GGGI Technical Report No. 4

Meeting Global Housing Needs with Low-Carbon Materials

May 2019

Part of GGGI's Technical Reports series

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Abstract

The global housing gap is expected to increase significantly in coming decades. Much of the housing demand will be concentrated in the expanding cities of Asia and Africa, where millions of urban poor already live in inadequate housing conditions. In meeting commitments under the Paris Agreement, municipal and national governments must now also balance such immense infrastructural demands with consideration to environmental impacts and emerging resource limitations. It is apparent that new materials and innovative methods will be required. Conventional construction materials, such as cement and steel, consume large amounts of energy in their production, exacerbating global warming and undermining sustainable material use.

This report proposes the greater use of low-carbon building materials in addressing the low-cost housing gap in cities. While this is not a technical design guide, this study provides a framework to support material selection in the design stages for low-cost housing. The study takes a life cycle approach to material selection and minimizes the externalization of energy demands of materials throughout their life-cycle. The report presents some low-carbon materials that have been successfully used for home-construction, followed by a detailed case study of two composite materials. In the later part of the report, supply chain constraints and opportunities from scaling up the use of a new construction material are discussed. The various roles that stakeholders can play to promote this shift towards low-carbon building materials is also presented.

Finally, in support of innovative methods to meeting growing needs within resource constraints, this report highlights the co-benefits of a green growth approach, namely; meeting housing needs of low-income city dwellers with lower environmental impacts; promoting innovative and scalable practices for housing solutions and; supporting local economies through job creation, skills upgrading and support to micro, small and medium enterprises (SMEs).

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List of Abbreviations

CBF	Cement Bamboo Frame
CSEB	Cement Stabilized Earth Blocks
CO_2	Carbon dioxide
GHG	Greenhouse gases
INBAR	International Network for Bamboo and Rattan
LDC(s)	Least Developed Country(ies)
NGO	Non-governmental organization
RICS	Royal Institute of Chartered Surveyors
SMEs	Small and Medium Enterprises
UN DESA	United Nations Department of Economic and Social Affairs
UN Environment	United Nations Environment Program

1 Introduction

The World Bank has estimated that 300 million additional houses will be needed by 2030 to ensure adequate housing for all (World Bank 2016). Most of this demand will be in the cities of Least Developed Countries (LDCs), where over one billion people are currently defined as homeless or living in insecure housing. The most intense housing needs in the coming decades will be concentrated in rapidly expanding urban centers, with an estimated growth in demand of 20 million homes each year. While addressing the need to deliver affordable housing to the urban poor, and in support of the Paris Agreement, the environmental impacts of construction at such scale needs to be carefully considered.

Through the provision of affordable housing, there is enormous opportunity to mitigate the greenhouse gas (GHG) emissions the new houses will generate, from their design, construction and ongoing operations. Efficient and well-designed homes require much lower energy to build and operate, while providing a healthy and comfortable environment for occupants. In addition, filling the housing gap will increase pressure and place demand upon existing and new infrastructure and services, such as energy, water, waste and transportation. Ensuring the new housing is connected to basic municipal services without proportionately raising environmental costs will require innovative approaches and tools.

In the coming decades, most urban population growth is expected in Asia and Africa, where urbanization is already the most rapid, and where the majority of informal settlers currently live. Concurrently, it will also be in cities of these regions where the largest housing needs will arise. To adequately address the economic and social need for more affordable housing, while considering the environmental implications of meeting this need, the material and energy usage of these new houses needs to be efficient and sustainable. The growing global demand for infrastructure and decreasing availability of concrete present the imperative to explore alternative building materials for housing (Gabbatiss 2017). This report makes the case for the use of locally-sourced raw materials for building materials, shifting away from dependence on concrete and steel for construction needs. Moving away from conventional materials for housing potentially relieves pressure on the material supply chain, avoiding the increased material costs from growing global demand while reducing transport-related GHG emissions. At the same time, it also provides opportunities for local economic development. This study takes a life cycle perspective to present the materials found to be suitable in supporting the transition towards low-carbon affordable housing at scale.

Photograph 1 Child in her earthen house. (Source: Global Urban Development)

1.1 Current Global Situation

The United Nations estimates that by 2050, there will be 2.5 billion more city inhabitants than there are today (UN DESA 2018). Much of the urban growth over the next few decades will take place in mid-sized cities, with majority growth expected across Africa and Asia. While urban growth is being driven through a combination of factors - rural-urban migration, population growth in cities and the reclassification of regions - the growing demand for housing will be from new migrants from lower income groups, moving to cities in search of a better life. They will need subsidized or low-cost housing at least at the start of their urban transition. The scale of urban housing needs in the immediate to medium term is a challenge, compounded by funding and capacity gaps as well as environmental constraints. Yet this situation also provides an opportunity for governments and the construction sector to explore new materials and new ways of infrastructure provision (Rizvi 2016).

As cities grow, the lag in provision of affordable and well-designed housing results in many people living in sub-optimal conditions. By 2030, two-thirds of global population will be urban, with half of these living in sub-standard housing. The low quality of the structures further exposes inhabitants to threats of fire, floods and illnesses from smoke inhalation, and vector breeding. Furthermore, poor design often means the houses do not provide the required thermal protection and comfort from climatic conditions. The house layouts and designs provided through mass housing schemes are often disconnected from the needs and desires of the actual occupants, which may change over time. Apart from quality of life, inadequately-designed and constructed houses incur high costs for heating, lighting and ventilation. Furthermore, inefficient housing locks-in such inefficiencies, often for decades, consuming much more energy without increased benefits. In many cities, the rapid pace of population growth and increase in infrastructure demand is not matched with municipal finances nor human and technical capacities to deliver these.

Buildings, including housing, account for 40% of global GHG emissions, and for low cost housing, material production generates 60% of this emission (Environmental Design Solutions, IMC Worldwide, IIEC 2011), mostly through cement and steel production. As building systems become more efficient, the embodied energies of buildings take on increasing significance in total building energy. This makes the selection of a low-carbon building material more critical in meeting emission reduction targets. Decisions made in the design, material selection, construction method and overall housing strategy determine the extent of energy and water consumption throughout the operational life of the houses. When done well, low-cost housing can promote human well-being, stimulate local economies and reduce environmental impacts. The provision of low-cost or subsidized housing has the potential to reduce GHG emissions through more efficient cooking, lighting and ventilation/insulation. It also reduces the vulnerability of low-income households to extreme weather events and other environmental threats. There are substantial opportunities for local job creation as well as capacity development. Initiatives to introduce green principles to low-cost housing generate multiple co-benefits, with potential to reduce CO_2 emissions by 45% of baseline (Lucon O. 2014).

1.2 Purpose and scope of the study

Following from the challenges and opportunities in the provision of adequate housing discussed in the previous section, this study aims to support the large-scale realization of affordable housing schemes and informal settlement upgrading through identification of low-carbon building materials that have the potential to meet local housing demand, while reducing associated GHG emissions and minimizing demand on concrete and steel. The materials presented have been used in the construction of housing, with proven benefits including reduced carbon emissions in production, transportation and disposal, creation of local jobs and enhanced thermal performance of houses at a low cost. While the starting point of the report is to provide adequate housing with reduced environmental demands, it also recognizes that such initiatives in developing countries also need to deliver local jobs, skills and economic opportunities.

While recognizing that the successful delivery of low-cost housing projects is contingent on many related factors including security of tenure, appropriate design, adequate supportive infrastructure, local livelihood opportunities and housing accessibility, this study also focuses on building materials as important components in meeting global housing needs. The aim of this study is to support development of local solutions that:

- Meet housing needs, especially for low-income city dwellers, with lower environmental requirements, including both embodied energy and operating energy for housing.
- Promote innovative and scalable practices for replicable housing solutions with reduced financial and environmental costs, while ensuring the quality, safety and durability of these housing options.
- Support the local economy through job creation, skills upgrading and support to micro, small and medium enterprises (SMEs).

LOW COST / AFFORDABLE HOUSING

Low cost / affordable housing in this study refers to durable housing meeting minimum quality standards, dedicated to low & low-middle income households. The actual provision standards and providers (in the case of social housing, government), differs from place to place.

This study proposes the use of low-cost, low-carbon materials for housing, to meet the large and growing need in affordable housing. In most cases, there are locally available options, which further reduce the long-distance transportation requirement of materials while providing local employment opportunities. There are potentially further flow-on benefits as related sectors such as material manufacturing and transportation, also take on a low-carbon approach. Diversifying building materials also enhances the resilience of the housing sector to price hikes due to shortages of sand (for concrete) and steel. Furthermore, when suitable waste materials are used for buildings, they are diverted from the waste stream and become a resource.

In a typical house without air-conditioning, the embodied energy of the building makes up 60% of the total building energy over 20 years (Environmental Design Solutions, IMC Worldwide, IIEC 2011). Building materials evidently influence the energy demands of affordable housing significantly. This study takes an evidence-based approach to assessing materials and technologies, presenting scenarios for utilizing local affordable green materials for low-cost housing development. In addition, some viable business models for adopting these materials are discussed as case studies. The major stakeholders to engage in the process and the policies required for a supportive regulatory environment are also presented in this report. This study presents only a qualitative assessment of the materials and processes for housing provision. Design development is not included in this study.

GREEN BUILDING MATERIALS

Green building materials in this study refers to construction materials that have lower carbon requirements throughout their life cycles, relative to conventional materials such as concrete and steel. These are obtained from abundant and renewable resources, require only locally accessible technology and are costed competitively against conventional materials.

This publication is targeted at a range of audience, most of whom are listed as key stakeholders in Section 5.1. These include decision and fund holders such as government departments and private developers. Local and international development organizations, community groups and research organizations promoting green low-cost housing will also find the information presented in this report relevant.

Additionally, this report will be useful to local businesses supplying materials and services to the construction industry.

2 Green Building Materials

2.1 Framework of Materials & Technologies Selection

There are opportunities throughout the life cycle of building materials for reducing environmental impacts and promoting local economies, including through the decisions on construction methods and material supply chains. The provision of affordable housing at scale needs to take an integrated life-cycle approach, from material selection to stakeholder engagement, design development, building operation and demolition. The materials and technologies presented in this report should subsequently be considered in line with local knowledge, appropriate design, materials availability and supply chain considerations. This study aims to present a range of materials, applicable over a wide spectrum of environmental condition, though it does not aim to be an exhaustive list. Table 1 below summarizes the framework used for assessing the suitability of green building materials for each local context.

The suitability of materials and construction methods depend on the local context and environmental factors such as proximity to seismic zones, vulnerability to floods, high winds and exposure to thermal extremities. While much of these contextual factors can be accommodated through appropriate design, integrating these considerations during material selection yields superior outcomes. With the local context in mind, potential materials can be assessed through a life-cycle perspective for their respective environmental impacts and potential to benefit local economies. Taking a life-cycle approach reduces overall wastage and promotes durable houses, with reduced GHG emissions over the long term.

BUILDING ENERGY CONSUMPTION

The **total energy** consumed by a building consists of two components; **embodied energy** (energy consumed in material production, transportation, assembly of building, maintenance and disposal), and **operational energy** (used by occupants for ventilation, heating, water and electricity).

Table 1 Framework for assessing suitability of green building materials

Local environmental conditions	
• Earthquake-prone area • Flood-prone area • High wind speeds (typhoon/coastal areas) • High thermal fluctuations • Extreme heat / extreme cold	
Life cycle environmental impacts	***Benefits to local economy***
1. Sustainable/renewable source 2. Local source (reduced transportation) 3. Low production energy & pollution 4. Recyclable/Biodegradable	1. Local production, economic opportunities. 2. Ease of construction (creates local low-skilled jobs). 3. Regulatory compliance 4. No toxic substances (health of manufacturers & occupants)

Local environmental conditions

Developing appropriate housing for distinct localities with unique environmental conditions, requires a deliberate design process, of which material selection is a part. Building materials require adequate technical specifications for their safe assembly or construction, according to the house design (for example, a multistoried earth block home in a hot and humid earthquake zone will be setup differently from a single-storied building in dry and continental area using the same material). Apart from structural requirements to withstand environmental stresses from earthquakes, typhoons, floods, etc., the designs of housing will incorporate other local considerations such as ventilation and insulation. Such requirements can be sufficiently addressed by considering material selection and building design as complementary, and sometimes iterative, processes. The same building material could result in distinct layouts for housing developments in different localities. Appropriate design helps to reduce energy needs during operation, improve occupant comfort, provides culturally appropriate layouts and interlinkages between the spaces, and interacts optimally with the local surrounding environment.

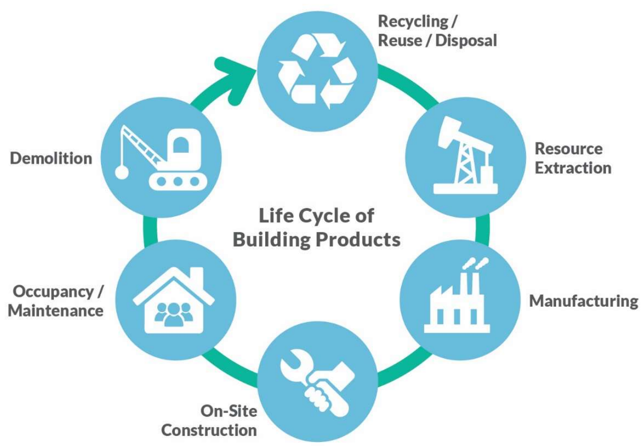

Figure 1 Life cycle of building products

Life cycle environmental impacts

The use of local and renewable resources for building materials considerably reduces GHGs emitted throughout the building lifespan. 'Thinking local' could be subjective in terms of actual distance and depends also on the efficiency of the material supply chain, discussed further in Chapter 3. Generally, building materials go through the processes shown in Figure 1. In a business-as-usual scenario, building materials follow a linear process "from cradle to grave".[1] Taking a life cycle approach closes the material loop through promoting reuse and recycling. This reduces the demand for raw materials as well as the need for management of construction waste. Extending the useful life of materials further reduce the embodied energy of buildings as well as the material costs for builders. The life cycle approach prevents externalizing environmental impacts of design decisions from one stage of the process to another, as illustrated in Figure 1.

In the coming decades, expanding cities and new urban centers will require more infrastructure. UN Environment estimates that urban material consumption will more than double from 40 billion tons in 2010 to about 90 billion tons in 2050 (IRP 2018). As building materials are typically mined from the environment, either from plants or the ground, the constantly growing demand for raw materials cannot be sustained. As a first rule, there is a need to avoid using raw materials where possible, re-using or recycling materials instead. Apart from improving material and design efficiencies, the reuse/recycle of materials from old buildings reduces the demand on landfills. The diversion of construction waste from landfills is a critical aspect of shifting the building industry towards more sustainable practices. With research on building materials routinely developing innovations on material reuse, the scope for this is increasing. Reusing and recycling materials significantly reduces their embodied energy and extends their useful life spans.

Throughout the life cycle of building materials, there are ways of reducing the total energy of buildings, often with accompanying financial savings for occupants. During material production, environmental impacts can be reduced through improving process efficiency, leveraging technology, innovations to reduce energy requirements (e.g. mixing non-clinker[2] alternatives during cement production reduces the temperature required for the process) and enhancing the quality of products to prolong lifespan of buildings.

By default, building designs are based on common materials such as concrete and steel. These are often imported, resulting in significant GHG emissions in the sea/air freight and subsequent land transportation to the manufacturing plant. When feasible, locally-available materials should be considered to minimize transportation demands. Reduced transportation distance also lowers the need for protective packaging

[1] Life cycle analysis is sometimes described as cradle to grave analysis and covers all the processes that materials go through from extraction to final disposal or re-use.

[2] Portland cement clinker is formed by heating ground limestone and clay to high temperatures and then ground to a fine powder to produce cement.

for materials, translating directly to cost savings for the developer. Increasing material efficiency through reducing wastage and material losses also has direct benefits on GHG emissions and water and energy requirements during construction. Although part of this is mitigated through construction planning, appropriate material selection and design further contributes to waste reduction during construction and assembly of buildings.

Post-construction, energy demand for operating and maintenance of houses is most effectively optimized through appropriate design and material selection. Using more durable materials extends the lifespan and reduces maintenance and repair needs and costs. Material properties and design complement each other to reduce the operational energy of buildings, through improved insulation, ventilation or heating.

At the end of building life, some components such as windows and doors, can be reused. Other materials, such as concrete walls and stone tiles can be crushed and recycled, replacing coarse aggregates in roads, pavements and new concrete. Recycling building materials reduces the amount of waste in landfills and incinerators and reduces the demand for raw materials. Table 2 summarizes the avenues for reducing the environmental footprint of materials throughout each stage of the life cycle. Through promoting the reuse and recycling of building materials, the carbon savings extend beyond the project life of a building. This approach to analyzing GHG reductions is compatible with industry standards, as outlined in the DIN EN 15978.[3]

Table 2 Potential avenues for reducing environmental impacts of construction material throughout life cycle

Construction material life cycle	Considerations for reducing environmental impacts
Raw material extraction	Reduce demand on raw materials, use only sustainable and renewable materials.
Manufacturing	Enhance process efficiency, leverage technology and improve quality of materials.
Delivery / Transportation	Maximize use of local materials, minimize transportation needs.
Construction / Assembly	Reduce material wastage and reduce water and energy use during construction.
Operation, Maintenance, Repair	Ensure context-sensitive design and material selection to reduce energy and maintenance needs.
Demolition, Deconstruction, Recycle	Reuse building components and maximize recycling. Disposal in landfill to be minimized.

Benefits to local economies

Selecting low-carbon building materials for the provision of low-cost housing to meet immediate needs provides further opportunities for supporting local economies. Specific opportunities on housing materials relies though on local availability of renewable resources (or at least a consistent part of its final content) and local availability of labor force with the required skills, capacity and access to required equipment. Table 3 summarizes ways that local economies could benefit from the use of locally-sourced building materials. In many developing countries, the opportunity exists for the large-scale cultivation of sustainable timber, rattan and other agricultural products to be used as housing materials. This supports local farmers, at household and community levels. Other locally-sourced materials like sand, gravel, soil, etc., provide job opportunities to the local community, though such sites require careful management to minimize social and environmental impacts.

Increasingly, there are local suppliers and factories with the required skills and equipment to produce green

[3] The European Standard entitled, "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method" provides detailed guidance on the use of life cycle analysis to assess the environmental performance of buildings. "

building materials. In cases where the technology has been developed elsewhere, there remains potential to train local producers and builders to produce and assemble low-carbon building materials. Ensuring durable knowledge transmission through dissemination of capacity building and skills training to local artisans and companies contributes to a country's human capital while supporting the transition from dependence on imported materials. Some materials that can be produced on site, such as earth blocks, provide further opportunities for house owners to become involved in the production of building materials. This enhances sustainability of houses as house owner/occupants are equipped with the skills to repair, maintain and adapt the structure over time.

While the aim is to minimize the need for transportation of building materials, locally or regionally-sourced materials can offer employment opportunities to small companies to move materials from extraction site to factory and onwards to building sites, the extent to which local labor, including prospective home owners, can be engaged in construction depends largely on the complexity of the process. Ideally, sufficient technical expertise should be built to ensure there is ongoing capacity to upscale and expand the building work to meet local housing needs. The local capacity built for material production and construction can perform regular maintenance and repairs to houses. This reduces the cost for home-owners while supporting local jobs. As deconstruction is a labor-intensive process, local labor can also be trained to dismantle and repair building elements for reuse. Valorizing and onward selling of construction waste provides income streams to small businesses.

Table 3 Potential avenues for supporting the local economy throughout life cycle

Construction material life cycle	Avenues for benefiting the local economy
Raw material extraction	Sustainable plantations, local jobs in sand and stone quarries.
Manufacturing	Skills transfer to local producers and SMEs to produce good quality, low-carbon materials.
Delivery / Transportation	Local businesses to manage material handling and transportation.
Construction / Assembly	Training and engagement of local artisans and builders, including home owners.
Operation, Maintenance, Repair	Training of local laborers in routine maintenance and repairs.
Demolition, Deconstruction, Recycle	Jobs for building deconstruction and repairs for material reuse.

2.2 Examples of green building materials

This study does not intend to be an exhaustive list of potential green housing materials. The materials listed below demonstrate how the application of the framework in Table 1 can support the material selection process to deliver results that are beneficial to both the environment and the local economy. There is no one "best" low-carbon material, as suitability and access are highly-contextual. The materials presented in this section are low-cost, relative to currently common materials, that have been used for affordable housing in developing countries and other applications. As this report is concerned with affordable solutions for low-cost housing (inclusive of informal settlement upgrading), the range of eco-materials often linked to high-cost transformation processes for premium green buildings are omitted from this report.

Plant-based materials

Many traditional buildings are constructed with raw materials from plants. Agricultural processes also produce waste materials that can be used for buildings. While opportunities differ across localities, there are commonalities in the material properties and processes for converting agricultural waste to construction material.

Examples of common agriculture-based building materials include rice or wheat straw, bamboo or wood, either as logs and planks or as chips and pulp, bagasse (sugar cane waste), hemp and coir (coconut waste fibers). All these products are widely available and often burned or sent to landfill. Using agricultural waste has numerous environmental benefits – as a resource for construction, reduction of solid waste sent to landfills and CO_2 storage.

Plant-based fiber boards are fabricated to varying densities, thicknesses and strengths, suited to a diversity of applications. These low-cost panels are durable, easy to manufacture and assemble, enabling local companies to build sustainable and profitable businesses across the value chain. Some common plant-based building materials are discussed further below. Plant-based materials are also biodegradable, reducing environmental costs of waste disposal.

Wood

Wood has been used for housing across many countries and cultures for centuries. In recent decades, there is renewed interest in wooden buildings, for their aesthetics, lower cost, shorter construction periods and lower environmental footprint. The Food and Agriculture Organization of the United Nations estimates that approximately 1,330Mm^3 of roundwood is harvested annually for building and construction, with use of wood-based panels and composites increasing across all regions over the past 5 years (FAOSTAT 2018). New construction methods have enhanced the performance and diversity of timber buildings including multi-storied residential and commercial buildings, though these are mostly in developed countries such as Australia and the United Kingdom.[4]

Photograph 2 Low cost housing development in Indonesia, Puri Harmoni 9. (Source: Vista Land Group)

Sustainably harvested and minimally processed timber from a local source is a good low-carbon building material, both for structure and cladding. As a building material, wood has low embodied energy, and can be produced by local artisans. It is generally available locally, saving on import costs, and timber houses are easy to construct. Being lighter than concrete buildings, timber buildings require less foundation and can be constructed with simple tools and machines. Maintenance of wooden houses provides local jobs. At the end of building life, building elements can be recovered for re-use in new developments. Wood is durable and flexible in use, allowing for short construction time frames.

The key concern about using wood for housing is in ensuring the timber source is sustainable. As the focus of this report is on developing cities, where deforestation is often poorly regulated, the use of wood for addressing large-scale housing gaps is not generally recommended as a single-source solution. The 2018 International Building Code, adopted throughout the United States of America and several other countries, includes a chapter on design guidance for wooden structures. Where timber buildings are desired, timber suppliers should be required to obtain certification demonstrating the sustainability of the raw material source. The Forest Stewardship Council based in Germany and the Programme for Endorsement of Forest Certification based in Geneva are the two major international forest certification schemes.

[4] 25 King is a 10-storey commercial building that opened in Brisbane in November 2018. At 45m tall, it is the tallest timber building in Australia. The structural frame is constructed of glued laminated timber and cross laminated timber. The Mjøs Tower in Sweden is 85.4 m tall with 18 floors. The mixed-use building is scheduled to open in March 2019 and will be the tallest timber building in the world.

Commercial developer Vista Land Group has been delivering low-cost housing in Indonesia since 2004. These are simple structures of hardwood frames with brick walls (Photograph 2). To date, about 20,000 such houses have been built. The government supports low-income houseowners with low interest home loans.

Bamboo

Photograph 3 CUBO: eco-friendly bamboo house, winner of 2018 RICS competition. (Source: RICS)

Bamboo is a fast-growing grass that is naturally abundant, with 80% of bamboo forests found in Asia and the Pacific. In this region and in South America, bamboo has historically been used for housing, furniture and craft. Bamboo houses are fast to construct and affordable, costing about US$5,000 for a 35m^2 home (INBAR 2016). The International Network for Bamboo and Rattan (INBAR) estimates, over 1 billion people around the world currently live in bamboo houses. Bamboo has high tensile and compressive strengths, good fire resistance and durability when properly processed. Due to their high strength-to-weight ratio, bamboo structures can withstand high velocity wind loads and moderate earthquake loading. The rigorous treatment process to ensure durability and specialized construction techniques pose barriers to the widescale adoption of bamboo (Kaur 2018).

Conversely, however, the stringent requirements also stimulate job creation and capacity/skill building opportunities for local artisans and businesses. An alternative to constructing with entire bamboo culms is forming composite products with bamboo waste from other industries, such as furniture or crafts. Ply-bamboo and bamboo medium/high density fiberboards are also used in house construction. Early research has also shown bamboo to be a cost-effective replacement for steel reinforcements in concrete, though industrialization of such application requires further research. Colombia is one of the pioneering countries which includes bamboo as a building material in the national building code. Bamboo structures and building products are well-established there, and the designs of Colombian architect, Simon Velez, have been built in countries across the world (more can be seen at his website, http://www.simonvelez.net/).

Companies specializing in building with bamboo and bamboo laminates are increasing in popularity. Building with bamboo is also changing from high-end products such as eco-resorts and ceremonial halls to the vernacular, such as schools, shelters and bridges. Due to regulatory lags, and to lack of familiarity among builders and customers, using bamboo for housing has yet to take off at scale.

Straw

Straw is very good in thermal and acoustic insulation and is abundant as agricultural waste. It has been used for roof thatching and floor lining for centuries. With the invention of the baling machine in the late 1800s, compressed straw bales were used as load-bearing walls in houses. Many straw buildings constructed in the 1800s are still operational today.

However, the insulation capacity of a straw wall is proportional to its thickness, making walls impractically thick in places where high level of insulation is needed. Another innovative use of straw as a building material is forming panels with compressed straw core and recycled cardboard cover. Application of a primer coat improves the water-resistance of the panels, which can then be installed as external walls. Most of these panels are currently produced and used in developed countries, but as the technology is improved and prices continue to fall, straw panels could become more common as a building material in LDCs.

As straw is not a common building material in modern economies, obtaining regulatory compliance and approvals may require additional tests and certifications, although this is being addressed in some countries such as the USA and the United Kingdom. In 2011, straw bale construction was included as a standard construction technique in the Professional Rules in Construction for France, enabling homeowners to obtain insurance for their straw homes (RFCP n.d.).

Recent interest in straw bale construction supported the formation of networks and associations of practitioners, designers and academics in the USA, Europe, Australia and New Zealand. These networks produce technical resources that are useful for other builders exploring the use of straw. Currently, there are an estimated 5,000 straw bale buildings in France, with 500 new buildings added annually (RFCP n.d.). In Pakistan, straw has also been successfully used as a low-cost building material.[5]

Where straw is readily available as a waste product, the costs savings in material production and transportation can be substantial. Diverting straw from the waste stream further stimulates local economy through value creation from waste. As straw needs to be kept dry to prevent deterioration of the material, it may not be suitable in places with high humidity. However, regulatory lag and the wider land area needed for straw bale walls make this an unlikely material to be adopted on a large scale for urban housing. Rather, structural straw panels and insulation blocks are likely to enter the materials market to provide a cost-effective alternative to concrete and brick walls.

Photograph 4 Construction of straw bale house in rural Pakistan. (Source:PAKSAB)

Strawtec Building Solutions in Rwanda produces compressed straw panels from local materials. These are supported on steel frames and are quick and easy to assemble, producing low-carbon houses of good quality. Several other companies such as Modcell (http://www.modcell.com/) in the United Kingdom and Agriboard (http://www.agriboard.com/index.html) in the United States of America have successfully built viable businesses around building with compressed straw panels, achieving good thermal performance in the houses built. However, due to initial costs and the novelty of the material, straw has not yet become a mainstream building material in these countries.

Earth

Earth buildings are found on every continent, except for Antarctica. By some estimates, about 50% of people in developing countries, the majority rural populations, and at least 20% of urban and suburban populations live in earth homes (Houben and Guillard 1989). These are spread across various climatic zones, including temperate, tropical and semi-arid deserts. Due to the high thermal mass of earth, building with earth has been favored by builders for the ability to average out extreme temperatures, enhancing occupant comfort without air conditioning.

In Kirinda, Sri Lanka, reconstruction after the 2004 tsunami included 100 houses designed by Japanese architect, Shigeru Ban. These are suited for the tropical climate and are built of compressed earth block walls and timber roofs from local sources.

[5] The Pakistan Straw Bale and Appropriate Building promotes straw bale housing for marginalized families in Pakistan through mobilizing donations and training local communities. More information can be found on their website, www.paksbab.org.

Photograph 5 Traditional mud houses in Burkina Faso. (Source: DAZULTERRA)

In recent decades, earth houses have transitioned from subterranean or earth-blanketed structures to construction with earth blocks. This process is faster for construction and requires less maintenance for prevention of moisture penetration. Typically, mud, adobe or earthen blocks are formed, as the basic building block. Where clay content of natural soil is low, additives can be added to enhance workability and durability. One particularly successful method is the Interlocking Hollow Compressed Stabilized Earth Brick (CSEB), discussed in further detail below. Compressed earth blocks require just over 10% of energy needed to produce the same weight in common fired clay bricks (Waziri, Lawan and Mala 2013). Stabilizing of earth blocks can be done with lime instead of cement to achieve comparable strength to concrete blocks. The stabilizer also helps earth blocks to withstand humid environments. Throughout the production and construction process, there is substantial opportunity for training and engaging local labor and businesses.

Earth is particularly suitable as low-carbon material for onsite/close to site production, reducing transportation costs. Many traditional communities use earth as a building material. However, general poor workmanship and lack of maintenance have resulted in widespread sentiment that earthen houses are of low quality. The effort to reintroduce the use of earth for buildings recent years focuses on the high quality of construction and cost savings of using earth. In the Great Lakes region in Africa, the use of earth blocks is promising due to the high clay content in the soil. In Rwanda, for example, earth houses are ubiquitous across the rural landscape. Brick producers and researchers are working to enhance the quality and standardization of earth blocks, collecting data to support regulators in governing the use of earth blocks as a building material. As in the case of straw, regulating earthen buildings is challenging due to the lack of standardization across contractors. In a few countries such as New Zealand, Germany, Spain and several others, guidelines, standards and codes supporting the propagation of earth block homes have been developed.[6] It is noteworthy that earth construction has picked up in countries where official technical guidance is published.

Stone

Stone has a long history of use as a structural element for homes, religious temples and monuments, with the Egyptian pyramids being the most elaborate demonstration of ancient stone structures. In dry and hot climates, stone provides heavy thermal mass that helps to keep building interiors comfortable. This makes it an attractive low-carbon building material if there is a local source.

Photograph 6 Stone house in Greece. (Source: Blogenville)

[6] In 2003. a review was commissioned by DTi Partners in Innovation Project to investigate the state of rammed earth construction in the United Kingdom. The review provides a useful overview of regulation of earth construction in several countries. http://staff.bath.ac.uk/abspw/rammedearth/review.pdf

The thermal performance and low embodied energy of stone as a building material is recognized in sustainability certification schemes such as LEED.[7] However quarries need to be carefully managed to ensure environmental protection throughout the extraction and rehabilitation process.[8] Improved technologies and equipment have enabled the extraction and use of stone for construction to be more efficient than in the past. The lack of tensile strength in stone structures is overcome by introduction of steel reinforcements, enabling increasingly complex designs to be constructed with stone. Construction stones can be reused, hence the deconstructing process for old buildings should seek to conserve the material.

Stone houses in developing countries are mostly built for their low-cost and durability. They can be found in rural and urban areas in many countries, including earthquake-prone countries such as Nepal, Turkey and Pakistan (Lutman 2011). These houses are easy to construct, and many are built by homeowners without formal training. The International Building Code and American building standards include specifications on stone and masonry construction, to guide designers and builders.[9]

Reused/Recycled materials

Reusing building materials is instrumental in reducing the volume of waste produced by the industry while reducing demands on raw materials. There are opportunities for reusing wooden elements such as doors and window frames, floor and wall tiles in new houses. Metal components are easily re-worked and painted for reapplication in a new structure. They can also be smelted and reformed for a completely new structural function. Crushed concrete is often mixed into fresh concrete or asphalt pavements as coarse aggregate to provide bearing strength. However, careful assessment should be made by qualified personnel when reusing materials for structural elements such as beams and columns. Stone waste, fly ash, and similar industrial waste could be used in a concrete mix partly replacing sand, stone and cement components. The reuse of broken bricks, concrete blocks or ceramic tiles for backfilling or compacting applications in the construction site is also viable.

Photograph 7 Resale door frames in a salvage yard. (Source: Madisonark)

In reuse and recycle of building materials, the issue frequently arising is a lack of anticipation and coordination from the beginning of a project. Regulators can work with developers to integrate plans for end-of-building-life into construction methods, facilitating retrieval of materials. Another recycling possibility is to

Increasingly, more companies supporting owners, designers and builders in planning for reuse of building materials are starting up. The Reuse People of America is a consultancy that deconstructs buildings and distributes used building materials. Recycled Building Center in Sydney, Australia collects used building parts for resale. In LDCs, enterprises collecting and retailing used building components have been operating both formally and informally. As the business case for material reuse become clearer, these services will be in higher demand globally.
The Kachra Mane, or “Scrap House”, is an extension to an existing house, built almost entirely of reused materials. The exterior glass walls and much of the wooden structure, furniture, lights, toilet fixtures are salvaged from demolished buildings. The house is located in Bangalore, India.

[7] Leadership in Energy and Environmental Design (LEED) is one of the most popular green building certification programs used worldwide. https://new.usgbc.org/leed

[8] Sustainable stone certification now recognized in both LEED v4 and International Living Future Initiative’s Living Building Challenge (LBC) version 3.1. More information can be found at Natural Stone Institute website. https://www.naturalstoneinstitute.org/about/news/press-releases/2016/102016/

[9] The International Code Councils develop codes and standards to guide the design, build and compliance process towards safe, sustainable, affordable and resilient structures. It is widely used across America as well as in many countries where building codes are not available. 2015 International Building Code. https://codes.iccsafe.org/content/IBC2015/chapter-21-masonry

work with a recycling facility, for example, in reworking steel frames for windows and doors, which could be utilized in another project therefore reducing the embodied energy of the steel and extending the material lifespan. Deconstruction and parts recycling are emerging industries in many countries and can provide new skills and opportunities. In Turkey, for example, salvage yards resell window and door frames and other building parts to owners of low-cost or informal housing (Elias-Ozkan 2002). The cost of such houses is estimated to be 40% lower than average houses.

Green concrete

Concrete is one of the most common building materials with cement production. There are many reasons for the popularity of concrete – it is versatile, has high compressive strength, is easy to construct, durable, fire resistant and can be adjusted to include other advantages through adding suitable admixtures. Adding to the environmental impacts from cement production, the steel reinforcements in concrete further increase the embodied energy of the material. Industry and academic research are leading innovative means to reduce the high embodied energy of concrete.

When a proportion of cement, fine or coarse aggregate in conventional concrete is replaced with alternatives, resulting in a robust structure with lower energy requirement, GHG emission or waste generation in the production, the material is referred to as Green Concrete.

Two common ways of greening the concrete mix without compromising strength include:

a. Integrate pozzolan alternatives: materials with high silicate ash content like coal fly ash, rice husk ash, volcanic ash, ground granulated blast-furnace slag (GGBS), and several other alternatives depending on availability of waste materials in different localities.[10]
b. Using recycled aggregates from demolition sites or stone crushing waste. Emission savings on material recycling is reduced if the aggregates source site is too far from the building site. An additional note that the strength of concrete is determined by the properties of the aggregates, hence only recyclables of sufficient strength should be used.

In Oakland, USA the Tassafaronga Village is a high-density affordable housing development featuring diverse housing types. Concrete2 used in the development contained 25% fly ash and 10% recycled aggregate.

While there is substantial research and experimentation on green concrete, the product remains largely a niche material due to the price and the need for customized engineering (Kamath and Khan 2017).

Photograph 8 The Kachra Mane, "Scrap House" in Bangalore, India. (Source: Maya Praxis Design Architecture)

[10] Some research shows that partially replacing cement content with fly ash increases concrete strength and reduces permeability. https://www.nature.com/news/green-cement-concrete-solutions-1.12460

3 Focused Assessment of Two Promising Materials

This section looks at two low-carbon building materials that are durable and financially viable for low-cost housing, showing potential for wide applications across different geographies. These materials must ensure required building performance while reducing environmental impact and providing economic opportunities for local SMEs (inclusive of the informal sector). Among the materials reviewed in the previous section of this study, two are discussed in further detail below. These materials have achieved quality and standardization in their production processes – an essential step towards production at scale. The two materials have been successful employed in construction of affordable housing and upgrading of informal housing across different climates and cultural contexts. Both materials have demonstrated results in supporting local employment, stimulating the local economy and creating positive social impacts while addressing climate change.

Case Study 1: Interlocking Hollow Compressed Stabilized Earth Brick (CSEB)

Material extraction – CSEB is composed of a mix of soil, sand and water, stabilized with 5-10% lime or cement. Basic training on soil identification and mix is required. The sources of soil, sand and water are typically harvested close to the site, reducing transportation costs and time. These are generally readily obtained, without expending large amounts of energy, facilitating the involvement of local companies in harvesting raw materials. However, quarries should be carefully managed or rehabilitated to prevent erosion and other environmental hazards.

Manufacture – The blocks are simple to produce, by manual compression with a hand-press machine or by hydraulic machines for larger scale production. Earth blocks can be produced with or without stabilization. With cement stabilization, compressed earth blocks demonstrate improved water resistance and compressive strength. This enables builders to construct multi-story buildings with slimmer walls using CSEB. On average, the production process of CSEB requires 10-25% of the energy required in the production of comparable mass of fired clay or concrete masonry blocks. The ease of block production means that local labor with minimal prior experience can be trained to produce the bricks as well as to construct the houses. This further provides an ongoing livelihood opportunity for local communities to produce blocks and construct in other sites, hence bring enduring social benefits beyond the infrastructure.

Transportation & Construction – With the import of materials substantially reduced, transnational transportation of materials is almost eliminated. Locally, the source of sand and soil should be selected from sources close to building site to reduce transportation requirements. Local transport companies can be hired to provide this service. Once the blocks are on site, the assembly of CSEB houses is relatively simple, guided by the vertical reinforcement bars linking the blocks. The interlocking feature provides an effective way to setup the blocks faster, with better alignment and levels. Blocks are stacked with mortar binding the blocks to the steel reinforcements. CSEB can also support multi-storied construction. The process is mostly manual, with little or no machinery required. Local laborers and SMEs can be trained and mobilized for CSEB construction work, embedding capacity while stimulating the local economy.

Operation & Demolition – CSEB is used as internal and external walls and, in some cases, for floor and roofs. Earth blocks introduce humidity control, improving occupant health and comfort. The air cavity in the bricks improve thermal and acoustic insulation, reduces the structural weight and allows for installation of steel reinforcements for multistory constructions. The thermal insulation of CSEB is far superior to clay bricks and reduces operation energy for heating in colder climates. The void in the blocks further facilitate the integration of electrical wiring setup for an affordable housing unit. The durability of CSEB is affected by excessive moisture, particularly through upward seepage of ground water, freeze-thaw cycles and surface erosion caused by wind-driven rain. Protective coatings and an impervious base layer may be required to extend the longevity of CSEB houses. Single-storied structures in non-seismic zones are sometimes built without the use of mortar. The CSEB walls are held by the interlocking features of the blocks. These can be easily deconstructed and re-used in other buildings. For blocks bound by mortar, demolition incurs medium to high levels of energy. However, further research is required on the end-of-life options for mortar-bound CSEBs.

Based on material costs in rural India, the cost of CSEB walls are about 25% lower than brick walls, with labor for soil extraction and block-making comprising over 40% of the cost.

CSEB in housing projects

One country where CSEB technology has been well-received is Nepal. After the devastating earthquake in 2015, **Build Up Nepal**, a local non-governmental organization (NGO), actively supported the reconstruction of rural homes and schools with the use of CSEB. A key consideration for house construction in Nepal is to have sufficient earthquake resistance. Hollow CSEB is an ideal material as the raw materials are available locally at low cost, and the interlocking features of the blocks, together with the steel reinforcement bonded to the blocks, provide good resistance to earthquake forces.

In partnership with local and international NGOs, Build Up Nepal has completed many housing projects across rural Nepal using interlocking CSEBs and training local groups and companies to manufacture and construct with CSEBs. Through these projects, Build Up Nepal sought to empower local entrepreneurs with equipment and skills while providing rural communities with affordable and earthquake-resistant homes. Working across the supply chain, the NGO supports local micro and SMEs to promote sustainable and affordable construction materials. CSEB houses are built with local materials and are sustainable, safe and affordable. The use of CSEB as a housing material is approved by the governments of Nepal, Thailand, India and several others.[11] Build Up Nepal estimates that building 50,000 CSEB houses with their design, 495,000 tons of CO_2 will be saved as compared with building with bricks, as is common in Nepal.

Photograph 9 House construction using CSEB. (Source: Build Up Nepal)

[11] Build Up Nepal is a local non-government organization that supports rural communities in Nepal in construction, with a strong focus on the use of CSEB. https://www.buildupnepal.com/

Table 4 Summary of CSEB benefits within the assessment framework.

Local condition analysis			
Interlocking CSEB structures are earthquake-resistant, suitable for earthquake-prone regions. In addition, CSEB allows for flexibility in building dimensions and layout. Insulating properties of CSEB maintains thermal comfort in houses across a range of external temperatures.			
Life cycle process	**Environmental impacts**	**Economic benefits**	**Other notes**
Material extraction	Mostly local and renewable material.	Promotes local suppliers and labor. Reduces import pressures.	Quarries to be managed and rehabilitated. Very low-cost material.
Manufacturing (testing, certification, storage)	Produces 25% of GHG emissions of equivalent fired bricks.	Low to medium technology supports local micro and SMEs.	Training on standardization with regular sample testing needed. Flexible production volume, reducing waste.
Delivery / transportation	Minimal transport requirements.	Cost savings on reduced transport.	Transportation GHG emissions very low.
Construction	Resource-efficient construction process with low environmental footprint. Minimal material wastage.	Low skill requirements, local jobs possible.	Easy and fast to construct, hollow blocks facilitate installation of steel reinforcements and electric wiring.
Operation / Maintenance	Good thermal and acoustic insulation, reducing heating needs. Protective coating enhances durability.	Local laborers/companies can be engaged for building maintenance.	Good for occupant health and comfort.
Demolition / Deconstruction	Can be demolished without heavy machinery. Used CSEB can be re-used for new CSEB production.	Local laborers/companies can be engaged for demolition.	Straightforward process, no hazardous materials present.

Photograph 10 Classrooms built with CSEB. (Source: Build Up Nepal)

Case Study 2: Cement Bamboo Frame (CBF)[12]

Material extraction – The main components of the Cement Bamboo Frame are bamboo, cement, sand and steel joints. To ensure that CBF supports a sustainable system, cultivation and harvesting of bamboo should be commonly undertaken by local communities or small local businesses. Sand is ideally dredged from quarries as close to construction sites as possible to reduce transportation needs. The bulk of the building materials is obtained locally. Cement and steel connections are procured from local retailers, though in many cases these are imported.

Manufacture – CBF houses sit on reinforced concrete footings and a concrete floor slab. Local builders are trained on the preparation and setting up of bamboo posts, which form the main structural frame of the houses. The bamboo frame is held together by customized steel connections. Finally, a plaster finish forms the walls, covering the structural members. The plaster walls enhance the durability of the structures and protect building occupants from wind, sun and rain. No bespoke equipment is needed, making this technology highly accessible and affordable to communities where bamboo is available.

Transportation & Construction – The key transportation needs, in terms of volume, are for bamboo and sand. The materials are obtained from local sources, preferably close to project sites. Transportation needs for materials to worksite is minimal and can be met by local businesses. Small quantities of cement and steel connections may be imported. The construction process utilizes simple technology and is suitable for labor-intensive construction. The reinforced concrete foundations and floor slabs are constructed first. Bamboo posts are supported on the concrete slabs and connected to form the skeletal frames for the houses. Walls are then plastered over the frames to complete the houses. Construction training conducted for local communities build skills that enable builders to find further employment in other construction projects.

Operation & Demolition - Well-constructed houses require minimal maintenance over the building life span. When taken apart, the plaster cladding can be recycled as aggregates for new buildings, though painted surfaces will require additional processing. Steel connections are re-used and bamboo is biodegradable. The deconstruction process can be completed manually, providing local employment and recycling opportunities. At the end of service life, CBF houses generate very little waste. Since CBF houses have only been constructed in the Philippines, cost estimates are based on prices in the country. Depending on the local availability of bamboo and climatic requirements of the housing development, CBF houses cost about 30% less than reinforced concrete houses in the Philippines.[13]

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[12] CBF is a proprietary product of Base Bahay Foundation, Inc., developed through support from HILTI Foundation and UN ESCAP. Product-specific information on CHB houses can be found at the foundation website. http://www.base-builds.com/

[13] Cost estimates by Base Bahay, based on 25m^2 house. https://www.pressreader.com/philippines/sun-star-bacolod/20171209/281685435183333

Photograph 11 CBF homes built by Base Bahay in the Bagong Silangan Kawayan Housing Initiative. (Source: Base Bahay)

CBF in housing projects

In 2011, HILTI Foundation developed the Cement Bamboo Frame technology and Base Bahay Foundation was incorporated to construct typhoon and earthquake-resistant homes for vulnerable communities across disaster-prone areas using the CBF technology. In 2016, the CBF technology received accreditation as an innovative technology for housing in the Philippines.

In the Philippines, builders and developers need to ensure that houses are able to withstand typhoons and earthquakes, which affect many parts of the country. CBF houses are strong, durable and resilient to wind and earthquake loads due to high tensile and flexural strength of bamboo. Base Bahay created customized house designs with local communities and trained communities and businesses to construct houses using CBF technology. From 2014-2018, about 400 CBF affordable homes were constructed, with more in the pipeline.

CBF houses are designed to be resistant to moisture, decay, pest infestation, fire, typhoon and earthquakes. Using a Life-Cycle Analysis method, Base Bahay estimates each housing unit saves around 7 tons of CO_2 equivalent in emissions, compared with conventional reinforced concrete houses. Based on this, CO_2 savings of about 3,000 tons have been achieved to date. In all projects, local labor is engaged, creating jobs and ownership over the projects. CBF houses are thus cheaper, less environmentally polluting and more beneficial to the local economy. Table 5 summarizes the environmental and economic benefits of using CBF in the provision of affordable housing.

Table 5 Summary of CBF benefits within the assessment framework.

Local condition analysis			
Bamboo frames and steel joints of CBF are strong and adequate for resisting typhoon and earthquake forces. CBF structures are slim and easy to configure, making it suitable for urban spaces.			
Life cycle process	**Environmental impacts**	**Economic benefits**	**Other notes**
Material extraction	Local bamboo provides renewable source.	Promotes local suppliers and labor. Reduces import dependence and cost.	-
Manufacturing (testing, certification, storage)	-	Simple and low technology suitable for supporting local micro and SMEs.	Accredited as "Innovative Technology for Housing" in the Philippines.
Delivery / transportation	Minimal local transportation requirements.	Cost savings on reduced transportation demands.	Transportation GHG emissions very low.
Construction	Resource-efficient construction process with low environmental footprint. Minimal material wastage.	Low skill requirements for workers.	
Operation / Maintenance	Disaster-resistant houses, minimal maintenance requirements.	Local laborers/companies can be engaged for building maintenance.	Good for occupant health and comfort.
Demolition / Deconstruction	Steel connections can be reused, mortar cladding is recyclable and bamboo frames are biodegradable.	Local laborers/companies can be engaged for demolition.	No hazardous materials present.

4 Construction Supply Chain Considerations

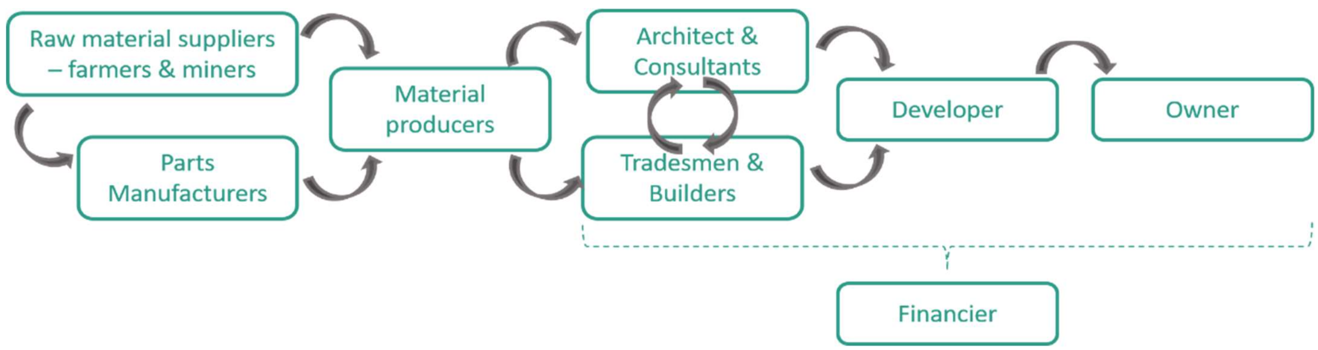

Figure 2 Key stakeholders and flow of services/goods in construction supply chain.

Construction management and supply chain management are keys in ensuring construction efficiency and successful completion of low-cost housing projects. Figure 2 shows a simplified flow of services and goods between key stakeholders in the construction process, though these flows sometimes differ from project to project. All stakeholders in the construction supply chain in Figure 2 contribute to project profitability and sustainability. In the case of low-cost housing, governments are sometimes owners of the developments, with government-owned banks financing the projects. Within the stakeholder groups, there are sub-contractors and sub-suppliers operating in differing scales and levels of specialization, with larger and more specialized companies holding more control over pricing and supply chain processes. Where monopolies exist within the supply chain, developers need to mitigate pricing and supply risks through inventory management, product substitution or other means.

In developing countries, where resources and capacities are limited, stakeholders often take on multiple or overlapping functions across the supply chain, making dynamics between stakeholders difficult to classify. In the case study of Build Up Nepal, the organization linked research on the building material to training of local communities to take on roles as suppliers, producers and builders. While with the case of Base Bahay, they took on the coordinating role of the developer while partnering with the parts manufacturer, HILTI, to develop the material technology and designs. As this study is focused on building materials, the innovations are focused on the raw materials and production phases. In other construction projects, innovations to reduce environmental impacts of buildings take place at all phases across the supply chain. Some supply chain considerations in introducing low carbon materials for low cost housing are described below.

4.1 Reliable Continuous Local Supply

Although the bulk of the low-carbon materials presented in this study are derived from cheap and abundant materials such as soil, sand and agricultural waste, the reliable and continued supply to sustain the industry needs to be ensured for the material to achieve commercial scale. If the source is far from the site, transportation costs could outweigh savings on material. Where possible, developers should work with multiple suppliers to secure the material supply at the required quality, quantity, timing and cost. The identification of multiple raw material sources is a priority in the early phases of the project. This could also be an opportunity for supporting local mining and agricultural communities in setting up sustainable businesses supporting sustainable win-win rural-urban economic linkages. Trainings on sustainable mining and logging build capacity among local businesses to prevent environmental degradation from material extraction while providing livelihood opportunities.

4.2 Manufacturing Facilities

Where possible, on-site manufacturing should be considered. The next alternative would be to establish a plant close to the site, to reduce transportation needs. Manufacturing facilities often require offices, sanitation, parking, and storage and sorting areas. Co-locating on-site reduces the need for duplicate facilities. It also facilitates the participation of local communities in the material production processes. Some basic equipment is used during the production process to ensure material quality assurance. With consistent quality, the building materials can be eligible to global standards and certification awards, which further secure investor and homeowner confidence.

4.3 Equipment & Skilled work force

Typically, the equipment required is based on simple technology and can be imported at low cost. Ongoing capacity support may be required to ensure consistent processing of the materials, efficient use and proper maintenance of the factory equipment. This time frame for this familiarization process will differ, depending on the existing skills of the local labor and companies. A managing team is also required to ensure effective monitoring, problem solving, efficiency optimization, operations planning for the factory, and taking care of the work force. Such training can be an opportunity for the local community while fostering ownership and further innovation in the new material among local SMEs.

4.4 Local Acceptance

Local acceptance of new materials is essential for the successful introduction of a material to a new locality and community consultations are important for understanding how new materials will be received. Awareness campaigns conducted by public institutions, international organizations and other local organizations sensitize local businesses and communities to the need for and benefits of low-carbon building materials. Local champions can also help to promote trust and acceptance of new technologies and products. A common perception of low-carbon materials is that they are of inferior quality compared with reinforced concrete, for example. When start-up finance is available, a demonstration project constructed with the new materials is invaluable in providing a first-hand experience of how the material will work in an affordable housing project.

4.5 Standards, Certifications and Regulations

Two main and related barriers to the wider uptake of low-carbon materials is the lack of data on structural properties and the perception that such materials are of low quality. Designers and developers choose to avoid the uncertainties of using a new material if there is no reason to do so. Obtaining independent accreditation of quality and performance of the new material is one way to offer regulators, financiers, owners, developers and builders, assurance of the strength, durability, health impacts and environmental performance of the material. The process of compliance documents material performance data and standardize production dimensions and installation requirements. Compliance with international standards enable designers and builders to appropriately use the materials to optimize the structural, thermal, acoustic and aesthetic properties of the material to achieve the designed outcomes. Universities and research laboratories play important roles in the research and product development process, as well as in building industry capacity to interpret material data to design and build (Medien 2015).

Building regulators influence public and industry perceptions towards low-carbon materials in numerous ways. A first step is to ensure that local building codes and regulations do not prohibit the use of low-carbon materials which conform to local codes, standards and certification schemes. Governments can further support the transition towards low-carbon materials through accounting for embodied carbon in procurement for public housing developments (Lehne 2018). Additionally, regulators can encourage developers to take a life-cycle approach towards housing design and material selection. By introducing the options for reducing carbon emissions throughout the project life-cycle, including through material selection, building regulators enable developers to optimize their projects, balancing between costs, environmental outcomes and housing quality.

4.6 Market integration

Many new products fail to achieve scale due to the inability to sufficiently engage with stakeholders across the supply chain. New (small and medium-sized) companies will need capacity development support in demand forecasting, production flexibility and marketing of new products through various avenues. A new transportation network may be required, if material movements differ from existing routes (from port to site/factories/warehouse or if extraction sites are very remote.) This could offer opportunities for new jobs and the establishment of new commodity transportation networks.[14]

Research facilities and government policies can support the introduction of new materials through the provision of financial and technical support to establish a demonstration project. To bring successful pilots to scale, regulators and other public institutions and private developers need to be engaged. Promotion of the new materials through mass media will help to raise awareness and market interest.

In addition, a retail network can be established, to facilitate the distribution and promotion of the new material. Training retailers on sharing information on the new material can help disseminate information to builders, simultaneously increasing the uptake of the new material while ensuring its proper usage.

The popularity of rammed earth housing in Western Australia has been falling since the 1980s. One reason is that rammed earth houses did not perform well in the computerized thermal simulations required by local regulations for all new buildings. Furthermore, the lack of a building standard for rammed earth construction across the country meant that designers and builders did not have a code or standard to follow.

In recent years, researchers at the University of Western Australia have disproved the poor thermal performance of rammed earth walls in computer simulations. Advocacy groups such as Earth Building Association of Australia are also working with the government to develop guidelines on earth construction, for incorporation to the Building Code.

[14] In the broader sense, material transportation should be minimized to reduce CO_2 emissions.

5 Business Development for Low-Carbon Building Material

5.1 Key Stakeholders

In some countries, the provision of affordable housing is done through government agencies, while in many others, all housing is privately built. In either case, the **government** remains a key stakeholder, as a housing regulator, land planning authority and custodian of policies influencing access to finance, introduction of new products and minimum performance requirements. For most countries, these responsibilities lie across numerous ministries, all of which should be engaged in the process of introducing new building materials.

As low-carbon building materials are typically obtained from local sources, local businesses and communities should be consulted and trained for the extraction of raw materials as far as possible. During the process of engaging **local businesses and communities**, capacity development and support for developing viable business models can be provided. Existing material suppliers should also be engaged to ensure that the introduction of new building materials does not lead to the displacement of economic opportunities for existing businesses. Ideally, communities which are moving into housing developments can also be consulted to co-design and build the houses. This enhances the acceptability of the low-carbon materials as well as the relevance of the design. Other industry stakeholders such as **builders, designers and developers** can be involved through sensitization outreach to the use of new building materials – the relative benefits and limitations, as well as the reliability of the supply chain.

Researchers and **tertiary centers** for education can further support the acceptance and use of low-carbon building materials by disseminating information and guidance on the use of such building materials, including through integration into industry training courses and other related events.

Financiers and investors for housing developments also need to be brought on board on the use of non-conventional materials for low-cost housing. **Local and international development organizations** in providing housing to the poorest communities are increasingly promoting low-carbon housing options, often demonstrating the financial case for such options.[15] Introducing the new housing materials through a demonstration project in partnership with a local non-governmental organization or international organizations has in places enhanced visibility of new materials and technologies among government, investors and developers, providing possibility of attracting funding support for upscaling.

5.2 Investments Needs and Financial Mechanisms

New building products compete with conventional products and other materials from international producers. There is a significant upfront cost to introducing a new product, which, if not supported in some way, undermines the price competitiveness of the product. Access to finance is essential for the successful propagation of low-carbon building materials. However, entrepreneurs and organizations introducing such materials to construction markets face challenges in accessing financing due to barriers such as research and development costs, high upfront costs, lack of consistent data and warranties on material performance, and regulatory gaps. Initial costs of product research and development, production line and supply chain set-up, are often deterrents for small companies and researchers. As with the introduction of new products to a market, support from the government can be instrumental to the success in accessing public and private financing to develop, market and mass produce low-carbon building materials.

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[15] One example is the Mainstreaming Sustainable Social Housing in India Project (MaS-SHIP). The project promotes the use of low-carbon building materials and renewable energy sources for street lighting. More information can be found at their website: https://www.mainstreamingsustainablehousing.org/.

Government initiatives at national, state and municipal levels perform different functions in influencing market forces. At the federal level, policies encouraging the use of low-carbon building materials and the reuse/recycling of building materials can translate directly to financial or non-financial incentives for developers and investors. Fiscal incentives governments often provide for “green” products and appliances such as solar panels and water/energy-efficient appliances can also be extended to low-carbon building materials. Dedicated institutions have been established by governments in the United Kingdom and Singapore, among others, to promote investments in green construction. States and municipalities have directly funded sustainable construction through grants and loan schemes funded by green bonds and targeted taxes and incentives. Where Public-Private Partnerships (PPP) are set-up to support the development of affordable housing, mechanisms need to be established to ensure that these partnerships are not exclusively accessible to the biggest companies only.

To date, bank loans, green bonds, international development funds, government grants, sometimes in the form of tax incentives and subsidies and private investment have been the prevalent forms of financing for construction of low-carbon buildings (Ming Shan 2017). While public funds and programs remain the most common forms of support for sustainable construction, banks and other private investors fill in the gaps in government funds and programs. Most private financiers invest in sustainable construction for financial profits and determine investment portfolios on the return on investment. Additionally, financiers often require warranties and verifiable product data that is not available for new materials.

International organizations fill the gap by supporting business start-ups in the processes between product development to profitability. The social and environmental benefits of investing in new economic models and products need to be clearly communicated when developing a business case. Development organizations can further support the introduction of low-carbon materials through demonstration projects. For building materials presented in this study to be successfully introduced to a new market, a demonstration project provides a natural entry point. Such demonstration projects enable local communities and businesses to observe how the material is produced and applied and to assess whether it will be socially-acceptable and commercially-viable.

Local SMEs can face additional challenges in competing with larger companies and international companies in accessing funding and government support. These smaller companies may rely on government incentives, tax exemptions, subsidies and other forms of support to pioneer new products, materials and technologies in the market. Start-up capital is one major hurdle for SMEs, particularly if dedicated production facilities need to be built. Public and private investors supporting the initial costs can open the gateway for local businesses to experiment with new products. Beyond start-up costs, businesses require funds to promote the new products and train builders on their use. Flexible credit may be needed to enable resellers to return the capital only after sales have been completed.

5.3 Key Enablers

Following the discussion above, some policies that can create the required supportive environment for the successful introduction of new low-carbon building materials are discussed below, broadly categorized into three groups: fiscal incentives, building regulations and a dedicated facility for green buildings.

Bamboo House India is a social enterprise promoting bamboo furniture and low-cost bamboo houses across India. Between 2016 to 2018, the enterprise sold over 150 bamboo houses.

In the initial phase, the enterprise faced challenges in navigating the regulatory requirements and restrictions, accessing technical expertise in bamboo preparation, overcoming skepticism about the durability of bamboo and making sales. While the difficulties were immense, business improved eventually, when they started selling bamboo structures. A rooftop shelter project attracted many subsequent orders, including a bamboo structure for the US Consulate in Hyderabad.

While many orders come from yoga centers and hotels, Bamboo House maintains a core catalogue of low-cost houses. Bamboo House India started off with 20 artisans and currently employs more than 150. Their achievements have been recognized by universities, the World Bank and foreign governments (Nitin 2017).

Fiscal incentives

These policies include tax incentives for the introduction of low-carbon for building materials. They can also extend to subsidies for low-cost housing developments utilizing energy efficient appliances, designs and production processes. Government incentives can encourage industry-wide adoption of products and practices that are energy-efficient, low in pollution and with improved life cycle performance. Other aspects that can be promoted through financial instruments include the use of local, rather than imported raw materials, recycling and reusing materials as well as the training of local labor and job creation. In some cases, financial support may be required for an extended period to enable the establishment of the new material supply chain and demand generation.

Building regulations

Normative instruments, such as minimum performance standards, green labels and certification, mainstreamed into building regulations support the durable success of low-carbon materials. The introduction of appropriate standards and certification schemes improves the standard of construction in the country while simultaneously transitioning the industry towards a low-carbon trajectory. In particular, this is important for low-cost housing, which is often unregulated, resulting in structures that are hazardous for the occupants.

Mainstreaming the use of low-carbon materials into building regulations and codes improves institutional communications and enhances capacity of the agencies responsible for monitoring compliance to regulations. Governments can reduce or prevent the use of toxic materials such as asbestos through guidance in building codes. Furthermore, specifying required material and building performance levels gives the industry clear information on the regulatory requirements and encourage the introduction of suitable low-carbon materials to the local markets. Where regulatory standards are difficult to introduce, enforce or monitor, voluntary certification schemes could be an entry point.

Dedicated Green Building Facility

A dedicated government agency can be set up, with the mandate for promoting awareness on green housing, using low-carbon, energy-efficient materials and through appropriate design. The agency will support research in building innovations to reduce energy, water and other environmental demands of housing and other buildings. It can also train developers, designers, builders and material suppliers, enhancing appreciation of and capacity to deliver low-carbon housing. Green housing options should not be limited to premium housing, but be mainstreamed across the sector, with possibilities to achieve energy and emission-savings at different costs. As low-cost housing will make up a significant volume of the building stock across many developing countries for decades to come, adopting low-carbon materials for low-cost housing can substantially reduce GHG emissions for the building sector, and thus contribute significantly to the Paris Agreement. Such a facility could also mobilize academic institutions and vocational training institutions in supporting research into new materials, methods and technologies and in designing new courses with green construction specialization, to ensure industry personnel have sufficient capacity to deliver on regulatory requirements.

6 Conclusions

In recent decades, building materials have predominantly been concrete and steel. However, the high embodied energies of these materials demonstrate the unsustainable environmental cost of meeting the global housing need with such conventional materials. This study highlights some low-carbon alternatives which can be used for low-cost housing construction. In the selection of building materials, design, location and local specificities must be considered holistically from the very early stage of any project. Furthermore, taking a life-cycle approach to assessing CO_2 emissions from building materials ensures that environmental impacts from various processes are not externalized. Materials under consideration need to be suitable for local manufacturing and construction. The availability of skills, tools and equipment also affects material selection. Some materials require additional coating or treatment if exposed to the elements to ensure their durability.

While some low-carbon housing materials have been around for many years, few are used on the commercial scale needed. The constructive engagement and partnership of major stakeholders is necessary for the establishment of low-carbon, low-cost building materials as a viable and attractive mainstream option. Key stakeholders include research institutions, government bodies, commercial producers and manufacturers, micro-entrepreneurs and communities. Each plays a critical role in ensuring the successful adoption of low-carbon building materials as a viable alternative for affordable housing at scale.

Substantial financial support is needed to support the up-front costs for these low-carbon materials to reach a production scale such that they become competitive with conventional building materials. Funding is also needed for the research and development of such materials, the consolidation of material data, and compliance to industry standards. Advertising and endorsements are needed to promote awareness and trust of developers and the end users, to instill confidence in the use of these materials for housing developments. Government regulatory clearance will also open the pathway for suppliers to access the market.

State support dedicated to green growth is needed to support new low-carbon materials to overcome market entry barriers. Government can introduce a suite of fiscal incentives, using instruments such as taxes, loans, grants, bonds and subsidies. Government policies influence the choice of materials and technologies favored by developers and builders. Conversely, the use of toxic and environmentally unsustainable materials can also be limited or restricted by regulations. The establishment of supportive institutional bodies such as a housing financing bank and micro-finance facility and a dedicated regulatory and training body for affordable housing is strongly recommended to ensure consistency between policy, market incentives and design awareness among industry practitioners. Academia and industrial laboratories can also be encouraged through government incentives to conduct research and conduct trainings to promote low-carbon housing.

The growing housing gap affecting the global poor, especially those in urban Asia and Africa, needs to be addressed while balancing environmental and resource constraints. Adequate and secure housing enables people to pursue economic and social opportunities and to live healthier, more productive lives. This study presents a framework for exploring the use of low-carbon building materials to meet low-cost housing needs, particularly in developing and rapidly expanding cities, where the need is most urgent. Economical and environmentally sustainable alternatives to conventional building materials exist. However, the industry-wide adoption of these requires the support of governments, producers and manufacturers, designers, engineers, researchers, developers and ultimately, the house occupants. This study has discussed some challenges and opportunities in the mainstreaming of low-carbon materials in housing provision. While the switch in materials is only one aspect of the transition towards more sustainable construction, it is an essential one and can simultaneously address other issues such as local economic development and poverty reduction.

Photograph 12 Fujian Tulou, a UNESCO World Heritage site. Communal buildings are constructed with a mixture of earth, wood, stone and bamboo. (Source: Global Heritage)

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About the Global Green Growth Institute

The Global Green Growth Institute was founded to support and promote a model of economic growth known as "green growth", which targets key aspects of economic performance such as poverty reduction, job creation, social inclusion and environmental sustainability.

Headquartered in Seoul, Republic of Korea, GGGI also has representation in a number of partner countries.

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