successful aspects from existing documents, a task that, in the context of US, should be pursued by an umbrella organization. Regional Life Cycle Inventory (LCI) data for earthen assemblies – such as the LCI developed in this dissertation – should be provided as part of an environmental minimum criteria in building codes.

As shown in Figure 167, the perceptual, technical, and policy research studies that were pursued as part of this dissertation critically contribute to the catalysis of academic development of training and educational programs for earthen building, as well as development of innovative earthen research projects, and collaboration with field advocates to promote mainstream adoption.

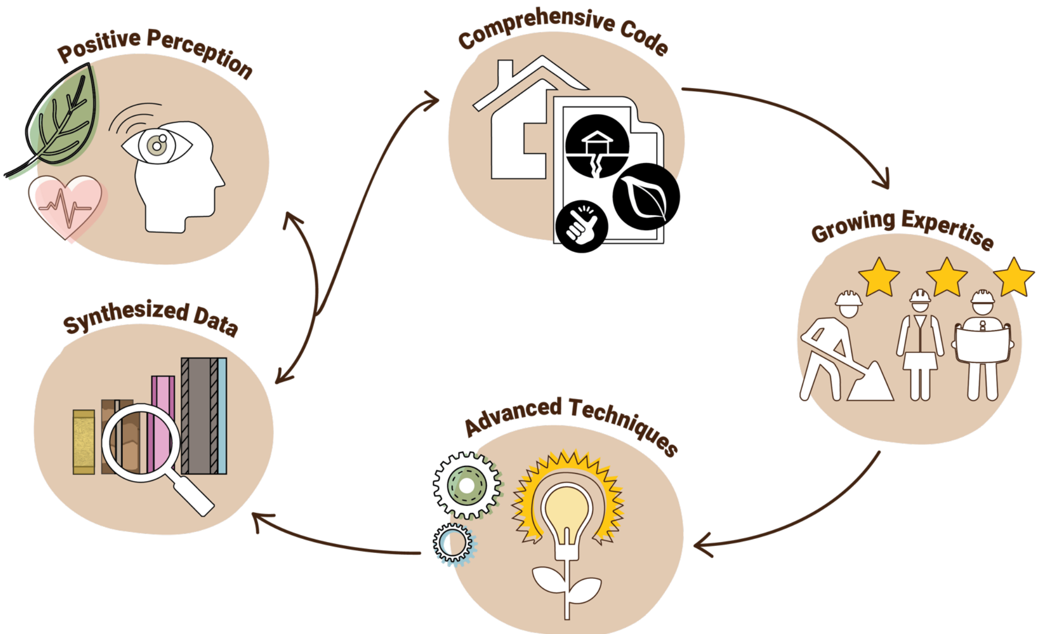


Figure 167: The future of earthen building: from gaps to pathways

The reduced environmental impacts of earthen building is imperative for sustainable architecture. If new homes utilized earthen building assemblies, and existing homes were retrofitted where possible, a significant reduction in the environmental impacts of residential housing could be realized. Instead of continuously extracting nonrenewable materials, as well as expanding transportation and materials processing procedures, renewed, advanced yet natural technology could become the future for both human and environmental health.

This dissertation highlights the importance of environmental and policy measures that could be used by policy makers and earthen building advocates in their efforts to catalyze the representation of earthen building materials and methods in mainstream construction. For developing regions, the impacts of this research are in providing regulatory trajectory to enhance traditional practices rather than replacing them with industrialized practices. Additionally, the long- term implication of this research is the development of a complete, safe, and user-friendly building regulations for earth that could be used in vast geographical contexts.

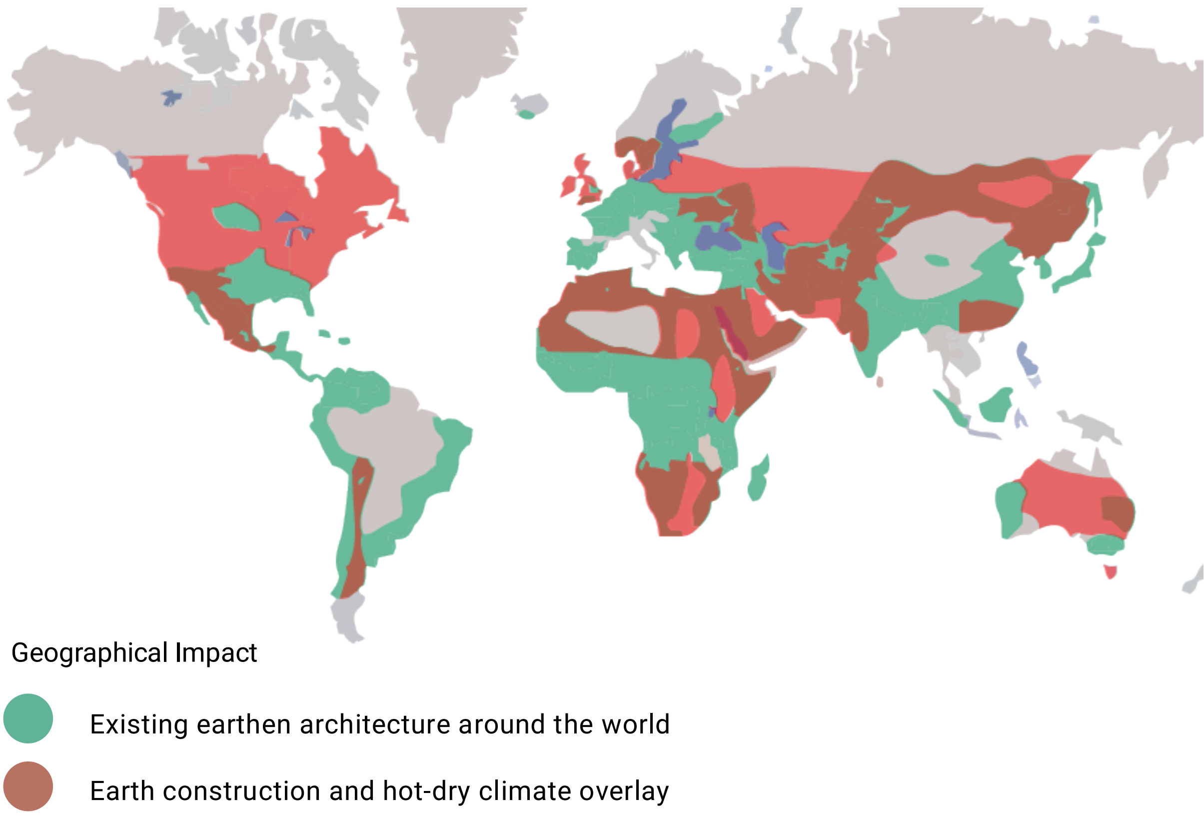


Figure 168: Geographical districbution of existing earthen architecture and hot-dry climate overlay, showing the significance of this research for both developed and developing regions

Key limitations and future research

The assumptions and conditions of each of the perceptual, technical, and regulatory studies delimit this dissertation. For the perceptual study that includes in-depth interviews and online surveys, limited number of participants were recruited; future studies should aim to reach a larger sample size, which is essential to draw statistically significant conclusions.

For the technical study that includes operational simulations and LCA, limitations of the acquired data, and of the simulation software employed, meant that the simulation results could not be interpreted as absolute, but rather they indicate the relative performance of the assemblies modeled. For instance, comparing inventories from different databases and limited geographical scope should be addressed in future research by developing a framework to other locations and building assemblies.

For the embodied impacts, one of the next stage projects that should expand on this environmental LCA is a Social Life Cycle Assessment (SLCA). SLCA is a relatively new and promising methodology that accounts for socio-ecological and socio-economic system outputs (Hossain et al., 2018). As shown in Figure 169, SLCA can capture and enumerate the social benefits of earthen building materials, including their community engagements and opportunities for affordable housing and sweat equity, circular economy and contribution to society by fostering job creation and community self–sufficiency, and product responsibility in terms of health and safety for both builders and tenants.

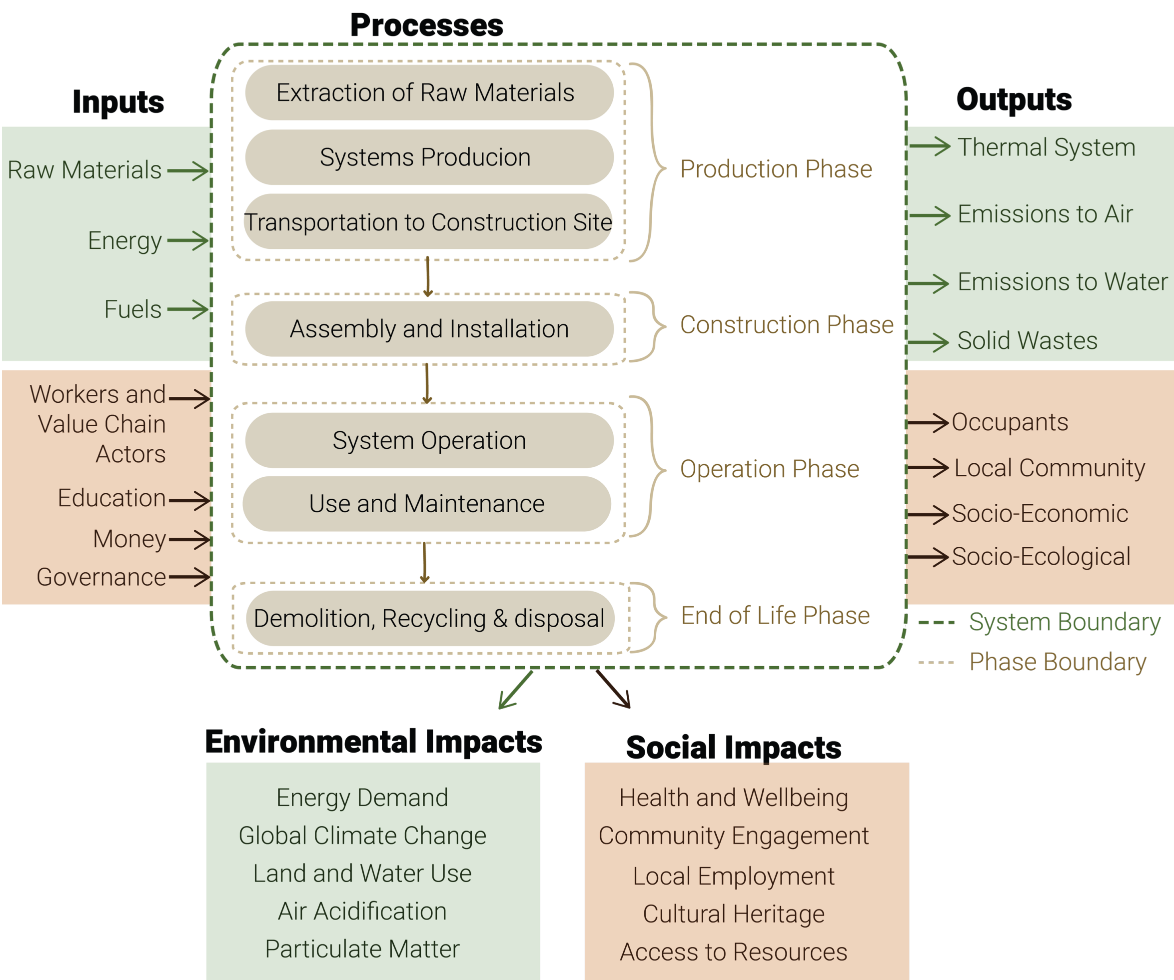


Figure 169: The conceptual framework of the earthen building library source

Future LCA analysis should account for a cradle to cradle lifecycle analysis, and include other types of wall systems (e.g., CEB instead of CMU), and insulation materials, both conventional (e.g., rock wool and Polyurethane Foam) and eco-friendly (e.g., cellulose and light straw clay). LCI data should be interpreted to be used for EPD for specific earthen building products to promote and incentivize users. Furthermore, innovative approaches to increasing the thermal resistance of earthen assemblies should be investigated and analyzed, such as the addition of pumice and the integration of various fibrous and mass layering within the assembly. Lastly, the chosen functional unit of 1 m^2 wall used in the LCA study should be expanded to actual structures of various scales.

For the operational thermal and LCA assessment, future research should further analyze the thermal, as well as the hygrothermal, properties for each wall assembly. Indoor relative humidity buffering should be analyzed, as well as the environmental impacts of the reduction of humidifying and dehumidifying energy loads. Future studies should examine loads and impact improvements for various enhanced hybrid assemblies and insulation locations within the walls. Strategies to help reduce heating and cooling loads should be examined, for instance, by reducing how often the heating and cooling system operates or allowing the temperature to drift to a lower (heating mode) or higher (cooling mode) temperatures (also known as setback temperatures). Future predicted TMY climate data should be explored to investigate future resiliency in the face of climate change.

For the policy assessment, language was the main barrier, as different codes are written in different language. Future regulatory and policy repair studies and technical field efforts should strive to pursue a unified US organization with federal and foundation funding that could develop a model code drawn from best practices from around the world but customized to each location. The EuroCode approach is a good model in this regard. Marketing, training and education programs should be developed through joint venture partnerships between the earthen organization, product developers, and leading academic institutions.

Lastly, this dissertation catalyzes the broader adoption of earthen materials and provides a framework that should be adopted for further promising natural and living materials that require similar analysis; Biological materials such as hempcrete, fungi-based blocks and tiles, and bacterial-induced concretes that require less cement and can self-heal – these are the next generation of building materials – and they all require additional environmental, thermal, and structural analysis to be implemented in mainstream construction, as shown in Figure 170.

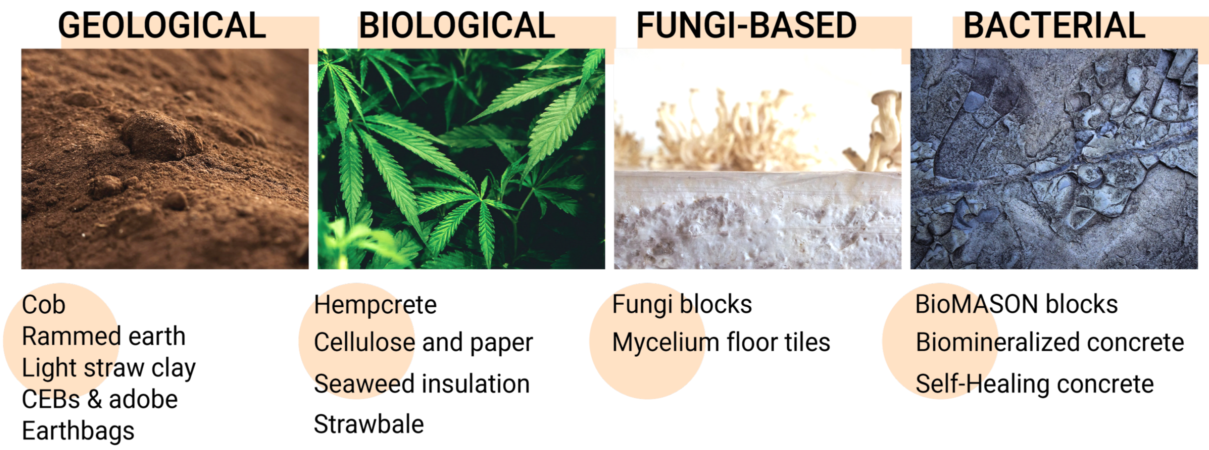


Figure 170: The conceptual framework of the earthen building library source

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Appendix A: In-depth interviews

Recruitment letter

Hello ______,

My name is Lola Ben-Alon and I'm a PhD student at the School of Architecture at Carnegie Mellon University. I received your name and contact information from _______. My research deals with the strengths and barriers to using earthen building materials and their implementation in mainstream construction. Specifically, I am hoping to develop a policy repair analysis that could bridge the interests of decision makers and grassroots advocates during the process of raising earthen buildings to mainstream applications.

As part of my research, I am conducting one-time interviews of experts in the field of earthen building materials as my goal is to analyze various barriers to earthen construction as well as establish the environmental and human gains from it. I am looking for interviewees who have completed real-size earthen construction projects over the last 5 years or more. As I understand, you answer this criteria, but please let me know if otherwise.

If you do answer the above criteria, I would be thrilled to have you as an interviewee for my research. As an expert in earthen construction, if you agree to participate, I will ask you various questions in regards to your experience with earthen construction, and possible barriers you might have encountered throughout your experience. The interview could be done via phone or Skype and is usually taking around 40-60 minutes. Since I will be audio-recording our interview, if we do the interview remotely, you will need to be in a private location so that the audio-recording won't incidentally pick up the voices of any non-participants. In addition, there is no compensation for the participation. Lastly, the interview will be used in my PhD thesis to generate a public policy repair analysis (i.e. analyze how can we fix the existing code).

I would be grateful to hear back from you soon, and would be excited to have you as an interviewee in my research.

Thanks!

Lola Ben-Alon

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Consent section

I am conducting this research as part of my PhD dissertation, that deals with the strengths and barriers to using earthen building materials and methods.

This interview involves questions about your professional experiences with earthen building methods, your experience with any engineering and regulatory barriers, and finally, your recommendations for addressing these barriers. The interview takes 40-60 minutes.

I would like to audio-record our interview. There is the potential risk of a breach of confidentiality, however we will minimize that risk by removing your name from the transcript and storing the data securely. No one but me will have access to the recording, which will be destroyed after I have transcribed it. I am also happy to make the transcription available to you. All identifying or sensitive information will be removed. In addition, there is no compensation to participating in the research.

Your participation in the interview is voluntary. Throughout the course of the interview, you are not obligated to respond to all questions. If, for example, you do not know how to respond or you feel uncomfortable responding, you may a decline to answer.

Are you willing to be interviewed?

Are you at least 18 years of age?

BRIEF DESCRIPTION OF THE STUDY:

Earthen building materials and methods offer a low-impact, truly sustainable alternative to conventional materials and methods currently used in mainstream construction of residential homes. However, the lack of inspiration, guidelines and appropriate codes and standards for these methods is a barrier to broader implementation in mainstream construction practice. In order to analyze this educational and regulatory gap, I am proposing a PhD dissertation to develop the insights and policy repairs that could bridge the interests of decision makers and grassroots advocates during the process of raising earthen buildings to mainstream applications. The approach will include (1) in-depth interviews to analyze the regulatory barriers and establish the environmental and human gains from earthen construction, (2) an overview of the engineering properties of each earthen building method, and (3) a comparative environmental impact analysis in the form of a Life-Cycle Assessment (LCA) to provide the catalyst for adoption of earthen construction.

Interview questions

Topic 1: Your Role in the realm of Earthen Buildings

Could you please describe your profession, and how it relates to earthen building materials?

What specific earthen materials and methods are you dealing with throughout your work?

From your own experience, could you please describe what are the main strengths and also barriers to the implementation of each of these earthen building methods? (Starting with the greatest strengths, then the lighter barriers)

Topic 2: The Role of Regulatory Barriers

Where does the regulatory barrier stands in relation to other barriers to implementing earthen construction?

From your own experience, could you please describe the interaction with local authorities and code officials in permitting earthen buildings?

Topic 3: Successful Permitting

Are there any successfully permitted earthen building projects that you know of / worked on? What made them successful and how was the permitting process handled?

From your own experience, what could be ameliorated in the process of permitting an earthen structure?

Could you please describe how do you think scientific and academic research could assist you and your profession in overcoming technical, educational or regulatory barriers?

Are there any particular thesis topics that have not been addressed and that are critically needed in the area of earthen building methods?

Conclusion: Do you have any questions for me?

I'm planning to use your responses to document the important insight and expertise that professionals rely on when they research earthen buildings. Thank you for your time and participation.

IRB Approval for the interviews and surveys

Carnegie Mellon University

APPROVAL OF SUBMISSION

August 30, 2017

Type of Review:	Initial Study
Title of Study:	Integrating Earthen Building Materials and Methods in the Mainstream of Housing Projects Throughout Design, Construction, and Commissioning stages
Investigator: Study Team Members:	Rachel Ben-Alon Vivian Loftness
IRB ID:	STUDY2017_00000295: Integrating Earthen Building Materials and Methods in the Mainstream of Housing Projects Throughout Design, Construction, and Commissioning stages
Funding:	None

The Carnegie Mellon University Institutional Review Board (IRB) has reviewed and granted **APPROVAL as Exempt on 8/30/2017, in accordance with 45 CFR 46.101(b)(2)**.

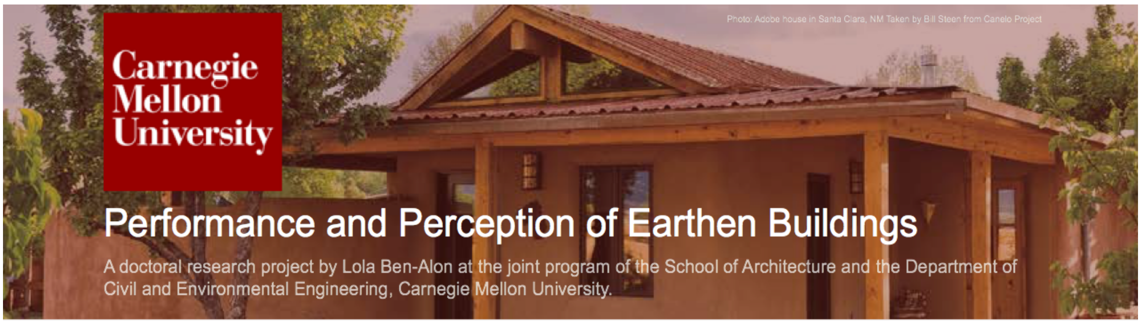
This approval does not expire. However, if you wish to make modifications to this protocol, please contact the IRB regarding these changes prior to their implementation to ensure compliance with this designation.

The Investigator(s) listed above in conducting this protocol agree(s) to follow the recommendations of the IRB of any conditions to or changes in procedure subsequent to this review. In undertaking the execution of the protocol, the investigator(s) further agree(s) to abide by all CMU research policies including, but not limited to the policies on responsible conduct research and conflict of interest.

Sincerely,

John Zimmerman
IRB Chair

Appendix B: Survey recruitment and questionnaire



Call and Information Sheet for Survey Respondents

Please **read** carefully and **share** with other potential respondents who might be interested

About the survey and its purpose

This 10-15 minutes survey is intended to collect data about the advantages and limitations to using earthen building materials and methods. It includes questions about the factors that affect interest in using earthen building materials and methods, as well as barriers to their implementation.

Who is the survey for?

You should participate in the survey if you answer "yes" to **at least one** of the following:

→ Are you **professionally involved in earthen building projects?** (e.g., engineering, designing, building, teaching, or researching earthen materials)

→ Do you **live in a house made of earthen materials?**

→ Are you **interested in earthen building materials?** (e.g., rammed earth, adobe, cob)

Link to access the survey

Your participation will require approximately 10-15 minutes. **To access the survey, please click on the following link:**
https://goo.gl/forms/JJGQE26TBcmAUAu92

The outcome and contribution of the survey

This survey is part of a larger study titled *Integrating Earthen Building Materials and Methods into the Mainstream of Housing Projects.*

The findings of the survey will be used to provide insights into factors that influence the demand as well as the barriers to implementing earthen building materials and methods by homeowners. In addition, homeowners will be asked about thermal comfort inside earthen houses and the associated utility bills. This data will be used to evaluate the environmental life cycle impacts of earthen houses. Eventually, the study will use these insights to assess policy changes required to affect broader acceptance of earthen materials in housing construction.

Ethics clearance

The survey is approved by the Institutional Review Board (IRB) of Carnegie Mellon University. Any potential risk of privacy breach will be minimized by keeping the data strictly confidential and reporting the results anonymously. You are not obligated to respond to all questions. In addition, your participation in the survey is voluntary.

Some of the responses might require further interviews to allow in-depth interpretation of the obtained data. Upon survey completion, you will be asked if you agree to be contacted by the main researcher for an interview.

What happens next?

The reported results will be analyzed and will become part of the researcher's PhD Thesis; it may be used in publications and presentations.

About the researcher: Lola Ben-Alon

I am currently a PhD candidate at Carnegie Mellon University, writing a thesis about earthen construction. In the past I have worked as a researcher and teacher at the Technion - Israel Institute of Technology Faculty of Civil and Environmental Engineering, and as an exhibitions curator at the Madatech - Israel National Museum of Science.

My interest in earthen construction began in 2013 when I participated in an earthen building workshop at the Negev desert, as part of a project by Engineers Without Borders' that deals with Compressed Earth Bricks (CEB) water storage systems for a school in Meskele, Ethiopia.

My long term aim is to catalyze the development of a complete, safe, and user-friendly earthen building code representation. My hope is that the outcomes of this research could be used by policy makers and give rise to top-down mainstream implementation of earthen building materials and methods in construction projects. For any further question please contact me at: rbenalon@andrew.cmu.edu

Earthen Building Materials - Perception and Performance

This survey is for three groups: homeowners of earthen homes (e.g., rammed earth, adobe, cob), earthen building materials experts (e.g., engineers, designers, teachers), or for people who are interested in earthen building materials.

Your participation will require approximately 10-15 minutes.

The survey involves questions about your interest in earthen building materials and methods, as well as barriers you might have encountered to implementing earthen construction. In addition, homeowners may dedicate further 5 minutes to complete a series of questions about the thermal performance of their house.

If you have any questions or concerns, or if you would like to receive a copy of the published results, you can contact the researcher Lola Ben-Alon at the email address below:
rbenalon@andrew.cmu.edu

~~~~~~
ETHICS CLEARANCE: The survey is approved by the Institutional Review Board (IRB) of Carnegie Mellon University. Any potential risk of privacy breach will be minimized by keeping the data strictly confidential and reporting the results anonymously. Throughout the course of the survey, you are not obligated to respond to all questions. If, for example, you do not know how to respond or you feel uncomfortable responding, you may a decline to answer. If you choose to participate in this survey you can withdraw at any time. In addition, there is no compensation to participating in the research, and your participation in the survey is voluntary.
The findings of the survey will enable to broaden the academic knowledge regarding earthen building materials. The principal researcher, Lola Ben Alon, a PhD candidate at Carnegie Mellon University, PA USA, will use the findings obtained from the survey to evaluate the environmental life cycle and required policy changes for earthen materials in housing construction. Any report of this research that is made available to the public will not include your individual information by which you could be identified.
~~~~~~

Clicking the "Next" button below indicates that you are 18 years of age or older, and indicates your consent to participate in this survey.

Skip to question 1.

YOUR FAMILIARITY WITH EARTHEN BUILDING MATERIALS

1. **Which of the following best describes your familiarity with earthen building materials? (e.g., rammed earth, adobe, cob)**
   Mark only one oval.

   ◯ I am professionally familiar with earthen building materials (e.g., I am a an earthen building designer, contractor, or researcher) *After the last question in this section, skip to question 3.*

   ◯ I am very familiar with earthen building materials, and have used/considered using them in the construction of my house *After the last question in this section, skip to question 27.*

   ◯ I am familiar with earthen building materials *After the last question in this section, skip to question 28.*

   ◯ I am somewhat familiar with earthen building materials *After the last question in this section, skip to question 28.*

   ◯ I am not familiar with earthen building materials at all *After the last question in this section, skip to question 74.*

2. **What city and country do you currently live in? (This question is for the purpose of establishing your climate)**
   For locations within the USA, please include state (e.g., Pittsburgh, PA, USA)

   ____

Skip to question 3.

YOUR PROFESSIONAL INFORMATION

3. **What is the highest degree or level of education you have completed?**
   Mark only one oval.

   ◯ Less than high school
   ◯ High school graduate (includes equivalency)
   ◯ Some college, no degree
   ◯ Associate's degree
   ◯ Bachelor's degree
   ◯ Graduate or professional degree
   ◯ Ph.D.
   ◯ Other: ________________________________

4. **Which of the following most closely matches your job title?**
Mark only one oval.

- ◯ Intern / student
- ◯ Teacher
- ◯ Builder / contractor
- ◯ Building project manager
- ◯ Architect / designer
- ◯ Structural engineer
- ◯ Researcher in Academia
- ◯ Other: ______________________

Skip to question 5.

YOUR EXPERIENCE IN EARTHEN BUILDING PROJECTS

For each of the following earthen building methods, in how many projects were you professionally involved in the past 20 years? (including academia research projects)

5. **Adobe (unfired mud bricks)**
Check all that apply.

	0 projects	1-5 projects	5-10 projects	More than 10 projects
Residential projects	☐	☐	☐	☐
Commercial projects	☐	☐	☐	☐

6. **Compressed earth bricks**
Check all that apply.

	0 projects	1-5 projects	5-10 projects	More than 10 projects
Residential projects	☐	☐	☐	☐
Commercial projects	☐	☐	☐	☐

7. **Cob (mix of straw, clay, and water)**
Check all that apply.

	0 projects	1-5 projects	5-10 projects	More than 10 projects
Residential projects	☐	☐	☐	☐
Commercial projects	☐	☐	☐	☐

8. **Rammed earth (compacted earth with aggregates)**
Check all that apply.

	0 projects	1-5 projects	5-10 projects	More than 10 projects
Residential projects	☐	☐	☐	☐
Commercial projects	☐	☐	☐	☐

9. **Earthbags (earth compacted in bags)**
Check all that apply.

	0 projects	1-5 projects	5-10 projects	More than 10 projects
Residential projects	☐	☐	☐	☐
Commercial projects	☐	☐	☐	☐

10. **Light straw clay (straw sprinkled with wet clay)**
Check all that apply.

	0 projects	1-5 projects	5-10 projects	More than 10 projects
Residential projects	☐	☐	☐	☐
Commercial projects	☐	☐	☐	☐

11. **Clay plaster (as a finish material)**
Check all that apply.

	0 projects	1-5 projects	5-10 projects	More than 10 projects
Residential projects	☐	☐	☐	☐
Commercial projects	☐	☐	☐	☐

12. **Are most of your earthen construction projects located near your living region?**
Mark only one oval.

◯ Yes
◯ No

13. If you answered "No" to the above, please specify the country/countries and city/cities where most of your earthen construction projects are located in/near:

____

Skip to question 14.

DEMAND AND BARRIERS TO USING EARTHEN MATERIALS

14. **For each climate zone, how likely are you to recommend using earthen building materials to your clients/colleagues?**
Mark only one oval per row.

	Not likely at all	-	-	Neutral/unsure	-	-	Very likely
Very cold/cold	◯	◯	◯	◯	◯	◯	◯
Mixed/hot-humid	◯	◯	◯	◯	◯	◯	◯
Mixed/hot-dry	◯	◯	◯	◯	◯	◯	◯
Marine	◯	◯	◯	◯	◯	◯	◯

15. **From your experience, what benefits motivate HOMEOWNERS to choose earthen building materials?**
Mark only one oval per row.

	Not motivating at all	-	-	Neutral/unsure	-	-	Very motivating
Earthen materials produce LOW CARBON EMISSIONS							
Earthen materials consume FEWER DEPLETABLE RESOURCES							
Earthen materials are AFFORDABLE							
Earthen materials provide HIGH INDOOR AIR QUALITY							
Earthen materials can LOWER UTILITY BILLS							
Earthen materials are BEAUTIFUL							

16. In addition to the above list, what other benefits motive homeowners to choose earthen building materials?

17. **From your point of view, what public benefits are most valuable for DECISION MAKERS in supporting earthen building policy?**
Mark only one oval per row.

	Not valuable at all	-	-	Neutral/unsure	-	-	Very valuable
Earthen materials produce LOW CARBON EMISSIONS							
Earthen materials consume FEWER DEPLETABLE RESOURCES							
Earthen materials are AFFORDABLE							
Earthen materials provide HIGH INDOOR AIR QUALITY							
Earthen materials are used TRADITIONALLY AND HAVE HISTORICAL VALUE							

18. In addition to the above list, what other public benefits are valuable for decisions makers?

19. **From your experience, to what extent does each of the following serve as a barrier to using earthen building materials?**
Mark only one oval per row.

	Not a barrier at all	-	-	Neutral/unsure	-	-	Strong barrier
Using earthen materials is LABOR INTENSIVE							
It is DIFFICULT TO FIND A CONTRACTOR that uses earthen materials							
It is HARD TO ACHIEVE BUILDING PERMITS for earthen buildings							
It is DIFFICULT TO FIND AN INSURANCE COMPANY that would insure an earthen structure							
Earthen materials require HIGH MAINTENANCE							

20. In addition to the above list, which other barrier do you see to using earthen materials?

____

____

____

____

____

21. **Are you familiar with any earthen building codes/standards?**
Mark only one oval.

- ◯ Yes *Skip to question 22.*
- ◯ No *Skip to question 26.*

Skip to question 22.

PERMITS AND CODES FOR EARTHEN BUILDINGS

22. **Which earthen building code/standard are you MOST FAMILIAR WITH OR TYPICALLY USE throughout your work?**
Mark only one oval.

- ◯ ASTM E2392-M10 Standard Guide for Design of Earthen Wall Building Systems
- ◯ New-Mexico 14.7.4 Earthen Building Materials Code
- ◯ Pima County Section 2114 Earthen Structures
- ◯ California Historical Building Code
- ◯ International Building Code Chapter 21: Masonry
- ◯ Indian earthen building standards
- ◯ New-Zealand Standards 4297, 4298, and/or 4299
- ◯ Australian Earth Building Handbook HB 195
- ◯ Peruvian Adobe Norms E-080
- ◯ German Earth Building Regulations: Lehmbau Regeln
- ◯ Other

23. **Which earthen material do you typically use the chosen code/standard for?**
Mark only one oval.

- ◯ Adobe (unfired mud bricks)
- ◯ Compressed earth bricks
- ◯ Cob (mix of straw, clay, and water)
- ◯ Earthbags (earth compacted in bags)
- ◯ Light straw clay (straw sprinkled with clay)
- ◯ Straw bales plastered with clay
- ◯ Other type of wall plastered with clay
- ◯ Other

24. **For the code/standard chosen above, to what extent do you agree or disagree with each of the following statements?**
Mark only one oval per row.

	Strongly disagree	-	-	Neutral/unsure	-	-	Strongly agree
The code/standard adequately represents the earthen material I am using	◯	◯	◯	◯	◯	◯	◯
The code/standard is user-friendly	◯	◯	◯	◯	◯	◯	◯
Building officials are familiar with this earthen building code/standard	◯	◯	◯	◯	◯	◯	◯
Building permits for this earthen material TAKE MORE TIME than other building materials	◯	◯	◯	◯	◯	◯	◯
Building permits for this earthen material ARE COSTLIER than other building material	◯	◯	◯	◯	◯	◯	◯

25. **If you find it challenging to achieve building permits for earthen buildings, what do you find to be the MAIN CAUSE for that challenge?**

Skip to question 26.

DO YOU ALSO LIVE IN AN EARTHEN HOUSE?

30. **Looking at the following pictures of earthen houses, to what extent does each picture make you interested in earthen building materials?**

Mark only one oval per row.

	Not interested at all	-	-	Somewhat interested	-	-	Very interested
1							
2							
3							
4							

31.

Mark only one oval per row.

	Not interested at all	-	-	Somewhat interested	-	-	Very interested
5							
6							
7							
8							

32.

Mark only one oval per row.

	Not interested at all	-	-	Somewhat interested	-	-	Very interested
9							
10							
11							
12							

LOCATION AND AGE OF HOUSE

40. **Is your earthen house located in the same place you currently live in? (This question is for the purpose of establishing your climate)**

Mark only one oval.

- Yes
- No

41. If you answered "No" to the above, please specify the country and city where your earthen house is located in/near:

____

42. **How many years have you been living in your house?**

____

43. **Which of the following best describes the area your earthen house is located in?**

Mark only one oval.

- Urban
- Suburban
- Rural

Skip to question 44.

44. **To aid in building your house, which of the following did you do? (check all that apply)**
Check all that apply.

- [ ] Independently researched using books and/or internet
- [ ] Consulted an earthen house homeowner
- [ ] Went to an earthen building workshop
- [ ] Hired an earthen building professional like an architect, contractor, or builder
- [ ] Other: ____________________

45. **What is your level of interest in earthen materials based on the following?**
Mark only one oval per row.

	Not interested at all	-	-	Neutral	-	-	Very interested
Construction of earthen houses produces low carbon emissions	◯	◯	◯	◯	◯	◯	◯
Construction of earthen houses consumes low amounts of fossil fuels	◯	◯	◯	◯	◯	◯	◯
Construction of earthen houses is affordable	◯	◯	◯	◯	◯	◯	◯
Earthen houses provide high indoor air quality	◯	◯	◯	◯	◯	◯	◯
Earthen houses have low utility bills	◯	◯	◯	◯	◯	◯	◯
Earthen houses are beautiful	◯	◯	◯	◯	◯	◯	◯

46. **To what extent did each of the following serve as a barrier to using earthen building materials in your house?**
Mark only one oval per row.

	Not a barrier at all	-	-	Neutral	-	-	Strong barrier
Construction of earthen houses is labor intense	◯	◯	◯	◯	◯	◯	◯
Construction of earthen houses have unexpected costs	◯	◯	◯	◯	◯	◯	◯
Permitting an earthen house is challenging (in terms of building codes)	◯	◯	◯	◯	◯	◯	◯
It is difficult to find an insurance company that would insure an earthen house	◯	◯	◯	◯	◯	◯	◯
Earthen houses require high maintenance	◯	◯	◯	◯	◯	◯	◯

47. **Were there any other significant barriers to your use of earthen materials in your house?**

____

48. **Looking back, would you use earthen building materials and methods again?**
Mark only one oval.

- Yes
- No
- Maybe

49. **Why?**

Skip to question 50.

DESIGN AND CONSTRUCTION

50. **What is the approximate floor area of your house (built area ONLY)?**
Please include units (e.g., 2000 square feet, or 100 square meters)

51. **What are the main exterior walls of your house made of? (check all that apply)**
Check all that apply.

- [ ] Adobe (unfired mud bricks)
- [ ] Compressed earth bricks
- [ ] Cob (mix of straw, clay, and water)
- [ ] Rammed earth (compacted earth with aggregates)
- [ ] Poured earth (stabilized earth mix in a fluid state)
- [ ] Tires filled with compacted earth (or any other technique that incorporate recycled materials)
- [ ] Earthbags (earth compacted in bags)
- [ ] Reinforced concrete
- [ ] Wood
- [ ] Steel
- [ ] Straw bales plastered with clay
- [ ] Other type of wall plastered with clay
- [ ] Other:

52. **What are the interior walls of your house made of? (check all that apply; e.g., “cob” and “glass bottles”)**

Check all that apply.

- [ ] Glass bottles
- [ ] Cement plaster
- [ ] Clay plaster
- [ ] Lime plaster
- [ ] Adobe (unfired mud bricks)
- [ ] Compressed earth bricks
- [ ] Cob (mix of straw, clay, and water)
- [ ] Rammed earth (compacted earth with aggregates)
- [ ] Poured earth (stabilized earth mix in a fluid state)
- [ ] Earthbags (earth compacted in bags)
- [ ] Light straw clay (mix of straw with very little amount of sprinkled earth with water)
- [ ] Dry wall timber frame
- [ ] Other: ____________________

53. **What are the foundations of the exterior walls of your house made of? (check all that apply)**

Check all that apply.

- [ ] “Natural” unstabilized earth (e.g. ground excavated and levelled)
- [ ] Stabilized earth (e.g. ground excavated, levelled AND STABILIZED by cement)
- [ ] Gravel trench (sometimes used in “natural” house constructions to avoid concrete footings)
- [ ] Reinforced Concrete (typical of many house constructions)
- [ ] Other: ____________________

54. **Were the walls assembled using manual labor and/or machinery?**

Mark only one oval.

- ( ) Manual labor
- ( ) Machinery
- ( ) Combination of both

55. If you used machinery, which machine did you use? (check all that apply)
Check all that apply.

- [ ] Tractor
- [ ] Mechanical Mixer
- [ ] Powered tamper
- [ ] Compressed earth blocks machine
- [ ] Other: ____________________

56. **What is your floor made of? (check all that apply e.g. "flagstone" and "cement mortar")**
Check all that apply.

- [ ] Mud/Compacted earth
- [ ] Flagstone
- [ ] Cement mortar
- [ ] Concrete (unreinforced)
- [ ] Concrete and steel (reinforced)
- [ ] Wood
- [ ] Other: ____________________

57. **What is your ROOF FRAME made of? (check all that apply)**
Check all that apply.

- [ ] Timber
- [ ] Steel
- [ ] Ferro cement
- [ ] Other: ____________________

58. **What is your ROOF INSULATION made of? (check all that apply)**
Check all that apply.

- [ ] Cellulose fiber
- [ ] Rock wool
- [ ] Glass wool
- [ ] Reflective foil
- [ ] Expanded Polystyrene board
- [ ] Other: ____________________

59. **What is your ROOF SURFACE made of? (check all that apply)**
Check all that apply.

- [ ] Wood shakes
- [ ] Clay tile
- [ ] Slate tile
- [ ] Metal
- [ ] Asphalt shingles
- [ ] "Green roof" (waterproof membrane and top soil)
- [ ] Other: ____________________

Skip to question 60.

PERFORMANCE OF EARTHEN HOUSES

60. **On the whole, how would you describe the conditions in your house during the following times of the year? (click the button that best corresponds to your perceptions)**
Mark only one oval per row.

	Very uncomfortable	-	-	Neutral	-	-	Very comfortable
Winter days	◯	◯	◯	◯	◯	◯	◯
Winter nights	◯	◯	◯	◯	◯	◯	◯
Summer days	◯	◯	◯	◯	◯	◯	◯
Summer nights	◯	◯	◯	◯	◯	◯	◯

61. **What kind of heating system do you use in your house? (check all that apply)**
Check all that apply.

- [ ] None
- [ ] Gas furnace
- [ ] Fireplace
- [ ] Wood-burning stove
- [ ] Built-in electric heater
- [ ] Portable electric heater(s)
- [ ] Heat pump/split-system
- [ ] Kerosene heater
- [ ] Other: ____________________

62. **At what times of the day or night do you usually use space heating during cold weather?**

Mark only one oval.

- ◯ All the time, day and night
- ◯ Day only
- ◯ Night only
- ◯ Afternoon/evening until bedtime
- ◯ Other: ____________________

63. **How many months in the year do you usually use space heating? (enter a whole number from 0 to 12)**

____

64. **What kind of cooling system do you have in your house? (check all that apply)**

Check all that apply.

- ☐ None
- ☐ Central air conditioner
- ☐ Ductless mini-split air conditioner
- ☐ Window air conditioner(s)
- ☐ Portable electric cooler(s)
- ☐ Other: ____________________

65. If you checked ductless/window/portable air conditioner in the above, please indicate how many units do you have in your house:

____

66. **At what times of the day or night do you usually use space cooling during warm weather?**

Mark only one oval.

- ◯ All the time, day and night
- ◯ Day only
- ◯ Night only
- ◯ Afternoon/evening until bedtime
- ◯ Other: ____________________

67. **How many months in the year do you usually use space cooling? (enter a whole number from 0 to 12)**

____

68. **How would you describe the humidity in your house for each season of the year?**
Mark only one oval per row.

	Too dry	-	-	Comfortable	-	-	Too humid
Summer	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Fall	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Winter	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Spring	⬭	⬭	⬭	⬭	⬭	⬭	⬭

69. **Do you have any problems with mold growing in the house (due to excessive humidity)?**
Mark only one oval.

	1	2	3	4	5	6	7	
No mold	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Lots of mold

70. **Approximately how much do you spend on utility bills per year?**
Mark only one oval per row.

	Less than $1,000	$1,000-$2,000	$2,000-$3,000	$3,000-$4,000	More than $4,000
Gas	⬭	⬭	⬭	⬭	⬭
Electricity	⬭	⬭	⬭	⬭	⬭

71. Can you estimate how much do you spend for SPACE COOLING per year? (please provide answer in USD)

____

72. Can you estimate how much do you spend for SPACE HEATING per year? (please provide answer in USD)

____

73. **Would you be willing to participate in a 15 minutes phone interview with the main researcher about the thermal performance of your house?**
If yes, please provide your email address, and the main researcher will contact you shortly (your email address will not be used for anything else beside establishing a time for a phone interview for the purpose of this academic research)

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Appendix C: Life cycle inventory data

Tap water inputs and air emission

System Process for 1 kg tap water			
Output	Comment	Value	Unit
Resources			
Carbon dioxide, in air	in air	1.53E-05	kg
Energy, gross calorific value, in biomass	biotic	0.000165	MJ
Occupation, construction site	land	1.21E-07	m2a
Occupation, dump site	land	1.62E-06	m2a
Occupation, forest, intensive	land	2.26E-05	m2a
Occupation, industrial area	land	1.5E-06	m2a
Occupation, mineral extraction site	land	3.29E-07	m2a
Occupation, shrub land, sclerophyllous	land	8.77E-09	m2a
Occupation, traffic area, rail network	land	7.91E-08	m2a
Occupation, traffic area, road network	land	3.21E-07	m2a
Occupation, urban, discontinuously built	land	1.08E-09	m2a
Transformation, from dump site, inert material landfill	land	1.11E-09	m2
Transformation, from dump site, residual material landfill	land	5.22E-10	m2
Transformation, from dump site, sanitary landfill	land	1.08E-10	m2
Transformation, from dump site, slag compartment	land	1.75E-11	m2
Transformation, from forest, extensive	land	1.64E-08	m2
Transformation, from industrial area	land	4.28E-10	m2
Transformation, from mineral extraction site	land	7.63E-09	m2
Transformation, from shrub land, sclerophyllous	land	3.35E-09	m2
Transformation, to dump site	land	1.31E-08	m2
Transformation, to dump site, inert material landfill	land	1.11E-09	m2
Transformation, to dump site, residual material landfill	land	5.22E-10	m2
Transformation, to dump site, sanitary landfill	land	1.08E-10	m2
Transformation, to dump site, slag compartment	land	1.75E-11	m2
Transformation, to forest, intensive	land	2.8E-07	m2
Transformation, to heterogeneous, agricultural	land	8.25E-10	m2
Transformation, to industrial area	land	3.22E-08	m2
Transformation, to mineral extraction site	land	3.63E-08	m2
Transformation, to shrub land, sclerophyllous	land	1.75E-09	m2
Transformation, to traffic area, rail network	land	1.83E-10	m2
Transformation, to traffic area, road network	land	1.86E-09	m2
Transformation, to urban, discontinuously built	land	2.22E-11	m2
Volume occupied, final repository for low-active radioactive waste	in ground	5.06E-12	m3
Volume occupied, final repository for radioactive waste	in ground	5.93E-13	m3
Volume occupied, reservoir	in water	7.13E-06	m3y
Volume occupied, underground deposit	in ground	5.28E-12	m3
Water, salt, ocean	in water	2.95E-08	m3
Water, salt, sole	in water	1.02E-08	m3
Wood, hard, standing	biotic	8.39E-09	m3
Wood, soft, standing	biotic	6.15E-09	m3
Occupation, forest, extensive	land	6.01E-08	m2a
Occupation, permanent crop	land	4.9E-09	m2a
Transformation, from forest, intensive	land	2.66E-07	m2
Transformation, from heterogeneous, agricultural	land	8.82E-13	m2
Transformation, from permanent crop	land	3.82E-10	m2
Transformation, from traffic area, road network	land	7.37E-13	m2
Transformation, to forest, extensive	land	5.96E-10	m2
Transformation, to permanent crop	land	3.91E-09	m2
Energy, gross calorific value, in biomass, primary forest	biotic	1.17E-06	MJ
Energy, kinetic (in wind), converted	in air	4.1E-05	MJ
Energy, solar, converted	in air	8.81E-08	MJ
Energy, geothermal, converted	in ground	1.17E-05	MJ
Energy, potential (in hydropower reservoir), converted	in water	0.000377	MJ
Water, unspecified natural origin, BR	in ground	7.73E-14	m3
Water, unspecified natural origin, CH	in ground	3.77E-13	m3
Water, unspecified natural origin, CN	in ground	2.78E-19	m3
Water, unspecified natural origin, CO	in ground	4.4E-14	m3
Water, unspecified natural origin, DE	in ground	5.12E-18	m3
Water, unspecified natural origin, HN	in ground	2.98E-14	m3
Water, unspecified natural origin, ID	in ground	7.17E-14	m3
Water, unspecified natural origin, IN	in ground	3.14E-14	m3
Water, unspecified natural origin, US	in ground	2.42E-16	m3
Water, unspecified natural origin, VN	in ground	1.37E-13	m3
Water, unspecified natural origin, AT	in water	9.56E-12	m3
Water, unspecified natural origin, AU	in water	2.12E-12	m3
Water, unspecified natural origin, BE	in water	1.9E-11	m3
Water, unspecified natural origin, BG	in water	3.41E-11	m3
Water, unspecified natural origin, BR	in water	2.11E-11	m3
Water, unspecified natural origin, CA	in water	1.25E-10	m3
Water, unspecified natural origin, CH	in water	6.58E-09	m3
Water, unspecified natural origin, CL	in water	1.31E-14	m3
Water, unspecified natural origin, CN	in water	2.13E-10	m3
Water, unspecified natural origin, CZ	in water	2.76E-12	m3
Water, unspecified natural origin, DE	in water	1.07E-10	m3
Water, unspecified natural origin, DK	in water	1.45E-11	m3
Water, unspecified natural origin, EE	in water	4E-13	m3
Water, unspecified natural origin, ES	in water	1.31E-11	m3
Water, unspecified natural origin, FI	in water	5.12E-12	m3
Water, unspecified natural origin, FR	in water	3.96E-11	m3
Water, unspecified natural origin, GB	in water	3.52E-11	m3
Water, unspecified natural origin, HU	in water	5.23E-12	m3
Water, unspecified natural origin, IN	in water	9.73E-12	m3
Water, unspecified natural origin, IT	in water	3.88E-11	m3
Water, unspecified natural origin, JP	in water	7.51E-10	m3
Water, unspecified natural origin, KR	in water	1.17E-10	m3
Water, unspecified natural origin, LU	in water	7.73E-13	m3
Water, unspecified natural origin, MX	in water	1.63E-12	m3
Water, unspecified natural origin, NL	in water	4.15E-11	m3
Water, unspecified natural origin, NO	in water	2.09E-12	m3
Water, unspecified natural origin, PH	in water	6.26E-13	m3
Water, unspecified natural origin, PL	in water	1.06E-12	m3
Water, unspecified natural origin, PT	in water	4.48E-12	m3
Water, unspecified natural origin, RU	in water	3.13E-09	m3
Water, unspecified natural origin, SE	in water	2.52E-11	m3
Water, unspecified natural origin, SK	in water	6.64E-13	m3
Water, unspecified natural origin, TH	in water	5.53E-13	m3
Water, unspecified natural origin, TR	in water	1.49E-11	m3
Water, unspecified natural origin, UA	in water	1.25E-13	m3
Water, unspecified natural origin, US	in water	2.79E-10	m3
Oxygen	in air	1.99E-05	kg
Nitrogen	in air	5.63E-05	kg
Water, unspecified natural origin, PG	in water	1.49E-12	m3
Occupation, arable land, unspecified use	land	2.33E-16	m2a
Occupation, permanent crop, irrigated	land	2.19E-08	m2a
Water, unspecified natural origin, Europe without Switzerland	in ground	1.75E-19	m3
Water, unspecified natural origin, GLO	in ground	8.38E-13	m3
Water, unspecified natural origin, RER	in ground	1.09E-13	m3
Water, unspecified natural origin, RNA	in ground	5.51E-20	m3
Water, unspecified natural origin, RoW	in ground	3.88E-12	m3
Water, lake, AT	in water	1.13E-15	m3
Water, lake, BE	in water	2.36E-15	m3
Water, lake, BG	in water	4.53E-15	m3
Water, lake, CA	in water	9.64E-10	m3
Water, lake, CH	in water	1.12E-10	m3
Water, lake, CN	in water	9.22E-15	m3
Water, lake, CZ	in water	1.52E-16	m3
Water, lake, DE	in water	5.01E-13	m3
Water, lake, DK	in water	1.91E-15	m3
Water, lake, ES	in water	1.68E-15	m3
Water, lake, Europe without Switzerland	in water	2.97E-09	m3
Water, lake, FI	in water	6.4E-16	m3
Water, lake, FR	in water	5.04E-15	m3
Water, lake, GB	in water	4.61E-15	m3
Water, lake, GLO	in water	1.24E-12	m3
Water, lake, HU	in water	6.85E-16	m3
Water, lake, IT	in water	4.93E-15	m3
Water, lake, JP	in water	8.22E-14	m3
Water, lake, KR	in water	6.82E-15	m3
Water, lake, LU	in water	1.02E-16	m3
Water, lake, NL	in water	5.19E-15	m3
Water, lake, NO	in water	2.64E-16	m3
Water, lake, PL	in water	9.51E-17	m3
Water, lake, PT	in water	5.91E-16	m3
Water, lake, RER	in water	9.91E-12	m3
Water, lake, RNA	in water	2.67E-15	m3
Water, lake, RoW	in water	8.84E-05	m3
Water, lake, RU	in water	3.04E-14	m3
Water, lake, SE	in water	5.35E-15	m3
Water, lake, SK	in water	5.79E-17	m3
Water, lake, TR	in water	1.28E-15	m3
Water, lake, TW	in water	3.07E-14	m3
Water, lake, US	in water	1.35E-13	m3
Water, river, AT	in water	2.59E-12	m3
Water, river, AU	in water	1.33E-10	m3
Water, river, BE	in water	5.43E-12	m3
Water, river, BG	in water	1.04E-11	m3
Water, river, BR	in water	2.57E-08	m3
Water, river, CA	in water	5.93E-08	m3
Water, river, CH	in water	1.9E-09	m3
Water, river, CN	in water	7.7E-09	m3
Water, river, CZ	in water	3.49E-13	m3
Water, river, DE	in water	4.19E-10	m3
Water, river, DK	in water	4.39E-12	m3
Water, river, ES	in water	1.17E-10	m3
Water, river, Europe without Switzerland	in water	4.72E-08	m3
Water, river, FI	in water	1.47E-12	m3
Water, river, FR	in water	2.93E-11	m3
Water, river, GB	in water	1.06E-11	m3
Water, river, GLO	in water	9.4E-09	m3
Water, river, HU	in water	1.57E-12	m3
Water, river, IN	in water	1.9E-08	m3
Water, river, IT	in water	1.13E-11	m3
Water, river, JP	in water	2.34E-10	m3
Water, river, KR	in water	1.01E-08	m3
Water, river, LU	in water	2.35E-13	m3
Water, river, MY	in water	1.32E-10	m3
Water, river, NL	in water	1.34E-11	m3
Water, river, NO	in water	6.06E-13	m3
Water, river, PE	in water	1.23E-13	m3
Water, river, PH	in water	7.87E-10	m3
Water, river, PL	in water	2.18E-13	m3
Water, river, PT	in water	1.36E-12	m3
Water, river, RAS	in water	2.58E-09	m3
Water, river, RER	in water	2.87E-07	m3
Water, river, RLA	in water	6.66E-10	m3
Water, river, RNA	in water	1.18E-09	m3
Water, river, RO	in water	7.15E-10	m3
Water, river, RoW	in water	0.000945	m3
Water, river, RU	in water	2.62E-09	m3
Water, river, SE	in water	1.01E-11	m3
Water, river, SK	in water	1.33E-13	m3
Water, river, TN	in water	6.2E-12	m3
Water, river, TR	in water	2.94E-12	m3
Water, river, TW	in water	7.06E-11	m3
Water, river, TZ	in water	1.88E-12	m3
Water, river, US	in water	8.65E-10	m3
Water, river, WEU	in water	1.51E-16	m3
Water, river, ZA	in water	9.78E-12	m3
Water, unspecified natural origin, Europe without Switzerland	in water	9.47E-10	m3
Water, unspecified natural origin, GLO	in water	4.42E-08	m3
Water, unspecified natural origin, RAF	in water	2.07E-09	m3
Water, unspecified natural origin, RER	in water	2.26E-08	m3
Water, unspecified natural origin, RNA	in water	6.25E-10	m3
Water, unspecified natural origin, RoW	in water	1.73E-07	m3
Water, unspecified natural origin, TW	in water	2.43E-10	m3
Water, unspecified natural origin, WEU	in water	1.63E-13	m3
Water, well, in ground, AT	in water	4.51E-14	m3
Water, well, in ground, AU	in water	3.81E-09	m3
Water, well, in ground, BE	in water	9.43E-14	m3
Water, well, in ground, BG	in water	1.8E-13	m3
Water, well, in ground, BR	in water	5.89E-09	m3
Water, well, in ground, CA	in water	9.66E-10	m3
Water, well, in ground, CH	in water	4.59E-10	m3
Water, well, in ground, CN	in water	1.46E-07	m3
Water, well, in ground, CZ	in water	6.07E-15	m3
Water, well, in ground, DE	in water	7.33E-11	m3
Water, well, in ground, DK	in water	7.64E-14	m3
Water, well, in ground, ES	in water	6.66E-11	m3
Water, well, in ground, Europe without Switzerland	in water	1.1E-08	m3
Water, well, in ground, FI	in water	2.56E-14	m3
Water, well, in ground, FR	in water	1.45E-11	m3
Water, well, in ground, GB	in water	1.84E-13	m3
Water, well, in ground, GLO	in water	3.23E-09	m3
Water, well, in ground, HU	in water	2.73E-14	m3
Water, well, in ground, ID	in water	6.7E-09	m3
Water, well, in ground, IN	in water	4.33E-09	m3
Water, well, in ground, IS	in water	1.81E-14	m3
Water, well, in ground, IT	in water	2.16E-13	m3
Water, well, in ground, JP	in water	3.29E-12	m3
Water, well, in ground, KR	in water	2.72E-13	m3
Water, well, in ground, LU	in water	4.08E-15	m3
Water, well, in ground, MA	in water	3.84E-11	m3
Water, well, in ground, MX	in water	2.02E-14	m3
Water, well, in ground, MY	in water	1.15E-11	m3
Water, well, in ground, NL	in water	2.07E-13	m3
Water, well, in ground, NO	in water	1.05E-14	m3
Water, well, in ground, NORDEL	in water	9.22E-12	m3
Water, well, in ground, PE	in water	1.99E-13	m3
Water, well, in ground, PG	in water	1.29E-11	m3
Water, well, in ground, PH	in water	1.23E-10	m3
Water, well, in ground, PL	in water	1.79E-09	m3
Water, well, in ground, PT	in water	2.41E-14	m3
Water, well, in ground, RER	in water	7.11E-09	m3
Water, well, in ground, RLA	in water	6E-10	m3
Water, well, in ground, RNA	in water	7.22E-09	m3
Water, well, in ground, RoW	in water	2.88E-07	m3
Water, well, in ground, RU	in water	3.75E-09	m3
Water, well, in ground, SE	in water	5.81E-13	m3
Water, well, in ground, SK	in water	2.31E-15	m3
Water, well, in ground, TH	in water	3.47E-18	m3
Water, well, in ground, TN	in water	9.54E-12	m3
Water, well, in ground, TR	in water	3.64E-13	m3
Water, well, in ground, TW	in water	1.23E-12	m3
Water, well, in ground, US	in water	1.68E-09	m3
Water, well, in ground, WEU	in water	5.64E-10	m3
Water, well, in ground, ZA	in water	1.59E-09	m3
Transformation, to traffic area, rail/road embankment	land	2.82E-09	m2
Occupation, traffic area, rail/road embankment	land	3.67E-07	m2a
Carbon, organic, in soil or biomass stock	in ground	3.54E-08	kg
Gangue, bauxite, in ground	in ground	4.35E-05	kg

Water, cooling, unspecified natural origin, LV	in water	9.72E-10	m3
Water, cooling, unspecified natural origin, MA	in water	7.89E-10	m3
Water, turbine use, unspecified natural origin, MK	in water	4.11E-08	m3
Water, cooling, unspecified natural origin, MK	in water	1.38E-09	m3
Water, cooling, unspecified natural origin, MT	in water	8.11E-10	m3
Water, turbine use, unspecified natural origin, MX	in water	4.38E-05	m3
Water, cooling, unspecified natural origin, MX	in water	3.76E-07	m3
Water, turbine use, unspecified natural origin, MY	in water	4.53E-06	m3
Water, cooling, unspecified natural origin, MY	in water	2.04E-07	m3
Water, turbine use, unspecified natural origin, NL	in water	2.32E-08	m3
Water, cooling, unspecified natural origin, NL	in water	2.46E-08	m3
Water, turbine use, unspecified natural origin, NO	in water	5.67E-07	m3
Water, cooling, unspecified natural origin, NO	in water	6.2E-10	m3
Water, turbine use, unspecified natural origin, PE	in water	5.26E-07	m3
Water, cooling, unspecified natural origin, PE	in water	3.59E-08	m3
Water, cooling, unspecified natural origin, PH	in water	2.5E-12	m3
Water, turbine use, unspecified natural origin, PL	in water	3.67E-07	m3
Water, cooling, unspecified natural origin, PL	in water	1.31E-07	m3
Water, turbine use, unspecified natural origin, PT	in water	6.5E-07	m3
Water, cooling, unspecified natural origin, PT	in water	5.14E-09	m3
Water, turbine use, unspecified natural origin, RER	in water	1.07E-09	m3
Water, cooling, unspecified natural origin, RER	in water	4.14E-07	m3
Water, turbine use, unspecified natural origin, RNA	in water	2.55E-12	m3
Water, cooling, unspecified natural origin, RNA	in water	3.2E-14	m3
Water, turbine use, unspecified natural origin, RO	in water	1.93E-06	m3
Water, cooling, unspecified natural origin, RO	in water	1.38E-08	m3
Water, turbine use, unspecified natural origin, RoW	in water	0.000696	m3
Water, cooling, unspecified natural origin, RoW	in water	6.63E-06	m3
Water, turbine use, unspecified natural origin, RU	in water	0.000128	m3
Water, cooling, unspecified natural origin, RU	in water	4.53E-06	m3
Water, cooling, unspecified natural origin, SA	in water	5.91E-07	m3
Water, turbine use, unspecified natural origin, SE	in water	1.18E-05	m3
Water, cooling, unspecified natural origin, SE	in water	1.93E-08	m3
Water, turbine use, unspecified natural origin, SI	in water	8.15E-07	m3
Water, cooling, unspecified natural origin, SI	in water	1.72E-08	m3
Water, turbine use, unspecified natural origin, SK	in water	7.02E-07	m3
Water, cooling, unspecified natural origin, SK	in water	1.8E-08	m3
Water, turbine use, unspecified natural origin, TH	in water	2.15E-06	m3
Water, cooling, unspecified natural origin, TH	in water	2.18E-07	m3
Water, turbine use, unspecified natural origin, TR	in water	4.8E-05	m3
Water, cooling, unspecified natural origin, TR	in water	2.75E-07	m3
Water, turbine use, unspecified natural origin, TW	in water	7.69E-06	m3
Water, cooling, unspecified natural origin, TW	in water	3.35E-07	m3
Water, turbine use, unspecified natural origin, TZ	in water	4.17E-07	m3
Water, cooling, unspecified natural origin, TZ	in water	8.52E-09	m3
Water, turbine use, unspecified natural origin, UA	in water	1.79E-06	m3
Water, cooling, unspecified natural origin, UA	in water	5.13E-08	m3
Water, turbine use, unspecified natural origin, US	in water	0.000298	m3
Water, cooling, unspecified natural origin, US	in water	4.81E-06	m3
Water, cooling, unspecified natural origin, WEU	in water	1.41E-12	m3
Water, turbine use, unspecified natural origin, ZA	in water	5.42E-07	m3
Water, cooling, unspecified natural origin, ZA	in water	3.82E-07	m3
Water, cooling, unspecified natural origin, RS	in water	6.9E-09	m3
Water, turbine use, unspecified natural origin, RS	in water	1.37E-06	m3
Carnallite	in water	3.23E-09	kg
Water, unspecified natural origin, UN-OCEANIA	in water	1.67E-11	m3
Transformation, from traffic area, rail/road embankment	land	1.77E-09	m2
Transformation, to forest, secondary (non-use)	land	8.68E-13	m2
Transformation, to wetland, inland (non-use)	land	2.75E-12	m2
Cobalt, Co 5.0E-2%, in mixed ore, in ground	in ground	3.4E-12	kg
Copper, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore	in ground	4.62E-11	kg
Gold, Au 1.0E-7%, in mixed ore, in ground	in ground	7.01E-16	kg
Nickel, Ni 2.5E+0%, in mixed ore, in ground	in ground	1.66E-10	kg
Palladium, Pd 1.6E-6%, in mixed ore, in ground	in ground	1.11E-14	kg
Platinum, Pt 4.7E-7%, in mixed ore, in ground	in ground	3.22E-15	kg
Rhodium, Rh 1.6E-7%, in mixed ore, in ground	in ground	1.09E-15	kg
Silver, Ag 1.8E-6%, in mixed ore, in ground	in ground	1.24E-14	kg
Water, unspecified natural origin, IAI Area, EU27 & EFTA	in water	1.37E-10	m3
Occupation, inland waterbody, unspecified	land	2.18E-10	m2a
Transformation, to grassland, natural (non-use)	land	1.28E-09	m2
Transformation, to inland waterbody, unspecified	land	2.18E-12	m2
Aluminium	in ground	8.55E-11	kg
Aluminium	in ground	4.1E-06	kg
Anhydrite	in ground	2.48E-12	kg
Argon	in air	1.04E-06	kg
Barite	in ground	1.09E-07	kg
Basalt	in ground	2.67E-08	kg
Borax	in ground	1.08E-10	kg
Bromine	in water	1.27E-11	kg
Cadmium	in ground	2.25E-09	kg
Calcite	in ground	1.95E-05	kg
Cerium	in ground	1.38E-12	kg
Chromium	in ground	8.39E-08	kg
Chrysotile	in ground	1.38E-10	kg
Cinnabar	in ground	1.85E-12	kg
Clay, bentonite	in ground	6.16E-08	kg
Clay, unspecified	in ground	3.99E-06	kg
Coal, brown	in ground	5.66E-05	kg
Coal, hard	in ground	0.000125	kg
Cobalt	in ground	4.28E-12	kg
Colemanite	in ground	1.93E-08	kg
Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	in ground	9.85E-09	kg
Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	in ground	6.69E-09	kg
Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	in ground	2.16E-09	kg
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	in ground	2.62E-08	kg
Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore	in ground	2.29E-09	kg
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	in ground	9.02E-09	kg
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore	in ground	1.1E-09	kg
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	in ground	3.62E-09	kg
Copper, Cu 0.2%, in mixed ore	in ground	2.67E-11	kg
Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore	in ground	1.16E-08	kg
Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	in ground	4.45E-10	kg
Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	in ground	8.15E-12	kg
Diatomite	in ground	1.85E-12	kg
Dolomite	in ground	1.04E-07	kg
Europium	in ground	3.45E-15	kg
Feldspar	in ground	2E-12	kg
Fluorine	in ground	2.16E-08	kg
Fluorine, 4.5% in apatite, 3% in crude ore	in ground	1.66E-09	kg
Fluorspar	in ground	5.66E-09	kg
Gadolinium	in ground	8.62E-15	kg
Gallium	in ground	1.42E-15	kg
Gas, mine, off-gas, process, coal mining/m3	in ground	1.15E-06	m3
Gas, natural/m3	in ground	3.87E-05	m3
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore	in ground	5.91E-14	kg
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	in ground	9.67E-14	kg
Gold	in ground	2.89E-13	kg
Gold, Au 1.8E-4%, in mixed ore	in ground	3.18E-14	kg
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	in ground	2.09E-14	kg
Gold, Au 4.3E-4%, in ore	in ground	5.63E-14	kg
Gold, Au 4.9E-5%, in ore	in ground	2.83E-13	kg
Gold, Au 5.4E-4%, Ag 1.5E-5%, in ore	in ground	3.5E-15	kg
Gold, Au 6.7E-4%, in ore	in ground	3.01E-13	kg
Gold, Au 6.8E-4%, Ag 1.5E-4%, in ore	in ground	4.76E-15	kg
Gold, Au 7.1E-4%, in ore	in ground	1.4E-13	kg
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	in ground	2.83E-13	kg
Gold, Au 9.7E-5%, Ag 7.6E-5%, in ore	in ground	1.72E-14	kg
Granite	in ground	1.29E-15	kg
Gravel	in ground	7.22E-05	kg
Gypsum	in ground	2.73E-07	kg
Indium	in ground	3.75E-11	kg
Iodine	in water	2.24E-12	kg
Iron	in ground	6.59E-06	kg

Iron	in ground	6.15E-10	kg
Kaolinite	in ground	2.12E-09	kg
Kieserite	in ground	7.63E-11	kg
Krypton	in air	9.77E-13	kg
Lanthanum	in ground	4.13E-13	kg
Lead	in ground	3.75E-08	kg
Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore	in ground	1.41E-09	kg
Lead, Pb 3.6E-1%, in mixed ore	in ground	4.8E-11	kg
Lithium	in ground	1.34E-11	kg
Magnesite	in ground	2.67E-08	kg
Manganese	in ground	1.85E-08	kg
Metamorphous rock, graphite containing	in ground	8.94E-11	kg
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore	in ground	1.05E-10	kg
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore	in ground	2.26E-11	kg
Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore	in ground	2.36E-10	kg
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore	in ground	1.49E-10	kg
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore	in ground	1.73E-10	kg
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore	in ground	1.8E-10	kg
Molybdenum	in ground	2.47E-10	kg
Neodymium	in ground	2.27E-13	kg
Nickel, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore	in ground	3.21E-10	kg
Nickel, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore	in ground	1.16E-11	kg
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore	in ground	4.46E-09	kg
Nickel, 1.98% in silicates, 1.04% in crude ore	in ground	5.39E-08	kg
Occupation, annual crop	land	3.76E-08	m2a
Occupation, annual crop, greenhouse	land	2.17E-11	m2a
Occupation, annual crop, irrigated	land	9.4E-10	m2a
Occupation, annual crop, irrigated, intensive	land	8.93E-10	m2a
Occupation, annual crop, non-irrigated	land	2.34E-10	m2a
Occupation, annual crop, non-irrigated, extensive	land	3.27E-09	m2a
Occupation, annual crop, non-irrigated, intensive	land	1.5E-07	m2a
Occupation, grassland, natural (non-use)	land	9.55E-08	m2a
Occupation, water bodies, artificial	land	1.28E-06	m2a
Occupation, pasture, man made, extensive	land	8.8E-11	m2a
Occupation, pasture, man made, intensive	land	5.17E-09	m2a
Occupation, permanent crop, irrigated, intensive	land	2.7E-10	m2a
Occupation, permanent crop, non-irrigated, intensive	land	3.23E-11	m2a
Occupation, water bodies, artificial	land	2.84E-07	m2a
Occupation, urban/industrial fallow (non-use)	land	1.73E-10	m2a
Oil, crude	in ground	1.71E-05	kg
Olivine	in ground	1.16E-12	kg
Palladium, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	2.27E-14	kg
Palladium, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	1.01E-13	kg
Peat	biotic	1.47E-07	kg
Perlite	in ground	4.45E-09	kg
Phosphorus	in ground	8.01E-09	kg
Phosphorus, 18% in apatite, 4% in crude ore	in ground	8.64E-08	kg
Praseodymium	in ground	2.41E-14	kg
Platinum, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	3.48E-14	kg
Platinum, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	5.34E-14	kg
Pumice	in ground	1.04E-08	kg
Rhodium, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	2.78E-15	kg
Rhodium, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	2.67E-15	kg
Rhenium	in ground	2.94E-15	kg
Samarium	in ground	1.72E-14	kg
Sand	in ground	1.14E-09	kg
Shale	in ground	1.52E-07	kg
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	in ground	5.47E-11	kg
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore	in ground	6.46E-16	kg
Silver, Ag 1.5E-4%, Au 6.8E-4%, in ore	in ground	1.07E-15	kg
Silver, Ag 1.5E-5%, Au 5.4E-4%, in ore	in ground	9.78E-17	kg
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore	in ground	2.13E-14	kg
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore	in ground	2.21E-12	kg
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore	in ground	3.45E-14	kg
Silver, Ag 5.4E-3%, in mixed ore	in ground	7.26E-13	kg
Silver, Ag 7.6E-5%, Au 9.7E-5%, in ore	in ground	1.35E-14	kg
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	in ground	1.43E-11	kg
Sodium chloride	in ground	3.31E-06	kg
Sodium nitrate	in ground	3.31E-16	kg
Sodium sulfate	in ground	1.05E-09	kg
Spodumene	in ground	4.05E-12	kg
Stibnite	in ground	1.92E-13	kg
Strontium	in ground	3.8E-11	kg
Sulfur	in ground	1.13E-09	kg
Potassium chloride	in ground	7.77E-09	kg
Talc	in ground	2.13E-10	kg
Tantalum	in ground	7.15E-12	kg
Tellurium	in ground	9.69E-17	kg
Tin	in ground	1.09E-10	kg
TiO2, 54% in ilmenite, 18% in crude ore	in ground	4.61E-10	kg
TiO2, 54% in ilmenite, 2.6% in crude ore	in ground	6.29E-09	kg
TiO2, 95% in rutile, 0.40% in crude ore	in ground	9.69E-10	kg
Transformation, from annual crop	land	2.42E-08	m2
Transformation, from annual crop, greenhouse	land	5.01E-11	m2
Transformation, from annual crop, irrigated, intensive	land	8.47E-10	m2
Transformation, from annual crop, non-irrigated	land	1.43E-07	m2
Transformation, from annual crop, non-irrigated, extensive	land	4.86E-09	m2
Transformation, from annual crop, non-irrigated, intensive	land	2.46E-08	m2
Transformation, from annual crop	land	8.69E-09	m2
Transformation, from forest, primary (non-use)	land	3.83E-09	m2
Transformation, from forest, unspecified	land	3.99E-08	m2
Transformation, from grassland, natural (non-use)	land	2.88E-10	m2
Transformation, from pasture, man made	land	9.08E-09	m2
Transformation, from pasture, man made, extensive	land	1.76E-12	m2
Transformation, from pasture, man made, intensive	land	5.21E-09	m2
Transformation, from permanent crop, irrigated	land	7.52E-10	m2
Transformation, from permanent crop, irrigated, intensive	land	2.19E-10	m2
Transformation, from permanent crop, non-irrigated, intensive	land	3.23E-11	m2
Transformation, from seabed, unspecified	land	4.29E-09	m2
Transformation, from unknown	land	5.43E-08	m2
Transformation, from unspecified, natural	land	2.58E-11	m2
Transformation, to annual crop	land	2.31E-08	m2
Transformation, to annual crop, greenhouse	land	5.01E-11	m2
Transformation, to annual crop, irrigated, extensive	land	4.47E-11	m2
Transformation, to annual crop, irrigated, intensive	land	1.94E-09	m2
Transformation, to annual crop, non-irrigated	land	6.2E-10	m2
Transformation, to annual crop, non-irrigated, extensive	land	5.23E-09	m2
Transformation, to annual crop, non-irrigated, intensive	land	1.79E-07	m2
Transformation, to annual crop	land	8.56E-09	m2
Transformation, to annual crop, fallow	land	9.08E-10	m2
Transformation, to forest, unspecified	land	3.35E-09	m2
Transformation, to water bodies, artificial	land	9.39E-09	m2
Transformation, to pasture, man made	land	4.31E-10	m2
Transformation, to pasture, man made, extensive	land	1.76E-12	m2
Transformation, to pasture, man made, intensive	land	4.33E-09	m2
Transformation, to permanent crop, irrigated	land	7.52E-10	m2
Transformation, to permanent crop, irrigated, intensive	land	2.19E-10	m2
Transformation, to permanent crop, non-irrigated	land	8.68E-13	m2
Transformation, to permanent crop, non-irrigated, intensive	land	3.23E-11	m2
Transformation, to water bodies, artificial	land	3.4E-09	m2
Transformation, to unknown	land	5.93E-10	m2
Transformation, to urban/industrial fallow	land	2.3E-12	m2
Ulexite	in ground	7.61E-11	kg
Uranium	in ground	1.18E-09	kg
Vermiculite	in ground	3.51E-09	kg
Water, unspecified natural origin, IAI Area, Africa	in water	1.26E-11	m3
Water, unspecified natural origin, IAI Area, Asia, without China and GCC	in water	2.33E-11	m3
Water, unspecified natural origin, IAI Area, Gulf Cooperation Council	in water	2.81E-11	m3
Water, unspecified natural origin, IAI Area, North America, without Quebec	in water	1.77E-11	m3
Water, unspecified natural origin, IAI Area, Russia & RER w/o EU27 & EFTA	in water	4.15E-11	m3
Water, unspecified natural origin, IAI Area, South America	in water	1.67E-11	m3
Wood, unspecified, standing/m3	biotic	7.19E-14	m3
Xenon	in air	1.15E-13	kg
Zinc	in ground	6.75E-08	kg
Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore	in ground	1.82E-09	kg
Zinc, Zn 3.1%, in mixed ore	in ground	4.12E-10	kg
Zirconium	in ground	9.41E-10	kg

Emissions to air			
Ammonia		5.96E-09	kg
Benzene		1.01E-09	kg
Pentane		1.19E-12	kg
Acetaldehyde		4.42E-11	kg
Acetic acid		2.23E-11	kg
Acetone		1.95E-12	kg
Acrolein		8.66E-12	kg
Benzaldehyde		6.51E-12	kg
Benzo(a)pyrene		8.05E-14	kg
Butane		1.19E-12	kg
Cobalt		7.32E-14	kg
Ethane		1.79E-11	kg
Ethanol		2.46E-15	kg
Ethene		1.13E-12	kg
Ethylene oxide		1.27E-15	kg
Ethyne		4.74E-13	kg
Fluoranthene		2.21E-16	kg
Formaldehyde		9.52E-11	kg
Heptane		1.43E-12	kg
Hexane		3.01E-18	kg
Isoprene		5.1E-18	kg
m-Xylene		4.66E-12	kg
Methanol		1.13E-11	kg
o-Xylene		1.9E-12	kg
Phenol		2.27E-13	kg
Propane		1.01E-12	kg
Propene		6.03E-13	kg
Propionic acid		1.32E-14	kg
Styrene		2.69E-12	kg
Toluene		1.52E-09	kg
Xylene		8.95E-10	kg
Phenanthrene		3.09E-15	kg
Chrysene		2.65E-18	kg
2-Propanol		7.06E-15	kg
Ammonia	low. pop.	1.56E-09	kg
Ammonia	low. pop., l	5.05E-13	kg
Ammonia	high. pop.	2.71E-09	kg
Benzene	low. pop.	1.44E-09	kg
Benzene	high. pop.	2.72E-10	kg
Benzene	stratosphe	5.42E-17	kg
Methane	high. pop.	2.29E-13	kg
Pentane	low. pop.	1.83E-09	kg
Pentane	high. pop.	1.27E-09	kg
1-Pentene	high. pop.	1.61E-15	kg
2,4-D	low. pop.	1.34E-14	kg
Acetaldehyde	low. pop.	1.59E-11	kg
Acetaldehyde	high. pop.	9.03E-11	kg
Acetic acid	low. pop.	2.01E-10	kg
Acetic acid	high. pop.	3.48E-10	kg
Acetone	low. pop.	5.26E-11	kg
Acetone	high. pop.	9.32E-11	kg
Acetonitrile	low. pop.	2.76E-12	kg
Acrolein	low. pop.	5.96E-12	kg
Acrolein	high. pop.	1.69E-14	kg
Atrazine	low. pop.	1.32E-15	kg
Benzaldehyde	low. pop.	1.22E-12	kg
Benzaldehyde	high. pop.	5.23E-15	kg
Benzo(a)pyrene	low. pop.	7.33E-12	kg
Benzo(a)pyrene	high. pop.	6.36E-14	kg
Butane	low. pop.	1.38E-09	kg
Butane	high. pop.	1.03E-09	kg
Butene	high. pop.	2.25E-11	kg
Cobalt	low. pop.	1.52E-11	kg
Cobalt	low. pop., l	4.69E-13	kg
Cobalt	high. pop.	1.36E-11	kg
Cyclohexane	high. pop.	7.51E-17	kg
Diethyl ether	high. pop.	1.79E-16	kg
Ethane	low. pop.	1.04E-08	kg
Ethane	high. pop.	4.94E-10	kg
Ethanol	low. pop.	7.44E-10	kg
Ethanol	high. pop.	1.7E-10	kg
Ethene	low. pop.	1.58E-09	kg
Ethene	high. pop.	2.47E-10	kg
Ethylene oxide	low. pop.	1.34E-16	kg
Ethylene oxide	high. pop.	2.3E-13	kg
Ethylene oxide	stratosphe	4.96E-16	kg
Ethyne	low. pop.	8.11E-13	kg
Ethyne	high. pop.	3.05E-11	kg
Formaldehyde	low. pop.	2.72E-10	kg
Formaldehyde	high. pop.	2.82E-10	kg
Formaldehyde	stratosphe	4.28E-16	kg
Formic acid	low. pop.	1.69E-11	kg
Formic acid	high. pop.	4.57E-14	kg
Heptane	high. pop.	2.25E-10	kg
Hexane	low. pop.	1.05E-09	kg
Hexane	high. pop.	4.92E-10	kg
Isoprene	low. pop.	2.46E-13	kg
m-Xylene	low. pop.	1.59E-15	kg
m-Xylene	high. pop.	1.23E-11	kg
Methanol	low. pop.	5.24E-11	kg
Methanol	high. pop.	1.86E-10	kg
Methyl ethyl ketone	low. pop.	4.54E-16	kg
Methyl ethyl ketone	high. pop.	3.74E-11	kg
Methyl formate	high. pop.	5.56E-16	kg
Metribuzin	low. pop.	1.79E-15	kg
o-Xylene	high. pop.	7.58E-15	kg
Phenol	low. pop.	3.1E-12	kg
Phenol	high. pop.	1.64E-12	kg
Propane	low. pop.	2.22E-09	kg
Propane	high. pop.	1.13E-09	kg
Propene	low. pop.	3.6E-11	kg
Propene	high. pop.	9.33E-11	kg
Propionic acid	low. pop.	2.07E-11	kg
Propionic acid	high. pop.	2.81E-13	kg
Styrene	low. pop.	5.36E-13	kg
Styrene	high. pop.	3.07E-13	kg
Toluene	low. pop.	2.99E-10	kg
Toluene	high. pop.	1.85E-10	kg
Trifluralin	low. pop.	1.99E-14	kg
Xylene	low. pop.	1.59E-09	kg
Xylene	high. pop.	1.35E-10	kg
Carbaryl	low. pop.	1.74E-16	kg
Glyphosate	low. pop.	4.34E-13	kg
Permethrin	low. pop.	1.81E-16	kg
Acephate	low. pop.	1.43E-15	kg
Metolachlor	low. pop.	4.69E-15	kg
Dichlorprop	low. pop.	4.88E-17	kg
Methomyl	low. pop.	8.15E-21	kg
Phosphoric acid	high. pop.	7.51E-17	kg
Acrylic acid	high. pop.	5.52E-16	kg
2-Propanol	low. pop.	1.73E-15	kg
2-Propanol	high. pop.	7.88E-12	kg
Diethylene glycol	high. pop.	2.5E-16	kg
Bentazone	low. pop.	6.15E-16	kg
Benzo(k)fluoranthene		2.08E-17	kg
Chlorpyrifos	low. pop.	6.53E-15	kg
Dibenz(a,h)anthracene		1.35E-17	kg

Hydrocarbons, chlorinated		3.9E-13	kg
Hydrocarbons, chlorinated	low. pop.	4.05E-12	kg
Hydrocarbons, chlorinated	high. pop.	2.36E-11	kg
Hydrocarbons, unspecified	low. pop.	5.61E-13	kg
Indeno(1,2,3-cd)pyrene		5.3E-18	kg
Sulfur trioxide		1.72E-14	kg
Sulfur trioxide	high. pop.	3.59E-14	kg
Sulfuric acid		1.99E-13	kg
Sulfuric acid	low. pop.	1.55E-11	kg
Sulfuric acid	high. pop.	4.45E-14	kg
Actinides, radioactive, unspecified	low. pop.	4.14E-05	Bq
Aerosols, radioactive, unspecified	low. pop.	3.1E-08	Bq
Aldehydes, unspecified		1.82E-12	kg
Aldehydes, unspecified	low. pop.	1.96E-11	kg
Aldehydes, unspecified	high. pop.	1.79E-12	kg
Ammonium carbonate	high. pop.	7.39E-14	kg
Antimony		8.78E-11	kg
Antimony	low. pop.	5.89E-12	kg
Antimony	low. pop., l	5.26E-14	kg
Antimony	high. pop.	1.64E-12	kg
Antimony-124	low. pop.	4.32E-11	Bq
Antimony-125	low. pop.	7.5E-10	Bq
Argon-41	low. pop.	2.48E-05	Bq
Arsenic		1.86E-13	kg
Arsenic	low. pop.	4.98E-11	kg
Arsenic	low. pop., l	3.09E-12	kg
Arsenic	high. pop.	5.66E-12	kg
Barium		3.41E-11	kg
Barium	low. pop.	1.31E-10	kg
Barium	low. pop., l	3.38E-12	kg
Barium	high. pop.	1.23E-11	kg
Barium-140	low. pop.	2.41E-08	Bq
Benzene, ethyl-		2.28E-16	kg
Benzene, ethyl-	low. pop.	2.25E-12	kg
Benzene, ethyl-	high. pop.	2.6E-11	kg
Benzene, hexachloro-		1.6E-14	kg
Benzene, hexachloro-	low. pop.	2.71E-23	kg
Benzene, hexachloro-	high. pop.	2.18E-16	kg
Benzene, pentachloro-	high. pop.	5.48E-16	kg
Beryllium		1.8E-14	kg
Beryllium	low. pop.	4.37E-13	kg
Beryllium	low. pop., l	7.37E-14	kg
Beryllium	high. pop.	9.1E-14	kg
Boron		8.86E-13	kg
Boron	low. pop.	1.73E-09	kg
Boron	low. pop., l	9.81E-13	kg
Boron	high. pop.	5.49E-11	kg
Bromine		4.58E-13	kg
Bromine	low. pop.	6.28E-10	kg
Bromine	high. pop.	2.89E-11	kg
Butadiene		1.2E-16	kg
Butadiene	low. pop.	1.39E-17	kg
Butadiene	high. pop.	3.23E-16	kg
Butadiene	stratosphe	5.13E-17	kg
Cadmium		1.96E-13	kg
Cadmium	low. pop.	1.15E-11	kg
Cadmium	low. pop., l	7.97E-14	kg
Cadmium	high. pop.	2.13E-12	kg
Cadmium	stratosphe	2.72E-20	kg
Calcium		1E-11	kg
Calcium	low. pop.	1.29E-11	kg
Calcium	low. pop., l	1.9E-10	kg
Calcium	high. pop.	9.12E-10	kg
Carbon dioxide, fossil		1.54E-05	kg
Carbon dioxide, fossil	low. pop.	0.000357	kg
Carbon dioxide, fossil	high. pop.	4.34E-05	kg
Carbon dioxide, fossil	stratosphe	8.55E-12	kg
Carbon disulfide		5.83E-18	kg
Carbon disulfide	low. pop.	6.24E-10	kg
Carbon disulfide	high. pop.	1.89E-14	kg
Carbon monoxide, fossil		1.44E-07	kg
Carbon monoxide, fossil	low. pop.	1.18E-07	kg
Carbon monoxide, fossil	high. pop.	3.51E-08	kg
Carbon monoxide, fossil	stratosphe	1E-14	kg
Carbon-14	low. pop.	0.002044	Bq
Cerium-141	low. pop.	5.85E-09	Bq
Cesium-134	low. pop.	2.8E-10	Bq
Cesium-137	low. pop.	5.08E-09	Bq
Chlorine		9.42E-12	kg
Chlorine	low. pop.	1.72E-13	kg
Chlorine	low. pop., l	7.24E-12	kg
Chlorine	high. pop.	1.43E-10	kg
Chloroform		2.65E-18	kg
Chloroform	low. pop.	1.96E-12	kg
Chloroform	high. pop.	9.85E-13	kg
Chromium		3.04E-12	kg
Chromium	low. pop.	3.05E-10	kg
Chromium	high. pop.	6.66E-12	kg
Chromium	stratosphe	1.36E-19	kg
Chromium VI		1.15E-14	kg
Chromium VI	low. pop.	1.03E-11	kg
Chromium VI	low. pop., l	3.76E-13	kg
Chromium VI	high. pop.	3.17E-13	kg
Chromium-51	low. pop.	3.75E-10	Bq
Cobalt-58	low. pop.	7.88E-10	Bq
Cobalt-60	low. pop.	5.84E-09	Bq
Copper		4.89E-11	kg
Copper	low. pop.	1.03E-10	kg
Copper	low. pop., l	4.94E-12	kg
Copper	high. pop.	2.2E-11	kg
Copper	stratosphe	4.62E-18	kg
Cumene		2.38E-19	kg
Cumene	low. pop.	1.09E-13	kg
Cumene	high. pop.	1E-11	kg
Cyanide		1.12E-16	kg
Cyanide	low. pop.	1.08E-10	kg
Cyanide	high. pop.	3.5E-11	kg
Dinitrogen monoxide		6.47E-09	kg
Dinitrogen monoxide	low. pop.	5.41E-09	kg
Dinitrogen monoxide	low. pop., l	4.74E-13	kg
Dinitrogen monoxide	high. pop.	2.69E-09	kg
Dinitrogen monoxide	stratosphe	8.15E-17	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a		1.4E-12	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	low. pop.	1.55E-12	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	high. pop.	1.87E-13	kg
Ethane, 1,2-dichloro-		2.11E-17	kg
Ethane, 1,2-dichloro-	low. pop.	7.98E-13	kg
Ethane, 1,2-dichloro-	high. pop.	3.5E-11	kg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	low. pop.	4.67E-12	kg
Ethane, hexafluoro-, HFC-116		3.77E-13	kg
Ethane, hexafluoro-, HFC-116	high. pop.	2.78E-15	kg
Ethene, chloro-		1.8E-18	kg
Ethene, chloro-	high. pop.	1.97E-11	kg
Ethene, tetrachloro-		3.89E-15	kg
Ethene, tetrachloro-	low. pop.	8.59E-13	kg
Ethene, tetrachloro-	high. pop.	1.03E-13	kg
Ethylene diamine	high. pop.	9.7E-15	kg
Fluorine		4.16E-14	kg
Fluorine	low. pop.	3.41E-12	kg
Fluorine	low. pop., l	3.56E-11	kg
Fluorine	high. pop.	5.13E-12	kg
Fluosilicic acid	high. pop.	1.81E-12	kg
Heat, waste		8.72E-07	MJ
Heat, waste	low. pop.	4.25E-09	MJ
Heat, waste	high. pop.	2.13E-05	MJ
Helium		1.03E-12	kg
Helium	low. pop.	5.01E-11	kg

Hydrocarbons, aliphatic, alkanes, cyclic	low. pop.	1.16E-11	kg
Hydrocarbons, aliphatic, alkanes, cyclic	high. pop.	6.66E-12	kg
Hydrocarbons, aliphatic, alkanes, unspecified		6.83E-10	kg
Hydrocarbons, aliphatic, alkanes, unspecified	low. pop.	4.63E-10	kg
Hydrocarbons, aliphatic, alkanes, unspecified	high. pop.	5.18E-10	kg
Hydrocarbons, aliphatic, unsaturated		3.58E-13	kg
Hydrocarbons, aliphatic, unsaturated	low. pop.	3.7E-10	kg
Hydrocarbons, aliphatic, unsaturated	high. pop.	3.75E-10	kg
Hydrocarbons, aromatic		2.35E-09	kg
Hydrocarbons, aromatic	low. pop.	3.66E-11	kg
Hydrocarbons, aromatic	high. pop.	4.62E-11	kg
Hydrogen		6.98E-12	kg
Hydrogen	high. pop.	1.12E-08	kg
Hydrogen chloride		4.75E-10	kg
Hydrogen chloride	low. pop.	5.86E-08	kg
Hydrogen chloride	high. pop.	3.57E-09	kg
Hydrogen chloride	stratospher	2.34E-18	kg
Hydrogen fluoride		2.85E-10	kg
Hydrogen fluoride	low. pop.	7.12E-09	kg
Hydrogen fluoride	high. pop.	1.95E-10	kg
Hydrogen sulfide		7.86E-11	kg
Hydrogen sulfide	low. pop.	6.9E-10	kg
Hydrogen sulfide	low. pop., l	7.47E-11	kg
Hydrogen sulfide	high. pop.	6.86E-12	kg
Hydrogen-3, Tritium	low. pop.	0.003939	Bq
Iodine		2E-13	kg
Iodine	low. pop.	3.27E-10	kg
Iodine	high. pop.	1.2E-11	kg
Iodine-129	low. pop.	7.09E-07	Bq
Iodine-131	low. pop.	3.88E-06	Bq
Iodine-133	low. pop.	5.84E-08	Bq
Iron		2.07E-10	kg
Iron	low. pop.	1.96E-11	kg
Iron	low. pop., l	6.35E-10	kg
Iron	high. pop.	2.96E-10	kg
Isocyanic acid	high. pop.	7.35E-12	kg
Krypton-85	low. pop.	9.43E-05	Bq
Krypton-85m	low. pop.	0.000508	Bq
Krypton-87	low. pop.	7.73E-05	Bq
Krypton-88	low. pop.	0.000102	Bq
Krypton-89	low. pop.	4.35E-05	Bq
Lanthanum-140	low. pop.	2.06E-09	Bq
Lead		1.98E-11	kg
Lead	low. pop.	1.67E-10	kg
Lead	low. pop., l	5.23E-12	kg
Lead	high. pop.	2.45E-11	kg
Lead	stratospher	5.43E-20	kg
Lead-210		8.56E-08	Bq
Lead-210	low. pop.	0.000139	Bq
Lead-210	high. pop.	7.41E-06	Bq
Magnesium		1.29E-12	kg
Magnesium	low. pop.	2.28E-10	kg
Magnesium	low. pop., l	5.82E-11	kg
Magnesium	high. pop.	2.63E-10	kg
Manganese		5.78E-12	kg
Manganese	low. pop.	8.47E-11	kg
Manganese	low. pop., l	1.31E-11	kg
Manganese	high. pop.	2.5E-11	kg
Manganese-54	low. pop.	1.92E-10	Bq
Mercury		3.86E-12	kg
Mercury	low. pop.	9.42E-12	kg
Mercury	low. pop., l	4.02E-14	kg
Mercury	high. pop.	9.87E-13	kg
Mercury	stratospher	1.9E-22	kg
Methane, bromochlorodifluoro-, Halon 1211	low. pop.	5.62E-13	kg
Methane, bromotrifluoro-, Halon 1301	low. pop.	1.22E-12	kg
Methane, bromotrifluoro-, Halon 1301	high. pop.	8.83E-17	kg
Methane, chlorodifluoro-, HCFC-22		1.1E-18	kg
Methane, chlorodifluoro-, HCFC-22	low. pop.	4.91E-12	kg
Methane, chlorodifluoro-, HCFC-22	high. pop.	2.47E-12	kg
Methane, dichloro-, HCC-30		2.43E-13	kg
Methane, dichloro-, HCC-30	low. pop.	5.8E-12	kg
Methane, dichloro-, HCC-30	high. pop.	3.96E-14	kg
Methane, dichlorodifluoro-, CFC-12		4.78E-18	kg
Methane, dichlorodifluoro-, CFC-12	low. pop.	1.14E-15	kg
Methane, dichlorodifluoro-, CFC-12	high. pop.	4.77E-13	kg
Methane, dichlorofluoro-, HCFC-21	high. pop.	5.71E-16	kg
Methane, fossil		1.03E-07	kg
Methane, fossil	low. pop.	1.35E-06	kg
Methane, fossil	high. pop.	1.49E-08	kg
Methane, fossil	stratospher	1.36E-16	kg
Methane, monochloro-, R-40	low. pop.	1.06E-11	kg
Methane, trichlorofluoro-, CFC-11	high. pop.	8.8E-16	kg
Methane, trifluoro-, HFC-23	high. pop.	1.82E-13	kg
Molybdenum		8.79E-12	kg
Molybdenum	low. pop.	3.19E-12	kg
Molybdenum	low. pop., l	1.02E-12	kg
Molybdenum	high. pop.	3.4E-12	kg
Monoethanolamine	high. pop.	1.11E-11	kg
Nickel		2.19E-12	kg
Nickel	low. pop.	1.2E-10	kg
Nickel	low. pop., l	1.07E-12	kg
Nickel	high. pop.	1.12E-10	kg
Nickel	stratospher	1.9E-19	kg
Niobium-95	low. pop.	0.000137	Bq
Nitrate		3.87E-12	kg
Nitrate	low. pop.	1.72E-12	kg
Nitrate	low. pop., l	5.01E-12	kg
Nitrate	high. pop.	1.07E-15	kg
Nitrobenzene	high. pop.	5.38E-15	kg
Nitrogen oxides		1.16E-07	kg
Nitrogen oxides	low. pop.	7.42E-07	kg
Nitrogen oxides	low. pop., l	8.58E-14	kg
Nitrogen oxides	high. pop.	1.46E-07	kg
Nitrogen oxides	stratospher	4.65E-12	kg
NMVOC, non-methane volatile organic compounds, unspecified origin		2.1E-08	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	low. pop.	4.94E-08	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	high. pop.	4.2E-09	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	stratospher	1.82E-15	kg
Noble gases, radioactive, unspecified	low. pop.	6.813182	Bq
Ozone		2.38E-09	kg
Ozone	high. pop.	1.93E-14	kg
PAH, polycyclic aromatic hydrocarbons		8.66E-12	kg
PAH, polycyclic aromatic hydrocarbons	low. pop.	3.29E-11	kg
PAH, polycyclic aromatic hydrocarbons	high. pop.	1.9E-12	kg
Paraffins	high. pop.	4.48E-13	kg
Particulates, < 2.5 um		8.04E-09	kg
Particulates, < 2.5 um	low. pop.	7.55E-07	kg
Particulates, < 2.5 um	low. pop., l	5.02E-10	kg
Particulates, < 2.5 um	high. pop.	4.6E-08	kg
Particulates, < 2.5 um	stratospher	1.03E-16	kg
Particulates, > 10 um		6.95E-09	kg
Particulates, > 10 um	low. pop.	5.6E-07	kg
Particulates, > 10 um	low. pop., l	1.16E-09	kg
Particulates, > 10 um	high. pop.	1.87E-08	kg
Particulates, > 2.5 um, and < 10um		4.32E-09	kg
Particulates, > 2.5 um, and < 10um	low. pop.	1.66E-07	kg
Particulates, > 2.5 um, and < 10um	low. pop., l	6.99E-10	kg
Particulates, > 2.5 um, and < 10um	high. pop.	1.02E-08	kg
Phenol, pentachloro-		2.79E-14	kg
Phenol, pentachloro-	low. pop.	3.23E-12	kg
Phenol, pentachloro-	high. pop.	8.7E-16	kg
Phosphorus		7.02E-15	kg
Phosphorus	low. pop.	1.23E-13	kg
Phosphorus	low. pop., l	9.81E-13	kg
Phosphorus	high. pop.	4.59E-11	kg
Platinum	low. pop.	4.53E-17	kg
Platinum	high. pop.	2.21E-19	kg

Plutonium-238	low. pop.	9.67E-14	Bq
Plutonium-alpha	low. pop.	2.22E-13	Bq
Polonium-210		1.56E-07	Bq
Polonium-210	low. pop.	0.000244	Bq
Polonium-210	high. pop.	1.36E-05	Bq
Polychlorinated biphenyls		3.92E-14	kg
Polychlorinated biphenyls	high. pop.	1.94E-17	kg
Potassium		1.3E-12	kg
Potassium	low. pop.	7.73E-13	kg
Potassium	low. pop., l	9.98E-11	kg
Potassium	high. pop.	2.47E-09	kg
Potassium-40		2.12E-08	Bq
Potassium-40	low. pop.	4.88E-05	Bq
Potassium-40	high. pop.	1.95E-06	Bq
Propanal		1.7E-17	kg
Propanal	low. pop.	3.29E-13	kg
Propanal	high. pop.	9.37E-15	kg
Propylene oxide	high. pop.	7.32E-12	kg
Protactinium-234	low. pop.	2.77E-06	Bq
Radioactive species, other beta emitters	low. pop.	3.15E-09	Bq
Radioactive species, other beta emitters	high. pop.	0.002978	Bq
Radium-226		2.21E-08	Bq
Radium-226	low. pop.	4.45E-05	Bq
Radium-226	high. pop.	1.92E-06	Bq
Radium-228		8.33E-09	Bq
Radium-228	low. pop.	1.25E-05	Bq
Radium-228	high. pop.	4.13E-06	Bq
Radon-220		4.41E-07	Bq
Radon-220	low. pop.	0.001114	Bq
Radon-220	high. pop.	2.53E-05	Bq
Radon-222		2.53E-07	Bq
Radon-222	low. pop.	0.626783	Bq
Radon-222	low. pop., l	22.33693	Bq
Radon-222	high. pop.	1.43E-05	Bq
Ruthenium-103	low. pop.	5E-12	Bq
Scandium		5.59E-17	kg
Scandium	low. pop.	4.38E-15	kg
Scandium	low. pop., l	2.09E-12	kg
Scandium	high. pop.	7.32E-14	kg
Selenium		1.98E-13	kg
Selenium	low. pop.	4.68E-11	kg
Selenium	low. pop., l	2.92E-13	kg
Selenium	high. pop.	3.15E-12	kg
Selenium	stratospher	2.72E-20	kg
Silicon		6.72E-11	kg
Silicon	low. pop.	1.17E-11	kg
Silicon	low. pop., l	1.3E-10	kg
Silicon	high. pop.	9.26E-10	kg
Silicon tetrafluoride	low. pop.	6.53E-13	kg
Silver		2.53E-16	kg
Silver	low. pop.	8.73E-16	kg
Silver	low. pop., l	8.74E-14	kg
Silver	high. pop.	6.45E-15	kg
Silver-110	low. pop.	1E-10	Bq
Sodium		7.99E-12	kg
Sodium	low. pop.	1.55E-11	kg
Sodium	low. pop., l	3.43E-11	kg
Sodium	high. pop.	2.96E-10	kg
Sodium chlorate	high. pop.	3.73E-10	kg
Sodium dichromate	high. pop.	3.75E-13	kg
Sodium formate	high. pop.	3.34E-14	kg
Strontium		5.69E-13	kg
Strontium	low. pop.	1.32E-10	kg
Strontium	low. pop., l	2.12E-12	kg
Strontium	high. pop.	1.52E-11	kg
Sulfate		3.35E-11	kg
Sulfate	low. pop.	1.4E-11	kg
Sulfate	low. pop., l	5.37E-10	kg
Sulfate	high. pop.	8.88E-08	kg
Sulfur dioxide		1.96E-07	kg
Sulfur dioxide	low. pop.	1.16E-06	kg
Sulfur dioxide	high. pop.	3.68E-07	kg
Sulfur dioxide	stratospher	2.72E-15	kg
Sulfur hexafluoride		7.96E-11	kg
Sulfur hexafluoride	low. pop.	3.17E-15	kg
Sulfur hexafluoride	high. pop.	1.66E-16	kg
t-Butyl methyl ether	high. pop.	1.13E-12	kg
Thallium		6.83E-14	kg
Thallium	low. pop.	1.92E-15	kg
Thallium	high. pop.	9.26E-14	kg
Thorium		1.57E-16	kg
Thorium	low. pop.	7.01E-16	kg
Thorium	high. pop.	1.09E-13	kg
Thorium-228		3.79E-09	Bq
Thorium-228	low. pop.	6.99E-06	Bq
Thorium-228	high. pop.	5.14E-07	Bq
Thorium-230	low. pop.	4.02E-06	Bq
Thorium-232		5.57E-09	Bq
Thorium-232	low. pop.	1.01E-05	Bq
Thorium-232	high. pop.	5.09E-07	Bq
Thorium-234	low. pop.	2.77E-06	Bq
Tin		6.33E-12	kg
Tin	low. pop.	5.07E-12	kg
Tin	low. pop., l	1.22E-13	kg
Tin	high. pop.	5.13E-14	kg
Titanium		3.85E-12	kg
Titanium	low. pop.	1.33E-13	kg
Titanium	low. pop., l	3.81E-11	kg
Titanium	high. pop.	2.22E-11	kg
Uranium		2.44E-16	kg
Uranium	low. pop.	8.05E-16	kg
Uranium	high. pop.	1.46E-13	kg
Uranium alpha	low. pop.	1.17E-05	Bq
Uranium-234	low. pop.	7.88E-06	Bq
Uranium-235	low. pop.	1.02E-07	Bq
Uranium-238		1.84E-08	Bq
Uranium-238	low. pop.	3.49E-05	Bq
Uranium-238	high. pop.	1.6E-06	Bq
Vanadium		7.89E-13	kg
Vanadium	low. pop.	5E-11	kg
Vanadium	low. pop., l	3.62E-12	kg
Vanadium	high. pop.	3.76E-10	kg
Xenon-131m	low. pop.	0.000406	Bq
Xenon-133	low. pop.	0.024694	Bq
Xenon-133m	low. pop.	1.42E-05	Bq
Xenon-135	low. pop.	0.008645	Bq
Xenon-135m	low. pop.	0.003755	Bq
Xenon-137	low. pop.	0.000119	Bq
Xenon-138	low. pop.	0.000886	Bq
Zinc		4.82E-11	kg
Zinc	low. pop.	2.84E-10	kg
Zinc	low. pop., l	3.75E-12	kg
Zinc	high. pop.	4.72E-11	kg
Zinc	stratospher	2.72E-18	kg
Zinc-65	low. pop.	9.58E-10	Bq
Zirconium	low. pop.	1.77E-15	kg
Zirconium-95	low. pop.	1.87E-09	Bq
Ethane, 1,1,1-trichloro-, HCFC-140		4.91E-18	kg
Ethane, 1,1,1-trichloro-, HCFC-140	low. pop.	4E-13	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113		5.88E-13	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	low. pop., l	5.16E-14	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	high. pop.	2.61E-17	kg
Ethane, 1,1-difluoro-, HFC-152a	low. pop.	8.69E-13	kg
Ethane, 1,1-difluoro-, HFC-152a	high. pop.	1.11E-12	kg
Methane, bromo-, Halon 1001		7.19E-18	kg
Methane, bromo-, Halon 1001	high. pop.	3.5E-15	kg
Carbonyl sulfide		1.29E-11	kg
Aniline	high. pop.	3.46E-15	kg
Boron trifluoride	high. pop.	1.42E-14	kg
Chloroacetic acid	high. pop.	2.95E-14	kg
Dimethylamine	high. pop.	4.66E-16	kg
Methyl acrylate	high. pop.	6.23E-16	kg
Phosphine	high. pop.	9.69E-14	kg
Acetamide	low. pop.	3.51E-16	kg

Straw production, harvesting, and baling

System Process for US LCI 1kg wheat grains and 1.3kg wheat straw			Allocation on a Mass Basis		Allocation on a Market Rate Basis	
Inputs			Wheat Grains	Wheat Straw	Wheat Grains	Wheat Straw
Water, well, in ground	m3	2.19E-02	9.52E-03	1.24E-02	5.73E-03	1.62E-02
Water, river	m3	3.76E-02	1.64E-02	2.13E-02	9.84E-03	2.78E-02
Coal, 26.4 MJ per kg, in ground	kg	6.47E-03	2.81E-03	3.65E-03	1.69E-03	4.77E-03
Gas, natural, in ground	m3	3.11E-02	1.35E-02	1.76E-02	8.13E-03	2.29E-02
Limestone, in ground	kg	3.51E-02	1.53E-02	1.98E-02	9.18E-03	2.59E-02
Oil, crude, in ground	kg	2.15E-02	9.33E-03	1.21E-02	5.61E-03	1.58E-02
Carbon Dioxide, in air	kg	1.51E+00				
Outputs						
Ammonia	kg	1.20E-05	5.22E-06	6.78E-06	3.14E-06	8.86E-06
Carbon Dioxide	kg	2.95E-02	1.28E-02	1.67E-02	7.72E-03	2.18E-02
Carbon Dioxide, Fossil	kg	8.43E-02	3.66E-02	4.76E-02	2.20E-02	6.22E-02
Methane	kg	3.77E-04	1.64E-04	2.13E-04	9.87E-05	2.79E-04
Methane, Fossil	kg	5.03E-05	2.19E-05	2.84E-05	1.32E-05	3.71E-05
Nitrogen oxides	kg	1.20E-03	5.24E-04	6.81E-04	3.15E-04	8.90E-04
Sulfur dioxide	kg	6.33E-04	2.75E-04	3.58E-04	1.66E-04	4.68E-04
PM2.5-10	kg	3.96E-05	1.72E-05	2.24E-05	1.04E-05	2.93E-05
Nitrogen in Water	kg	3.48E-03	1.51E-03	1.97E-03	9.09E-04	2.57E-03
Sodium in Water	kg	1.78E-03	7.74E-04	1.01E-03	4.65E-04	1.31E-03
Solved solids in Water	kg	7.78E-03	3.38E-03	4.40E-03	2.04E-03	5.75E-03
Suspended solids in Water	kg	2.90E+00	1.26E+00	1.64E+00	7.59E-01	2.14E+00

Straw Baling Process Information		
Bale Mass	360	kg
Total Production Volume	2,498,660.47	units
Total Mass Produced	899,517,769	kg
Total Small Bales Produced	55,006,355	bales

System Process, economically allocated for 1 straw Bale: "Combine Harvesting | Alloc Def, S"			
Output	**Comment**	**Value**	**Unit**
Combine harvesting	Functional Unit	2.82E-03	small bale
Ammonia		3.99E-06	kg
Carbon dioxide, biogenic		5.40E-05	kg
Carbon dioxide, biogenic	low. pop.	6.39E-05	kg
Carbon dioxide, biogenic	high. pop.	4.19E-03	kg
Carbon dioxide, fossil		2.00E-02	kg
Carbon dioxide, fossil	low. pop.	1.39E-01	kg
Carbon dioxide, fossil	high. pop.	4.14E-02	kg
Carbon dioxide, fossil	stratosphere + troposphere	6.41E-09	kg
Carbon monoxide, biogenic		1.64E-09	kg
Carbon monoxide, biogenic	low. pop.	2.58E-06	kg
Carbon monoxide, biogenic	high. pop.	1.27E-05	kg
Carbon monoxide, fossil		4.52E-04	kg
Carbon monoxide, fossil	low. pop.	3.87E-04	kg
Carbon monoxide, fossil	high. pop.	9.31E-04	kg
Carbon monoxide, fossil	stratosphere + troposphere	7.53E-12	kg
Methane, biogenic		3.62E-10	kg
Methane, biogenic	low. pop.	6.35E-06	kg
Methane, biogenic	high. pop.	4.02E-07	kg
Methane, fossil		1.44E-05	kg
Methane, fossil	low. pop.	3.06E-04	kg
Methane, fossil	high. pop.	4.32E-05	kg
Methane, fossil	stratosphere + troposphere	1.02E-13	kg
Nitrogen oxides		6.31E-05	kg
Nitrogen oxides	low. pop.	1.76E-03	kg
Nitrogen oxides	high. pop.	8.46E-05	kg
Nitrogen oxides	stratosphere + troposphere	3.15E-08	kg
NMVOC, non-methane volatile organic compounds, unspec		8.90E-06	kg
NMVOC, non-methane volat	low. pop.	2.15E-04	kg
NMVOC, non-methane volat	high. pop.	1.26E-04	kg
NMVOC, non-methane volat	stratosphere + troposphere	1.37E-12	kg
Particulates, < 2.5 um		9.14E-06	kg
Particulates, < 2.5 um	low. pop.	1.91E-04	kg
Particulates, < 2.5 um	low. pop., long-term	1.28E-07	kg
Particulates, < 2.5 um	high. pop.	1.49E-05	kg
Particulates, < 2.5 um	stratosphere + troposphere	7.73E-14	kg
Particulates, > 10 um		1.77E-05	kg
Particulates, > 10 um	low. pop.	1.09E-04	kg
Particulates, > 10 um	low. pop., long-term	2.84E-07	kg
Particulates, > 10 um	high. pop.	1.05E-05	kg
Particulates, > 2.5 um, and < 10um		2.29E-06	kg
Particulates, > 2.5 um, and < 1	low. pop.	5.48E-05	kg
Particulates, > 2.5 um, and < 1	low. pop., long-term	1.70E-07	kg
Particulates, > 2.5 um, and < 1	high. pop.	4.59E-06	kg
Sulfur dioxide		5.47E-05	kg
Sulfur dioxide	low. pop.	3.33E-04	kg
Sulfur dioxide	high. pop.	2.09E-04	kg
Sulfur dioxide	stratosphere + troposphere	2.04E-12	kg
Input	**Comment**	**Value**	**Unit**
Gas, mine, off-gas, process, coal mining/m3		2.39E-04	m3
Energy, kinetic (in wind), converted		2.37E-03	MJ
Energy, solar, converted		7.93E-06	MJ
Energy, geothermal, converted		3.85E-03	MJ
Energy, potential (in hydropower reservoir), converted		5.02E-02	MJ
Coal, brown		3.01E-03	kg
Coal, hard		2.65E-02	kg
Oil, crude		4.39E-02	kg
Gas, natural/m3		7.92E-03	m3
Water		3.54E-01	m3

Straw Baling | System process for 1 Bale			
Output	**Comment**	**Value**	**Unit**
Ammonia		8.8E-13	kg
Carbon dioxide, biogenic		1.4E-11	kg
Carbon dioxide, biogenic	low. pop.	1.1E-11	kg
Carbon dioxide, biogenic	high. pop.	1.2E-09	kg
Carbon dioxide, fossil		6.3E-09	kg
Carbon dioxide, fossil	low. pop.	5.4E-08	kg
Carbon dioxide, fossil	high. pop.	1.3E-08	kg
Carbon dioxide, fossil	stratosphere +	1.5E-15	kg
Carbon monoxide, biogenic		5.1E-16	kg
Carbon monoxide, biogenic	low. pop.	3.4E-13	kg
Carbon monoxide, biogenic	high. pop.	4.0E-12	kg
Carbon monoxide, fossil		1.4E-10	kg
Carbon monoxide, fossil	low. pop.	9.8E-11	kg
Carbon monoxide, fossil	high. pop.	3.3E-10	kg
Carbon monoxide, fossil	stratosphere +	1.7E-18	kg
Methane, biogenic		9.1E-17	kg
Methane, biogenic	low. pop.	1.7E-12	kg
Methane, biogenic	high. pop.	1.3E-13	kg
Methane, fossil		4.2E-12	kg
Methane, fossil	low. pop.	9.6E-11	kg
Methane, fossil	high. pop.	1.3E-11	kg
Methane, fossil	stratosphere +	2.3E-20	kg
Nitrogen oxides		1.8E-11	kg
Nitrogen oxides	low. pop.	6.0E-10	kg
Nitrogen oxides	high. pop.	2.3E-11	kg
Nitrogen oxides	stratosphere +	9.3E-16	kg
NMVOC, non-methane volatile organic compounds, unsp		2.4E-12	kg
NMVOC, non-methane volatile organic cor	low. pop.	6.0E-11	kg
NMVOC, non-methane volatile organic cor	high. pop.	4.1E-11	kg
NMVOC, non-methane volatile organic cor	stratosphere +	3.1E-19	kg
Particulates, < 2.5 um		2.8E-12	kg
Particulates, < 2.5 um	low. pop.	7.9E-11	kg
Particulates, < 2.5 um	low. pop., long	3.8E-14	kg
Particulates, < 2.5 um	high. pop.	4.2E-12	kg
Particulates, < 2.5 um	stratosphere +	1.8E-20	kg
Particulates, > 10 um		4.7E-12	kg
Particulates, > 10 um	low. pop.	3.4E-11	kg
Particulates, > 10 um	low. pop., long	8.6E-14	kg
Particulates, > 10 um	high. pop.	3.3E-12	kg
Particulates, > 2.5 um, and < 10um		4.9E-13	kg
Particulates, > 2.5 um, and < 10um	low. pop.	1.8E-11	kg
Particulates, > 2.5 um, and < 10um	low. pop., long	5.1E-14	kg
Particulates, > 2.5 um, and < 10um	high. pop.	1.3E-12	kg
Sulfur dioxide		1.4E-11	kg
Sulfur dioxide	low. pop.	9.7E-11	kg
Sulfur dioxide	high. pop.	6.3E-11	kg
Sulfur dioxide	stratosphere +	4.7E-19	kg
Inputs	**Comment**	**Value**	**Unit**
Gas, mine, off-gas, coal mining		7.05E-11	m3
Energy, solar, converted		3.45E-12	MJ
Energy, geothermal, converted		1.18E-09	MJ
Energy, hydro, converted		1.31E-08	MJ
Energy, wind, converted		7.30E-10	MJ
Energy, biomass		7.56E-11	MJ
Coal, brown		8.63E-10	kg
Coal, hard		7.83E-09	kg
Oil, crude		1.80E-08	kg
Gas, natural		2.45E-09	m3
Water		9.84E-08	m3

Sand inputs and air emissions

System Process for 1 kg gravel and sand (Output includes 35% sand and 65% gravel)			
Output	Comment	Value	Unit
Inputs from Nature			
Carbon dioxide, in air	in air	0.000118	kg
Energy, gross calorific value, in biomass	biotic	0.001262	MJ
Occupation, construction site	land	1.94E-07	m2a
Occupation, dump site	land	1.11E-05	m2a
Occupation, forest, intensive	land	0.000185	m2a
Occupation, industrial area	land	0.000114	m2a
Occupation, mineral extraction site	land	0.00029	m2a
Occupation, shrub land, sclerophyllous	land	1.11E-07	m2a
Occupation, traffic area, rail network	land	4.86E-07	m2a
Occupation, traffic area, road network	land	3.83E-05	m2a
Occupation, urban, discontinuously built	land	9.31E-09	m2a
Transformation, from dump site, inert material landfill	land	1.58E-08	m2
Transformation, from dump site, residual material landfill	land	4.87E-09	m2
Transformation, from dump site, sanitary landfill	land	1.26E-09	m2
Transformation, from dump site, slag compartment	land	3.48E-10	m2
Transformation, from forest, extensive	land	1.90E-07	m2
Transformation, from industrial area	land	2.41E-09	m2
Transformation, from mineral extraction site	land	8.52E-06	m2
Transformation, from shrub land, sclerophyllous	land	3.21E-08	m2
Transformation, to dump site	land	8.85E-08	m2
Transformation, to dump site, inert material landfill	land	1.58E-08	m2
Transformation, to dump site, residual material landfill	land	4.87E-09	m2
Transformation, to dump site, sanitary landfill	land	1.26E-09	m2
Transformation, to dump site, slag compartment	land	3.48E-10	m2
Transformation, to forest, intensive	land	2.29E-06	m2
Transformation, to heterogeneous, agricultural	land	1.87E-08	m2
Transformation, to industrial area	land	2.30E-06	m2
Transformation, to mineral extraction site	land	2.95E-05	m2
Transformation, to shrub land, sclerophyllous	land	2.23E-08	m2
Transformation, to traffic area, rail network	land	1.12E-09	m2
Transformation, to traffic area, road network	land	7.25E-07	m2
Transformation, to urban, discontinuously built	land	2.10E-10	m2
Volume occupied, final repository for low-active radioactive waste	in ground	9.09E-11	m3
Volume occupied, final repository for radioactive waste	in ground	3.98E-12	m3
Volume occupied, reservoir	in water	4.25E-05	m3y
Volume occupied, underground deposit	in ground	4.52E-11	m3
Water, salt, ocean	in water	3.42E-07	m3
Water, salt, sole	in water	3.20E-07	m3
Wood, hard, standing	biotic	5.25E-08	m3
Wood, soft, standing	biotic	6.25E-08	m3
Occupation, forest, extensive	land	7.87E-07	m2a
Occupation, permanent crop	land	2.04E-07	m2a
Transformation, from forest, intensive	land	2.11E-06	m2
Transformation, from heterogeneous, agricultural	land	1.19E-11	m2
Transformation, from permanent crop	land	1.23E-08	m2
Transformation, from traffic area, road network	land	4.16E-12	m2
Transformation, to forest, extensive	land	8.29E-09	m2
Transformation, to permanent crop	land	3.23E-08	m2
Energy, gross calorific value, in biomass, primary forest	biotic	7.14E-06	MJ
Energy, kinetic (in wind), converted	in air	0.000314	MJ
Energy, solar, converted	in air	6.03E-07	MJ
Energy, geothermal, converted	in ground	6.56E-05	MJ
Energy, potential (in hydropower reservoir), converted	in water	0.002322	MJ
Water, unspecified natural origin, BR	in ground	1.13E-12	m3
Water, unspecified natural origin, CH	in ground	4.31E-12	m3
Water, unspecified natural origin, CN	in ground	4.37E-18	m3
Water, unspecified natural origin, CO	in ground	6.41E-13	m3
Water, unspecified natural origin, DE	in ground	7.02E-17	m3
Water, unspecified natural origin, HN	in ground	4.34E-13	m3
Water, unspecified natural origin, ID	in ground	1.04E-12	m3
Water, unspecified natural origin, IN	in ground	4.57E-13	m3
Water, unspecified natural origin, US	in ground	4.60E-17	m3
Water, unspecified natural origin, VN	in ground	2.00E-12	m3
Water, unspecified natural origin, AT	in water	4.17E-10	m3
Water, unspecified natural origin, AU	in water	1.01E-11	m3
Water, unspecified natural origin, BE	in water	8.34E-10	m3
Water, unspecified natural origin, BG	in water	2.16E-10	m3
Water, unspecified natural origin, BR	in water	1.03E-10	m3
Water, unspecified natural origin, CA	in water	2.26E-09	m3
Water, unspecified natural origin, CH	in water	6.71E-08	m3
Water, unspecified natural origin, CL	in water	6.46E-14	m3
Water, unspecified natural origin, CN	in water	9.82E-09	m3
Water, unspecified natural origin, CZ	in water	1.25E-10	m3
Water, unspecified natural origin, DE	in water	4.41E-09	m3
Water, unspecified natural origin, DK	in water	5.95E-10	m3
Water, unspecified natural origin, EE	in water	1.46E-11	m3
Water, unspecified natural origin, ES	in water	5.44E-10	m3
Water, unspecified natural origin, FI	in water	2.17E-10	m3
Water, unspecified natural origin, FR	in water	1.69E-09	m3
Water, unspecified natural origin, GB	in water	1.53E-09	m3
Water, unspecified natural origin, HU	in water	1.06E-10	m3
Water, unspecified natural origin, IN	in water	4.99E-11	m3
Water, unspecified natural origin, IT	in water	1.68E-09	m3
Water, unspecified natural origin, JP	in water	3.56E-09	m3
Water, unspecified natural origin, KR	in water	5.52E-10	m3
Water, unspecified natural origin, LU	in water	3.45E-11	m3
Water, unspecified natural origin, MX	in water	7.75E-12	m3
Water, unspecified natural origin, NL	in water	1.57E-09	m3
Water, unspecified natural origin, NO	in water	8.46E-11	m3
Water, unspecified natural origin, PH	in water	3.53E-11	m3
Water, unspecified natural origin, PL	in water	3.50E-11	m3
Water, unspecified natural origin, PT	in water	1.84E-10	m3
Water, unspecified natural origin, RU	in water	9.20E-08	m3
Water, unspecified natural origin, SE	in water	1.08E-09	m3
Water, unspecified natural origin, SK	in water	2.86E-11	m3
Water, unspecified natural origin, TH	in water	9.00E-12	m3
Water, unspecified natural origin, TR	in water	7.06E-11	m3
Water, unspecified natural origin, UA	in water	4.90E-12	m3
Water, unspecified natural origin, US	in water	4.52E-09	m3
Oxygen	in air	4.02E-05	kg
Nitrogen	in air	1.81E-05	kg
Water, unspecified natural origin, PG	in water	4.94E-12	m3
Occupation, arable land, unspecified use	land	2.98E-15	m2a
Occupation, permanent crop, irrigated	land	2.33E-07	m2a
Water, unspecified natural origin, Europe without Switzerland	in ground	8.40E-19	m3
Water, unspecified natural origin, GLO	in ground	4.02E-12	m3
Water, unspecified natural origin, RER	in ground	2.46E-12	m3
Water, unspecified natural origin, RNA	in ground	8.66E-19	m3
Water, unspecified natural origin, RoW	in ground	3.33E-11	m3
Water, lake, AT	in water	4.93E-14	m3
Water, lake, BE	in water	1.03E-13	m3
Water, lake, BG	in water	2.86E-14	m3
Water, lake, CA	in water	1.17E-08	m3
Water, lake, CH	in water	2.61E-09	m3
Water, lake, CN	in water	1.45E-13	m3
Water, lake, CZ	in water	7.06E-15	m3
Water, lake, DE	in water	7.23E-12	m3
Water, lake, DK	in water	7.85E-14	m3
Water, lake, ES	in water	6.94E-14	m3
Water, lake, Europe without Switzerland	in water	2.41E-07	m3
Water, lake, FI	in water	2.73E-14	m3
Water, lake, FR	in water	2.15E-13	m3
Water, lake, GB	in water	2.00E-13	m3
Water, lake, GLO	in water	3.49E-11	m3
Water, lake, HU	in water	1.37E-14	m3
Water, lake, IT	in water	2.13E-13	m3
Water, lake, JP	in water	3.89E-13	m3
Water, lake, KR	in water	3.22E-14	m3
Water, lake, LU	in water	4.55E-15	m3
Water, lake, NL	in water	1.97E-13	m3
Water, lake, NO	in water	1.06E-14	m3
Water, lake, PL	in water	2.78E-15	m3
Water, lake, PT	in water	2.43E-14	m3
Water, lake, RER	in water	4.61E-11	m3
Water, lake, RNA	in water	4.20E-14	m3
Water, lake, RoW	in water	7.27E-07	m3
Water, lake, RU	in water	1.47E-13	m3
Water, lake, SE	in water	1.94E-13	m3
Water, lake, SK	in water	2.49E-15	m3
Water, lake, TR	in water	6.05E-15	m3
Water, lake, TW	in water	1.45E-13	m3
Water, lake, US	in water	2.56E-14	m3
Water, river, AT	in water	1.13E-10	m3
Water, river, AU	in water	3.40E-09	m3
Water, river, BE	in water	2.38E-10	m3
Water, river, BG	in water	6.56E-11	m3
Water, river, BR	in water	1.29E-07	m3
Water, river, CA	in water	3.29E-07	m3
Water, river, CH	in water	1.82E-08	m3
Water, river, CN	in water	4.64E-08	m3
Water, river, CZ	in water	1.62E-11	m3
Water, river, DE	in water	1.74E-08	m3
Water, river, DK	in water	1.80E-10	m3
Water, river, ES	in water	1.21E-09	m3
Water, river, Europe without Switzerland	in water	3.76E-06	m3
Water, river, FI	in water	6.27E-11	m3
Water, river, FR	in water	6.68E-10	m3
Water, river, GB	in water	4.59E-10	m3
Water, river, GLO	in water	9.24E-08	m3
Water, river, HU	in water	3.16E-11	m3
Water, river, IN	in water	9.63E-08	m3
Water, river, IT	in water	4.89E-10	m3
Water, river, JP	in water	1.11E-09	m3
Water, river, KR	in water	4.82E-08	m3
Water, river, LU	in water	1.05E-11	m3
Water, river, MY	in water	4.52E-09	m3
Water, river, NL	in water	4.64E-10	m3
Water, river, NO	in water	2.45E-11	m3
Water, river, PE	in water	4.01E-13	m3
Water, river, PH	in water	1.58E-08	m3
Water, river, PL	in water	6.40E-12	m3
Water, river, PT	in water	5.58E-11	m3
Water, river, RAS	in water	9.03E-08	m3
Water, river, RER	in water	1.65E-06	m3
Water, river, RLA	in water	2.69E-08	m3
Water, river, RNA	in water	5.03E-08	m3
Water, river, RO	in water	3.28E-08	m3
Water, river, RoW	in water	9.17E-06	m3
Water, river, RU	in water	1.55E-08	m3
Water, river, SE	in water	4.52E-10	m3
Water, river, SK	in water	5.73E-12	m3
Water, river, TN	in water	5.58E-11	m3
Water, river, TR	in water	1.39E-11	m3
Water, river, TW	in water	3.34E-10	m3
Water, river, TZ	in water	6.10E-12	m3
Water, river, US	in water	8.49E-09	m3
Water, river, WEU	in water	1.77E-15	m3
Water, river, ZA	in water	2.18E-10	m3
Water, unspecified natural origin, Europe without Switzerland	in water	1.43E-08	m3
Water, unspecified natural origin, GLO	in water	3.95E-07	m3
Water, unspecified natural origin, RAF	in water	6.49E-08	m3
Water, unspecified natural origin, RER	in water	3.07E-07	m3
Water, unspecified natural origin, RNA	in water	4.93E-09	m3
Water, unspecified natural origin, RoW	in water	0.001382	m3
Water, unspecified natural origin, TW	in water	1.15E-09	m3
Water, unspecified natural origin, WEU	in water	1.85E-12	m3
Water, well, in ground, AT	in water	1.97E-12	m3
Water, well, in ground, AU	in water	2.79E-08	m3
Water, well, in ground, BE	in water	4.13E-12	m3
Water, well, in ground, BG	in water	1.14E-12	m3
Water, well, in ground, BR	in water	2.95E-08	m3
Water, well, in ground, CA	in water	9.59E-09	m3
Water, well, in ground, CH	in water	9.26E-09	m3
Water, well, in ground, CN	in water	8.65E-07	m3
Water, well, in ground, CZ	in water	2.82E-13	m3
Water, well, in ground, DE	in water	1.19E-09	m3
Water, well, in ground, DK	in water	3.14E-12	m3
Water, well, in ground, ES	in water	6.23E-10	m3
Water, well, in ground, Europe without Switzerland	in water	8.71E-07	m3
Water, well, in ground, FI	in water	1.09E-12	m3
Water, well, in ground, FR	in water	1.49E-10	m3
Water, well, in ground, GB	in water	7.98E-12	m3
Water, well, in ground, GLO	in water	6.27E-08	m3
Water, well, in ground, HU	in water	5.49E-13	m3
Water, well, in ground, ID	in water	4.79E-08	m3
Water, well, in ground, IN	in water	3.12E-08	m3
Water, well, in ground, IS	in water	1.01E-13	m3
Water, well, in ground, IT	in water	8.60E-12	m3
Water, well, in ground, JP	in water	1.56E-11	m3
Water, well, in ground, KR	in water	1.29E-12	m3
Water, well, in ground, LU	in water	1.82E-13	m3
Water, well, in ground, MA	in water	1.18E-11	m3
Water, well, in ground, MX	in water	1.13E-13	m3
Water, well, in ground, MY	in water	3.93E-10	m3
Water, well, in ground, NL	in water	7.87E-12	m3
Water, well, in ground, NO	in water	4.25E-13	m3
Water, well, in ground, NORDEL	in water	2.42E-10	m3
Water, well, in ground, PE	in water	6.51E-13	m3
Water, well, in ground, PG	in water	4.26E-11	m3
Water, well, in ground, PH	in water	2.47E-09	m3
Water, well, in ground, PL	in water	2.64E-08	m3
Water, well, in ground, PT	in water	9.72E-13	m3
Water, well, in ground, RER	in water	2.93E-07	m3
Water, well, in ground, RLA	in water	4.82E-09	m3
Water, well, in ground, RNA	in water	4.57E-08	m3
Water, well, in ground, RoW	in water	3.58E-06	m3
Water, well, in ground, RU	in water	2.48E-08	m3
Water, well, in ground, SE	in water	2.79E-11	m3
Water, well, in ground, SK	in water	9.95E-14	m3
Water, well, in ground, TH	in water	1.94E-17	m3
Water, well, in ground, TN	in water	8.58E-11	m3
Water, well, in ground, TR	in water	4.05E-13	m3
Water, well, in ground, TW	in water	5.81E-12	m3
Water, well, in ground, US	in water	1.33E-08	m3
Water, well, in ground, WEU	in water	2.18E-08	m3
Water, well, in ground, ZA	in water	1.00E-08	m3
Transformation, to traffic area, rail/road embankment	land	2.46E-08	m2
Occupation, traffic area, rail/road embankment	land	2.96E-06	m2a
Carbon, organic, in soil or biomass stock	in ground	2.65E-07	kg
Gangue, bauxite, in ground	in ground	4.75E-05	kg
Water, unspecified natural origin, RME	in water	6.38E-07	m3
Occupation, seabed, drilling and mining	land	8.09E-08	m2a
Occupation, seabed, infrastructure	land	8.60E-10	m2a
Transformation, from cropland fallow (non-use)	land	8.95E-10	m2
Transformation, from forest, secondary (non-use)	land	6.98E-09	m2
Transformation, from seabed, infrastructure	land	2.06E-12	m2
Transformation, from wetland, inland (non-use)	land	8.67E-11	m2
Transformation, to seabed, drilling and mining	land	8.09E-08	m2
Transformation, to seabed, infrastructure	land	1.33E-09	m2
Transformation, to seabed, unspecified	land	2.06E-12	m2
Water, turbine use, unspecified natural origin, AT	in water	0.000274	m3
Water, cooling, unspecified natural origin, AT	in water	1.68E-07	m3
Water, turbine use, unspecified natural origin, AU	in water	9.36E-05	m3
Water, cooling, unspecified natural origin, AU	in water	1.85E-06	m3
Water, turbine use, unspecified natural origin, BA	in water	1.14E-05	m3
Water, cooling, unspecified natural origin, BA	in water	8.21E-08	m3
Water, turbine use, unspecified natural origin, BE	in water	4.25E-06	m3
Water, cooling, unspecified natural origin, BE	in water	7.03E-07	m3
Water, turbine use, unspecified natural origin, BG	in water	2.56E-05	m3
Water, cooling, unspecified natural origin, BG	in water	4.43E-07	m3
Water, turbine use, unspecified natural origin, BR	in water	0.00049	m3
Water, cooling, unspecified natural origin, BR	in water	6.95E-07	m3
Water, turbine use, unspecified natural origin, CA	in water	0.000443	m3
Water, cooling, unspecified natural origin, CA	in water	3.31E-06	m3
Water, turbine use, unspecified natural origin, CH	in water	8.69E-05	m3
Water, cooling, unspecified natural origin, CH	in water	3.93E-07	m3
Water, turbine use, unspecified natural origin, CL	in water	0.00013	m3
Water, cooling, unspecified natural origin, CL	in water	3.21E-07	m3
Water, turbine use, unspecified natural origin, CN	in water	0.005754	m3
Water, cooling, unspecified natural origin, CN	in water	2.92E-05	m3
Water, cooling, unspecified natural origin, CY	in water	4.17E-08	m3
Water, turbine use, unspecified natural origin, CZ	in water	1.69E-05	m3
Water, cooling, unspecified natural origin, CZ	in water	3.82E-06	m3
Water, turbine use, unspecified natural origin, DE	in water	0.000147	m3
Water, cooling, unspecified natural origin, DE	in water	5.27E-06	m3
Water, turbine use, unspecified natural origin, DK	in water	1.46E-07	m3
Water, cooling, unspecified natural origin, DK	in water	1.51E-07	m3
Water, turbine use, unspecified natural origin, EE	in water	3.93E-07	m3
Water, cooling, unspecified natural origin, EE	in water	1.28E-07	m3
Water, turbine use, unspecified natural origin, ES	in water	0.000108	m3
Water, cooling, unspecified natural origin, ES	in water	1.90E-06	m3
Water, cooling, unspecified natural origin, Europe without Switzerland	in water	3.48E-07	m3
Water, turbine use, unspecified natural origin, FI	in water	4.42E-05	m3
Water, cooling, unspecified natural origin, FI	in water	3.97E-07	m3
Water, turbine use, unspecified natural origin, FR	in water	0.000384	m3
Water, cooling, unspecified natural origin, FR	in water	5.66E-06	m3
Water, turbine use, unspecified natural origin, GB	in water	3.84E-05	m3
Water, cooling, unspecified natural origin, GB	in water	2.48E-06	m3
Water, turbine use, unspecified natural origin, GLO	in water	8.61E-11	m3
Water, cooling, unspecified natural origin, GLO	in water	2.46E-07	m3
Water, turbine use, unspecified natural origin, GR	in water	3.03E-05	m3
Water, cooling, unspecified natural origin, GR	in water	1.26E-06	m3
Water, turbine use, unspecified natural origin, HR	in water	1.91E-06	m3
Water, cooling, unspecified natural origin, HR	in water	7.03E-08	m3
Water, turbine use, unspecified natural origin, HU	in water	1.78E-06	m3
Water, cooling, unspecified natural origin, HU	in water	4.05E-07	m3
Water, turbine use, unspecified natural origin, ID	in water	1.54E-05	m3
Water, cooling, unspecified natural origin, ID	in water	1.56E-06	m3
Water, turbine use, unspecified natural origin, IE	in water	5.58E-06	m3
Water, cooling, unspecified natural origin, IE	in water	1.67E-07	m3
Water, turbine use, unspecified natural origin, IN	in water	0.000112	m3
Water, cooling, unspecified natural origin, IN	in water	8.65E-06	m3
Water, turbine use, unspecified natural origin, IR	in water	8.13E-05	m3
Water, cooling, unspecified natural origin, IR	in water	2.45E-06	m3
Water, turbine use, unspecified natural origin, IS	in water	2.46E-05	m3
Water, cooling, unspecified natural origin, IS	in water	4.52E-11	m3
Water, turbine use, unspecified natural origin, IT	in water	0.000103	m3
Water, cooling, unspecified natural origin, IT	in water	1.66E-06	m3
Water, turbine use, unspecified natural origin, JP	in water	0.000398	m3
Water, cooling, unspecified natural origin, JP	in water	5.61E-06	m3
Water, turbine use, unspecified natural origin, KR	in water	2.15E-05	m3
Water, cooling, unspecified natural origin, KR	in water	3.93E-06	m3
Water, turbine use, unspecified natural origin, LT	in water	3.03E-06	m3
Water, cooling, unspecified natural origin, LT	in water	4.26E-08	m3
Water, turbine use, unspecified natural origin, LU	in water	2.55E-06	m3
Water, cooling, unspecified natural origin, LU	in water	2.82E-08	m3
Water, turbine use, unspecified natural origin, LV	in water	2.47E-05	m3
Water, cooling, unspecified natural origin, LV	in water	2.92E-08	m3
Water, cooling, unspecified natural origin, MA	in water	2.03E-10	m3
Water, turbine use, unspecified natural origin, MK	in water	1.51E-06	m3
Water, cooling, unspecified natural origin, MK	in water	5.02E-08	m3
Water, cooling, unspecified natural origin, MT	in water	2.92E-08	m3
Water, turbine use, unspecified natural origin, MX	in water	0.000208	m3
Water, cooling, unspecified natural origin, MX	in water	1.79E-06	m3
Water, turbine use, unspecified natural origin, MY	in water	2.16E-05	m3
Water, cooling, unspecified natural origin, MY	in water	9.70E-07	m3
Water, turbine use, unspecified natural origin, NL	in water	7.97E-07	m3
Water, cooling, unspecified natural origin, NL	in water	8.20E-07	m3
Water, turbine use, unspecified natural origin, NO	in water	2.40E-05	m3
Water, cooling, unspecified natural origin, NO	in water	2.60E-08	m3
Water, turbine use, unspecified natural origin, PE	in water	2.50E-06	m3
Water, cooling, unspecified natural origin, PE	in water	1.70E-07	m3
Water, cooling, unspecified natural origin, PH	in water	1.41E-10	m3
Water, turbine use, unspecified natural origin, PL	in water	1.60E-05	m3
Water, cooling, unspecified natural origin, PL	in water	5.70E-06	m3
Water, turbine use, unspecified natural origin, PT	in water	2.99E-05	m3
Water, cooling, unspecified natural origin, PT	in water	2.22E-07	m3
Water, turbine use, unspecified natural origin, RER	in water	4.85E-08	m3
Water, cooling, unspecified natural origin, RER	in water	1.85E-06	m3
Water, turbine use, unspecified natural origin, RNA	in water	4.00E-11	m3
Water, cooling, unspecified natural origin, RNA	in water	5.04E-13	m3
Water, turbine use, unspecified natural origin, RO	in water	8.85E-05	m3
Water, cooling, unspecified natural origin, RO	in water	6.00E-07	m3
Water, turbine use, unspecified natural origin, RoW	in water	0.004331	m3
Water, cooling, unspecified natural origin, RoW	in water	2.10E-05	m3
Water, turbine use, unspecified natural origin, RU	in water	0.000799	m3
Water, cooling, unspecified natural origin, RU	in water	2.18E-05	m3
Water, cooling, unspecified natural origin, SA	in water	2.77E-06	m3
Water, turbine use, unspecified natural origin, SE	in water	0.000525	m3
Water, cooling, unspecified natural origin, SE	in water	8.48E-07	m3
Water, turbine use, unspecified natural origin, SI	in water	3.76E-05	m3
Water, cooling, unspecified natural origin, SI	in water	7.82E-07	m3
Water, turbine use, unspecified natural origin, SK	in water	3.07E-05	m3
Water, cooling, unspecified natural origin, SK	in water	7.64E-07	m3
Water, turbine use, unspecified natural origin, TH	in water	1.02E-05	m3
Water, cooling, unspecified natural origin, TH	in water	1.04E-06	m3
Water, turbine use, unspecified natural origin, TR	in water	0.00023	m3
Water, cooling, unspecified natural origin, TR	in water	1.30E-06	m3
Water, turbine use, unspecified natural origin, TW	in water	3.65E-05	m3
Water, cooling, unspecified natural origin, TW	in water	1.59E-06	m3
Water, turbine use, unspecified natural origin, TZ	in water	2.07E-06	m3

Water, cooling, unspecified natural origin, TZ	in water	4.22E-08	m3
Water, turbine use, unspecified natural origin, UA	in water	7.22E-05	m3
Water, cooling, unspecified natural origin, UA	in water	2.02E-06	m3
Water, turbine use, unspecified natural origin, US	in water	0.001442	m3
Water, cooling, unspecified natural origin, US	in water	2.28E-05	m3
Water, cooling, unspecified natural origin, WEU	in water	1.37E-11	m3
Water, turbine use, unspecified natural origin, ZA	in water	2.84E-06	m3
Water, cooling, unspecified natural origin, ZA	in water	1.95E-06	m3
Water, cooling, unspecified natural origin, RS	in water	3.08E-07	m3
Water, turbine use, unspecified natural origin, RS	in water	6.19E-05	m3
Carnallite	in water	1.28E-09	kg
Water, unspecified natural origin, UN-OCEANIA	in water	9.49E-10	m3
Transformation, from traffic area, rail/road embankment	land	1.34E-08	m2
Transformation, to forest, secondary (non-use)	land	4.90E-12	m2
Transformation, to wetland, inland (non-use)	land	1.55E-11	m2
Cobalt, Co 5.0E-2%, in mixed ore, in ground	in ground	7.56E-12	kg
Copper, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore	in ground	1.03E-10	kg
Gold, Au 1.0E-7%, in mixed ore, in ground	in ground	1.56E-15	kg
Nickel, Ni 2.5E+0%, in mixed ore, in ground	in ground	3.70E-10	kg
Palladium, Pd 1.6E-6%, in mixed ore, in ground	in ground	2.47E-14	kg
Platinum, Pt 4.7E-7%, in mixed ore, in ground	in ground	7.15E-15	kg
Rhodium, Rh 1.6E-7%, in mixed ore, in ground	in ground	2.43E-15	kg
Silver, Ag 1.8E-6%, in mixed ore, in ground	in ground	2.76E-14	kg
Water, unspecified natural origin, IAI Area, EU27 & EFTA	in water	7.76E-09	m3
Occupation, inland waterbody, unspecified	land	6.77E-09	m2a
Transformation, to grassland, natural (non-use)	land	7.53E-09	m2
Transformation, to inland waterbody, unspecified	land	6.77E-11	m2
Aluminium	in ground	1.12E-09	kg
Aluminium	in ground	4.47E-06	kg
Anhydrite	in ground	4.93E-11	kg
Argon	in air	3.36E-07	kg
Barite	in ground	2.31E-06	kg
Basalt	in ground	6.33E-06	kg
Borax	in ground	1.28E-09	kg
Bromine	in water	9.27E-11	kg
Cadmium	in ground	5.39E-08	kg
Calcite	in ground	0.000173	kg
Cerium	in ground	1.29E-11	kg
Chromium	in ground	2.08E-06	kg
Chrysotile	in ground	1.18E-10	kg
Cinnabar	in ground	1.86E-12	kg
Clay, bentonite	in ground	1.62E-06	kg
Clay, unspecified	in ground	0.000168	kg
Coal, brown	in ground	0.000356	kg
Coal, hard	in ground	0.00083	kg
Cobalt	in ground	6.45E-11	kg
Colemanite	in ground	1.01E-08	kg
Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	in ground	3.46E-07	kg
Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	in ground	2.86E-07	kg
Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	in ground	1.67E-07	kg
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	in ground	3.39E-07	kg
Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore	in ground	1.40E-08	kg
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	in ground	3.70E-07	kg
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore	in ground	3.09E-08	kg
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	in ground	9.56E-08	kg
Copper, Cu 0.2%, in mixed ore	in ground	5.64E-10	kg
Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore	in ground	3.46E-07	kg
Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	in ground	1.22E-08	kg
Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	in ground	1.82E-10	kg
Diatomite	in ground	3.01E-11	kg
Dolomite	in ground	3.47E-06	kg
Europium	in ground	3.24E-14	kg
Feldspar	in ground	2.18E-11	kg
Fluorine	in ground	5.57E-09	kg
Fluorine, 4.5% in apatite, 3% in crude ore	in ground	1.05E-09	kg
Fluorspar	in ground	7.60E-08	kg
Gadolinium	in ground	8.10E-14	kg
Gallium	in ground	7.02E-15	kg
Gas, mine, off-gas, process, coal mining/m3	in ground	7.68E-06	m3
Gas, natural/m3	in ground	0.000228	m3
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore	in ground	2.91E-13	kg
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	in ground	3.17E-13	kg
Gold	in ground	9.35E-13	kg
Gold, Au 1.8E-4%, in mixed ore	in ground	6.73E-13	kg
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	in ground	6.91E-14	kg
Gold, Au 4.3E-4%, in ore	in ground	1.83E-13	kg
Gold, Au 4.9E-5%, in ore	in ground	9.16E-13	kg
Gold, Au 5.4E-4%, Ag 1.5E-5%, in ore	in ground	1.55E-14	kg
Gold, Au 6.7E-4%, in ore	in ground	9.77E-13	kg
Gold, Au 6.8E-4%, Ag 1.5E-4%, in ore	in ground	2.10E-14	kg
Gold, Au 7.1E-4%, in ore	in ground	4.52E-13	kg
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	in ground	8.43E-12	kg
Gold, Au 9.7E-5%, Ag 7.6E-5%, in ore	in ground	7.60E-14	kg
Granite	in ground	6.91E-14	kg
Gravel	in ground	1.040606	kg
Gypsum	in ground	4.45E-06	kg
Indium	in ground	8.98E-10	kg
Iodine	in water	1.64E-11	kg
Iron	in ground	0.000123	kg
Iron	in ground	7.37E-09	kg
Kaolinite	in ground	2.56E-08	kg
Kieserite	in ground	1.22E-09	kg
Krypton	in air	1.61E-11	kg
Lanthanum	in ground	3.88E-12	kg
Lead	in ground	8.98E-07	kg
Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore	in ground	4.18E-08	kg
Lead, Pb 3.6E-1%, in mixed ore	in ground	1.02E-09	kg
Lithium	in ground	1.84E-10	kg
Magnesite	in ground	1.58E-06	kg
Manganese	in ground	1.41E-06	kg
Metamorphous rock, graphite containing	in ground	4.34E-09	kg
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore	in ground	2.78E-09	kg
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore	in ground	6.34E-10	kg
Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore	in ground	8.30E-09	kg
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore	in ground	6.39E-09	kg
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore	in ground	4.50E-09	kg
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore	in ground	7.37E-09	kg
Molybdenum	in ground	1.90E-08	kg
Neodymium	in ground	2.13E-12	kg
Nickel, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore	in ground	8.78E-09	kg
Nickel, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore	in ground	2.59E-10	kg
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore	in ground	2.72E-08	kg
Nickel, 1.98% in silicates, 1.04% in crude ore	in ground	1.41E-06	kg
Occupation, annual crop	land	4.63E-07	m2a
Occupation, annual crop, greenhouse	land	3.16E-10	m2a
Occupation, annual crop, irrigated	land	1.74E-08	m2a
Occupation, annual crop, irrigated, intensive	land	1.21E-08	m2a
Occupation, annual crop, non-irrigated	land	5.10E-08	m2a
Occupation, annual crop, non-irrigated, extensive	land	4.60E-08	m2a
Occupation, annual crop, non-irrigated, intensive	land	9.89E-07	m2a
Occupation, grassland, natural (non-use)	land	5.60E-07	m2a
Occupation, water bodies, artificial	land	7.23E-05	m2a
Occupation, pasture, man made, extensive	land	1.48E-09	m2a
Occupation, pasture, man made, intensive	land	6.84E-08	m2a
Occupation, permanent crop, irrigated, intensive	land	3.70E-09	m2a
Occupation, permanent crop, non-irrigated, intensive	land	4.71E-10	m2a
Occupation, water bodies, artificial	land	2.00E-06	m2a
Occupation, urban/industrial fallow (non-use)	land	8.99E-10	m2a
Oil, crude	in ground	0.000526	kg
Olivine	in ground	2.29E-11	kg
Palladium, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	5.05E-13	kg
Palladium, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	2.77E-12	kg
Peat	biotic	3.78E-06	kg
Perlite	in ground	2.65E-09	kg
Phosphorus	in ground	2.75E-08	kg
Phosphorus, 18% in apatite, 4% in crude ore	in ground	2.23E-08	kg
Praseodymium	in ground	2.27E-13	kg
Platinum, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	9.50E-13	kg
Platinum, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	1.19E-12	kg
Pumice	in ground	1.72E-07	kg
Rhodium, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	7.59E-14	kg
Rhodium, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	5.95E-14	kg
Rhenium	in ground	5.87E-14	kg
Samarium	in ground	1.62E-13	kg
Sand	in ground	1.97E-08	kg
Shale	in ground	9.03E-07	kg
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	in ground	1.31E-09	kg
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore	in ground	4.65E-15	kg
Silver, Ag 1.5E-4%, Au 6.8E-4%, in ore	in ground	4.72E-15	kg
Silver, Ag 1.5E-5%, Au 5.4E-4%, in ore	in ground	4.32E-16	kg
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore	in ground	7.03E-14	kg
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore	in ground	1.09E-11	kg
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore	in ground	1.13E-13	kg
Silver, Ag 5.4E-3%, in mixed ore	in ground	1.54E-11	kg
Silver, Ag 7.6E-5%, Au 9.7E-5%, in ore	in ground	5.96E-14	kg
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	in ground	4.26E-10	kg
Sodium chloride	in ground	3.68E-06	kg
Sodium nitrate	in ground	7.00E-15	kg
Sodium sulfate	in ground	1.65E-08	kg
Spodumene	in ground	5.67E-11	kg
Stibnite	in ground	3.13E-12	kg
Strontium	in ground	1.18E-09	kg
Sulfur	in ground	1.91E-08	kg
Potassium chloride	in ground	9.13E-08	kg
Talc	in ground	3.74E-09	kg
Tantalum	in ground	6.73E-11	kg
Tellurium	in ground	6.98E-16	kg
Tin	in ground	2.54E-08	kg
TiO2, 54% in ilmenite, 18% in crude ore	in ground	5.53E-09	kg
TiO2, 54% in ilmenite, 2.6% in crude ore	in ground	7.36E-08	kg
TiO2, 95% in rutile, 0.40% in crude ore	in ground	1.13E-08	kg
Transformation, from annual crop	land	4.23E-07	m2
Transformation, from annual crop, greenhouse	land	7.29E-10	m2
Transformation, from annual crop, irrigated, intensive	land	1.23E-08	m2
Transformation, from annual crop, non-irrigated	land	8.36E-07	m2
Transformation, from annual crop, non-irrigated, extensive	land	6.87E-08	m2
Transformation, from annual crop, non-irrigated, intensive	land	3.88E-07	m2
Transformation, from annual crop	land	1.37E-07	m2
Transformation, from forest, primary (non-use)	land	2.26E-08	m2
Transformation, from forest, unspecified	land	6.72E-07	m2
Transformation, from grassland, natural (non-use)	land	1.61E-09	m2
Transformation, from pasture, man made	land	4.92E-08	m2
Transformation, from pasture, man made, extensive	land	2.96E-11	m2
Transformation, from pasture, man made, intensive	land	7.19E-08	m2
Transformation, from permanent crop, irrigated	land	7.25E-09	m2
Transformation, from permanent crop, irrigated, intensive	land	3.18E-09	m2
Transformation, from permanent crop, non-irrigated, intensive	land	4.71E-10	m2
Transformation, from seabed, unspecified	land	8.22E-08	m2
Transformation, from unknown	land	3.82E-05	m2
Transformation, from unspecified, natural	land	1.45E-10	m2
Transformation, to annual crop	land	2.56E-07	m2
Transformation, to annual crop, greenhouse	land	7.29E-10	m2
Transformation, to annual crop, irrigated, extensive	land	6.50E-10	m2
Transformation, to annual crop, irrigated, intensive	land	2.67E-08	m2
Transformation, to annual crop, non-irrigated	land	1.36E-07	m2
Transformation, to annual crop, non-irrigated, extensive	land	7.38E-08	m2
Transformation, to annual crop, non-irrigated, intensive	land	1.31E-06	m2
Transformation, to annual crop	land	1.40E-07	m2
Transformation, to annual crop, fallow	land	1.68E-09	m2
Transformation, to forest, unspecified	land	8.51E-06	m2
Transformation, to water bodies, artificial	land	6.35E-06	m2
Transformation, to pasture, man made	land	9.06E-10	m2
Transformation, to pasture, man made, extensive	land	2.96E-11	m2
Transformation, to pasture, man made, intensive	land	5.95E-08	m2
Transformation, to permanent crop, irrigated	land	7.25E-09	m2
Transformation, to permanent crop, irrigated, intensive	land	3.18E-09	m2
Transformation, to permanent crop, non-irrigated	land	4.90E-12	m2
Transformation, to permanent crop, non-irrigated, intensive	land	4.71E-10	m2
Transformation, to water bodies, artificial	land	2.30E-08	m2
Transformation, to unknown	land	1.70E-08	m2
Transformation, to urban/industrial fallow	land	1.20E-11	m2
Ulexite	in ground	9.75E-10	kg
Uranium	in ground	9.29E-09	kg
Vermiculite	in ground	5.80E-08	kg
Water, unspecified natural origin, IAI Area, Africa	in water	7.15E-10	m3
Water, unspecified natural origin, IAI Area, Asia, without China and GCC	in water	1.32E-09	m3
Water, unspecified natural origin, IAI Area, Gulf Cooperation Council	in water	1.59E-09	m3
Water, unspecified natural origin, IAI Area, North America, without Quebec	in water	1.01E-09	m3
Water, unspecified natural origin, IAI Area, Russia & RER w/o EU27 & EFTA	in water	2.35E-09	m3
Water, unspecified natural origin, IAI Area, South America	in water	9.46E-10	m3
Wood, unspecified, standing/m3	biotic	1.64E-12	m3
Xenon	in air	1.89E-12	kg
Zinc	in ground	1.62E-06	kg
Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore	in ground	5.42E-08	kg
Zinc, Zn 3.1%, in mixed ore	in ground	8.72E-09	kg
Zirconium	in ground	1.10E-08	kg

Emissions to air			
Ammonia		4.39E-07	kg
Benzene		5.34E-09	kg
Pentane		7.19E-12	kg
Acetaldehyde		5.38E-10	kg
Acetic acid		1.43E-09	kg
Acetone		2.51E-11	kg
Acrolein		7.47E-11	kg
Benzaldehyde		5.69E-11	kg
Benzo(a)pyrene		1.36E-11	kg
Butane		8.72E-12	kg
Cobalt		6.96E-13	kg
Ethane		4.51E-10	kg
Ethanol		2.63E-14	kg
Ethene		6.66E-12	kg
Ethylene oxide		1.70E-14	kg
Ethyne		2.00E-11	kg
Fluoranthene		3.72E-15	kg
Formaldehyde		2.65E-09	kg
Heptane		1.25E-11	kg
Hexane		1.45E-17	kg
Isoprene		2.45E-17	kg
m-Xylene		4.07E-11	kg
Methanol		7.21E-10	kg
o-Xylene		1.66E-11	kg
Phenol		1.57E-11	kg
Propane		7.20E-12	kg
Propene		3.11E-12	kg
Propionic acid		6.81E-14	kg
Styrene		2.34E-11	kg
Toluene		7.39E-09	kg
Xylene		4.37E-09	kg
Phenanthrene		5.21E-14	kg
Chrysene		4.46E-17	kg
2-Propanol		9.82E-14	kg
Ammonia	low. pop.	1.63E-08	kg
Ammonia	low. pop., long-ter	3.29E-12	kg
Ammonia	high. pop.	1.48E-08	kg
Benzene	low. pop.	2.88E-08	kg
Benzene	high. pop.	8.96E-09	kg
Benzene	stratosphere + tro	7.40E-16	kg
Methane	high. pop.	2.15E-11	kg
Pentane	low. pop.	1.37E-08	kg
Pentane	high. pop.	7.89E-08	kg
1-Pentene	high. pop.	7.82E-14	kg
2,4-D	low. pop.	2.49E-13	kg
Acetaldehyde	low. pop.	9.78E-11	kg
Acetaldehyde	high. pop.	5.10E-10	kg
Acetic acid	low. pop.	1.08E-09	kg
Acetic acid	high. pop.	2.38E-09	kg
Acetone	low. pop.	1.11E-09	kg
Acetone	high. pop.	4.83E-10	kg
Acetonitrile	low. pop.	2.01E-11	kg
Acrolein	low. pop.	3.09E-11	kg
Acrolein	high. pop.	4.53E-12	kg
Atrazine	low. pop.	2.32E-14	kg
Benzaldehyde	low. pop.	8.99E-12	kg
Benzaldehyde	high. pop.	2.15E-12	kg
Benzo(a)pyrene	low. pop.	1.90E-10	kg
Benzo(a)pyrene	high. pop.	1.05E-11	kg
Butane	low. pop.	7.81E-09	kg
Butane	high. pop.	3.01E-08	kg
Butene	high. pop.	6.93E-10	kg
Cobalt	low. pop.	1.64E-10	kg
Cobalt	low. pop., long-ter	3.70E-12	kg
Cobalt	high. pop.	1.06E-10	kg
Cyclohexane	high. pop.	4.31E-16	kg
Diethyl ether	high. pop.	9.37E-16	kg
Ethane	low. pop.	3.99E-08	kg
Ethane	high. pop.	2.03E-08	kg
Ethanol	low. pop.	1.62E-10	kg
Ethanol	high. pop.	8.80E-10	kg
Ethene	low. pop.	4.77E-10	kg
Ethene	high. pop.	2.66E-08	kg
Ethylene oxide	low. pop.	1.84E-15	kg
Ethylene oxide	high. pop.	6.37E-12	kg
Ethylene oxide	stratosphere + tro	6.78E-15	kg
Ethyne	low. pop.	6.39E-12	kg
Ethyne	high. pop.	4.11E-09	kg
Formaldehyde	low. pop.	2.60E-09	kg
Formaldehyde	high. pop.	1.86E-09	kg
Formaldehyde	stratosphere + tro	5.85E-15	kg
Formic acid	low. pop.	1.23E-10	kg
Formic acid	high. pop.	1.33E-13	kg
Heptane	high. pop.	6.94E-09	kg
Hexane	low. pop.	5.59E-09	kg
Hexane	high. pop.	1.53E-08	kg
Isoprene	low. pop.	1.78E-12	kg
m-Xylene	low. pop.	6.43E-15	kg
m-Xylene	high. pop.	1.18E-10	kg
Methanol	low. pop.	7.87E-10	kg
Methanol	high. pop.	1.00E-09	kg
Methyl ethyl ketone	low. pop.	3.95E-15	kg
Methyl ethyl ketone	high. pop.	1.24E-10	kg
Methyl formate	high. pop.	3.80E-15	kg
Metribuzin	low. pop.	3.32E-14	kg
o-Xylene	high. pop.	7.23E-13	kg
Phenol	low. pop.	9.27E-10	kg
Phenol	high. pop.	2.10E-10	kg
Propane	low. pop.	1.29E-08	kg
Propane	high. pop.	3.80E-08	kg
Propene	low. pop.	2.22E-10	kg
Propene	high. pop.	5.78E-09	kg
Propionic acid	low. pop.	1.09E-10	kg
Propionic acid	high. pop.	1.77E-12	kg
Styrene	low. pop.	3.52E-12	kg
Styrene	high. pop.	1.48E-10	kg
Toluene	low. pop.	1.96E-09	kg
Toluene	high. pop.	5.49E-09	kg
Trifluralin	low. pop.	3.68E-13	kg
Xylene	low. pop.	9.15E-09	kg
Xylene	high. pop.	4.05E-09	kg
Carbaryl	low. pop.	3.16E-15	kg
Glyphosate	low. pop.	8.03E-12	kg
Permethrin	low. pop.	3.35E-15	kg
Acephate	low. pop.	2.64E-14	kg
Metolachlor	low. pop.	8.53E-14	kg
Dichlorprop	low. pop.	4.95E-16	kg
Methomyl	low. pop.	8.10E-20	kg
Phosphoric acid	high. pop.	4.31E-16	kg
Acrylic acid	high. pop.	1.62E-15	kg
2-Propanol	low. pop.	1.51E-14	kg
2-Propanol	high. pop.	2.25E-11	kg
Diethylene glycol	high. pop.	1.34E-15	kg
Bentazone	low. pop.	1.12E-14	kg
Benzo(k)fluoranthene		3.50E-16	kg
Chlorpyrifos	low. pop.	1.21E-13	kg
Dibenz(a,h)anthracene		2.27E-16	kg
Hydrocarbons, chlorinated		5.95E-10	kg
Hydrocarbons, chlorinated	low. pop.	2.01E-11	kg
Hydrocarbons, chlorinated	high. pop.	6.55E-10	kg
Hydrocarbons, unspecified	low. pop.	1.03E-11	kg
Indeno(1,2,3-cd)pyrene		8.93E-17	kg
Sulfur trioxide		2.46E-13	kg
Sulfur trioxide	high. pop.	3.33E-13	kg
Sulfuric acid		6.18E-12	kg
Sulfuric acid	low. pop.	3.52E-10	kg
Sulfuric acid	high. pop.	1.55E-13	kg
Actinides, radioactive, unspecified	low. pop.	0.000205	Bq
Aerosols, radioactive, unspecified	low. pop.	9.66E-07	Bq
Aldehydes, unspecified		8.75E-12	kg
Aldehydes, unspecified	low. pop.	9.86E-11	kg
Aldehydes, unspecified	high. pop.	2.91E-11	kg
Ammonium carbonate	high. pop.	7.11E-13	kg
Antimony		7.65E-10	kg
Antimony	low. pop.	1.00E-10	kg
Antimony	low. pop., long-ter	4.15E-13	kg
Antimony	high. pop.	1.17E-11	kg
Antimony-124	low. pop.	2.73E-10	Bq
Antimony-125	low. pop.	4.71E-09	Bq
Argon-41	low. pop.	0.000555	Bq
Arsenic		1.97E-12	kg
Arsenic	low. pop.	8.75E-10	kg
Arsenic	low. pop., long-ter	2.44E-11	kg
Arsenic	high. pop.	1.23E-10	kg
Barium		2.97E-10	kg
Barium	low. pop.	6.84E-10	kg
Barium	low. pop., long-ter	2.67E-11	kg
Barium	high. pop.	3.98E-10	kg
Barium-140	low. pop.	1.53E-07	Bq
Benzene, ethyl-		2.15E-15	kg
Benzene, ethyl-	low. pop.	1.20E-11	kg
Benzene, ethyl-	high. pop.	7.48E-10	kg
Benzene, hexachloro-		1.04E-12	kg
Benzene, hexachloro-	low. pop.	1.91E-22	kg
Benzene, hexachloro-	high. pop.	3.17E-15	kg
Benzene, pentachloro-	high. pop.	7.99E-15	kg
Beryllium		2.58E-13	kg
Beryllium	low. pop.	2.45E-12	kg
Beryllium	low. pop., long-ter	5.81E-13	kg
Beryllium	high. pop.	4.96E-12	kg
Boron		5.11E-12	kg
Boron	low. pop.	1.02E-08	kg
Boron	low. pop., long-ter	7.73E-12	kg
Boron	high. pop.	2.02E-09	kg
Bromine		2.80E-12	kg
Bromine	low. pop.	3.42E-09	kg
Bromine	high. pop.	2.37E-10	kg
Butadiene		1.64E-15	kg
Butadiene	low. pop.	1.90E-16	kg
Butadiene	high. pop.	2.00E-15	kg
Butadiene	stratosphere + tro	7.01E-16	kg
Cadmium		8.46E-12	kg
Cadmium	low. pop.	2.55E-10	kg
Cadmium	low. pop., long-ter	6.29E-13	kg
Cadmium	high. pop.	3.19E-11	kg
Cadmium	stratosphere + tro	3.71E-19	kg
Calcium		8.24E-11	kg
Calcium	low. pop.	8.65E-11	kg
Calcium	low. pop., long-ter	1.50E-09	kg
Calcium	high. pop.	1.76E-08	kg
Carbon dioxide, fossil		0.001348	kg
Carbon dioxide, fossil	low. pop.	0.002007	kg
Carbon dioxide, fossil	high. pop.	0.0006	kg
Carbon dioxide, fossil	stratosphere + tro	1.17E-10	kg
Carbon disulfide		2.80E-17	kg
Carbon disulfide	low. pop.	2.12E-08	kg
Carbon disulfide	high. pop.	2.14E-13	kg

Carbon monoxide, fossil		7.85E-06	kg
Carbon monoxide, fossil	low. pop.	9.90E-07	kg
Carbon monoxide, fossil	high. pop.	2.17E-05	kg
Carbon monoxide, fossil	stratosphere + tro	1.37E-13	kg
Carbon-14	low. pop.	0.021731	Bq
Cerium-141	low. pop.	3.70E-08	Bq
Cesium-134	low. pop.	1.77E-09	Bq
Cesium-137	low. pop.	3.21E-08	Bq
Chlorine		1.01E-10	kg
Chlorine	low. pop.	1.32E-12	kg
Chlorine	low. pop., long-ter	5.71E-11	kg
Chlorine	high. pop.	3.87E-09	kg
Chloroform		1.27E-17	kg
Chloroform	low. pop.	9.72E-12	kg
Chloroform	high. pop.	1.31E-11	kg
Chromium		1.60E-10	kg
Chromium	low. pop.	7.16E-09	kg
Chromium	high. pop.	9.25E-11	kg
Chromium	stratosphere + tro	1.86E-18	kg
Chromium VI		8.85E-14	kg
Chromium VI	low. pop.	1.92E-10	kg
Chromium VI	low. pop., long-ter	2.97E-12	kg
Chromium VI	high. pop.	2.32E-12	kg
Chromium-51	low. pop.	2.37E-09	Bq
Cobalt-58	low. pop.	4.95E-09	Bq
Cobalt-60	low. pop.	3.68E-08	Bq
Copper		1.05E-09	kg
Copper	low. pop.	2.37E-09	kg
Copper	low. pop., long-ter	3.90E-11	kg
Copper	high. pop.	2.04E-10	kg
Copper	stratosphere + tro	6.31E-17	kg
Cumene		1.14E-18	kg
Cumene	low. pop.	5.40E-13	kg
Cumene	high. pop.	6.42E-10	kg
Cyanide		5.39E-16	kg
Cyanide	low. pop.	7.85E-10	kg
Cyanide	high. pop.	4.07E-10	kg
Dinitrogen monoxide		7.63E-08	kg
Dinitrogen monoxide	low. pop.	3.11E-08	kg
Dinitrogen monoxide	low. pop., long-ter	2.97E-12	kg
Dinitrogen monoxide	high. pop.	2.49E-08	kg
Dinitrogen monoxide	stratosphere + tro	1.11E-15	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a		9.79E-12	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	low. pop.	8.02E-12	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	high. pop.	5.19E-12	kg
Ethane, 1,2-dichloro-		3.68E-16	kg
Ethane, 1,2-dichloro-	low. pop.	3.96E-12	kg
Ethane, 1,2-dichloro-	high. pop.	5.59E-10	kg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	low. pop.	3.77E-11	kg
Ethane, hexafluoro-, HFC-116		2.13E-11	kg
Ethane, hexafluoro-, HFC-116	high. pop.	1.58E-14	kg
Ethene, chloro-		8.63E-18	kg
Ethene, chloro-	high. pop.	2.97E-10	kg
Ethene, tetrachloro-		1.87E-14	kg
Ethene, tetrachloro-	low. pop.	4.26E-12	kg
Ethene, tetrachloro-	high. pop.	2.73E-12	kg
Ethylene diamine	high. pop.	1.07E-13	kg
Fluorine		9.03E-13	kg
Fluorine	low. pop.	1.15E-10	kg
Fluorine	low. pop., long-ter	2.80E-10	kg
Fluorine	high. pop.	4.83E-11	kg
Fluosilicic acid	high. pop.	1.03E-10	kg
Heat, waste		1.37E-05	MJ
Heat, waste	low. pop.	5.25E-08	MJ
Heat, waste	high. pop.	0.000265	MJ
Helium		4.41E-12	kg
Helium	low. pop.	1.22E-09	kg
Hydrocarbons, aliphatic, alkanes, cyclic	low. pop.	5.74E-11	kg
Hydrocarbons, aliphatic, alkanes, cyclic	high. pop.	9.58E-11	kg
Hydrocarbons, aliphatic, alkanes, unspecified		1.93E-08	kg
Hydrocarbons, aliphatic, alkanes, unspecified	low. pop.	2.73E-09	kg
Hydrocarbons, aliphatic, alkanes, unspecified	high. pop.	8.00E-09	kg
Hydrocarbons, aliphatic, unsaturated		2.16E-12	kg
Hydrocarbons, aliphatic, unsaturated	low. pop.	2.12E-09	kg
Hydrocarbons, aliphatic, unsaturated	high. pop.	7.26E-09	kg
Hydrocarbons, aromatic		1.50E-08	kg
Hydrocarbons, aromatic	low. pop.	2.63E-10	kg
Hydrocarbons, aromatic	high. pop.	3.84E-10	kg
Hydrogen		1.53E-10	kg
Hydrogen	high. pop.	4.65E-09	kg
Hydrogen chloride		1.82E-07	kg
Hydrogen chloride	low. pop.	3.07E-07	kg
Hydrogen chloride	high. pop.	5.42E-08	kg
Hydrogen chloride	stratosphere + tro	3.19E-17	kg
Hydrogen fluoride		1.54E-08	kg
Hydrogen fluoride	low. pop.	3.83E-08	kg
Hydrogen fluoride	high. pop.	3.58E-09	kg
Hydrogen sulfide		2.32E-09	kg
Hydrogen sulfide	low. pop.	3.96E-09	kg
Hydrogen sulfide	low. pop., long-ter	2.67E-10	kg
Hydrogen sulfide	high. pop.	5.30E-09	kg
Hydrogen-3, Tritium	low. pop.	0.051003	Bq
Iodine		1.13E-12	kg
Iodine	low. pop.	1.78E-09	kg
Iodine	high. pop.	1.13E-10	kg
Iodine-129	low. pop.	4.76E-06	Bq
Iodine-131	low. pop.	0.00013	Bq
Iodine-133	low. pop.	3.66E-07	Bq
Iron		2.58E-09	kg
Iron	low. pop.	1.45E-10	kg
Iron	low. pop., long-ter	5.01E-09	kg
Iron	high. pop.	1.78E-08	kg
Isocyanic acid	high. pop.	9.05E-11	kg
Krypton-85	low. pop.	0.001821	Bq
Krypton-85m	low. pop.	0.003209	Bq
Krypton-87	low. pop.	0.0005	Bq
Krypton-88	low. pop.	0.000656	Bq
Krypton-89	low. pop.	0.000276	Bq
Lanthanum-140	low. pop.	1.30E-08	Bq
Lead		5.24E-10	kg
Lead	low. pop.	2.72E-09	kg
Lead	low. pop., long-ter	4.13E-11	kg
Lead	high. pop.	5.37E-10	kg
Lead	stratosphere + tro	7.42E-19	kg
Lead-210		4.83E-07	Bq
Lead-210	low. pop.	0.000719	Bq
Lead-210	high. pop.	0.000205	Bq
Magnesium		6.60E-12	kg
Magnesium	low. pop.	4.73E-09	kg
Magnesium	low. pop., long-ter	4.59E-10	kg
Magnesium	high. pop.	1.50E-08	kg
Manganese		1.43E-10	kg
Manganese	low. pop.	7.03E-10	kg
Manganese	low. pop., long-ter	1.04E-10	kg
Manganese	high. pop.	3.13E-10	kg
Manganese-54	low. pop.	1.21E-09	Bq
Mercury		1.28E-10	kg
Mercury	low. pop.	6.36E-11	kg
Mercury	low. pop., long-ter	3.17E-13	kg
Mercury	high. pop.	1.07E-11	kg
Mercury	stratosphere + tro	2.60E-21	kg
Methane, bromochlorodifluoro-, Halon 1211	low. pop.	3.97E-12	kg
Methane, bromotrifluoro-, Halon 1301	low. pop.	2.72E-11	kg
Methane, bromotrifluoro-, Halon 1301	high. pop.	1.44E-15	kg
Methane, chlorodifluoro-, HCFC-22		1.58E-17	kg
Methane, chlorodifluoro-, HCFC-22	low. pop.	9.26E-11	kg
Methane, chlorodifluoro-, HCFC-22	high. pop.	4.31E-11	kg
Methane, dichloro-, HCC-30		4.09E-12	kg
Methane, dichloro-, HCC-30	low. pop.	2.87E-11	kg
Methane, dichloro-, HCC-30	high. pop.	4.68E-13	kg
Methane, dichlorodifluoro-, CFC-12		2.30E-17	kg
Methane, dichlorodifluoro-, CFC-12	low. pop.	8.72E-15	kg
Methane, dichlorodifluoro-, CFC-12	high. pop.	1.13E-11	kg
Methane, dichlorofluoro-, HCFC-21	high. pop.	8.29E-15	kg
Methane, fossil		5.59E-07	kg
Methane, fossil	low. pop.	9.21E-06	kg
Methane, fossil	high. pop.	7.55E-07	kg
Methane, fossil	stratosphere + tro	1.86E-15	kg
Methane, monochloro-, R-40	low. pop.	5.25E-11	kg
Methane, trichlorofluoro-, CFC-11	high. pop.	1.32E-14	kg
Methane, trifluoro-, HFC-23	high. pop.	2.64E-12	kg
Molybdenum		7.66E-11	kg
Molybdenum	low. pop.	1.73E-11	kg
Molybdenum	low. pop., long-ter	8.01E-12	kg
Molybdenum	high. pop.	3.89E-11	kg
Monoethanolamine	high. pop.	3.22E-10	kg
Nickel		1.05E-10	kg
Nickel	low. pop.	1.84E-09	kg
Nickel	low. pop., long-ter	8.45E-12	kg
Nickel	high. pop.	8.60E-10	kg
Nickel	stratosphere + tro	2.60E-18	kg
Niobium-95	low. pop.	0.000706	Bq
Nitrate		3.37E-11	kg
Nitrate	low. pop.	1.36E-11	kg
Nitrate	low. pop., long-ter	3.95E-11	kg
Nitrate	high. pop.	8.33E-14	kg
Nitrobenzene	high. pop.	4.72E-14	kg
Nitrogen oxides		1.64E-05	kg
Nitrogen oxides	low. pop.	4.44E-06	kg
Nitrogen oxides	low. pop., long-ter	5.48E-13	kg
Nitrogen oxides	high. pop.	1.05E-06	kg
Nitrogen oxides	stratosphere + tro	2.62E-10	kg
NMVOC, non-methane volatile organic compounds, unspecified origin		2.01E-06	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	low. pop.	8.46E-07	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	high. pop.	1.88E-07	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	stratosphere + tro	2.49E-14	kg
Noble gases, radioactive, unspecified	low. pop.	45.78075	Bq
Ozone		1.40E-08	kg
Ozone	high. pop.	3.14E-13	kg
PAH, polycyclic aromatic hydrocarbons		1.48E-09	kg
PAH, polycyclic aromatic hydrocarbons	low. pop.	2.22E-10	kg
PAH, polycyclic aromatic hydrocarbons	high. pop.	1.62E-11	kg
Paraffins	high. pop.	7.20E-12	kg
Particulates, < 2.5 um		1.52E-06	kg
Particulates, < 2.5 um	low. pop.	3.92E-06	kg
Particulates, < 2.5 um	low. pop., long-ter	3.80E-09	kg
Particulates, < 2.5 um	high. pop.	3.29E-07	kg
Particulates, < 2.5 um	stratosphere + tro	1.41E-15	kg
Particulates, > 10 um		1.67E-07	kg
Particulates, > 10 um	low. pop.	3.54E-06	kg
Particulates, > 10 um	low. pop., long-ter	9.18E-09	kg
Particulates, > 10 um	high. pop.	2.86E-07	kg
Particulates, > 2.5 um, and < 10um		1.60E-07	kg
Particulates, > 2.5 um, and < 10um	low. pop.	1.16E-06	kg
Particulates, > 2.5 um, and < 10um	low. pop., long-ter	5.51E-09	kg
Particulates, > 2.5 um, and < 10um	high. pop.	1.33E-07	kg
Phenol, pentachloro-		1.99E-13	kg
Phenol, pentachloro-	low. pop.	8.38E-11	kg
Phenol, pentachloro-	high. pop.	8.41E-15	kg
Phosphorus		5.28E-14	kg
Phosphorus	low. pop.	2.28E-12	kg
Phosphorus	low. pop., long-ter	7.73E-12	kg
Phosphorus	high. pop.	6.95E-10	kg
Platinum	low. pop.	6.45E-16	kg
Platinum	high. pop.	1.97E-18	kg
Plutonium-238	low. pop.	6.49E-13	Bq
Plutonium-alpha	low. pop.	1.49E-12	Bq
Polonium-210		8.83E-07	Bq
Polonium-210	low. pop.	0.001266	Bq
Polonium-210	high. pop.	0.000374	Bq
Polychlorinated biphenyls		1.82E-12	kg
Polychlorinated biphenyls	high. pop.	1.06E-15	kg
Potassium		1.14E-11	kg
Potassium	low. pop.	1.82E-11	kg
Potassium	low. pop., long-ter	7.87E-10	kg
Potassium	high. pop.	2.72E-08	kg
Potassium-40		1.19E-07	Bq
Potassium-40	low. pop.	0.00025	Bq
Potassium-40	high. pop.	5.81E-05	Bq
Propanal		8.19E-17	kg
Propanal	low. pop.	2.43E-12	kg
Propanal	high. pop.	1.95E-12	kg
Propylene oxide	high. pop.	1.42E-11	kg
Protactinium-234	low. pop.	1.45E-05	Bq
Radioactive species, other beta emitters	low. pop.	3.32E-08	Bq
Radioactive species, other beta emitters	high. pop.	0.049411	Bq
Radium-226		1.25E-07	Bq
Radium-226	low. pop.	0.000245	Bq
Radium-226	high. pop.	5.29E-05	Bq
Radium-228		4.69E-08	Bq
Radium-228	low. pop.	6.45E-05	Bq
Radium-228	high. pop.	0.000243	Bq
Radon-220		2.49E-06	Bq
Radon-220	low. pop.	0.005864	Bq
Radon-220	high. pop.	0.000153	Bq
Radon-222		1.43E-06	Bq
Radon-222	low. pop.	4.942133	Bq
Radon-222	low. pop., long-ter	176.1376	Bq
Radon-222	high. pop.	8.80E-05	Bq
Ruthenium-103	low. pop.	3.17E-11	Bq
Scandium		3.19E-16	kg
Scandium	low. pop.	5.96E-14	kg
Scandium	low. pop., long-ter	1.65E-11	kg
Scandium	high. pop.	4.71E-12	kg
Selenium		4.79E-12	kg
Selenium	low. pop.	3.05E-10	kg
Selenium	low. pop., long-ter	2.30E-12	kg
Selenium	high. pop.	4.89E-11	kg
Selenium	stratosphere + tro	3.71E-19	kg
Silicon		5.72E-10	kg
Silicon	low. pop.	4.99E-10	kg
Silicon	low. pop., long-ter	1.03E-09	kg
Silicon	high. pop.	6.85E-08	kg
Silicon tetrafluoride	low. pop.	1.68E-13	kg
Silver		2.33E-15	kg
Silver	low. pop.	1.09E-14	kg
Silver	low. pop., long-ter	6.89E-13	kg
Silver	high. pop.	7.22E-14	kg
Silver-110	low. pop.	6.30E-10	Bq
Sodium		7.09E-11	kg
Sodium	low. pop.	4.17E-11	kg
Sodium	low. pop., long-ter	2.70E-10	kg
Sodium	high. pop.	4.81E-09	kg
Sodium chlorate	high. pop.	3.07E-12	kg
Sodium dichromate	high. pop.	6.03E-12	kg
Sodium formate	high. pop.	1.26E-12	kg
Strontium		4.69E-12	kg
Strontium	low. pop.	6.86E-10	kg
Strontium	low. pop., long-ter	1.67E-11	kg
Strontium	high. pop.	5.66E-10	kg
Sulfate		2.95E-10	kg
Sulfate	low. pop.	1.07E-10	kg
Sulfate	low. pop., long-ter	4.24E-09	kg
Sulfate	high. pop.	7.30E-09	kg
Sulfur dioxide		1.50E-06	kg
Sulfur dioxide	low. pop.	7.98E-06	kg
Sulfur dioxide	high. pop.	2.85E-06	kg
Sulfur dioxide	stratosphere + tro	3.71E-14	kg
Sulfur hexafluoride		4.38E-10	kg
Sulfur hexafluoride	low. pop.	8.12E-14	kg
Sulfur hexafluoride	high. pop.	9.53E-16	kg
t-Butyl methyl ether	high. pop.	1.92E-11	kg
Thallium		1.11E-12	kg
Thallium	low. pop.	4.44E-14	kg
Thallium	high. pop.	5.85E-12	kg
Thorium		9.10E-16	kg
Thorium	low. pop.	2.95E-14	kg
Thorium	high. pop.	5.74E-12	kg
Thorium-228		2.14E-08	Bq
Thorium-228	low. pop.	3.61E-05	Bq
Thorium-228	high. pop.	2.21E-05	Bq
Thorium-230	low. pop.	1.77E-05	Bq
Thorium-232		3.15E-08	Bq
Thorium-232	low. pop.	5.25E-05	Bq
Thorium-232	high. pop.	1.51E-05	Bq
Thorium-234	low. pop.	1.45E-05	Bq
Tin		1.07E-10	kg
Tin	low. pop.	1.38E-10	kg
Tin	low. pop., long-ter	9.60E-13	kg
Tin	high. pop.	2.88E-12	kg
Titanium		3.46E-11	kg
Titanium	low. pop.	4.44E-12	kg
Titanium	low. pop., long-ter	3.01E-10	kg
Titanium	high. pop.	1.43E-09	kg
Uranium		1.42E-15	kg
Uranium	low. pop.	1.50E-14	kg
Uranium	high. pop.	7.33E-12	kg
Uranium alpha	low. pop.	9.26E-05	Bq
Uranium-234	low. pop.	4.11E-05	Bq
Uranium-235	low. pop.	8.06E-07	Bq
Uranium-238		1.04E-07	Bq
Uranium-238	low. pop.	0.000181	Bq
Uranium-238	high. pop.	4.40E-05	Bq
Vanadium		9.92E-12	kg
Vanadium	low. pop.	2.05E-10	kg
Vanadium	low. pop., long-ter	2.85E-11	kg
Vanadium	high. pop.	2.41E-09	kg
Xenon-131m	low. pop.	0.002632	Bq
Xenon-133	low. pop.	0.156889	Bq
Xenon-133m	low. pop.	0.000102	Bq
Xenon-135	low. pop.	0.054947	Bq
Xenon-135m	low. pop.	0.02403	Bq
Xenon-137	low. pop.	0.000754	Bq
Xenon-138	low. pop.	0.005635	Bq
Zinc		1.89E-09	kg
Zinc	low. pop.	6.28E-09	kg
Zinc	low. pop., long-ter	2.96E-11	kg
Zinc	high. pop.	9.38E-10	kg
Zinc	stratosphere + tro	3.71E-17	kg
Zinc-65	low. pop.	6.06E-09	Bq
Zirconium	low. pop.	7.60E-14	kg
Zirconium-95	low. pop.	1.18E-08	Bq
Ethane, 1,1,1-trichloro-, HCFC-140		2.36E-17	kg
Ethane, 1,1,1-trichloro-, HCFC-140	low. pop.	1.98E-12	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113		4.26E-12	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	low. pop., long-ter	1.31E-12	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	high. pop.	7.65E-17	kg
Ethane, 1,1-difluoro-, HFC-152a	low. pop.	4.24E-12	kg
Ethane, 1,1-difluoro-, HFC-152a	high. pop.	1.84E-11	kg
Methane, bromo-, Halon 1001		3.45E-17	kg
Methane, bromo-, Halon 1001	high. pop.	1.91E-14	kg
Carbonyl sulfide		1.47E-10	kg
Aniline	high. pop.	3.17E-14	kg
Boron trifluoride	high. pop.	8.15E-14	kg
Chloroacetic acid	high. pop.	2.43E-13	kg
Dimethylamine	high. pop.	1.16E-14	kg
Methyl acrylate	high. pop.	1.83E-15	kg
Phosphine	high. pop.	5.56E-13	kg
Acetamide	low. pop.	6.50E-15	kg
Alachlor	low. pop.	2.57E-14	kg
Bromoxynil	low. pop.	3.84E-16	kg
Diflubenzuron	low. pop.	3.33E-16	kg
Fomesafen	low. pop.	4.01E-14	kg
Lactofen	low. pop.	5.12E-15	kg
Pendimethalin	low. pop.	2.28E-13	kg
Propiconazole	low. pop.	3.93E-15	kg
Sethoxydim	low. pop.	2.67E-15	kg
Thiodicarb	low. pop.	1.30E-15	kg
Sodium hydroxide	high. pop.	6.57E-13	kg
Tungsten	low. pop.	4.07E-15	kg
Tungsten	low. pop., long-ter	1.86E-12	kg
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124		4.26E-12	kg
Acenaphthene		4.34E-13	kg
Acenaphthene	low. pop.	5.59E-14	kg
Acenaphthylene		2.12E-14	kg
Acifluorfen	low. pop.	3.63E-15	kg
Azoxystrobin	low. pop.	1.20E-14	kg
Benzo(b)fluoranthene		4.83E-16	kg
Cyfluthrin	low. pop.	6.33E-16	kg
Cyhalothrin, gamma-	low. pop.	7.26E-15	kg
Dicamba	low. pop.	9.51E-15	kg
Dimethenamid	low. pop.	4.68E-16	kg
Ethephon	low. pop.	2.37E-20	kg
Flufenacet	low. pop.	2.66E-15	kg
Flumetsulam	low. pop.	6.23E-16	kg
Flumiclorac-pentyl	low. pop.	1.07E-15	kg
Fluorene		3.38E-15	kg
Furan		1.83E-18	kg
Furan	low. pop.	5.35E-10	kg
Hydrogen peroxide	high. pop.	1.90E-13	kg
Imazamox	low. pop.	1.60E-15	kg
Imazaquin	low. pop.	5.09E-15	kg
Imazethapyr	low. pop.	1.05E-14	kg
MCPB	low. pop.	6.79E-16	kg
Paraquat	low. pop.	2.14E-14	kg
Pyrene		2.72E-15	kg
Sulfentrazone	low. pop.	2.56E-14	kg
Tebuconazole	low. pop.	5.51E-21	kg
Tefluthrin	low. pop.	1.20E-16	kg
1-Pentanol	high. pop.	4.56E-15	kg
Ethylamine	high. pop.	7.92E-14	kg
Nitrogen fluoride	high. pop.	2.38E-16	kg
Trimethylamine	high. pop.	2.79E-15	kg
Esfenvalerate	low. pop.	3.78E-15	kg
Fluazifop-p-butyl	low. pop.	7.11E-15	kg
Benzal chloride		1.51E-16	kg
1,4-Butanediol	high. pop.	1.19E-13	kg
2-Methyl-1-propanol	high. pop.	1.12E-14	kg
Arsine	high. pop.	1.87E-20	kg
Boric acid	high. pop.	1.22E-17	kg
Butyrolactone	high. pop.	8.05E-14	kg
Chlorosilane, trimethyl-	high. pop.	5.06E-12	kg
Ethyl acetate	high. pop.	1.23E-10	kg
Ethyl cellulose	high. pop.	1.99E-13	kg
Methyl borate	high. pop.	5.75E-15	kg
Tetramethyl ammonium hydroxide	high. pop.	5.71E-12	kg
4-Methyl-2-pentanone	low. pop.	3.29E-16	kg
Terpenes	low. pop.	1.67E-11	kg
Lambda-cyhalothrin	low. pop.	7.50E-22	kg
Chlorimuron-ethyl	low. pop.	6.06E-15	kg
Aluminium		1.35E-07	kg
Aluminium	low. pop.	1.68E-10	kg
Aluminium	low. pop., long-ter	4.60E-09	kg
Aluminium	high. pop.	4.05E-08	kg
Methyl acetate	high. pop.	1.34E-15	kg
Chlorosulfonic acid		1.77E-15	kg
2-Aminopropanol	high. pop.	5.26E-15	kg
2-Nitrobenzoic acid	high. pop.	5.79E-15	kg
Anthranilic acid	high. pop.	4.49E-15	kg
Chloramine	high. pop.	5.46E-14	kg
Chlorosulfonic acid	high. pop.	1.01E-14	kg
Cyanoacetic acid	high. pop.	8.28E-15	kg
Diethylamine	high. pop.	1.71E-14	kg
Dimethyl malonate	high. pop.	1.04E-14	kg
Dipropylamine	high. pop.	7.95E-15	kg
Formamide	high. pop.	8.35E-15	kg
Isopropylamine	high. pop.	4.32E-14	kg
Lactic acid	high. pop.	6.23E-15	kg
Methanesulfonic acid	high. pop.	8.36E-15	kg
Methyl lactate	high. pop.	6.84E-15	kg
Phosphorus trichloride	high. pop.	1.96E-12	kg
Propylamine	high. pop.	2.37E-15	kg
t-Butylamine	high. pop.	2.68E-14	kg
Carfentrazone-ethyl	low. pop.	3.33E-16	kg
Clethodim	low. pop.	1.79E-14	kg
Flumioxazin	low. pop.	1.08E-14	kg
Fenoxaprop	low. pop.	4.95E-15	kg
Thifensulfuron	low. pop.	3.64E-16	kg
Trifloxystrobin	low. pop.	2.33E-16	kg
Sulfur oxides		6.34E-11	kg
Cloransulam-methyl	low. pop.	3.16E-15	kg
Lithium	high. pop.	1.04E-15	kg
Argon-40		1.19E-07	kg
Water/m3		1.70E-05	m3
Chromium IV	high. pop.	1.06E-17	kg
Organic carbon	high. pop.	1.51E-11	kg
Water/m3	high. pop.	6.90E-08	m3
Water/m3	low. pop.	1.02E-06	m3
Water/m3	stratosphere + tro	4.60E-14	m3
Silicon tetrachloride	high. pop.	8.46E-13	kg
Chlorinated solvents, unspecified	low. pop.	1.63E-12	kg
Naphtalene		2.71E-13	kg
2,4-D ester	low. pop.	4.03E-15	kg
Prothioconazol	low. pop.	2.07E-21	kg
2-Butene, 2-methyl-	high. pop.	6.02E-16	kg
Pentane, 3-methyl-	high. pop.	6.54E-12	kg
2,4-D amines	low. pop.	3.45E-16	kg
Butyric acid, 4-(2,4-dichlorophenoxy)-	low. pop.	2.09E-15	kg
Benzo(a)anthracene		4.09E-16	kg
Benzene, 1,2-dichloro-	high. pop.	4.00E-14	kg
Benzo(g,h,i)perylene		2.98E-17	kg
1-Butanol	high. pop.	9.18E-15	kg
Carbon dioxide, land transformation		1.40E-07	kg
Carbon dioxide, land transformation	low. pop.	6.78E-06	kg
Carbon dioxide, biogenic		2.04E-06	kg
Carbon dioxide, biogenic	low. pop.	8.08E-06	kg
Carbon dioxide, biogenic	high. pop.	0.000112	kg
Carbon monoxide, land transformation	low. pop.	1.16E-08	kg
Carbon monoxide, biogenic		3.05E-11	kg
Carbon monoxide, biogenic	low. pop.	2.11E-08	kg
Carbon monoxide, biogenic	high. pop.	3.48E-07	kg
Cyclohexane	high. pop.	3.89E-13	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-		1.39E-15	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	low. pop.	3.00E-16	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	low. pop., long-ter	2.03E-20	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	high. pop.	4.21E-16	kg
Carbon	high. pop.	6.07E-12	kg
2-Methyl-4-chlorophenoxyacetic acid	low. pop.	6.88E-16	kg
Methane, land transformation	low. pop.	8.05E-10	kg
Methane, biogenic		6.78E-09	kg
Methane, biogenic	low. pop.	1.58E-07	kg
Methane, biogenic	high. pop.	8.54E-09	kg
Methane, tetrachloro-, CFC-10		1.03E-14	kg
Methane, tetrachloro-, CFC-10	high. pop.	3.99E-12	kg
Methane, tetrafluoro-, CFC-14		2.91E-10	kg
Methane, tetrafluoro-, CFC-14	high. pop.	2.20E-14	kg
Methylamine	high. pop.	3.47E-14	kg
Parathion, methyl	low. pop.	4.10E-15	kg
Nitrogen, atmospheric		3.45E-09	kg
Benzene, 1-methyl-2-nitro-	high. pop.	5.00E-15	kg
Phenol, 2,4-dichloro-		1.27E-14	kg
Phenol, 2,4-dichloro-	high. pop.	1.74E-14	kg
1-Propanol	low. pop.	9.51E-19	kg
1-Propanol	high. pop.	1.20E-10	kg
Pyraclostrobin (prop)	low. pop.	9.26E-15	kg
Quizalofop ethyl ester	low. pop.	1.24E-15	kg
Sodium tetrahydroborate	high. pop.	1.58E-13	kg
Toluene, 2-chloro-	high. pop.	2.32E-14	kg
Cypermethrin	low. pop.	1.53E-15	kg

Clay-rich soil inputs and air emission

__1 Bovine meat and milk, EU27	-7.40E-09	kg
__2 Pigs, EU27	6.84E-09	kg
__3 Poultry and animals n.e.c., EU27	8.82E-09	kg
__4 Grain crops, EU27	3.23E-06	kg
__5 Crops n.e.c., EU27	7.03E-07	kg
__6 Agricultural services n.e.c., EU27	8.78E-07	EUR2003
__7 Forest products, EU27	9.55E-05	kg
__8 Recycling of waste wood, EU27	0	kg
__9 Fish, EU27	7.11E-10	kg
_10 Coal, lignite, peat, EU27	-0.00022	kg
_11 Crude petroleum and natural gas, EU27	0	kg
_12 Iron ores from mine, EU27	-2.80E-06	kg
_13 Bauxite from mine, EU27	-1.80E-07	kg
_14 Copper from mine, EU27	-1.50E-07	kg
_15 Metals from mine n.e.c., EU27	-1.10E-07	kg
_16 Sand, gravel and stone from quarry, EU27	0	kg
_17 Clay and soil from quarry, EU27	1.32E-05	kg
_18 Minerals from mine n.e.c., EU27	0	kg
_19 Meat and fish products, EU27	8.78E-07	kg
_20 Dairy products, EU27	1.22E-06	kg
_21 Fruits and vegetables, processed, EU27	5.17E-07	kg
_22 Vegetable and animal oils and fats, EU27	4.79E-07	kg
_23 Flour, EU27	1.97E-06	kg
_24 Sugar, EU27	1.54E-06	kg
_25 Animal feeds, EU27	3.23E-06	kg
_26 Food preparations n.e.c., EU27	8.15E-07	kg
_27 Beverages, EU27	5.20E-07	kg
_28 Tobacco products, EU27	9.80E-08	kg
_29 Textiles, EU27	4.48E-06	kg
_30 Wearing apparel and furs, EU27	2.53E-08	kg
_31 Leather products, footwear, EU27	5.71E-11	kg
_32 Wood products, except furniture, EU27	9.88E-05	kg
_33 Pulp, virgin, EU27	3.76E-06	kg
_34 Recycling of waste paper, EU27	6.03E-05	kg
_35 Paper and paper products, EU27	6.21E-05	kg
_36 Printed matter and recorded media, EU27	1.20E-05	kg
_37 Refined petroleum products and fuels, EU27	0.001088	kg
_38 Recycling of waste oil, EU27	0	kg
_39 Fertiliser, N, EU27	6.48E-05	kg
_40 Fertiliser, other than N, EU27	1.24E-05	kg
_41 Plastics basic, virgin, EU27	1.27E-05	kg
_42 Recycling of plastics basic, EU27	7.07E-06	kg
_43 Chemicals n.e.c., EU27	0.000159	kg
_44 Rubber and plastic products, EU27	3.39E-05	kg
_45 Glass, mineral wool and ceramic goods, virgin, EU27	0.000737	kg
_46 Recycling of glass, mineral wool and ceramic goods, EU27	0.000191	kg
_47 Cement, virgin, EU27	6.20E-05	kg
_48 Recycling of slags and ashes, EU27	8.34E-05	kg
_49 Concrete, asphalt and other mineral products, EU27	-0.00134	kg
_50 Recycling of concrete, asphalt and other mineral products, EU27	4.73E-05	kg
_51 Bricks, EU27	-0.00023	kg
_52 Recycling of bricks, EU27	0	kg
_53 Iron basic, virgin, EU27	3.96E-05	kg
_54 Recycling of iron basic, EU27	0.000379	kg
_55 Aluminium basic, virgin, EU27	-3.60E-08	kg
_56 Recycling of aluminium basic, EU27	3.60E-05	kg
_57 Copper basic, virgin, EU27	9.74E-08	kg
_58 Recycling of copper basic, EU27	2.92E-06	kg
_59 Metals basic, n.e.c., virgin, EU27	-1.00E-07	kg
_60 Recycling of metals basic, n.e.c., EU27	2.68E-07	kg
_61 Iron, after first processing, EU27	-3.00E-07	kg
_62 Aluminium, after first processing, EU27	1.11E-07	kg
_63 Copper, after first processing, EU27	9.05E-08	kg
_64 Metals n.e.c., after first processing, EU27	3.00E-08	kg
_65 Fabricated metal products, except machinery, EU27	8.74E-05	kg
_66 Machinery and equipment n.e.c., EU27	0.000354	kg
_67 Office machinery and computers, EU27	3.30E-07	kg
_68 Electrical machinery n.e.c., EU27	1.42E-05	kg
_69 Radio, television and communication equipment, EU27	1.88E-06	kg
_70 Instruments, medical, precision, optical, clocks, EU27	1.38E-07	kg
_71 Motor vehicles and trailers, EU27	4.97E-05	EUR2003
_72 Transport equipment n.e.c., EU27	1.41E-05	EUR2003
_73 Furniture and other manufactured goods n.e.c., EU27	2.51E-06	kg
_74 Recycling services, EU27	-1.50E-05	EUR2003
_75 Electricity, steam and hot water, EU27	0.004912	kWh
_76 Gas, EU27	0.000194	kg
_77 Water, fresh, EU27	1.42E-05	EUR2003
_78 Buildings, residential, EU27	-5.80E-06	EUR2003
_79 Buildings, non-residential, EU27	-3.80E-05	EUR2003
_80 Infrastructure, excluding buildings, EU27	-1.20E-05	EUR2003
_81 Trade and repair of motor vehicles and service stations, EU27	0.000229	EUR2003
_82 Wholesale trade, EU27	0.000181	EUR2003
_83 Retail trade and repair services, EU27	0.00041	EUR2003
_84 Hotels and restaurants, EU27	2.68E-05	EUR2003
_85 Land transport and transport via pipelines, EU27	0.000405	EUR2003
_86 Transport by ship, EU27	-5.00E-06	EUR2003
_87 Air transport, EU27	2.09E-05	EUR2003
_88 Cargo handling, harbours and travel agencies, EU27	0.000238	EUR2003
_89 Post and telecommunication, EU27	9.21E-05	EUR2003
_90 Financial intermediation, EU27	0.000249	EUR2003
_91 Insurance and pension funding, EU27	6.56E-05	EUR2003
_92 Services auxiliary to financial intermediation, EU27	1.41E-05	EUR2003
_93 Real estate services, EU27	0.000124	EUR2003
_94 Renting of machinery and equipment etc., EU27	4.31E-05	EUR2003
_95 Computer and related services, EU27	4.80E-05	EUR2003
_96 Research and development, EU27	4.28E-05	EUR2003
_97 Business services n.e.c., EU27	0.00044	EUR2003
_98 Public service and security, EU27	4.13E-06	EUR2003
_99 Education services, EU27	3.68E-05	EUR2003
100 Health and social work, EU27	9.07E-06	EUR2003
101 Waste treatment, Incineration of waste, Food, EU27	4.40E-07	kg
102 Waste treatment, Incineration of waste, Paper, EU27	8.70E-06	kg
103 Waste treatment, Incineration of waste, Plastic, EU27	1.01E-05	kg
104 Waste treatment, Incineration of waste, Metals, EU27	6.22E-06	kg
105 Waste treatment, Incineration of waste, Glass/inert, EU27	4.74E-06	kg
106 Waste treatment, Incineration of waste, Textiles, EU27	1.66E-06	kg
107 Waste treatment, Incineration of waste, Wood, EU27	7.37E-06	kg
108 Waste treatment, Incineration of waste, Oil/Hazardous waste, EU27	4.34E-07	kg
109 Waste treatment, Biogasification of food waste, EU27	7.38E-08	kg
110 Waste treatment, Biogasification of paper, EU27	0	kg
111 Waste treatment, Biogasification of sewage slugde, EU27	0	kg
112 Waste treatment, Composting of food waste, EU27	5.18E-08	kg
113 Waste treatment, Composting of paper and wood, EU27	1.74E-05	kg
114 Waste treatment, Waste water treatment, food, EU27	4.17E-07	kg
115 Waste treatment, Waste water treatment, other, EU27	0	kg
116 Waste treatment, Landfill of waste, Food, EU27	3.77E-06	kg
117 Waste treatment, Landfill of waste, Paper, EU27	8.70E-06	kg
118 Waste treatment, Landfill of waste, Plastic, EU27	1.39E-05	kg
119 Waste treatment, Landfill of waste, Iron, EU27	4.40E-05	kg
120 Waste treatment, Landfill of waste, Alu, EU27	4.38E-06	kg
121 Waste treatment, Landfill of waste, Copper, EU27	2.52E-06	kg
122 Waste treatment, Landfill of waste, Metals nec, EU27	1.64E-05	kg
123 Waste treatment, Landfill of waste, Glass/inert, EU27	7.91E-06	kg
124 Waste treatment, Landfill of waste, Mine waste, EU27	3.81E-06	kg
125 Waste treatment, Landfill of waste, Textiles, EU27	1.66E-06	kg
126 Waste treatment, Landfill of waste, Wood, EU27	8.67E-06	kg
127 Waste treatment, Landfill of waste, Oil/Hazardous waste, EU27	4.34E-07	kg
128 Waste treatment, Landfill of waste, Slag/ash, EU27	1.67E-05	kg
129 Waste treatment, Land application of compost, EU27	0	kg
130 Membership organisations, EU27	6.20E-06	EUR2003
131 Recreational and cultural services, EU27	2.33E-05	EUR2003
132 Services n.e.c., EU27	-4.30E-05	EUR2003
133 Household use, Clothing, EU27	0	EUR2003
134 Household use, Communication, EU27	0	EUR2003
135 Household use, Education, EU27	0	EUR2003
136 Household use, Health care, EU27	0	EUR2003
137 Household use, Housing, EU27	0	EUR2003
138 Household use, Hygiene, EU27	0	EUR2003
139 Household use, Leisure, EU27	0	EUR2003
140 Household use, Meals, EU27	0	EUR2003
141 Household use, Security, EU27	0	EUR2003
142 Household use, Social care, EU27	0	EUR2003
Electricity/heat		
Emissions to air		
Ammonia	1.79E-10	kg
Carbon dioxide, biogenic	1.41E-04	kg
Carbon dioxide, fossil	0.004154	kg
Carbon monoxide	2.39E-05	kg
Dinitrogen monoxide	1.41E-07	kg
Methane	7.00E-07	kg
Nitrogen dioxide	1.79E-05	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	9.38E-06	kg
Sulfur dioxide	4.74E-06	kg

Clay plaster inputs and air emissions

System Process for 1 kg clay plaster			
Output	Comment	Value	Unit
Inputs from Nature			
Carbon dioxide, in air	in air	0.001977	kg
Energy, gross calorific value, in biomass	biotic	0.021284	MJ
Occupation, construction site	land	6.22E-06	m2a
Occupation, dump site	land	0.000153	m2a
Occupation, forest, intensive	land	0.002939	m2a
Occupation, industrial area	land	0.000235	m2a
Occupation, mineral extraction site	land	0.000237	m2a
Occupation, shrub land, sclerophyllous	land	1.78E-06	m2a
Occupation, traffic area, rail network	land	1.99E-05	m2a
Occupation, traffic area, road network	land	0.000394	m2a
Occupation, urban, discontinuously built	land	8.63E-08	m2a
Transformation, from dump site, inert material landfill	land	3.24E-07	m2
Transformation, from dump site, residual material landfill	land	2.31E-08	m2
Transformation, from dump site, sanitary landfill	land	6.99E-09	m2
Transformation, from dump site, slag compartment	land	2.47E-09	m2
Transformation, from forest, extensive	land	1.43E-06	m2
Transformation, from industrial area	land	3.36E-08	m2
Transformation, from mineral extraction site	land	9.35E-06	m2
Transformation, from shrub land, sclerophyllous	land	4.56E-07	m2
Transformation, to dump site	land	1.24E-06	m2
Transformation, to dump site, inert material landfill	land	3.24E-07	m2
Transformation, to dump site, residual material landfill	land	2.31E-08	m2
Transformation, to dump site, sanitary landfill	land	6.99E-09	m2
Transformation, to dump site, slag compartment	land	2.47E-09	m2
Transformation, to forest, intensive	land	3.69E-05	m2
Transformation, to heterogeneous, agricultural	land	1.63E-07	m2
Transformation, to industrial area	land	4.00E-06	m2
Transformation, to mineral extraction site	land	2.20E-05	m2
Transformation, to shrub land, sclerophyllous	land	3.57E-07	m2
Transformation, to traffic area, rail network	land	4.61E-08	m2
Transformation, to traffic area, road network	land	2.14E-06	m2
Transformation, to urban, discontinuously built	land	1.80E-09	m2
Volume occupied, final repository for low-active radioactive waste	in ground	7.96E-10	m3
Volume occupied, final repository for radioactive waste	in ground	4.40E-11	m3
Volume occupied, reservoir	in water	0.000453	m3y
Volume occupied, underground deposit	in ground	7.05E-10	m3
Water, salt, ocean	in water	4.07E-06	m3
Water, salt, sole	in water	2.54E-06	m3
Wood, hard, standing	biotic	1.06E-06	m3
Wood, soft, standing	biotic	8.50E-07	m3
Occupation, forest, extensive	land	1.02E-05	m2a
Occupation, permanent crop	land	1.24E-06	m2a
Transformation, from forest, intensive	land	3.56E-05	m2
Transformation, from heterogeneous, agricultural	land	1.29E-10	m2
Transformation, from permanent crop	land	7.86E-08	m2
Transformation, from traffic area, road network	land	5.74E-11	m2
Transformation, to forest, extensive	land	1.07E-07	m2
Transformation, to permanent crop	land	2.99E-07	m2
Energy, gross calorific value, in biomass, primary forest	biotic	8.19E-05	MJ
Energy, kinetic (in wind), converted	in air	0.003446	MJ
Energy, solar, converted	in air	1.77E-05	MJ
Energy, geothermal, converted	in ground	0.00072	MJ
Energy, potential (in hydropower reservoir), converted	in water	0.023705	MJ
Water, unspecified natural origin, BR	in ground	9.67E-12	m3
Water, unspecified natural origin, CH	in ground	5.76E-11	m3
Water, unspecified natural origin, CN	in ground	6.10E-17	m3
Water, unspecified natural origin, CO	in ground	5.51E-12	m3
Water, unspecified natural origin, DE	in ground	7.18E-16	m3
Water, unspecified natural origin, HN	in ground	3.73E-12	m3
Water, unspecified natural origin, ID	in ground	8.98E-12	m3
Water, unspecified natural origin, IN	in ground	3.93E-12	m3
Water, unspecified natural origin, US	in ground	3.40E-16	m3
Water, unspecified natural origin, VN	in ground	1.72E-11	m3
Water, unspecified natural origin, AT	in water	5.96E-09	m3
Water, unspecified natural origin, AU	in water	1.14E-10	m3
Water, unspecified natural origin, BE	in water	1.18E-08	m3
Water, unspecified natural origin, BG	in water	6.10E-08	m3
Water, unspecified natural origin, BR	in water	1.15E-09	m3
Water, unspecified natural origin, CA	in water	4.03E-08	m3
Water, unspecified natural origin, CH	in water	3.13E-05	m3
Water, unspecified natural origin, CL	in water	8.34E-13	m3
Water, unspecified natural origin, CN	in water	4.60E-08	m3
Water, unspecified natural origin, CZ	in water	1.49E-09	m3
Water, unspecified natural origin, DE	in water	6.57E-08	m3
Water, unspecified natural origin, DK	in water	1.01E-08	m3
Water, unspecified natural origin, EE	in water	1.74E-10	m3
Water, unspecified natural origin, ES	in water	8.91E-09	m3
Water, unspecified natural origin, FI	in water	3.29E-09	m3
Water, unspecified natural origin, FR	in water	2.54E-08	m3
Water, unspecified natural origin, GB	in water	2.22E-08	m3
Water, unspecified natural origin, HU	in water	7.03E-09	m3
Water, unspecified natural origin, IN	in water	6.20E-10	m3
Water, unspecified natural origin, IT	in water	2.48E-08	m3
Water, unspecified natural origin, JP	in water	4.40E-08	m3
Water, unspecified natural origin, KR	in water	6.27E-09	m3
Water, unspecified natural origin, LU	in water	4.70E-10	m3
Water, unspecified natural origin, MX	in water	8.75E-11	m3
Water, unspecified natural origin, NL	in water	2.29E-08	m3
Water, unspecified natural origin, NO	in water	1.18E-09	m3
Water, unspecified natural origin, PH	in water	2.24E-10	m3
Water, unspecified natural origin, PL	in water	9.28E-10	m3
Water, unspecified natural origin, PT	in water	3.14E-09	m3
Water, unspecified natural origin, RU	in water	7.36E-07	m3
Water, unspecified natural origin, SE	in water	1.62E-08	m3
Water, unspecified natural origin, SK	in water	3.93E-10	m3
Water, unspecified natural origin, TH	in water	3.50E-11	m3
Water, unspecified natural origin, TR	in water	8.41E-10	m3
Water, unspecified natural origin, UA	in water	6.06E-11	m3
Water, unspecified natural origin, US	in water	2.22E-08	m3
Oxygen	in air	0.000189	kg
Nitrogen	in air	8.69E-05	kg
Water, unspecified natural origin, PG	in water	8.94E-11	m3
Occupation, arable land, unspecified use	land	2.70E-14	m2a
Occupation, permanent crop, irrigated	land	2.06E-06	m2a
Water, unspecified natural origin, Europe without Switzerland	in ground	9.39E-18	m3
Water, unspecified natural origin, GLO	in ground	4.54E-11	m3
Water, unspecified natural origin, RER	in ground	2.11E-11	m3
Water, unspecified natural origin, RNA	in ground	1.25E-17	m3
Water, unspecified natural origin, RoW	in ground	3.37E-10	m3
Water, lake, AT	in water	7.16E-13	m3
Water, lake, BE	in water	1.48E-12	m3
Water, lake, BG	in water	8.09E-12	m3
Water, lake, CA	in water	6.35E-08	m3
Water, lake, CH	in water	8.51E-08	m3
Water, lake, CN	in water	2.02E-12	m3
Water, lake, CZ	in water	8.31E-14	m3
Water, lake, DE	in water	7.67E-11	m3
Water, lake, DK	in water	1.33E-12	m3
Water, lake, ES	in water	1.15E-12	m3
Water, lake, Europe without Switzerland	in water	4.85E-06	m3
Water, lake, FI	in water	4.19E-13	m3
Water, lake, FR	in water	3.27E-12	m3
Water, lake, GB	in water	2.90E-12	m3
Water, lake, GLO	in water	2.38E-10	m3
Water, lake, HU	in water	9.29E-13	m3
Water, lake, IT	in water	3.16E-12	m3
Water, lake, JP	in water	4.89E-12	m3
Water, lake, KR	in water	3.68E-13	m3
Water, lake, LU	in water	6.21E-14	m3
Water, lake, NL	in water	2.90E-12	m3
Water, lake, NO	in water	1.49E-13	m3
Water, lake, PL	in water	9.68E-14	m3
Water, lake, PT	in water	4.15E-13	m3
Water, lake, RER	in water	2.59E-10	m3
Water, lake, RNA	in water	6.09E-13	m3
Water, lake, RoW	in water	1.45E-05	m3
Water, lake, RU	in water	1.80E-12	m3
Water, lake, SE	in water	2.50E-12	m3
Water, lake, SK	in water	3.71E-14	m3
Water, lake, TR	in water	7.31E-14	m3
Water, lake, TW	in water	1.85E-12	m3
Water, lake, US	in water	1.90E-13	m3
Water, river, AT	in water	1.65E-09	m3
Water, river, AU	in water	2.36E-08	m3
Water, river, BE	in water	3.41E-09	m3
Water, river, BG	in water	1.85E-08	m3
Water, river, BR	in water	1.52E-06	m3
Water, river, CA	in water	3.11E-06	m3
Water, river, CH	in water	3.27E-07	m3
Water, river, CN	in water	4.83E-07	m3
Water, river, CZ	in water	1.91E-10	m3
Water, river, DE	in water	1.99E-07	m3
Water, river, DK	in water	3.06E-09	m3
Water, river, ES	in water	1.31E-08	m3
Water, river, Europe without Switzerland	in water	7.50E-05	m3
Water, river, FI	in water	9.61E-10	m3
Water, river, FR	in water	9.28E-09	m3
Water, river, GB	in water	6.67E-09	m3
Water, river, GLO	in water	4.36E-07	m3
Water, river, HU	in water	2.13E-09	m3
Water, river, IN	in water	1.04E-06	m3
Water, river, IT	in water	7.26E-09	m3
Water, river, JP	in water	1.36E-08	m3
Water, river, KR	in water	5.27E-07	m3
Water, river, LU	in water	1.43E-10	m3
Water, river, MY	in water	2.85E-08	m3
Water, river, NL	in water	6.78E-09	m3
Water, river, NO	in water	3.43E-10	m3
Water, river, PE	in water	7.36E-12	m3
Water, river, PH	in water	1.16E-07	m3
Water, river, PL	in water	2.22E-10	m3
Water, river, PT	in water	9.53E-10	m3
Water, river, RAS	in water	5.37E-07	m3
Water, river, RER	in water	1.81E-05	m3
Water, river, RLA	in water	1.48E-07	m3
Water, river, RNA	in water	2.69E-07	m3
Water, river, RO	in water	3.57E-07	m3
Water, river, RoW	in water	0.00014	m3
Water, river, RU	in water	1.60E-07	m3
Water, river, SE	in water	5.49E-09	m3
Water, river, SK	in water	8.53E-11	m3
Water, river, TN	in water	5.46E-10	m3
Water, river, TR	in water	1.68E-10	m3
Water, river, TW	in water	4.25E-09	m3
Water, river, TZ	in water	1.13E-10	m3
Water, river, US	in water	8.16E-08	m3
Water, river, WEU	in water	2.08E-14	m3
Water, river, ZA	in water	1.83E-09	m3
Water, unspecified natural origin, Europe without Switzerland	in water	5.49E-08	m3
Water, unspecified natural origin, GLO	in water	2.12E-06	m3
Water, unspecified natural origin, RAF	in water	5.16E-07	m3
Water, unspecified natural origin, RER	in water	1.73E-06	m3
Water, unspecified natural origin, RNA	in water	5.54E-08	m3
Water, unspecified natural origin, RoW	in water	0.000777	m3
Water, unspecified natural origin, TW	in water	1.46E-08	m3
Water, unspecified natural origin, WEU	in water	2.20E-11	m3
Water, well, in ground, AT	in water	2.86E-11	m3
Water, well, in ground, AU	in water	5.32E-07	m3
Water, well, in ground, BE	in water	5.92E-11	m3
Water, well, in ground, BG	in water	3.22E-10	m3
Water, well, in ground, BR	in water	3.49E-07	m3
Water, well, in ground, CA	in water	5.39E-08	m3
Water, well, in ground, CH	in water	1.97E-07	m3
Water, well, in ground, CN	in water	1.27E-05	m3
Water, well, in ground, CZ	in water	3.32E-12	m3
Water, well, in ground, DE	in water	9.06E-09	m3
Water, well, in ground, DK	in water	5.31E-11	m3
Water, well, in ground, ES	in water	6.20E-09	m3
Water, well, in ground, Europe without Switzerland	in water	1.75E-05	m3
Water, well, in ground, FI	in water	1.67E-11	m3
Water, well, in ground, FR	in water	1.56E-09	m3
Water, well, in ground, GB	in water	1.16E-10	m3
Water, well, in ground, GLO	in water	3.26E-07	m3
Water, well, in ground, HU	in water	3.70E-11	m3
Water, well, in ground, ID	in water	9.28E-07	m3
Water, well, in ground, IN	in water	3.14E-07	m3
Water, well, in ground, IS	in water	1.11E-12	m3
Water, well, in ground, IT	in water	1.27E-10	m3
Water, well, in ground, JP	in water	1.96E-10	m3
Water, well, in ground, KR	in water	1.47E-11	m3
Water, well, in ground, LU	in water	2.48E-12	m3
Water, well, in ground, MA	in water	1.90E-09	m3
Water, well, in ground, MX	in water	1.24E-12	m3
Water, well, in ground, MY	in water	2.48E-09	m3
Water, well, in ground, NL	in water	1.16E-10	m3
Water, well, in ground, NO	in water	5.96E-12	m3
Water, well, in ground, NORDEL	in water	2.69E-09	m3
Water, well, in ground, PE	in water	1.19E-11	m3
Water, well, in ground, PG	in water	7.72E-10	m3
Water, well, in ground, PH	in water	1.82E-08	m3
Water, well, in ground, PL	in water	4.35E-07	m3
Water, well, in ground, PT	in water	1.66E-11	m3
Water, well, in ground, RER	in water	3.48E-06	m3
Water, well, in ground, RLA	in water	1.02E-07	m3
Water, well, in ground, RNA	in water	4.04E-07	m3
Water, well, in ground, RoW	in water	5.97E-05	m3
Water, well, in ground, RU	in water	4.46E-07	m3
Water, well, in ground, SE	in water	1.92E-10	m3
Water, well, in ground, SK	in water	1.48E-12	m3
Water, well, in ground, TH	in water	2.13E-16	m3
Water, well, in ground, TN	in water	8.40E-10	m3
Water, well, in ground, TR	in water	5.65E-12	m3
Water, well, in ground, TW	in water	7.38E-11	m3
Water, well, in ground, US	in water	1.51E-07	m3
Water, well, in ground, WEU	in water	3.02E-07	m3
Water, well, in ground, ZA	in water	1.60E-07	m3
Transformation, to traffic area, rail/road embankment	land	5.24E-07	m2
Occupation, traffic area, rail/road embankment	land	0.000122	m2a
Carbon, organic, in soil or biomass stock	in ground	2.92E-06	kg
Gangue, bauxite, in ground	in ground	0.000225	kg
Water, unspecified natural origin, RME	in water	5.08E-06	m3
Occupation, seabed, drilling and mining	land	6.86E-07	m2a
Occupation, seabed, infrastructure	land	7.56E-09	m2a
Transformation, from cropland fallow (non-use)	land	4.25E-09	m2
Transformation, from forest, secondary (non-use)	land	7.05E-08	m2
Transformation, from seabed, infrastructure	land	2.15E-11	m2
Transformation, from wetland, inland (non-use)	land	1.19E-09	m2
Transformation, to seabed, drilling and mining	land	6.86E-07	m2
Transformation, to seabed, infrastructure	land	1.32E-08	m2
Transformation, to seabed, unspecified	land	2.15E-11	m2
Water, turbine use, unspecified natural origin, AT	in water	0.003118	m3
Water, cooling, unspecified natural origin, AT	in water	1.88E-06	m3
Water, turbine use, unspecified natural origin, AU	in water	0.000956	m3
Water, cooling, unspecified natural origin, AU	in water	1.97E-05	m3
Water, turbine use, unspecified natural origin, BA	in water	5.91E-05	m3
Water, cooling, unspecified natural origin, BA	in water	8.98E-07	m3
Water, turbine use, unspecified natural origin, BE	in water	4.73E-05	m3
Water, cooling, unspecified natural origin, BE	in water	7.77E-06	m3
Water, turbine use, unspecified natural origin, BG	in water	0.000285	m3
Water, cooling, unspecified natural origin, BG	in water	6.00E-06	m3
Water, turbine use, unspecified natural origin, BR	in water	0.005253	m3
Water, cooling, unspecified natural origin, BR	in water	7.46E-06	m3
Water, turbine use, unspecified natural origin, CA	in water	0.003272	m3
Water, cooling, unspecified natural origin, CA	in water	3.58E-05	m3
Water, turbine use, unspecified natural origin, CH	in water	0.001643	m3
Water, cooling, unspecified natural origin, CH	in water	7.17E-06	m3
Water, turbine use, unspecified natural origin, CL	in water	0.001424	m3
Water, cooling, unspecified natural origin, CL	in water	3.51E-06	m3
Water, turbine use, unspecified natural origin, CN	in water	0.06256	m3
Water, cooling, unspecified natural origin, CN	in water	0.000314	m3
Water, cooling, unspecified natural origin, CY	in water	4.57E-07	m3
Water, turbine use, unspecified natural origin, CZ	in water	0.000188	m3
Water, cooling, unspecified natural origin, CZ	in water	5.23E-05	m3
Water, turbine use, unspecified natural origin, DE	in water	0.001648	m3
Water, cooling, unspecified natural origin, DE	in water	6.26E-05	m3
Water, turbine use, unspecified natural origin, DK	in water	1.63E-06	m3
Water, cooling, unspecified natural origin, DK	in water	1.82E-06	m3
Water, turbine use, unspecified natural origin, EE	in water	4.36E-06	m3
Water, cooling, unspecified natural origin, EE	in water	1.42E-06	m3
Water, turbine use, unspecified natural origin, ES	in water	0.001189	m3
Water, cooling, unspecified natural origin, ES	in water	2.08E-05	m3
Water, cooling, unspecified natural origin, Europe without Switzerland	in water	3.02E-06	m3
Water, turbine use, unspecified natural origin, FI	in water	0.000491	m3
Water, cooling, unspecified natural origin, FI	in water	4.51E-06	m3
Water, turbine use, unspecified natural origin, FR	in water	0.004714	m3
Water, cooling, unspecified natural origin, FR	in water	6.42E-05	m3
Water, turbine use, unspecified natural origin, GB	in water	0.000425	m3
Water, cooling, unspecified natural origin, GB	in water	2.75E-05	m3
Water, turbine use, unspecified natural origin, GLO	in water	2.93E-08	m3
Water, cooling, unspecified natural origin, GLO	in water	1.57E-06	m3
Water, turbine use, unspecified natural origin, GR	in water	0.000329	m3
Water, cooling, unspecified natural origin, GR	in water	1.41E-05	m3
Water, turbine use, unspecified natural origin, HR	in water	2.12E-05	m3
Water, cooling, unspecified natural origin, HR	in water	7.54E-07	m3
Water, turbine use, unspecified natural origin, HU	in water	1.98E-05	m3
Water, cooling, unspecified natural origin, HU	in water	4.53E-06	m3
Water, turbine use, unspecified natural origin, ID	in water	0.000169	m3
Water, cooling, unspecified natural origin, ID	in water	1.71E-05	m3
Water, turbine use, unspecified natural origin, IE	in water	6.19E-05	m3
Water, cooling, unspecified natural origin, IE	in water	1.82E-06	m3
Water, turbine use, unspecified natural origin, IN	in water	0.001221	m3
Water, cooling, unspecified natural origin, IN	in water	9.35E-05	m3
Water, turbine use, unspecified natural origin, IR	in water	0.000887	m3
Water, cooling, unspecified natural origin, IR	in water	2.68E-05	m3
Water, turbine use, unspecified natural origin, IS	in water	0.000206	m3
Water, cooling, unspecified natural origin, IS	in water	4.45E-10	m3
Water, turbine use, unspecified natural origin, IT	in water	0.001142	m3
Water, cooling, unspecified natural origin, IT	in water	1.84E-05	m3
Water, turbine use, unspecified natural origin, JP	in water	0.004359	m3
Water, cooling, unspecified natural origin, JP	in water	6.15E-05	m3
Water, turbine use, unspecified natural origin, KR	in water	0.000235	m3

Water, cooling, unspecified natural origin, KR	in water	4.32E-05	m3
Water, turbine use, unspecified natural origin, LT	in water	3.36E-05	m3
Water, cooling, unspecified natural origin, LT	in water	4.56E-07	m3
Water, turbine use, unspecified natural origin, LU	in water	2.83E-05	m3
Water, cooling, unspecified natural origin, LU	in water	3.04E-07	m3
Water, turbine use, unspecified natural origin, LV	in water	0.000274	m3
Water, cooling, unspecified natural origin, LV	in water	2.64E-07	m3
Water, cooling, unspecified natural origin, MA	in water	3.89E-08	m3
Water, turbine use, unspecified natural origin, MK	in water	1.68E-05	m3
Water, cooling, unspecified natural origin, MK	in water	5.52E-07	m3
Water, cooling, unspecified natural origin, MT	in water	3.25E-07	m3
Water, turbine use, unspecified natural origin, MX	in water	0.002275	m3
Water, cooling, unspecified natural origin, MX	in water	1.95E-05	m3
Water, turbine use, unspecified natural origin, MY	in water	0.000236	m3
Water, cooling, unspecified natural origin, MY	in water	1.06E-05	m3
Water, turbine use, unspecified natural origin, NL	in water	8.76E-06	m3
Water, cooling, unspecified natural origin, NL	in water	8.93E-06	m3
Water, turbine use, unspecified natural origin, NO	in water	0.000254	m3
Water, cooling, unspecified natural origin, NO	in water	2.86E-07	m3
Water, turbine use, unspecified natural origin, PE	in water	2.73E-05	m3
Water, cooling, unspecified natural origin, PE	in water	1.85E-06	m3
Water, cooling, unspecified natural origin, PH	in water	8.96E-10	m3
Water, turbine use, unspecified natural origin, PL	in water	0.00018	m3
Water, cooling, unspecified natural origin, PL	in water	6.54E-05	m3
Water, turbine use, unspecified natural origin, PT	in water	0.000332	m3
Water, cooling, unspecified natural origin, PT	in water	2.41E-06	m3
Water, turbine use, unspecified natural origin, RER	in water	4.23E-07	m3
Water, cooling, unspecified natural origin, RER	in water	9.91E-06	m3
Water, turbine use, unspecified natural origin, RNA	in water	5.80E-10	m3
Water, cooling, unspecified natural origin, RNA	in water	7.30E-12	m3
Water, turbine use, unspecified natural origin, RO	in water	0.00096	m3
Water, cooling, unspecified natural origin, RO	in water	6.44E-06	m3
Water, turbine use, unspecified natural origin, RoW	in water	0.038879	m3
Water, cooling, unspecified natural origin, RoW	in water	0.000197	m3
Water, turbine use, unspecified natural origin, RU	in water	0.007553	m3
Water, cooling, unspecified natural origin, RU	in water	0.00024	m3
Water, cooling, unspecified natural origin, SA	in water	3.01E-05	m3
Water, turbine use, unspecified natural origin, SE	in water	0.005798	m3
Water, cooling, unspecified natural origin, SE	in water	9.47E-06	m3
Water, turbine use, unspecified natural origin, SI	in water	0.000407	m3
Water, cooling, unspecified natural origin, SI	in water	9.08E-06	m3
Water, turbine use, unspecified natural origin, SK	in water	0.000331	m3
Water, cooling, unspecified natural origin, SK	in water	9.02E-06	m3
Water, turbine use, unspecified natural origin, TH	in water	0.000112	m3
Water, cooling, unspecified natural origin, TH	in water	1.14E-05	m3
Water, turbine use, unspecified natural origin, TR	in water	0.002514	m3
Water, cooling, unspecified natural origin, TR	in water	1.41E-05	m3
Water, turbine use, unspecified natural origin, TW	in water	0.0004	m3
Water, cooling, unspecified natural origin, TW	in water	1.75E-05	m3
Water, turbine use, unspecified natural origin, TZ	in water	2.24E-05	m3
Water, cooling, unspecified natural origin, TZ	in water	4.58E-07	m3
Water, turbine use, unspecified natural origin, UA	in water	0.000801	m3
Water, cooling, unspecified natural origin, UA	in water	2.21E-05	m3
Water, turbine use, unspecified natural origin, US	in water	0.015573	m3
Water, cooling, unspecified natural origin, US	in water	0.000249	m3
Water, cooling, unspecified natural origin, WEU	in water	1.71E-10	m3
Water, turbine use, unspecified natural origin, ZA	in water	2.99E-05	m3
Water, cooling, unspecified natural origin, ZA	in water	2.08E-05	m3
Water, cooling, unspecified natural origin, RS	in water	3.42E-06	m3
Water, turbine use, unspecified natural origin, RS	in water	0.000688	m3
Carnallite	in water	8.01E-09	kg
Water, unspecified natural origin, UN-OCEANIA	in water	4.30E-09	m3
Transformation, from traffic area, rail/road embankment	land	2.30E-07	m2
Transformation, to forest, secondary (non-use)	land	6.76E-11	m2
Transformation, to wetland, inland (non-use)	land	2.14E-10	m2
Cobalt, Co 5.0E-2%, in mixed ore, in ground	in ground	7.63E-11	kg
Copper, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore	in ground	1.04E-09	kg
Gold, Au 1.0E-7%, in mixed ore, in ground	in ground	1.57E-14	kg
Nickel, Ni 2.5E+0%, in mixed ore, in ground	in ground	3.74E-09	kg
Palladium, Pd 1.6E-6%, in mixed ore, in ground	in ground	2.50E-13	kg
Platinum, Pt 4.7E-7%, in mixed ore, in ground	in ground	7.23E-14	kg
Rhodium, Rh 1.6E-7%, in mixed ore, in ground	in ground	2.45E-14	kg
Silver, Ag 1.8E-6%, in mixed ore, in ground	in ground	2.79E-13	kg
Water, unspecified natural origin, IAI Area, EU27 & EFTA	in water	3.51E-08	m3
Occupation, inland waterbody, unspecified	land	1.85E-08	m2a
Transformation, to grassland, natural (non-use)	land	8.20E-08	m2
Transformation, to inland waterbody, unspecified	land	1.85E-10	m2
Aluminium	in ground	5.96E-09	kg
Aluminium	in ground	2.12E-05	kg
Anhydrite	in ground	2.63E-10	kg
Argon	in air	1.61E-06	kg
Barite	in ground	1.88E-05	kg
Basalt	in ground	1.78E-05	kg
Borax	in ground	1.11E-08	kg
Bromine	in water	9.81E-10	kg
Cadmium	in ground	1.78E-07	kg
Calcite	in ground	0.000798	kg
Cerium	in ground	1.44E-10	kg
Chromium	in ground	9.05E-06	kg
Chrysotile	in ground	7.31E-10	kg
Cinnabar	in ground	1.40E-11	kg
Clay, bentonite	in ground	9.54E-06	kg
Clay, unspecified	in ground	0.250496	kg
Coal, brown	in ground	0.003827	kg
Coal, hard	in ground	0.012187	kg
Cobalt	in ground	7.96E-10	kg
Colemanite	in ground	1.69E-07	kg
Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	in ground	2.06E-06	kg
Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	in ground	1.53E-06	kg
Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	in ground	6.79E-07	kg
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	in ground	2.32E-06	kg
Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore	in ground	1.09E-07	kg
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	in ground	2.02E-06	kg
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore	in ground	2.10E-07	kg
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	in ground	6.53E-07	kg
Copper, Cu 0.2%, in mixed ore	in ground	2.12E-09	kg
Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore	in ground	2.27E-06	kg
Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	in ground	9.26E-08	kg
Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	in ground	1.52E-09	kg
Diatomite	in ground	3.90E-10	kg
Dolomite	in ground	1.90E-05	kg
Europium	in ground	3.61E-13	kg
Feldspar	in ground	1.56E-10	kg
Fluorine	in ground	1.06E-06	kg
Fluorine, 4.5% in apatite, 3% in crude ore	in ground	8.42E-08	kg
Fluorspar	in ground	6.03E-07	kg
Gadolinium	in ground	9.01E-13	kg
Gallium	in ground	8.19E-14	kg
Gas, mine, off-gas, process, coal mining/m3	in ground	0.000114	m3
Gas, natural/m3	in ground	0.002277	m3
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore	in ground	3.75E-12	kg
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	in ground	5.80E-12	kg
Gold	in ground	1.73E-11	kg
Gold, Au 1.8E-4%, in mixed ore	in ground	2.53E-12	kg
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	in ground	1.26E-12	kg
Gold, Au 4.3E-4%, in ore	in ground	3.37E-12	kg
Gold, Au 4.9E-5%, in ore	in ground	1.69E-11	kg
Gold, Au 5.4E-4%, Ag 1.5E-5%, in ore	in ground	2.05E-13	kg
Gold, Au 6.7E-4%, in ore	in ground	1.80E-11	kg
Gold, Au 6.8E-4%, Ag 1.5E-4%, in ore	in ground	2.78E-13	kg
Gold, Au 7.1E-4%, in ore	in ground	8.35E-12	kg
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	in ground	5.54E-11	kg
Gold, Au 9.7E-5%, Ag 7.6E-5%, in ore	in ground	1.01E-12	kg
Granite	in ground	6.67E-13	kg
Gravel	in ground	0.605243	kg
Gypsum	in ground	1.71E-05	kg
Indium	in ground	2.97E-09	kg
Iodine	in water	1.75E-10	kg
Iron	in ground	0.000649	kg
Iron	in ground	8.72E-08	kg
Kaolinite	in ground	4.61E-07	kg
Kieserite	in ground	7.37E-09	kg
Krypton	in air	1.86E-10	kg
Lanthanum	in ground	4.32E-11	kg
Lead	in ground	2.97E-06	kg
Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore	in ground	2.75E-07	kg
Lead, Pb 3.6E-1%, in mixed ore	in ground	3.81E-09	kg
Lithium	in ground	8.80E-10	kg
Magnesite	in ground	7.68E-06	kg
Manganese	in ground	5.75E-06	kg
Metamorphous rock, graphite containing	in ground	2.12E-08	kg
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore	in ground	1.90E-08	kg
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore	in ground	4.32E-09	kg
Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore	in ground	4.93E-08	kg
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore	in ground	3.41E-08	kg
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore	in ground	3.07E-08	kg
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore	in ground	4.02E-08	kg
Molybdenum	in ground	7.75E-08	kg
Neodymium	in ground	2.37E-11	kg
Nickel, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore	in ground	6.69E-08	kg
Nickel, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore	in ground	2.17E-09	kg
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore	in ground	2.13E-07	kg
Nickel, 1.98% in silicates, 1.04% in crude ore	in ground	6.11E-06	kg
Occupation, annual crop	land	4.86E-06	m2a
Occupation, annual crop, greenhouse	land	2.72E-09	m2a
Occupation, annual crop, irrigated	land	2.02E-07	m2a
Occupation, annual crop, irrigated, intensive	land	1.44E-07	m2a
Occupation, annual crop, non-irrigated	land	4.20E-08	m2a
Occupation, annual crop, non-irrigated, extensive	land	6.22E-07	m2a
Occupation, annual crop, non-irrigated, intensive	land	1.08E-05	m2a
Occupation, grassland, natural (non-use)	land	6.09E-06	m2a
Occupation, water bodies, artificial	land	0.000115	m2a
Occupation, pasture, man made, extensive	land	1.29E-08	m2a
Occupation, pasture, man made, intensive	land	7.13E-07	m2a
Occupation, permanent crop, irrigated, intensive	land	3.24E-08	m2a
Occupation, permanent crop, non-irrigated, intensive	land	4.04E-09	m2a
Occupation, water bodies, artificial	land	3.06E-05	m2a
Occupation, urban/industrial fallow (non-use)	land	1.00E-08	m2a
Oil, crude	in ground	0.004175	kg
Olivine	in ground	1.38E-10	kg
Palladium, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	4.24E-12	kg

Palladium, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	4.24E-12	kg
Palladium, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	2.11E-11	kg
Peat	biotic	4.20E-05	kg
Perlite	in ground	3.18E-08	kg
Phosphorus	in ground	6.31E-07	kg
Phosphorus, 18% in apatite, 4% in crude ore	in ground	4.26E-06	kg
Praseodymium	in ground	2.52E-12	kg
Platinum, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	7.23E-12	kg
Platinum, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	9.97E-12	kg
Pumice	in ground	2.18E-06	kg
Rhodium, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore	in ground	5.78E-13	kg
Rhodium, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore	in ground	4.99E-13	kg
Rhenium	in ground	7.01E-13	kg
Samarium	in ground	1.80E-12	kg
Sand	in ground	1.62E-07	kg
Shale	in ground	8.95E-06	kg
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	in ground	4.33E-09	kg
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore	in ground	4.56E-14	kg
Silver, Ag 1.5E-4%, Au 6.8E-4%, in ore	in ground	6.25E-14	kg
Silver, Ag 1.5E-5%, Au 5.4E-4%, in ore	in ground	5.72E-15	kg
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore	in ground	1.28E-12	kg
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore	in ground	1.40E-10	kg
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore	in ground	2.07E-12	kg
Silver, Ag 5.4E-3%, in mixed ore	in ground	5.76E-11	kg
Silver, Ag 7.6E-5%, Au 9.7E-5%, in ore	in ground	7.89E-13	kg
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	in ground	2.80E-09	kg
Sodium chloride	in ground	2.37E-05	kg
Sodium nitrate	in ground	3.58E-14	kg
Sodium sulfate	in ground	1.23E-07	kg
Spodumene	in ground	2.95E-10	kg
Stibnite	in ground	4.05E-11	kg
Strontium	in ground	3.23E-09	kg
Sulfur	in ground	1.43E-07	kg
Potassium chloride	in ground	1.05E-06	kg
Talc	in ground	3.14E-08	kg
Tantalum	in ground	5.86E-10	kg
Tellurium	in ground	6.84E-15	kg
Tin	in ground	2.52E-07	kg
TiO2, 54% in ilmenite, 18% in crude ore	in ground	6.54E-08	kg
TiO2, 54% in ilmenite, 2.6% in crude ore	in ground	8.63E-07	kg
TiO2, 95% in rutile, 0.40% in crude ore	in ground	1.33E-07	kg
Transformation, from annual crop	land	3.79E-06	m2
Transformation, from annual crop, greenhouse	land	6.27E-09	m2
Transformation, from annual crop, irrigated, intensive	land	1.06E-07	m2
Transformation, from annual crop, non-irrigated	land	8.55E-06	m2
Transformation, from annual crop, non-irrigated, extensive	land	8.28E-07	m2
Transformation, from annual crop, non-irrigated, intensive	land	2.99E-06	m2
Transformation, from annual crop	land	1.59E-06	m2
Transformation, from forest, primary (non-use)	land	2.55E-07	m2
Transformation, from forest, unspecified	land	5.59E-06	m2
Transformation, from grassland, natural (non-use)	land	1.88E-08	m2
Transformation, from pasture, man made	land	7.24E-07	m2
Transformation, from pasture, man made, extensive	land	2.58E-10	m2
Transformation, from pasture, man made, intensive	land	8.21E-07	m2
Transformation, from permanent crop, irrigated	land	6.70E-08	m2
Transformation, from permanent crop, irrigated, intensive	land	2.73E-08	m2
Transformation, from permanent crop, non-irrigated, intensive	land	4.04E-09	m2
Transformation, from seabed, unspecified	land	6.99E-07	m2
Transformation, from unknown	land	3.28E-05	m2
Transformation, from unspecified, natural	land	1.59E-09	m2
Transformation, to annual crop	land	4.07E-06	m2
Transformation, to annual crop, greenhouse	land	6.27E-09	m2
Transformation, to annual crop, irrigated, extensive	land	5.59E-09	m2
Transformation, to annual crop, irrigated, intensive	land	2.93E-07	m2
Transformation, to annual crop, non-irrigated	land	1.12E-07	m2
Transformation, to annual crop, non-irrigated, extensive	land	9.37E-07	m2
Transformation, to annual crop, non-irrigated, intensive	land	1.40E-05	m2
Transformation, to annual crop	land	1.63E-06	m2
Transformation, to annual crop, fallow	land	9.26E-07	m2
Transformation, to forest, unspecified	land	6.18E-06	m2
Transformation, to water bodies, artificial	land	4.21E-06	m2
Transformation, to pasture, man made	land	2.20E-08	m2
Transformation, to pasture, man made, extensive	land	2.58E-10	m2
Transformation, to pasture, man made, intensive	land	6.34E-07	m2
Transformation, to permanent crop, irrigated	land	6.70E-08	m2
Transformation, to permanent crop, irrigated, intensive	land	2.73E-08	m2
Transformation, to permanent crop, non-irrigated	land	6.76E-11	m2
Transformation, to permanent crop, non-irrigated, intensive	land	4.04E-09	m2
Transformation, to water bodies, artificial	land	3.22E-07	m2
Transformation, to unknown	land	4.27E-06	m2
Transformation, to urban/industrial fallow	land	1.34E-10	m2
Ulexite	in ground	9.12E-09	kg
Uranium	in ground	1.04E-07	kg
Vermiculite	in ground	7.33E-07	kg
Water, unspecified natural origin, IAI Area, Africa	in water	3.24E-09	m3
Water, unspecified natural origin, IAI Area, Asia, without China and GCC	in water	5.99E-09	m3
Water, unspecified natural origin, IAI Area, Gulf Cooperation Council	in water	7.21E-09	m3
Water, unspecified natural origin, IAI Area, North America, without Quebec	in water	4.56E-09	m3
Water, unspecified natural origin, IAI Area, Russia & RER w/o EU27 & EFTA	in water	1.07E-08	m3
Water, unspecified natural origin, IAI Area, South America	in water	4.29E-09	m3
Wood, unspecified, standing/m3	biotic	1.36E-11	m3
Xenon	in air	2.18E-11	kg
Zinc	in ground	5.34E-06	kg
Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore	in ground	3.56E-07	kg
Zinc, Zn 3.1%, in mixed ore	in ground	3.27E-08	kg
Zirconium	in ground	1.29E-07	kg
Materials/fuels			
Electricity/heat			
Emissions to air			
Ammonia		1.55E-06	kg
Benzene		7.20E-08	kg
Pentane		4.59E-10	kg
Acetaldehyde		1.25E-07	kg
Acetic acid		4.83E-09	kg
Acetone		2.10E-10	kg
Acrolein		1.13E-08	kg
Benzaldehyde		8.73E-09	kg
Benzo(a)pyrene		2.95E-11	kg
Butane		9.91E-10	kg
Cobalt		3.88E-11	kg
Ethane		3.14E-09	kg
Ethanol		1.12E-12	kg
Ethene		8.35E-11	kg
Ethylene oxide		1.58E-13	kg
Ethyne		8.85E-11	kg
Fluoranthene		1.33E-14	kg
Formaldehyde		2.42E-07	kg
Heptane		1.91E-09	kg
Hexane		1.52E-16	kg
Isoprene		2.57E-16	kg
m-Xylene		6.25E-09	kg
Methanol		2.44E-09	kg
o-Xylene		2.55E-09	kg
Phenol		5.89E-11	kg
Propane		6.80E-10	kg
Propene		3.67E-11	kg
Propionic acid		8.94E-13	kg
Styrene		3.57E-09	kg
Toluene		1.10E-07	kg
Xylene		6.99E-08	kg
Phenanthrene		1.86E-13	kg
Chrysene		1.59E-16	kg
2-Propanol		1.38E-12	kg
Ammonia	low. pop.	2.09E-07	kg
Ammonia	low. pop., long-ter	4.30E-11	kg
Ammonia	high. pop.	2.18E-07	kg
Benzene	low. pop.	2.08E-07	kg
Benzene	high. pop.	1.06E-07	kg
Benzene	stratosphere + tro	6.69E-15	kg
Methane	high. pop.	6.56E-11	kg
Pentane	low. pop.	1.20E-07	kg
Pentane	high. pop.	4.04E-07	kg
1-Pentene	high. pop.	2.87E-13	kg
2,4-D	low. pop.	2.88E-12	kg
Acetaldehyde	low. pop.	1.13E-09	kg
Acetaldehyde	high. pop.	7.54E-09	kg
Acetic acid	low. pop.	1.14E-08	kg
Acetic acid	high. pop.	2.75E-08	kg
Acetone	low. pop.	7.53E-09	kg
Acetone	high. pop.	6.91E-09	kg
Acetonitrile	low. pop.	2.22E-10	kg
Acrolein	low. pop.	3.34E-10	kg
Acrolein	high. pop.	5.52E-12	kg
Atrazine	low. pop.	2.66E-13	kg
Benzaldehyde	low. pop.	1.59E-10	kg
Benzaldehyde	high. pop.	2.23E-12	kg
Benzo(a)pyrene	low. pop.	1.23E-09	kg
Benzo(a)pyrene	high. pop.	1.76E-11	kg
Butane	low. pop.	8.10E-08	kg
Butane	high. pop.	2.43E-07	kg

Butene	high. pop.	5.53E-09	kg
Cobalt	low. pop.	1.05E-09	kg
Cobalt	low. pop., long-ter	4.15E-11	kg
Cobalt	high. pop.	1.60E-09	kg
Cyclohexane	high. pop.	4.46E-15	kg
Diethyl ether	high. pop.	9.92E-15	kg
Ethane	low. pop.	3.78E-07	kg
Ethane	high. pop.	2.37E-07	kg
Ethanol	low. pop.	1.20E-09	kg
Ethanol	high. pop.	1.28E-08	kg
Ethene	low. pop.	4.53E-09	kg
Ethene	high. pop.	3.57E-07	kg
Ethylene oxide	low. pop.	1.66E-14	kg
Ethylene oxide	high. pop.	2.93E-11	kg
Ethylene oxide	stratosphere + tro	6.13E-14	kg
Ethyne	low. pop.	7.25E-11	kg
Ethyne	high. pop.	5.72E-08	kg
Formaldehyde	low. pop.	2.51E-08	kg
Formaldehyde	high. pop.	3.78E-08	kg
Formaldehyde	stratosphere + tro	5.29E-14	kg
Formic acid	low. pop.	1.36E-09	kg
Formic acid	high. pop.	2.76E-12	kg
Heptane	high. pop.	5.53E-08	kg
Hexane	low. pop.	5.94E-08	kg
Hexane	high. pop.	1.22E-07	kg
Isoprene	low. pop.	1.97E-11	kg
m-Xylene	low. pop.	7.47E-14	kg
m-Xylene	high. pop.	2.39E-09	kg
Methanol	low. pop.	6.50E-09	kg
Methanol	high. pop.	1.63E-08	kg
Methyl ethyl ketone	low. pop.	3.40E-14	kg
Methyl ethyl ketone	high. pop.	2.28E-09	kg
Methyl formate	high. pop.	4.65E-14	kg
Metribuzin	low. pop.	3.85E-13	kg
o-Xylene	high. pop.	2.19E-12	kg
Phenol	low. pop.	2.41E-09	kg
Phenol	high. pop.	5.74E-10	kg
Propane	low. pop.	1.31E-07	kg
Propane	high. pop.	3.56E-07	kg
Propene	low. pop.	2.44E-09	kg
Propene	high. pop.	6.98E-08	kg
Propionic acid	low. pop.	1.15E-09	kg
Propionic acid	high. pop.	2.72E-11	kg
Styrene	low. pop.	3.34E-11	kg
Styrene	high. pop.	3.95E-10	kg
Toluene	low. pop.	2.95E-08	kg
Toluene	high. pop.	5.70E-08	kg
Trifluralin	low. pop.	4.27E-12	kg
Xylene	low. pop.	1.04E-07	kg
Xylene	high. pop.	4.63E-08	kg
Carbaryl	low. pop.	3.66E-14	kg
Glyphosate	low. pop.	9.30E-11	kg
Permethrin	low. pop.	3.88E-14	kg
Acephate	low. pop.	3.06E-13	kg
Metolachlor	low. pop.	9.88E-13	kg
Dichlorprop	low. pop.	5.63E-15	kg
Methomyl	low. pop.	9.58E-19	kg
Phosphoric acid	high. pop.	4.46E-15	kg
Acrylic acid	high. pop.	3.24E-14	kg
2-Propanol	low. pop.	1.30E-13	kg
2-Propanol	high. pop.	4.89E-10	kg
Diethylene glycol	high. pop.	1.43E-14	kg
Bentazone	low. pop.	1.30E-13	kg
Benzo(k)fluoranthene		1.25E-15	kg
Chlorpyrifos	low. pop.	1.40E-12	kg
Dibenz(a,h)anthracene		8.10E-16	kg
Hydrocarbons, chlorinated		1.48E-09	kg
Hydrocarbons, chlorinated	low. pop.	2.17E-10	kg
Hydrocarbons, chlorinated	high. pop.	6.36E-09	kg
Hydrocarbons, unspecified	low. pop.	1.20E-10	kg
Indeno(1,2,3-cd)pyrene		3.19E-16	kg
Sulfur trioxide		2.27E-12	kg
Sulfur trioxide	high. pop.	3.22E-12	kg
Sulfuric acid		1.69E-11	kg
Sulfuric acid	low. pop.	9.62E-10	kg
Sulfuric acid	high. pop.	2.87E-12	kg
Actinides, radioactive, unspecified	low. pop.	0.002221	Bq
Aerosols, radioactive, unspecified	low. pop.	1.10E-05	Bq
Aldehydes, unspecified		9.17E-11	kg
Aldehydes, unspecified	low. pop.	1.07E-09	kg
Aldehydes, unspecified	high. pop.	2.46E-10	kg
Ammonium carbonate	high. pop.	5.57E-12	kg
Antimony		1.17E-07	kg
Antimony	low. pop.	7.45E-10	kg
Antimony	low. pop., long-ter	4.66E-12	kg
Antimony	high. pop.	2.02E-10	kg
Antimony-124	low. pop.	3.04E-09	Bq
Antimony-125	low. pop.	5.22E-08	Bq
Argon-41	low. pop.	0.006206	Bq
Arsenic		9.66E-11	kg
Arsenic	low. pop.	6.26E-09	kg
Arsenic	low. pop., long-ter	2.74E-10	kg
Arsenic	high. pop.	3.23E-09	kg
Barium		4.53E-08	kg
Barium	low. pop.	7.38E-09	kg
Barium	low. pop., long-ter	3.00E-10	kg
Barium	high. pop.	1.44E-08	kg
Barium-140	low. pop.	1.71E-06	Bq
Benzene, ethyl-		5.96E-13	kg
Benzene, ethyl-	low. pop.	1.30E-10	kg
Benzene, ethyl-	high. pop.	7.97E-09	kg
Benzene, hexachloro-		4.99E-12	kg
Benzene, hexachloro-	low. pop.	2.85E-21	kg
Benzene, hexachloro-	high. pop.	2.35E-14	kg
Benzene, pentachloro-	high. pop.	5.89E-14	kg
Beryllium		1.04E-12	kg
Beryllium	low. pop.	2.47E-11	kg
Beryllium	low. pop., long-ter	6.53E-12	kg
Beryllium	high. pop.	1.42E-10	kg
Boron		1.37E-10	kg
Boron	low. pop.	1.12E-07	kg
Boron	low. pop., long-ter	8.69E-11	kg
Boron	high. pop.	5.54E-08	kg
Bromine		1.84E-10	kg
Bromine	low. pop.	3.72E-08	kg
Bromine	high. pop.	4.21E-09	kg
Butadiene		1.48E-14	kg
Butadiene	low. pop.	1.71E-15	kg
Butadiene	high. pop.	2.29E-14	kg
Butadiene	stratosphere + tro	6.34E-15	kg
Cadmium		8.18E-11	kg
Cadmium	low. pop.	1.78E-09	kg
Cadmium	low. pop., long-ter	7.06E-12	kg
Cadmium	high. pop.	4.09E-10	kg
Cadmium	stratosphere + tro	3.36E-18	kg
Calcium		1.11E-08	kg
Calcium	low. pop.	6.76E-10	kg
Calcium	low. pop., long-ter	1.68E-08	kg
Calcium	high. pop.	2.94E-07	kg
Carbon dioxide, fossil		0.008077	kg
Carbon dioxide, fossil	low. pop.	0.022604	kg
Carbon dioxide, fossil	high. pop.	0.013967	kg
Carbon dioxide, fossil	stratosphere + tro	1.06E-09	kg
Carbon disulfide		2.94E-16	kg
Carbon disulfide	low. pop.	1.16E-07	kg
Carbon disulfide	high. pop.	2.15E-12	kg
Carbon monoxide, fossil		4.56E-05	kg
Carbon monoxide, fossil	low. pop.	9.58E-06	kg
Carbon monoxide, fossil	high. pop.	2.50E-05	kg
Carbon monoxide, fossil	stratosphere + tro	1.24E-12	kg
Carbon-14	low. pop.	0.209273	Bq
Cerium-141	low. pop.	4.14E-07	Bq
Cesium-134	low. pop.	1.98E-08	Bq
Cesium-137	low. pop.	3.60E-07	Bq
Chlorine		4.80E-09	kg
Chlorine	low. pop.	1.48E-11	kg
Chlorine	low. pop., long-ter	6.41E-10	kg
Chlorine	high. pop.	1.93E-08	kg
Chloroform		1.34E-16	kg
Chloroform	low. pop.	1.05E-10	kg
Chloroform	high. pop.	1.68E-10	kg
Chromium		8.55E-10	kg
Chromium	low. pop.	3.14E-08	kg
Chromium	high. pop.	3.01E-09	kg
Chromium	stratosphere + tro	1.68E-17	kg
Chromium VI		9.10E-13	kg
Chromium VI	low. pop.	9.32E-10	kg
Chromium VI	low. pop., long-ter	3.33E-11	kg
Chromium VI	high. pop.	3.18E-10	kg
Chromium-51	low. pop.	2.65E-08	Bq
Cobalt-58	low. pop.	5.51E-08	Bq
Cobalt-60	low. pop.	4.10E-07	Bq
Copper		6.56E-08	kg
Copper	low. pop.	1.58E-08	kg
Copper	low. pop., long-ter	4.38E-10	kg
Copper	high. pop.	4.40E-09	kg
Copper	stratosphere + tro	5.70E-16	kg
Cumene		1.20E-17	kg
Cumene	low. pop.	5.84E-12	kg
Cumene	high. pop.	2.61E-09	kg

Cyanide		5.65E-15	kg
Cyanide	low. pop.	7.73E-09	kg
Cyanide	high. pop.	3.97E-09	kg
Dinitrogen monoxide		5.60E-07	kg
Dinitrogen monoxide	low. pop.	3.54E-07	kg
Dinitrogen monoxide	low. pop., long-ter	3.89E-11	kg
Dinitrogen monoxide	high. pop.	3.48E-07	kg
Dinitrogen monoxide	stratosphere + tro	1.01E-14	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a		1.21E-10	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	low. pop.	9.09E-11	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	high. pop.	4.07E-11	kg
Ethane, 1,2-dichloro-		3.09E-15	kg
Ethane, 1,2-dichloro-	low. pop.	4.28E-11	kg
Ethane, 1,2-dichloro-	high. pop.	4.41E-09	kg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	low. pop.	4.21E-10	kg
Ethane, hexafluoro-, HFC-116		9.67E-11	kg
Ethane, hexafluoro-, HFC-116	high. pop.	2.89E-13	kg
Ethene, chloro-		9.05E-17	kg
Ethene, chloro-	high. pop.	2.30E-09	kg
Ethene, tetrachloro-		1.96E-13	kg
Ethene, tetrachloro-	low. pop.	4.60E-11	kg
Ethene, tetrachloro-	high. pop.	1.84E-11	kg
Ethylene diamine	high. pop.	1.02E-12	kg
Fluorine		8.03E-12	kg
Fluorine	low. pop.	6.09E-10	kg
Fluorine	low. pop., long-ter	3.15E-09	kg
Fluorine	high. pop.	9.96E-10	kg
Fluosilicic acid	high. pop.	4.66E-10	kg
Heat, waste		5.02E-05	MJ
Heat, waste	low. pop.	4.64E-07	MJ
Heat, waste	high. pop.	0.001243	MJ
Helium		4.52E-11	kg
Helium	low. pop.	9.85E-09	kg
Hydrocarbons, aliphatic, alkanes, cyclic	low. pop.	6.20E-10	kg
Hydrocarbons, aliphatic, alkanes, cyclic	high. pop.	7.17E-10	kg
Hydrocarbons, aliphatic, alkanes, unspecified		1.16E-07	kg
Hydrocarbons, aliphatic, alkanes, unspecified	low. pop.	2.93E-08	kg
Hydrocarbons, aliphatic, alkanes, unspecified	high. pop.	1.56E-07	kg
Hydrocarbons, aliphatic, unsaturated		1.08E-10	kg
Hydrocarbons, aliphatic, unsaturated	low. pop.	2.32E-08	kg
Hydrocarbons, aliphatic, unsaturated	high. pop.	1.29E-07	kg
Hydrocarbons, aromatic		1.34E-07	kg
Hydrocarbons, aromatic	low. pop.	2.66E-09	kg
Hydrocarbons, aromatic	high. pop.	1.29E-08	kg
Hydrogen		1.10E-09	kg
Hydrogen	high. pop.	3.91E-08	kg
Hydrogen chloride		4.83E-07	kg
Hydrogen chloride	low. pop.	3.34E-06	kg
Hydrogen chloride	high. pop.	4.59E-06	kg
Hydrogen chloride	stratosphere + tro	2.89E-16	kg
Hydrogen fluoride		6.92E-08	kg
Hydrogen fluoride	low. pop.	4.18E-07	kg
Hydrogen fluoride	high. pop.	1.51E-07	kg
Hydrogen sulfide		1.26E-08	kg
Hydrogen sulfide	low. pop.	4.06E-08	kg
Hydrogen sulfide	low. pop., long-ter	2.71E-09	kg
Hydrogen sulfide	high. pop.	3.45E-09	kg
Hydrogen-3, Tritium	low. pop.	0.510325	Bq
Iodine		4.47E-11	kg
Iodine	low. pop.	1.93E-08	kg
Iodine	high. pop.	2.26E-09	kg
Iodine-129	low. pop.	5.27E-05	Bq
Iodine-131	low. pop.	0.001461	Bq
Iodine-133	low. pop.	4.06E-06	Bq
Iron		2.52E-07	kg
Iron	low. pop.	5.66E-10	kg
Iron	low. pop., long-ter	5.62E-08	kg
Iron	high. pop.	5.05E-07	kg
Isocyanic acid	high. pop.	9.31E-09	kg
Krypton-85	low. pop.	0.020383	Bq
Krypton-85m	low. pop.	0.035716	Bq
Krypton-87	low. pop.	0.005598	Bq
Krypton-88	low. pop.	0.007348	Bq
Krypton-89	low. pop.	0.003088	Bq
Lanthanum-140	low. pop.	1.46E-07	Bq
Lead		1.02E-08	kg
Lead	low. pop.	1.84E-08	kg
Lead	low. pop., long-ter	4.63E-10	kg
Lead	high. pop.	1.18E-08	kg
Lead	stratosphere + tro	6.71E-18	kg
Lead-210		1.87E-05	Bq
Lead-210	low. pop.	0.007801	Bq
Lead-210	high. pop.	0.005605	Bq
Magnesium		8.00E-11	kg
Magnesium	low. pop.	1.42E-08	kg
Magnesium	low. pop., long-ter	5.16E-09	kg
Magnesium	high. pop.	4.31E-07	kg
Manganese		3.57E-09	kg
Manganese	low. pop.	6.13E-09	kg
Manganese	low. pop., long-ter	1.16E-09	kg
Manganese	high. pop.	6.31E-09	kg
Manganese-54	low. pop.	1.36E-08	Bq
Mercury		6.23E-10	kg
Mercury	low. pop.	6.17E-10	kg
Mercury	low. pop., long-ter	3.56E-12	kg
Mercury	high. pop.	3.58E-10	kg
Mercury	stratosphere + tro	2.35E-20	kg
Methane, bromochlorodifluoro-, Halon 1211	low. pop.	4.06E-11	kg
Methane, bromotrifluoro-, Halon 1301	low. pop.	2.21E-10	kg
Methane, bromotrifluoro-, Halon 1301	high. pop.	1.86E-14	kg
Methane, chlorodifluoro-, HCFC-22		1.85E-16	kg
Methane, chlorodifluoro-, HCFC-22	low. pop.	6.49E-10	kg
Methane, chlorodifluoro-, HCFC-22	high. pop.	5.16E-10	kg
Methane, dichloro-, HCC-30		1.46E-11	kg
Methane, dichloro-, HCC-30	low. pop.	3.11E-10	kg
Methane, dichloro-, HCC-30	high. pop.	5.70E-12	kg
Methane, dichlorodifluoro-, CFC-12		2.41E-16	kg
Methane, dichlorodifluoro-, CFC-12	low. pop.	8.93E-14	kg
Methane, dichlorodifluoro-, CFC-12	high. pop.	9.20E-11	kg
Methane, dichlorofluoro-, HCFC-21	high. pop.	1.06E-13	kg
Methane, fossil		5.34E-06	kg
Methane, fossil	low. pop.	0.000129	kg
Methane, fossil	high. pop.	2.75E-06	kg
Methane, fossil	stratosphere + tro	1.68E-14	kg
Methane, monochloro-, R-40	low. pop.	5.68E-10	kg
Methane, trichlorofluoro-, CFC-11	high. pop.	1.69E-13	kg
Methane, trifluoro-, HFC-23	high. pop.	3.37E-11	kg
Molybdenum		1.17E-08	kg
Molybdenum	low. pop.	1.86E-10	kg
Molybdenum	low. pop., long-ter	9.00E-11	kg
Molybdenum	high. pop.	8.51E-10	kg
Monoethanolamine	high. pop.	1.60E-09	kg
Nickel		9.33E-10	kg
Nickel	low. pop.	1.76E-08	kg
Nickel	low. pop., long-ter	9.49E-11	kg
Nickel	high. pop.	1.47E-08	kg
Nickel	stratosphere + tro	2.35E-17	kg
Niobium-95	low. pop.	0.007719	Bq
Nitrate		5.15E-09	kg
Nitrate	low. pop.	1.53E-10	kg
Nitrate	low. pop., long-ter	4.44E-10	kg
Nitrate	high. pop.	2.52E-13	kg
Nitrobenzene	high. pop.	4.65E-13	kg
Nitrogen oxides		5.94E-05	kg
Nitrogen oxides	low. pop.	5.79E-05	kg
Nitrogen oxides	low. pop., long-ter	7.17E-12	kg
Nitrogen oxides	high. pop.	3.35E-05	kg
Nitrogen oxides	stratosphere + tro	1.19E-09	kg
NMVOC, non-methane volatile organic compounds, unspecified origin		8.37E-06	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	low. pop.	7.27E-06	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	high. pop.	9.08E-07	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	stratosphere + tro	2.25E-13	kg
Noble gases, radioactive, unspecified	low. pop.	506.7633	Bq
Ozone		1.52E-07	kg
Ozone	high. pop.	1.92E-12	kg
PAH, polycyclic aromatic hydrocarbons		3.12E-09	kg
PAH, polycyclic aromatic hydrocarbons	low. pop.	2.53E-09	kg
PAH, polycyclic aromatic hydrocarbons	high. pop.	2.87E-10	kg
Paraffins	high. pop.	9.23E-11	kg
Particulates, < 2.5 um		4.58E-06	kg
Particulates, < 2.5 um	low. pop.	4.17E-05	kg
Particulates, < 2.5 um	low. pop., long-ter	4.26E-08	kg
Particulates, < 2.5 um	high. pop.	6.60E-06	kg
Particulates, < 2.5 um	stratosphere + tro	1.28E-14	kg
Particulates, > 10 um		5.91E-06	kg
Particulates, > 10 um	low. pop.	4.13E-05	kg
Particulates, > 10 um	low. pop., long-ter	1.03E-07	kg
Particulates, > 10 um	high. pop.	2.61E-06	kg

Particulates, > 2.5 um, and < 10um		2.77E-06	kg
Particulates, > 2.5 um, and < 10um	low. pop.	1.04E-05	kg
Particulates, > 2.5 um, and < 10um	low. pop., long-ter	6.19E-08	kg
Particulates, > 2.5 um, and < 10um	high. pop.	2.94E-06	kg
Phenol, pentachloro-		2.27E-12	kg
Phenol, pentachloro-	low. pop.	5.43E-10	kg
Phenol, pentachloro-	high. pop.	1.65E-13	kg
Phosphorus		2.41E-12	kg
Phosphorus	low. pop.	1.42E-11	kg
Phosphorus	low. pop., long-ter	8.69E-11	kg
Phosphorus	high. pop.	1.48E-08	kg
Platinum	low. pop.	6.95E-15	kg
Platinum	high. pop.	4.77E-17	kg
Plutonium-238	low. pop.	7.19E-12	Bq
Plutonium-alpha	low. pop.	1.65E-11	Bq
Polonium-210		3.42E-05	Bq
Polonium-210	low. pop.	0.013712	Bq
Polonium-210	high. pop.	0.010249	Bq
Polychlorinated biphenyls		9.04E-12	kg
Polychlorinated biphenyls	high. pop.	4.70E-15	kg
Potassium		2.06E-09	kg
Potassium	low. pop.	6.48E-11	kg
Potassium	low. pop., long-ter	8.84E-09	kg
Potassium	high. pop.	6.06E-07	kg
Potassium-40		4.62E-06	Bq
Potassium-40	low. pop.	0.0027	Bq
Potassium-40	high. pop.	0.00161	Bq
Propanal		8.59E-16	kg
Propanal	low. pop.	4.29E-11	kg
Propanal	high. pop.	2.14E-12	kg
Propylene oxide	high. pop.	4.93E-10	kg
Protactinium-234	low. pop.	0.000158	Bq
Radioactive species, other beta emitters	low. pop.	3.70E-07	Bq
Radioactive species, other beta emitters	high. pop.	0.627425	Bq
Radium-226		4.84E-06	Bq
Radium-226	low. pop.	0.002714	Bq
Radium-226	high. pop.	0.001447	Bq
Radium-228		1.55E-06	Bq
Radium-228	low. pop.	0.000698	Bq
Radium-228	high. pop.	0.007292	Bq
Radon-220		9.93E-05	Bq
Radon-220	low. pop.	0.063642	Bq
Radon-220	high. pop.	0.002306	Bq
Radon-222		5.62E-05	Bq
Radon-222	low. pop.	55.53233	Bq
Radon-222	low. pop., long-ter	1978.528	Bq
Radon-222	high. pop.	0.001347	Bq
Ruthenium-103	low. pop.	3.54E-10	Bq
Scandium		3.76E-15	kg
Scandium	low. pop.	4.17E-13	kg
Scandium	low. pop., long-ter	1.85E-10	kg
Scandium	high. pop.	1.41E-10	kg
Selenium		8.67E-11	kg
Selenium	low. pop.	3.09E-09	kg
Selenium	low. pop., long-ter	2.59E-11	kg
Selenium	high. pop.	1.39E-09	kg
Selenium	stratosphere + tro	3.36E-18	kg
Silicon		8.36E-08	kg
Silicon	low. pop.	1.98E-09	kg
Silicon	low. pop., long-ter	1.15E-08	kg
Silicon	high. pop.	1.77E-06	kg
Silicon tetrafluoride	low. pop.	3.22E-11	kg
Silver		4.89E-13	kg
Silver	low. pop.	7.13E-14	kg
Silver	low. pop., long-ter	7.74E-12	kg
Silver	high. pop.	1.20E-12	kg
Silver-110	low. pop.	6.98E-09	Bq
Sodium		1.05E-08	kg
Sodium	low. pop.	2.13E-10	kg
Sodium	low. pop., long-ter	3.04E-09	kg
Sodium	high. pop.	1.14E-07	kg
Sodium chlorate	high. pop.	4.74E-11	kg
Sodium dichromate	high. pop.	7.70E-11	kg
Sodium formate	high. pop.	4.03E-12	kg
Strontium		6.56E-10	kg
Strontium	low. pop.	7.42E-09	kg
Strontium	low. pop., long-ter	1.88E-10	kg
Strontium	high. pop.	2.15E-08	kg
Sulfate		4.48E-08	kg
Sulfate	low. pop.	1.20E-09	kg
Sulfate	low. pop., long-ter	4.76E-08	kg
Sulfate	high. pop.	1.41E-07	kg
Sulfur dioxide		1.12E-05	kg
Sulfur dioxide	low. pop.	9.51E-05	kg
Sulfur dioxide	high. pop.	7.70E-05	kg
Sulfur dioxide	stratosphere + tro	3.36E-13	kg
Sulfur hexafluoride		4.74E-09	kg
Sulfur hexafluoride	low. pop.	5.76E-13	kg
Sulfur hexafluoride	high. pop.	9.86E-15	kg
t-Butyl methyl ether	high. pop.	4.28E-09	kg
Thallium		4.34E-12	kg
Thallium	low. pop.	2.60E-13	kg
Thallium	high. pop.	1.76E-10	kg
Thorium		1.09E-14	kg
Thorium	low. pop.	7.57E-14	kg
Thorium	high. pop.	2.11E-10	kg
Thorium-228		7.90E-07	Bq
Thorium-228	low. pop.	0.000391	Bq
Thorium-228	high. pop.	0.000632	Bq
Thorium-230	low. pop.	0.000234	Bq
Thorium-232		1.21E-06	Bq
Thorium-232	low. pop.	0.000569	Bq
Thorium-232	high. pop.	0.000418	Bq
Thorium-234	low. pop.	0.000158	Bq
Tin		8.48E-09	kg
Tin	low. pop.	8.06E-10	kg
Tin	low. pop., long-ter	1.08E-11	kg
Tin	high. pop.	7.33E-11	kg
Titanium		5.04E-09	kg
Titanium	low. pop.	1.17E-11	kg
Titanium	low. pop., long-ter	3.38E-09	kg
Titanium	high. pop.	4.24E-08	kg
Uranium		1.71E-14	kg
Uranium	low. pop.	4.03E-14	kg
Uranium	high. pop.	2.81E-10	kg
Uranium alpha	low. pop.	0.00104	Bq
Uranium-234	low. pop.	0.000492	Bq
Uranium-235	low. pop.	9.05E-06	Bq
Uranium-238		4.03E-06	Bq
Uranium-238	low. pop.	0.002007	Bq
Uranium-238	high. pop.	0.001206	Bq
Vanadium		8.11E-10	kg
Vanadium	low. pop.	1.95E-09	kg
Vanadium	low. pop., long-ter	3.21E-10	kg
Vanadium	high. pop.	3.83E-08	kg
Xenon-131m	low. pop.	0.029477	Bq
Xenon-133	low. pop.	1.743392	Bq
Xenon-133m	low. pop.	0.001147	Bq
Xenon-135	low. pop.	0.611629	Bq
Xenon-135m	low. pop.	0.269134	Bq
Xenon-137	low. pop.	0.008446	Bq
Xenon-138	low. pop.	0.063109	Bq
Zinc		3.74E-08	kg
Zinc	low. pop.	2.47E-08	kg
Zinc	low. pop., long-ter	3.32E-10	kg
Zinc	high. pop.	9.13E-09	kg
Zinc	stratosphere + tro	3.36E-16	kg
Zinc-65	low. pop.	6.79E-08	Bq
Zirconium	low. pop.	7.34E-13	kg
Zirconium-95	low. pop.	1.30E-07	Bq
Ethane, 1,1,1-trichloro-, HCFC-140		2.47E-16	kg
Ethane, 1,1,1-trichloro-, HCFC-140	low. pop.	2.14E-11	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113		5.87E-11	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	low. pop., long-ter	2.33E-11	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	high. pop.	1.53E-15	kg
Ethane, 1,1-difluoro-, HFC-152a	low. pop.	4.84E-11	kg
Ethane, 1,1-difluoro-, HFC-152a	high. pop.	1.57E-10	kg
Methane, bromo-, Halon 1001		3.62E-16	kg
Methane, bromo-, Halon 1001	high. pop.	2.55E-13	kg
Carbonyl sulfide		1.71E-09	kg
Aniline	high. pop.	3.07E-13	kg
Boron trifluoride	high. pop.	8.44E-13	kg
Chloroacetic acid	high. pop.	3.51E-12	kg
Dimethylamine	high. pop.	2.06E-13	kg
Methyl acrylate	high. pop.	3.66E-14	kg
Phosphine	high. pop.	5.75E-12	kg
Acetamide	low. pop.	7.54E-14	kg
Alachlor	low. pop.	2.98E-13	kg
Bromoxynil	low. pop.	4.36E-15	kg
Diflubenzuron	low. pop.	3.86E-15	kg
Fomesafen	low. pop.	4.65E-13	kg
Lactofen	low. pop.	5.94E-14	kg
Pendimethalin	low. pop.	2.64E-12	kg
Propiconazole	low. pop.	4.56E-14	kg
Sethoxydim	low. pop.	3.10E-14	kg
Thiodicarb	low. pop.	1.51E-14	kg
Sodium hydroxide	high. pop.	1.26E-11	kg
Tungsten	low. pop.	4.58E-14	kg
Tungsten	low. pop., long-ter	2.09E-11	kg
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124		5.87E-11	kg
Acenaphthene		3.70E-12	kg
Acenaphthene	low. pop.	6.03E-13	kg
Acenaphthylene		7.55E-14	kg
Acifluorfen	low. pop.	4.21E-14	kg
Azoxystrobin	low. pop.	1.39E-13	kg
Benzo(b)fluoranthene		1.72E-15	kg
Cyfluthrin	low. pop.	7.33E-15	kg
Cyhalothrin, gamma-	low. pop.	8.42E-14	kg
Dicamba	low. pop.	1.04E-13	kg
Dimethenamid	low. pop.	5.01E-15	kg
Ethephon	low. pop.	2.80E-19	kg
Flufenacet	low. pop.	3.09E-14	kg
Flumetsulam	low. pop.	7.23E-15	kg
Flumiclorac-pentyl	low. pop.	1.24E-14	kg
Fluorene		1.21E-14	kg
Furan		1.92E-17	kg
Furan	low. pop.	5.92E-09	kg
Hydrogen peroxide	high. pop.	3.57E-12	kg
Imazamox	low. pop.	1.85E-14	kg
Imazaquin	low. pop.	5.90E-14	kg
Imazethapyr	low. pop.	1.22E-13	kg
MCPB	low. pop.	7.74E-15	kg
Paraquat	low. pop.	2.48E-13	kg
Pyrene		9.70E-15	kg

Sulfentrazone	low. pop.	2.96E-13	kg
Tebuconazole	low. pop.	6.51E-20	kg
Tefluthrin	low. pop.	1.28E-15	kg
1-Pentanol	high. pop.	4.97E-14	kg
Ethylamine	high. pop.	1.00E-12	kg
Nitrogen fluoride	high. pop.	2.46E-15	kg
Trimethylamine	high. pop.	3.28E-14	kg
Esfenvalerate	low. pop.	4.39E-14	kg
Fluazifop-p-butyl	low. pop.	8.24E-14	kg
Benzal chloride		1.58E-15	kg
1,4-Butanediol	high. pop.	7.80E-13	kg
2-Methyl-1-propanol	high. pop.	1.22E-13	kg
Arsine	high. pop.	3.75E-19	kg
Boric acid	high. pop.	1.26E-16	kg
Butyrolactone	high. pop.	3.56E-13	kg
Chlorosilane, trimethyl-	high. pop.	1.31E-11	kg
Ethyl acetate	high. pop.	2.28E-09	kg
Ethyl cellulose	high. pop.	4.36E-12	kg
Methyl borate	high. pop.	6.35E-14	kg
Tetramethyl ammonium hydroxide	high. pop.	5.91E-11	kg
4-Methyl-2-pentanone	low. pop.	2.83E-15	kg
Terpenes	low. pop.	1.85E-10	kg
Lambda-cyhalothrin	low. pop.	8.86E-21	kg
Chlorimuron-ethyl	low. pop.	7.02E-14	kg
Aluminium		1.37E-06	kg
Aluminium	low. pop.	6.69E-10	kg
Aluminium	low. pop., long-ter	5.17E-08	kg
Aluminium	high. pop.	1.20E-06	kg
Methyl acetate	high. pop.	1.58E-14	kg
Chlorosulfonic acid		2.74E-14	kg
2-Aminopropanol	high. pop.	5.66E-14	kg
2-Nitrobenzoic acid	high. pop.	6.80E-14	kg
Anthranilic acid	high. pop.	5.28E-14	kg
Chloramine	high. pop.	5.93E-13	kg
Chlorosulfonic acid	high. pop.	1.21E-13	kg
Cyanoacetic acid	high. pop.	9.90E-14	kg
Diethylamine	high. pop.	1.68E-13	kg
Dimethyl malonate	high. pop.	1.24E-13	kg
Dipropylamine	high. pop.	7.50E-14	kg
Formamide	high. pop.	9.09E-14	kg
Isopropylamine	high. pop.	5.19E-13	kg
Lactic acid	high. pop.	5.87E-14	kg
Methanesulfonic acid	high. pop.	1.00E-13	kg
Methyl lactate	high. pop.	6.45E-14	kg
Phosphorus trichloride	high. pop.	2.69E-11	kg
Propylamine	high. pop.	2.52E-14	kg
t-Butylamine	high. pop.	3.47E-13	kg
Carfentrazone-ethyl	low. pop.	3.86E-15	kg
Clethodim	low. pop.	2.08E-13	kg
Flumioxazin	low. pop.	1.25E-13	kg
Fenoxaprop	low. pop.	5.74E-14	kg
Thifensulfuron	low. pop.	4.22E-15	kg
Trifloxystrobin	low. pop.	2.70E-15	kg
Sulfur oxides		1.49E-09	kg
Cloransulam-methyl	low. pop.	3.66E-14	kg
Lithium	high. pop.	3.14E-15	kg
Argon-40		4.85E-07	kg
Water/m3		0.000263	m3
Chromium IV	high. pop.	3.22E-17	kg
Organic carbon	high. pop.	4.57E-11	kg
Water/m3	high. pop.	8.74E-07	m3
Water/m3	low. pop.	1.11E-05	m3
Water/m3	stratosphere + tro	4.16E-13	m3
Silicon tetrachloride	high. pop.	9.98E-12	kg
Chlorinated solvents, unspecified	low. pop.	1.74E-11	kg
Naphtalene		2.31E-12	kg
2,4-D ester	low. pop.	4.59E-14	kg
Prothioconazol	low. pop.	2.44E-20	kg
2-Butene, 2-methyl-	high. pop.	2.87E-15	kg
Pentane, 3-methyl-	high. pop.	1.98E-11	kg
2,4-D amines	low. pop.	3.93E-15	kg
Butyric acid, 4-(2,4-dichlorophenoxy)-	low. pop.	2.23E-14	kg
Benzo(a)anthracene		1.46E-15	kg
Benzene, 1,2-dichloro-	high. pop.	4.66E-13	kg
Benzo(g,h,i)perylene		1.06E-16	kg
1-Butanol	high. pop.	9.50E-14	kg
Carbon dioxide, land transformation		8.49E-07	kg
Carbon dioxide, land transformation	low. pop.	7.10E-05	kg
Carbon dioxide, biogenic		2.59E-05	kg
Carbon dioxide, biogenic	low. pop.	8.53E-05	kg
Carbon dioxide, biogenic	high. pop.	0.002127	kg
Carbon monoxide, land transformation	low. pop.	1.28E-07	kg
Carbon monoxide, biogenic		1.40E-09	kg
Carbon monoxide, biogenic	low. pop.	1.64E-07	kg
Carbon monoxide, biogenic	high. pop.	6.07E-06	kg
Cyclohexane	high. pop.	1.18E-12	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-		9.03E-15	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	low. pop.	2.39E-15	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	low. pop., long-ter	2.65E-19	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	high. pop.	3.70E-15	kg
Carbon	high. pop.	1.84E-11	kg
2-Methyl-4-chlorophenoxyacetic acid	low. pop.	7.83E-15	kg
Methane, land transformation	low. pop.	8.76E-09	kg
Methane, biogenic		7.32E-08	kg
Methane, biogenic	low. pop.	1.62E-06	kg
Methane, biogenic	high. pop.	7.06E-08	kg
Methane, tetrachloro-, CFC-10		1.08E-13	kg
Methane, tetrachloro-, CFC-10	high. pop.	3.36E-11	kg
Methane, tetrafluoro-, CFC-14		1.32E-09	kg
Methane, tetrafluoro-, CFC-14	high. pop.	3.83E-13	kg
Methylamine	high. pop.	1.88E-13	kg
Parathion, methyl	low. pop.	4.76E-14	kg
Nitrogen, atmospheric		3.86E-08	kg
Benzene, 1-methyl-2-nitro-	high. pop.	5.88E-14	kg
Phenol, 2,4-dichloro-		1.88E-13	kg
Phenol, 2,4-dichloro-	high. pop.	2.02E-13	kg
1-Propanol	low. pop.	8.18E-18	kg
1-Propanol	high. pop.	1.41E-09	kg
Pyraclostrobin (prop)	low. pop.	1.07E-13	kg
Quizalofop ethyl ester	low. pop.	1.44E-14	kg
Sodium tetrahydroborate	high. pop.	1.64E-12	kg
Toluene, 2-chloro-	high. pop.	2.40E-13	kg
Cypermethrin	low. pop.	1.78E-14	kg

Sand, soil, and clay plaster - factored inventory

	Sand	Soil	Plaster	Units	Conversion Factor		Sand	Soil	Plaster
Natural Gas	0.000228	0.000194	0.002277	1m3	38.29	MJeq	8.7E-03	9.1E-03	8.7E-02
Crude oil	0.000526	0.001088	0.004175	1kg	45.8	MJeq	2.4E-02	5.0E-02	1.9E-01
Gas, mine, off-gas				1m3	39.8	MJeq	0.0E+00	0.0E+00	0.0E+00
Coal, brown	0.000356		0.003827	1kg	9.9	MJeq	3.5E-03	0.0E+00	3.8E-02
Coal, hard	0.00083			1kg	19.1	MJeq	1.6E-02	0.0E+00	0.0E+00
Gas, mine, off-gas, coal mining	7.68E-06			1MJ	1	MJeq	7.7E-06	0.0E+00	0.0E+00
Energy, solar, converted	6.03E-07			1MJ	1	MJeq	6.0E-07	0.0E+00	0.0E+00
Energy, geothermal, converted	6.56E-05			1MJ	1	MJeq	6.6E-05	0.0E+00	0.0E+00
Energy, hydro, converted	0.002322			1MJ	1	MJeq	2.3E-03	0.0E+00	0.0E+00
Energy, wind, converted	0.000314			1MJ	1	MJeq	3.1E-04	0.0E+00	0.0E+00
Energy, biomass	7.14E-06			1MJ	1	MJeq	7.1E-06	0.0E+00	0.0E+00
Electricity		0.004912		1kWh	3.6	MJeq	0.0E+00	1.8E-02	0.0E+00
Total Energy Input							5.5E-02	7.7E-02	3.2E-01

	Carbon dioxide, fc	Sulfur dioxide	Nitrogen oxides		Methane, fossil	Carbon Monoxide		
	CO2	SO2	NOx	VOC	CH4	CO	TPM	Water input
Sand	0.001348	1.50E-06	1.64E-05	9.01E-12	5.59E-07	7.85E-06	1.85E-06	1.41E-03
Soil	0.004154	4.74E-06	1.79E-05	9.38E-06	7.00E-07	2.39E-05	NA	1.42E-05
Plaster	0.008077	1.12E-05	5.94E-05	7.68E-11	5.34E-06	4.56E-05	1.33E-05	1.14E-03

Transportation

UNIT PROCESS			
Transport, Combination Truck, Diesel Powered.			
Outputs	**Value**	**Unit**	**Comments**
Transport, Combination Truck, Diesel Powe	**1.00E+00**	**t*km**	
Carbon Dioxide, biogenic	7.99E-02	kg	Air Emissions
Carbon Monoxide, fossil	1.27E-04	kg	Air Emissions
Nitrogen oxides	5.32E-04	kg	Air Emissions
Inputs	**Value**	**Unit**	**Comments**
Diesel, at refinery	2.63E-05	kg	

*SYSTEM PROCESS PER 1 TON*KM*			
Outputs	**Value**	**Unit**	
Carbon dioxide, fossil	8.93E-02	kg	Air Emissions
Carbon monoxide, fossil	4.67E-04	kg	Air Emissions
Methane	1.07E-04	kg	Air Emissions
Methane, fossil	5.32E-06	kg	Air Emissions
Nitrogen oxides	6.06E-04	kg	Air Emissions
PM2.5-10	1.09E-05	kg	Air Emissions
Sulfur Dioxide	4.22E-05	kg	Air Emissions
Sulfur Oxides	8.50E-05	kg	Air Emissions
VOCs	2.92E-05	kg	Air Emissions
Barium	1.13E-04	kg	Water Emissions
Calcium, ion	3.07E-04	kg	Water Emissions
Chloride	3.45E-03	kg	Water Emissions
Sodium, ion	9.74E-04	kg	Water Emissions
Solved solids	4.26E-03	kg	Water Emissions
Transport, Combination Truck, Diesel Powe	**1.00E+00**	**t*km**	
Inputs	**Value**	**Unit**	**Comments**
Coal, 26.4 MJ per kg, in ground	1.37E-03	kg	
Oil, crude, in ground	2.56E-02	kg	
Gas, natural, in ground	1.41E-03	m3	

Operational substance inventory and impacts

	Load type	Sustance	COB	LSC	RE	IRE	IWF	CMU	ICMU
Tucson AZ	Cooling (Electricity	Carbon dioxide, fossil	1.58E+01	9.66E+00	1.94E+01	1.17E+01	1.19E+01	2.03E+01	1.22E+01
		Coal	7.41E+00	4.54E+00	9.11E+00	5.49E+00	5.60E+00	9.53E+00	5.73E+00
		Natural Gas	5.00E-01	3.06E-01	6.15E-01	3.70E-01	3.78E-01	6.43E-01	3.86E-01
		Oil, crude	1.37E-01	8.40E-02	1.68E-01	1.01E-01	1.04E-01	1.76E-01	1.06E-01
		Sulfur dioxide	1.08E-01	6.59E-02	1.32E-01	7.97E-02	8.13E-02	1.38E-01	8.31E-02
		Nitrogen oxides	4.51E-02	2.76E-02	5.54E-02	3.34E-02	3.41E-02	5.80E-02	3.48E-02
		Methane	3.04E-02	1.86E-02	3.73E-02	2.25E-02	2.29E-02	3.90E-02	2.35E-02
		PM2.5-10	7.79E-04	4.78E-04	9.58E-04	5.77E-04	5.88E-04	1.00E-03	6.02E-04
		Carbon Monoxide, fossil	5.25E-03	3.22E-03	6.45E-03	3.88E-03	3.96E-03	6.74E-03	4.05E-03
		Total Energy Demand MJeq	**2.21E+02**	**1.36E+02**	**2.72E+02**	**1.64E+02**	**1.67E+02**	**2.84E+02**	**1.71E+02**
		Total GWO (kg CO2eq)	**3.00E+01**	**1.84E+01**	**3.68E+01**	**2.22E+01**	**2.26E+01**	**3.85E+01**	**2.31E+01**
		Total Acidification (kg SO2eq)	**1.39E-01**	**8.53E-02**	**1.71E-01**	**1.03E-01**	**1.05E-01**	**1.79E-01**	**1.08E-01**
		Total Particulate (PM2.5eq)	**7.36E-03**	**4.51E-03**	**9.04E-03**	**5.45E-03**	**5.56E-03**	**9.45E-03**	**5.68E-03**
	Heating (NG)	Carbon dioxide, fossil	7.12E+00	3.35E+00	9.15E+00	4.24E+00	4.65E+00	8.83E+00	4.46E+00
		Coal	5.01E-02	2.36E-02	6.44E-02	2.98E-02	3.28E-02	6.22E-02	3.14E-02
		Natural Gas	3.64E+00	1.71E+00	4.68E+00	2.17E+00	2.38E+00	4.51E+00	2.28E+00
		Oil, crude	2.77E-02	1.31E-02	3.56E-02	1.65E-02	1.81E-02	3.44E-02	1.74E-02
		Sulfur dioxide	6.40E-02	3.01E-02	8.22E-02	3.81E-02	4.18E-02	7.94E-02	4.01E-02
		Nitrogen oxides	6.65E-03	3.13E-03	8.54E-03	3.96E-03	4.34E-03	8.24E-03	4.17E-03
		Methane	3.23E-02	1.52E-02	4.15E-02	1.92E-02	2.11E-02	4.01E-02	2.02E-02
		PM2.5-10	4.43E-04	2.09E-04	5.70E-04	2.64E-04	2.90E-04	5.49E-04	2.78E-04
		Carbon Monoxide, fossil	5.51E-03	2.60E-03	7.08E-03	3.28E-03	3.60E-03	6.83E-03	3.45E-03
		Total Energy Demand MJeq	**1.42E+02**	**6.69E+01**	**1.82E+02**	**8.45E+01**	**9.28E+01**	**1.76E+02**	**8.90E+01**
		Total GWO (kg CO2eq)	**9.90E+00**	**4.67E+00**	**1.27E+01**	**5.90E+00**	**6.47E+00**	**1.23E+01**	**6.21E+00**
		Total Acidification (kg SO2eq)	**6.86E-02**	**3.23E-02**	**8.82E-02**	**4.09E-02**	**4.49E-02**	**8.51E-02**	**4.30E-02**
		Total Particulate (PM2.5eq)	**4.35E-03**	**2.05E-03**	**5.60E-03**	**2.59E-03**	**2.85E-03**	**5.40E-03**	**2.73E-03**
	Total Annual	**Total Energy Demand MJeq**	**3.63E+02**	**2.02E+02**	**4.54E+02**	**2.48E+02**	**2.60E+02**	**4.60E+02**	**2.60E+02**
		Total GWO (kg CO2eq)	**3.99E+01**	**2.30E+01**	**4.96E+01**	**2.81E+01**	**2.91E+01**	**5.08E+01**	**2.93E+01**
		Total Acidification (kg SO2eq)	**2.08E-01**	**1.18E-01**	**2.59E-01**	**1.44E-01**	**1.50E-01**	**2.64E-01**	**1.51E-01**
		Total Particulate (PM2.5eq)	**1.17E-02**	**6.56E-03**	**1.46E-02**	**8.04E-03**	**8.40E-03**	**1.49E-02**	**8.41E-03**
Los Angeles, CA	Cooling (Electricity	Carbon dioxide, fossil	3.25E-05	5.84E-02	0.00E+00	3.90E-03	4.50E-01	1.89E-01	1.72E-01
		Coal	1.53E-05	2.74E-02	0.00E+00	1.84E-03	2.12E-01	8.91E-02	8.07E-02
		Natural Gas	1.03E-06	1.85E-03	0.00E+00	1.24E-04	1.43E-02	6.01E-03	5.45E-03
		Oil, crude	2.82E-07	5.08E-04	0.00E+00	3.40E-05	3.92E-03	1.65E-03	1.49E-03
		Sulfur dioxide	2.22E-07	3.98E-04	0.00E+00	2.67E-05	3.07E-03	1.29E-03	1.17E-03
		Nitrogen oxides	9.29E-08	1.67E-04	0.00E+00	1.12E-05	1.29E-03	5.42E-04	4.91E-04
		Methane	6.25E-08	1.12E-04	0.00E+00	7.52E-06	8.67E-04	3.65E-04	3.31E-04
		PM2.5-10	1.60E-09	2.88E-06	0.00E+00	1.93E-07	2.23E-05	9.37E-06	8.49E-06
		Carbon Monoxide, fossil	1.08E-08	1.94E-05	0.00E+00	1.30E-06	1.50E-04	6.31E-05	5.71E-05
		Total Energy Demand MJeq	**4.55E-04**	**8.19E-01**	**0.00E+00**	**5.48E-02**	**6.32E+00**	**2.66E+00**	**2.41E+00**
		Total GWO (kg CO2eq)	**6.17E-05**	**1.11E-01**	**0.00E+00**	**7.42E-03**	**8.56E-01**	**3.60E-01**	**3.26E-01**
		Total Acidification (kg SO2eq)	**2.87E-07**	**5.15E-04**	**0.00E+00**	**3.45E-05**	**3.98E-03**	**1.67E-03**	**1.52E-03**
		Total Particulate (PM2.5eq)	**1.51E-08**	**2.72E-05**	**0.00E+00**	**1.82E-06**	**2.10E-04**	**8.84E-05**	**8.01E-05**
	Heating (NG)	Carbon dioxide, fossil	4.45E+00	1.66E+00	5.88E+00	2.40E+00	3.03E+00	5.63E+00	2.49E+00
		Coal	3.13E-02	1.17E-02	4.14E-02	1.69E-02	2.14E-02	3.97E-02	1.75E-02
		Natural Gas	2.27E+00	8.49E-01	3.01E+00	1.23E+00	1.55E+00	2.88E+00	1.27E+00
		Oil, crude	1.73E-02	6.47E-03	2.29E-02	9.37E-03	1.18E-02	2.19E-02	9.70E-03
		Sulfur dioxide	4.00E-02	1.49E-02	5.29E-02	2.16E-02	2.73E-02	5.07E-02	2.24E-02
		Nitrogen oxides	4.15E-03	1.55E-03	5.50E-03	2.25E-03	2.83E-03	5.26E-03	2.32E-03
		Methane	2.02E-02	7.54E-03	2.67E-02	1.09E-02	1.38E-02	2.56E-02	1.13E-02
		PM2.5-10	2.77E-04	1.03E-04	3.66E-04	1.50E-04	1.89E-04	3.51E-04	1.55E-04
		Carbon Monoxide, fossil	3.44E-03	1.29E-03	4.55E-03	1.86E-03	2.35E-03	4.36E-03	1.93E-03
		Total Energy Demand MJeq	**8.86E+01**	**3.31E+01**	**1.17E+02**	**4.80E+01**	**6.05E+01**	**1.12E+02**	**4.96E+01**
		Total GWO (kg CO2eq)	**6.19E+00**	**2.31E+00**	**8.19E+00**	**3.35E+00**	**4.22E+00**	**7.84E+00**	**3.46E+00**
		Total Acidification (kg SO2eq)	**4.29E-02**	**1.60E-02**	**5.68E-02**	**2.32E-02**	**2.92E-02**	**5.43E-02**	**2.40E-02**
		Total Particulate (PM2.5eq)	**2.72E-03**	**1.02E-03**	**3.60E-03**	**1.47E-03**	**1.85E-03**	**3.45E-03**	**1.52E-03**
	Total	**Total Energy Demand MJeq**	**8.86E+01**	**3.40E+01**	**1.17E+02**	**4.80E+01**	**6.68E+01**	**1.15E+02**	**5.20E+01**
		Total GWO (kg CO2eq)	**6.19E+00**	**2.42E+00**	**8.19E+00**	**3.35E+00**	**5.07E+00**	**8.20E+00**	**3.79E+00**
		Total Acidification (kg SO2eq)	**4.29E-02**	**1.65E-02**	**5.68E-02**	**2.32E-02**	**3.32E-02**	**5.60E-02**	**2.55E-02**
		Total Particulate (PM2.5eq)	**2.72E-03**	**1.04E-03**	**3.60E-03**	**1.47E-03**	**2.07E-03**	**3.54E-03**	**1.60E-03**
Portland OR	Cooling (Electricity	Carbon dioxide, fossil	4.04E-01	4.20E-01	4.19E-01	2.87E-01	1.09E+00	1.21E+00	7.31E-01
		Coal	1.90E-01	1.98E-01	1.97E-01	1.35E-01	5.11E-01	5.68E-01	3.44E-01
		Natural Gas	1.28E-02	1.33E-02	1.33E-02	9.10E-03	3.45E-02	3.83E-02	2.32E-02
		Oil, crude	3.51E-03	3.65E-03	3.65E-03	2.49E-03	9.46E-03	1.05E-02	6.35E-03
		Sulfur dioxide	2.76E-03	2.87E-03	2.86E-03	1.96E-03	7.42E-03	8.24E-03	4.99E-03
		Nitrogen oxides	1.15E-03	1.20E-03	1.20E-03	8.21E-04	3.11E-03	3.45E-03	2.09E-03
		Methane	7.77E-04	8.09E-04	8.08E-04	5.53E-04	2.09E-03	2.33E-03	1.41E-03
		PM2.5-10	1.99E-05	2.08E-05	2.07E-05	1.42E-05	5.38E-05	5.97E-05	3.61E-05
		Carbon Monoxide, fossil	1.34E-04	1.40E-04	1.40E-04	9.55E-05	3.62E-04	4.02E-04	2.43E-04
		Total Energy Demand MJeq	**5.66E+00**	**5.89E+00**	**5.88E+00**	**4.02E+00**	**1.53E+01**	**1.69E+01**	**1.02E+01**
		Total GWO (kg CO2eq)	**7.67E-01**	**7.99E-01**	**7.97E-01**	**5.45E-01**	**2.07E+00**	**2.30E+00**	**1.39E+00**
		Total Acidification (kg SO2eq)	**3.56E-03**	**3.71E-03**	**3.70E-03**	**2.53E-03**	**9.60E-03**	**1.07E-02**	**6.45E-03**
		Total Particulate (PM2.5eq)	**1.88E-04**	**1.96E-04**	**1.96E-04**	**1.34E-04**	**5.08E-04**	**5.63E-04**	**3.41E-04**
	Heating (NG)	Carbon dioxide, fossil	2.42E+01	1.23E+01	3.20E+01	1.66E+01	1.66E+01	3.08E+01	1.64E+01
		Coal	1.71E-01	8.64E-02	2.25E-01	1.17E-01	1.17E-01	2.17E-01	1.15E-01
		Natural Gas	1.24E+01	6.27E+00	1.63E+01	8.48E+00	8.48E+00	1.58E+01	8.38E+00
		Oil, crude	9.44E-02	4.78E-02	1.25E-01	6.46E-02	6.46E-02	1.20E-01	6.38E-02
		Sulfur dioxide	2.18E-01	1.10E-01	2.87E-01	1.49E-01	1.49E-01	2.77E-01	1.47E-01
		Nitrogen oxides	2.26E-02	1.15E-02	2.99E-02	1.55E-02	1.55E-02	2.88E-02	1.53E-02
		Methane	1.10E-01	5.57E-02	1.45E-01	7.53E-02	7.53E-02	1.40E-01	7.44E-02
		PM2.5-10	1.51E-03	7.63E-04	1.99E-03	1.03E-03	1.03E-03	1.92E-03	1.02E-03
		Carbon Monoxide, fossil	1.87E-02	9.49E-03	2.47E-02	1.28E-02	1.28E-02	2.38E-02	1.27E-02
		Total Energy Demand MJeq	**4.83E+02**	**2.44E+02**	**6.38E+02**	**3.31E+02**	**3.31E+02**	**6.14E+02**	**3.27E+02**
		Total GWO (kg CO2eq)	**3.37E+01**	**1.71E+01**	**4.45E+01**	**2.31E+01**	**2.31E+01**	**4.29E+01**	**2.28E+01**
		Total Acidification (kg SO2eq)	**2.34E-01**	**1.18E-01**	**3.08E-01**	**1.60E-01**	**1.60E-01**	**2.97E-01**	**1.58E-01**
		Total Particulate (PM2.5eq)	**1.48E-02**	**7.50E-03**	**1.96E-02**	**1.02E-02**	**1.02E-02**	**1.89E-02**	**1.00E-02**
	Total	**Total Energy Demand MJeq**	**4.89E+02**	**2.50E+02**	**6.44E+02**	**3.35E+02**	**3.46E+02**	**6.31E+02**	**3.37E+02**
		Total GWO (kg CO2eq)	**3.45E+01**	**1.79E+01**	**4.53E+01**	**2.36E+01**	**2.52E+01**	**4.52E+01**	**2.42E+01**
		Total Acidification (kg SO2eq)	**2.37E-01**	**1.22E-01**	**3.12E-01**	**1.63E-01**	**1.70E-01**	**3.08E-01**	**1.64E-01**
		Total Particulate (PM2.5eq)	**1.50E-02**	**7.70E-03**	**1.98E-02**	**1.03E-02**	**1.07E-02**	**1.94E-02**	**1.04E-02**

Denver CO	Cooling (Electricity)	Carbon dioxide, fossil	2.69E+00	2.06E+00	2.95E+00	2.13E+00	3.00E+00	4.12E+00	2.66E+00
		Coal	1.26E+00	9.69E-01	1.39E+00	1.00E+00	1.41E+00	1.94E+00	1.25E+00
		Natural Gas	8.53E-02	6.54E-02	9.37E-02	6.75E-02	9.51E-02	1.31E-01	8.44E-02
		Oil, crude	2.34E-02	1.79E-02	2.57E-02	1.85E-02	2.61E-02	3.58E-02	2.31E-02
		Sulfur dioxide	1.84E-02	1.41E-02	2.02E-02	1.45E-02	2.05E-02	2.81E-02	1.82E-02
		Nitrogen oxides	7.69E-03	5.90E-03	8.45E-03	6.08E-03	8.58E-03	1.18E-02	7.61E-03
		Methane	5.18E-03	3.97E-03	5.69E-03	4.10E-03	5.77E-03	7.93E-03	5.12E-03
		PM2.5-10	1.33E-04	1.02E-04	1.46E-04	1.05E-04	1.48E-04	2.04E-04	1.31E-04
		Carbon Monoxide, fossil	8.95E-04	6.86E-04	9.84E-04	7.08E-04	9.98E-04	1.37E-03	8.85E-04
		Total Energy Demand MJeq	**3.77E+01**	**2.89E+01**	**4.14E+01**	**2.98E+01**	**4.20E+01**	**5.78E+01**	**3.73E+01**
		Total GWO (kg CO2eq)	**5.11E+00**	**3.92E+00**	**5.62E+00**	**4.04E+00**	**5.70E+00**	**7.83E+00**	**5.06E+00**
		Total Acidification (kg SO2eq)	**2.37E-02**	**1.82E-02**	**2.61E-02**	**1.88E-02**	**2.65E-02**	**3.64E-02**	**2.35E-02**
		Total Particulate (PM2.5eq)	**1.25E-03**	**9.62E-04**	**1.38E-03**	**9.92E-04**	**1.40E-03**	**1.92E-03**	**1.24E-03**
	Heating (NG)	Carbon dioxide, fossil	3.38E+01	1.74E+01	4.45E+01	2.30E+01	2.13E+01	4.19E+01	2.23E+01
		Coal	2.38E-01	1.23E-01	3.14E-01	1.62E-01	1.50E-01	2.95E-01	1.57E-01
		Natural Gas	1.73E+01	8.92E+00	2.28E+01	1.18E+01	1.09E+01	2.14E+01	1.14E+01
		Oil, crude	1.31E-01	6.80E-02	1.74E-01	8.95E-02	8.29E-02	1.63E-01	8.68E-02
		Sulfur dioxide	3.03E-01	1.57E-01	4.00E-01	2.07E-01	1.91E-01	3.76E-01	2.00E-01
		Nitrogen oxides	3.15E-02	1.63E-02	4.16E-02	2.15E-02	1.99E-02	3.91E-02	2.08E-02
		Methane	1.53E-01	7.92E-02	2.02E-01	1.04E-01	9.65E-02	1.90E-01	1.01E-01
		PM2.5-10	2.10E-03	1.09E-03	2.77E-03	1.43E-03	1.32E-03	2.61E-03	1.39E-03
		Carbon Monoxide, fossil	2.61E-02	1.35E-02	3.45E-02	1.78E-02	1.65E-02	3.24E-02	1.72E-02
		Total Energy Demand MJeq	**6.73E+02**	**3.48E+02**	**8.88E+02**	**4.58E+02**	**4.24E+02**	**8.35E+02**	**4.44E+02**
		Total GWO (kg CO2eq)	**4.70E+01**	**2.43E+01**	**6.20E+01**	**3.20E+01**	**2.96E+01**	**5.83E+01**	**3.10E+01**
		Total Acidification (kg SO2eq)	**3.26E-01**	**1.68E-01**	**4.30E-01**	**2.22E-01**	**2.05E-01**	**4.04E-01**	**2.15E-01**
		Total Particulate (PM2.5eq)	**2.07E-02**	**1.07E-02**	**2.73E-02**	**1.41E-02**	**1.30E-02**	**2.56E-02**	**1.36E-02**
	Total	**Total Energy Demand MJeq**	**7.11E+02**	**3.77E+02**	**9.30E+02**	**4.88E+02**	**4.66E+02**	**8.93E+02**	**4.82E+02**
		Total GWO (kg CO2eq)	**5.21E+01**	**2.82E+01**	**6.76E+01**	**3.60E+01**	**3.53E+01**	**6.61E+01**	**3.61E+01**
		Total Acidification (kg SO2eq)	**3.49E-01**	**1.86E-01**	**4.56E-01**	**2.40E-01**	**2.32E-01**	**4.40E-01**	**2.38E-01**
		Total Particulate (PM2.5eq)	**2.19E-02**	**1.16E-02**	**2.86E-02**	**1.51E-02**	**1.44E-02**	**2.75E-02**	**1.49E-02**
Albq NM	Cooling (Electricity)	Carbon dioxide, fossil	4.75E+00	3.29E+00	5.53E+00	3.72E+00	4.46E+00	6.48E+00	4.15E+00
		Coal	2.23E+00	1.55E+00	2.60E+00	1.75E+00	2.10E+00	3.05E+00	1.95E+00
		Natural Gas	1.51E-01	1.04E-01	1.75E-01	1.18E-01	1.41E-01	2.06E-01	1.32E-01
		Oil, crude	4.13E-02	2.86E-02	4.81E-02	3.24E-02	3.88E-02	5.64E-02	3.61E-02
		Sulfur dioxide	3.24E-02	2.25E-02	3.78E-02	2.54E-02	3.04E-02	4.43E-02	2.83E-02
		Nitrogen oxides	1.36E-02	9.41E-03	1.58E-02	1.07E-02	1.27E-02	1.85E-02	1.19E-02
		Methane	9.15E-03	6.34E-03	1.07E-02	7.17E-03	8.58E-03	1.25E-02	7.99E-03
		PM2.5-10	2.35E-04	1.63E-04	2.73E-04	1.84E-04	2.20E-04	3.20E-04	2.05E-04
		Carbon Monoxide, fossil	1.58E-03	1.09E-03	1.84E-03	1.24E-03	1.48E-03	2.16E-03	1.38E-03
		Total Energy Demand MJeq	**6.66E+01**	**4.61E+01**	**7.76E+01**	**5.22E+01**	**6.25E+01**	**9.09E+01**	**5.82E+01**
		Total GWO (kg CO2eq)	**9.02E+00**	**6.25E+00**	**1.05E+01**	**7.08E+00**	**8.47E+00**	**1.23E+01**	**7.88E+00**
		Total Acidification (kg SO2eq)	**4.19E-02**	**2.90E-02**	**4.88E-02**	**3.29E-02**	**3.93E-02**	**5.72E-02**	**3.66E-02**
		Total Particulate (PM2.5eq)	**2.22E-03**	**1.54E-03**	**2.58E-03**	**1.74E-03**	**2.08E-03**	**3.03E-03**	**1.94E-03**
	Heating (NG)	Carbon dioxide, fossil	2.28E+01	1.15E+01	2.98E+01	1.50E+01	1.41E+01	2.78E+01	1.48E+01
		Coal	1.61E-01	8.09E-02	2.10E-01	1.06E-01	9.93E-02	1.96E-01	1.04E-01
		Natural Gas	1.17E+01	5.87E+00	1.52E+01	7.68E+00	7.21E+00	1.42E+01	7.58E+00
		Oil, crude	8.89E-02	4.48E-02	1.16E-01	5.85E-02	5.49E-02	1.08E-01	5.78E-02
		Sulfur dioxide	2.05E-01	1.03E-01	2.68E-01	1.35E-01	1.27E-01	2.50E-01	1.33E-01
		Nitrogen oxides	2.13E-02	1.07E-02	2.78E-02	1.40E-02	1.32E-02	2.59E-02	1.39E-02
		Methane	1.04E-01	5.21E-02	1.35E-01	6.82E-02	6.40E-02	1.26E-01	6.73E-02
		PM2.5-10	1.42E-03	7.15E-04	1.85E-03	9.36E-04	8.78E-04	1.73E-03	9.24E-04
		Carbon Monoxide, fossil	1.77E-02	8.89E-03	2.31E-02	1.16E-02	1.09E-02	2.15E-02	1.15E-02
		Total Energy Demand MJeq	**4.55E+02**	**2.29E+02**	**5.94E+02**	**3.00E+02**	**2.81E+02**	**5.54E+02**	**2.96E+02**
		Total GWO (kg CO2eq)	**3.18E+01**	**1.60E+01**	**4.15E+01**	**2.09E+01**	**1.96E+01**	**3.86E+01**	**2.06E+01**
		Total Acidification (kg SO2eq)	**2.20E-01**	**1.11E-01**	**2.87E-01**	**1.45E-01**	**1.36E-01**	**2.68E-01**	**1.43E-01**
		Total Particulate (PM2.5eq)	**1.40E-02**	**7.03E-03**	**1.82E-02**	**9.20E-03**	**8.63E-03**	**1.70E-02**	**9.08E-03**
	Total	**Total Energy Demand MJeq**	**5.22E+02**	**2.75E+02**	**6.72E+02**	**3.52E+02**	**3.44E+02**	**6.45E+02**	**3.54E+02**
		Total GWO (kg CO2eq)	**4.08E+01**	**2.22E+01**	**5.20E+01**	**2.80E+01**	**2.81E+01**	**5.10E+01**	**2.85E+01**
		Total Acidification (kg SO2eq)	**2.62E-01**	**1.40E-01**	**3.36E-01**	**1.78E-01**	**1.75E-01**	**3.25E-01**	**1.80E-01**
		Total Particulate (PM2.5eq)	**1.62E-02**	**8.56E-03**	**2.08E-02**	**1.09E-02**	**1.07E-02**	**2.00E-02**	**1.10E-02**
El Paso TX	Cooling (Electricity)	Carbon dioxide, fossil	1.20E+01	5.89E+00	1.53E+01	7.58E+00	7.99E+00	1.47E+01	7.54E+00
		Coal	5.65E+00	2.77E+00	7.22E+00	3.56E+00	3.76E+00	6.90E+00	3.55E+00
		Natural Gas	3.81E-01	1.87E-01	4.87E-01	2.40E-01	2.54E-01	4.66E-01	2.39E-01
		Oil, crude	1.04E-01	5.12E-02	1.33E-01	6.59E-02	6.95E-02	1.28E-01	6.56E-02
		Sulfur dioxide	8.20E-02	4.02E-02	1.05E-01	5.17E-02	5.46E-02	1.00E-01	5.15E-02
		Nitrogen oxides	3.44E-02	1.68E-02	4.39E-02	2.17E-02	2.29E-02	4.20E-02	2.16E-02
		Methane	2.31E-02	1.13E-02	2.96E-02	1.46E-02	1.54E-02	2.83E-02	1.45E-02
		PM2.5-10	5.94E-04	2.91E-04	7.59E-04	3.75E-04	3.95E-04	7.26E-04	3.73E-04
		Carbon Monoxide, fossil	4.00E-03	1.96E-03	5.11E-03	2.52E-03	2.66E-03	4.89E-03	2.51E-03
		Total Energy Demand MJeq	**1.68E+02**	**8.26E+01**	**2.15E+02**	**1.06E+02**	**1.12E+02**	**2.06E+02**	**1.06E+02**
		Total GWO (kg CO2eq)	**2.28E+01**	**1.12E+01**	**2.92E+01**	**1.44E+01**	**1.52E+01**	**2.79E+01**	**1.43E+01**
		Total Acidification (kg SO2eq)	**1.06E-01**	**5.20E-02**	**1.35E-01**	**6.69E-02**	**7.06E-02**	**1.30E-01**	**6.66E-02**
		Total Particulate (PM2.5eq)	**5.60E-03**	**2.75E-03**	**7.16E-03**	**3.54E-03**	**3.73E-03**	**6.85E-03**	**3.52E-03**
	Heating (NG)	Carbon dioxide, fossil	1.03E+01	6.68E+00	1.24E+01	7.91E+00	8.38E+00	1.35E+01	8.36E+00
		Coal	7.28E-02	4.71E-02	8.76E-02	5.57E-02	5.90E-02	9.48E-02	5.89E-02
		Natural Gas	5.28E+00	3.42E+00	6.36E+00	4.05E+00	4.28E+00	6.88E+00	4.27E+00
		Oil, crude	4.02E-02	2.60E-02	4.84E-02	3.08E-02	3.26E-02	5.24E-02	3.26E-02
		Sulfur dioxide	9.29E-02	6.01E-02	1.12E-01	7.11E-02	7.53E-02	1.21E-01	7.52E-02
		Nitrogen oxides	9.65E-03	6.24E-03	1.16E-02	7.39E-03	7.82E-03	1.26E-02	7.81E-03
		Methane	4.69E-02	3.03E-02	5.64E-02	3.59E-02	3.80E-02	6.11E-02	3.79E-02
		PM2.5-10	6.43E-04	4.16E-04	7.74E-04	4.93E-04	5.22E-04	8.38E-04	5.20E-04
		Carbon Monoxide, fossil	7.99E-03	5.17E-03	9.62E-03	6.12E-03	6.48E-03	1.04E-02	6.47E-03
		Total Energy Demand MJeq	**2.06E+02**	**1.33E+02**	**2.48E+02**	**1.58E+02**	**1.67E+02**	**2.68E+02**	**1.67E+02**
		Total GWO (kg CO2eq)	**1.44E+01**	**9.30E+00**	**1.73E+01**	**1.10E+01**	**1.17E+01**	**1.87E+01**	**1.16E+01**
		Total Acidification (kg SO2eq)	**9.96E-02**	**6.44E-02**	**1.20E-01**	**7.63E-02**	**8.08E-02**	**1.30E-01**	**8.06E-02**
		Total Particulate (PM2.5eq)	**6.32E-03**	**4.09E-03**	**7.61E-03**	**4.84E-03**	**5.13E-03**	**8.24E-03**	**5.11E-03**
	Total	**Total Energy Demand MJeq**	**3.74E+02**	**2.16E+02**	**4.63E+02**	**2.64E+02**	**2.79E+02**	**4.74E+02**	**2.73E+02**
		Total GWO (kg CO2eq)	**3.72E+01**	**2.05E+01**	**4.65E+01**	**2.54E+01**	**2.69E+01**	**4.66E+01**	**2.60E+01**
		Total Acidification (kg SO2eq)	**2.06E-01**	**1.16E-01**	**2.55E-01**	**1.43E-01**	**1.51E-01**	**2.59E-01**	**1.47E-01**
		Total Particulate (PM2.5eq)	**1.19E-02**	**6.83E-03**	**1.48E-02**	**8.38E-03**	**8.86E-03**	**1.51E-02**	**8.64E-03**