Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

REVIEWS

Sustainability in Human Settlements: Imminent Material and Energy Challenges for Buildings in India

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Abstract | Sustainability in the living environment requires a paradigm transition to environmentally conducive habitats based on judicious energy and resource use to foster a community that is happy, harmonious, healthy and productive. Habitats, or the living environment, comprise the *built*- and the *natural* environment. The built-environment is responsible for the single largest share of resource and energy consumption and demand. This paper provides an overview of sustainability in the context of human settlements with a focus on imminent material resources and energy challenges for buildings in India. Basic arguments on sustainability and well-being in human settlements, and the role of community attitude and behaviour have been highlighted. The paper discusses imminent impacts attributed to unbridled dependence on mined material resources, emissions and pollution due to energy expenditure in buildings, and particularly draws attention to implications of unperceived *modernizing* rural transitions.

Rural habitations, in India have thus far lived off the land with negligible demands on energy and process-intensive materials for sustenance. With a booming economy, increased affordability and exposure to urban lifestyles, the aspirations of rural habitations is now akin to middle-income urbanites. As rural habitations respond to the modernising aspirations of its inhabitants, an *unrecognized* but steady transition is evident from traditional local-materials based buildings to non-local high-process material based dwellings, viz., *zero-energy to high-energy.* The consequence is an unperceived but significant resource and energy footprint, that requires to be carefully discerned and regulated for sustainability. Key avenues for promoting sustainability in the built environment include effecting minimum alteration to (exhaustible) natural material, recycling non-organic solid waste into building products, adopting renewable construction materials and regulating energy and emissions in buildings.

1 Introduction

The concept of sustainable development is indisputably desirable for humanity[1] and should *support economies that cause no irreparable damage to the environment.*[2] Habitats, or the living environment, comprise the *built*- and the *natural* environment. The nature of systemic interactions between the built- and natural-environments determines the

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state of the environment that sustains life (and there by sustainability).[3] So far, these interactions have been increasingly disruptive, and human civilization currently stands at a juncture wherein a paradigm change in the built-environment is needed for sustainability.

Rapid industrialization based modernization, and globalization, have seen the growth of buildings that carry an international appeal, but becoming increasingly unsuited to local climatic and environmental conditions and insensitive to local availability of building materials and traditional building skills (that are potentially low-energy and resource sustainable). Buildings (construction, operation and maintenance) account for the single largest energy and ecological footprint. Globally, buildings consume one third of the world's resources,[4] including approximately one third of primary energy supply.[5] An estimated 20–25% of India's total energy demand is attributed to the manufacture of materials for the building sector, with an additional 15% attributed to the running/operation of buildings.[6] While India's total Green House Gases (GHG) emissions is the third largest in the world (1.8 billion tonnes of CO_2 in 2010), its per-capita energy footprint is one of the lowest at 1.5 tonnes.[7] The predominant share of India's GHG emissions is characteristically representative of the urban habitations which accounts for just 35% of the total population.[8]

Globally, the general breakup of energy consumption in buildings is 16:84 the former being the percentage attributed to manufacturing, construction, material transport and maintenance (including renovation) of a building, while the latter includes the energy share attributed to appliances and space conditioning and operation.[9] It is crucial to note that this assessment is valid primarily for highly evolved urban areas, and may not apply to cities in progressive nations. However, energy efficiency and utilization of renewable energy in buildings offer extensive options tying sustainability with GHG reduction. The most critical of these for progressing and lesser developed countries includes safe and efficient cooking stoves, which in addition to cutting GHG emissions also supports a clean indoor living environment. Amongst highly urbanized (and developed) regions, retrofitting buildings for energy-efficient performance can yield significant result in regulating GHG emissions.[10] Thus far, in published literature, most strategies for energy-efficiency in building including retrofitting are primarily for buildings in colder regions of Europe and USA. Studies in the recent decade are evaluating low-energy and sustainable performances in naturally ventilated (vernacular dwellings) and inadequacies of modern building forms in urban areas around the world. Moreover, the phenomenon of rural transitions in progressing nations and economies in transition (EIT) is yet to be recognized for its potential significant impact on building CO_2 contribution.[11]

Following a systematic study into modern transition in rural India, the authors estimate that rural dwellings adopting modern building materials have a clear potential to increase by 8.5 to 10% projected 2031 GHG emission figures estimated between 7.3 to 4.0 billion tonnes of CO_2-eq[12] respectively. This range is significant in terms of climate-change mitigation. Thus far, rural habitations have adopted climate-responsive building practices relying on local resources (with minimum embodied energy) and energy (for comfort and quality of life). These habitations, many of which can actually be called zero-energy, hold potential answers to enable transition from high-energy urban habitations to zero/low energy habitations. With increasing access to modern amenities (television, mobile phones, internet), rural habitations now aspire for a quality of life (and habitation) akin to urban areas. These aspirations are resulting in transitions from local-resource dependent habitations' to non-local resource based high-energy urban-style habitations. Further, these transitions are resulting in the habitations becoming increasingly unsuited to the local climatic conditions with increasing discomfort, ill-health, CO_2 emissions and environmental disruption.

The following sections discuss sustainability in the context of human settlements including the role of community attitude and behavior, followed by specific discussions attributed to buildings (and construction) in India and the significance of resource and energy use on sustainability. The terms 'material' and 'resources' have been used interchangeably in the current paper and essentially imply natural resource based materials used for buildings. The final section presents salient results and likely resourced-energy implications attributed to rural transitions in India.

2 Sustainability in Human Settlements

According to the 1976 Vancouver Declaration on Human Settlements,[13] "Human settlements involve the totality of the human community—whether tribe, village, town, or city—with all social, material, organisational, spiritual and cultural elements that sustain it". Sustainability of human settlements is vital to support human development. The living environment must support quality of life, including basic human needs of food, clothing, shelter, water supply and sanitation, waste removal, health care and primary education.[14] According to the UN General Assembly resolution 44/228,[15] human settlements sustainability relates to seven main issues in the living environment:

i. Protection of the atmosphere
ii. Protection of the quality and supply of freshwater resources
iii. Protection of oceans and coastal areas
iv. Protection and management of land resources
v. Environmentally sound management of wastes
vi. Improvement of the living and working conditions of the urban and rural poor
vii. Protection of human health conditions

The fundamental sustainability challenge to human settlements lies in restoring, maintaining and enhancing the health of the natural environment, besides managing human-settlement resource demands and the waste generated. This would imply that human settlements adopt a framework for the conservation and recycling of non-renewable resources, the introduction and development of technologies for efficiently utilising renewable resources, and the management of the natural environment such that its life-support systems are restored, maintained and preserved for future generations. Particularly, in the context of future generations, consideration should be given to the usage of three different kinds of planetary assets:[13]

a. Finite stock of *non-renewable resources* (e.g. fossil fuels, minerals, etc.).
b. *Renewable resources* (e.g. solar energy, wind energy, forest produce, etc.).
c. *Capacity to absorb pollutants/by-products of human development* (e.g. toxic chemicals, plastics, chlorofluorocarbons (CFCs), etc.).

The well-being of people is commonly defined in terms of their health, comfort and happiness, which corresponds with Vitruvius's firmness, commodity and delight.[16] Health and happiness, in the recent decade are gaining much attention as a measure of a country's/community's progress. Most findings have revealed the poorest of nations to be the happiest, with India ranked among the top five globally.[17] Further, more quantitative studies have indicated two extremes of correlation between happiness/contentment with life and ecological footprint. Poor nations with the lowest levels of ecological footprint were just as happy (satisfaction with life) as nations with the highest ecological footprint: Bangladesh 5.6/10 satisfaction with life at 0.5 global hectares (gha)/capita ecological footprint; India 5.4/10 satisfaction with life at 0.7 gha/capita; UK 7.2/10 satisfaction with life at 6.5 gha/capita; USA 7.5/10 satisfaction with life at 9.8 gha/capita.[18] An average home size in the US is 200 m^2 while that for India is 40 m^2; further energy use for buildings (residential) in the US is around 3.4 TWh (2003) while those for India (residential) is around 0.5 TWh (2003).[19] Per capita energy consumption in India in 2006 was 510 kgoe (kilograms of oil equivalent) while that for high income countries was 5416 kgoe. Per capita CO_2 emissions for India in 2005 was 1.3 MT while that for high income countries was 12.6 MT.[20]

A distinction must however be made between luxurious living and cultural development. Cultural development implies a positive societal development, when the community has time beyond that required for basic survival, and the time is devoted towards art, architecture, literature, music, and other activities involving the betterment and refinement of human intellect and skills.[2,21] A luxurious life, on the other hand, need not be sustainable, as it does not necessarily imply a positive societal development. Crime, drugs, and violence are indications of an affluent society going wrong. A two-way flight from Delhi to Washington equals to as much energy as 35 km of daily car travel for a year; further, a single 35 km daily travel by car equals to an LED based single-dwelling lighting for an entire year.[22] Both freedom of choice and access to travel (by air and/or by car) and rural electrification are acceptable *development* outcomes; however the scale and order of impact of the former is incomparable to that of the later, with the former being impossible to equitably make available for every individual on the planet.

It has usually been found that the resources required to fulfill a community's luxuries are far greater than the resources required to fulfill basic needs.[8,23] To meet resource requirements, every modern human settlement depends on an area much larger than that actually occupied by the settlement itself.[18,24] Also, the waste and other outputs generated are dispersed over an area far beyond the settlement limits and boundary. The total combined area required to satisfy these inputs and outputs is described as the *ecological footprint* for the human settlement under consideration. Measuring or judging the ecological footprint of a settlement is a well-accepted indicator of the sustainability of the community. The larger the ecological footprint of a particular community, the more is the threat to its sustainability. When considering the global human settlement, it has been estimated that human societies occupy approximately 2% of the planet's surface area, but consume 75% of the planet's resources.[25] Nearly 40% of world's consumption of materials translates to the built environment, and 30% of energy use is attributable to housing.[5] Rising living standards results into more energy demand for heating, cooling, lighting and communicating. Building heating and cooling are the most energy intensive, followed by energy for lighting and appliances. With global urban population expected to grow from 47% share in 2000 to 70% share in 2050,[26] the envisaged resource and energy demand would be mindboggling.

Recent ideologies of a sustainable habitation, though currently limited to the urban settlements, are zero-energy and low-carbon/ecological footprint habitations. Zero-energy in the context of modern buildings represent buildings that generate and satisfice their own energy requirements. On the other hand zero-energy in the context of tribal (and most vernacular) habitations requires no active energy, whatsoever, at all. Carbon/ecological footprint are an assessment of the global environmental (geographical) coverage attributed to habitation resource and energy demands. Another recent approach to a sustainable living is *The 100-Mile Diet*[27] wherein the community resolves to sustain on food available within 100 miles of their habitation. This is primarily to reduce the fuel consumption involved in transporting exotic food resources from distant places.

Another dimension that has been completely unaccounted for is the transition in rural habitations, particularly in India (and other progressive nations and economies in transition including China), mimicking urban habitations. This is characterised by adoption of exotic modern building materials and moving away from near-zero energy vernacular architecture and practices. Accompanied by these transitions is a loss of physiological resilience towards prevalent climatic variations and increasing dependence on power (electricity) for maintaining indoor thermal comfort.[28]

3 Sustainability—Community Attitude and Role of Behavior

There exists a strong relation between the kind of lifestyles pursued by a community and their sustainability, and as a community's attitude determines its lifestyles, there is a very strong connection between community attitude and sustainability. Noe and Snow[29] noticed an emerging change in people's attitudes, from the then dominant social paradigm of progress, development, science and technology, to the environmental paradigm involving issues such as limits to growth, steady-state economy and natural resource preservation.

Button[30] and Camagnia *et al.*,[31] assert that change in personal lifestyles is one of the lesser known but very strong policy interventions to achieve sustainable development, particularly in the context of modern urban settlements. Sustainability is, above all, a mental question and reflects our understanding of hierarchy of needs and of who is responsible for whom and for what in making sure that the world functions in a productive, effective and sustainable way. Tradition of ethics of sustainability is to be seeded, changing steadily patterns of action, rules, values, and norms and creating a new ethical, moral and sustainable society—very different from the current one.[32]

Levine et al.,[10] acknowledge occupant behaviour, culture and consumer choice and use of technologies to be major determinants of energy use in buildings that play a fundamental role in determining CO_2 emissions. In developing countries (and economies in transition) safe and high-efficiency cooking devices and high-efficiency electric lighting would not only abate substantial GHG emissions, but would reduce mortality and morbidity due to indoor air pollution by millions of cases worldwide annually. Research has demonstrated that occupants are more comfortable when they have increased freedom of choice to adapt their conditions in a straightforward and intuitive way, which prevailed in vernacular dwellings unlike extensively automated modern dwelling. Further more dramatic differences in physiological comfort[33] and resilience are visible in passively regulated dwellings. A transition from vernacular to modern first vitiates the resilience of the inhabitants to withstand prevalent climatic conditions, leading to a compelling dependence on active energy for comfort.

Steemers and Manchanda[16] concur that low energy designs have potential to achieve highest levels of occupant satisfaction, further stress the fact that '*perceptions of control, contact with nature, general pleasantness, are important for the overall well-being of the occupants' and sustainability of the habitat*'. As inhabitants and dwellings evolve together, the bond between the two should be reviewed in pursuit of green buildings. As on today green building assessment still have no measure to assess the connect between inhabitant's and their living environment, and primarily aim to assess the level of automation in achieving energy efficiency in the built-environment alone.

Despite availability of high-efficiency technologies and practices, energy use in buildings continues to be much higher than necessary, pointing to occupant/user behavior related consequences. Despite application of various policies aimed at reducing building related CO_2 emissions in many developed countries and despite growing interest in key developing and transition economies, global CO_2 emissions attributed to energy use in buildings have increased at an average 2.7% per year (1999–2004). CO_2 emissions for residential buildings grew at 1.7% annual for residential buildings, with the largest regional increase being from buildings in Developing Asia (42%).[10]

Sant[22] recommends a three-pronged strategy to avert economic hardship and climate-change mitigation, viz., replacing conventional energy by renewables, adoption of super-efficient appliances, vehicles and buildings, and curtailing unabated energy-intensive activities, including improved urban habitats that reduce commuting distance, and improving social interaction (for harmony). Green buildings are the new paradigm, with energy efficiency, low-embodied energy, low-carbon building materials and environmental conducive designs being the new mantra. The WBCSD identifies buildings as one of the five main users of energy where megatrends are needed to improve energy efficiency to reduce CO_2 emissions. While there is significant awareness, there is a reluctance in the adoption of green buildings (India: 64% Aware; 13% Consider; 5% Involve).[34]

4 Sustainability: Role of Material and Energy in buildings

There are five modes of energy consumption attributed to buildings, viz., embodied energy, energy for transport (grey energy), energy for construction (induced energy), energy for operation and maintenance, and finally energy for the demolition and recycling/disposal.[35] With regards, building materials, manufacture of construction materials requires two essential resources: raw materials and energy. The raw materials include soil, stone, sand, variety of minerals and chemicals, and biomass apart from water. Except biomass and water, all other raw materials are limited in quantity and are mined. Hence, these materials are exhaustible.

Todorović[36] states that energy-related impacts of buildings must be considered through their life-cycle and environmental analysis focusing on factors that affect energy consumption: facades concepts/building envelope alternatives, glazing and fenestration, types of building thermal mass and insulation, natural and artificial lighting, natural versus mechanical ventilation, energy-recovery opportunities, indoor and outdoor air quality and environmental protection.

Targeting low-hanging fruits for immediate measures to abating GHG emissions through energy-efficiency carries the risk of a rebound effect[37] and also limited applicability in EITs as energy efficient gadgets tend to be priced higher. Rebound effect can be attributed to the energy efficiency improvements lowering the effective cost of using energy and actually encouraging greater consumption. Both direct and indirect rebound effects could actually result in an overall increase in energy consumption rather than energy saving.[10,37] It is crucial to note that while many reports acknowledge the reality of rebound effect, a clear estimate (energy or emission) attributed to the same is yet to be made. Between 1971–2004 CO_2 emissions for commercial buildings increased at 2.5% per year and at 1.7% per year for residential buildings.[10] In India the effective household energy per person increased by factors of 1.4 in urban areas and 1.2 in rural areas (between 1990–2003).[38]

Table 1 gives the annual consumption of construction materials consumed in bulk quantities

Table 1: Annual consumption of materials consumed in bulk quantity.

Sl. no	Material	Annual consumption (tonnes) India	Global	Source
1	Burnt clay bricks	450×10^6	3300×10^6	39, 40
2	Cement	210×10^6	3400×10^6	41, 42
3	Steel [a]	72.2×10^6	1527×10^6	43
4	Aggregates [b]	1.20×10^9	16.50×10^9	estimated
5	Plywood/timber etc. [c]	10.4×10^6	74×10^6	44, 45
6	Glass [c]	1.22×10^6	42×10^6	46
7	Aluminium	1.7×10^6	44×10^6	47
8	Paints	0.61×10^6	105×10^6	48
9	Ceramic tiles [c]	6.0×10^6	143×10^6	49
Total consumption (tonnes)		2.0×10^9	25×10^9	

[a]*World steel association estimates (total in all sectors);*

[b]*Assumed a ratio of 1:5/6 (cement:aggregates);*

[c]*Volume/area converted to weight.*

in India and the world. It is very difficult to obtain the exact data on the quantum of construction materials produced and the related material resources consumed. Annual consumption of construction materials in India is in excess of 2 billion tonnes, which amounts to per capita annual consumption of 1.8 tonnes. The global consumption of construction materials is in excess of 25 billion tonnes amounting to annual per capita consumption of 3.6 tonnes. The world average is much more than the Indian average. It is alarming to note that aggregates used in concrete and mortar account for 60% of total construction materials consumed and are derived from river beds and rocky outcrops. This places a heavy environmental price on aggregates, which is usually not accounted for.

Mining raw materials for the construction has disastrous consequences on the environment leading to conflicts among various sectors attributed to depletion of natural resources. For example agriculture/forestry and construction sectors are in conflict as the basic resources, viz., soil, stones and sand get exhausted due to indiscriminate mining. Another specific example is the requirement of fertile soil for burnt clay-brick making and agriculture. It is alarming to note that 300 mm depth of fertile top soil in India will be consumed for burnt clay brick production in about 60 years.[39] Exploitation of natural stone for the aggregates can wipe out rocky outcrops or create large craters. This will further stress already dwindling natural resources and biodiversity.

Major problem with the consumption of raw materials for the manufacture of construction products is permanent changes occurring to the mined raw materials. Basic raw materials undergo permanent structural or physical changes during the processing and manufacture of construction materials. One typical example is the case of burnt clay products. Burnt clay bricks/blocks, terracotta and ceramic products represent some of the burnt clay building materials. Generally, soils with high clay content (fertile soils) are used for the production of such building products. In such products clay minerals present in the soil undergo structural changes during the firing process (800–1000°C) resulting in the formation of water insoluble bonds among the sand and silt particles. Transformed clay minerals are the binding materials in such products.

The life cycle of burnt clay product is illustrated in Figure 1. Soil and clay minerals are formed due to the weathering of rocks over millions of years. Considering the geological time scales, the soil

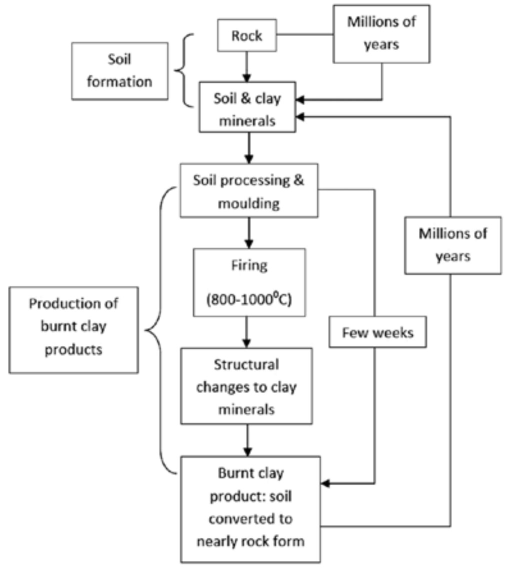

Figure 1: Life cycle of burnt clay building products.

reserves on the earth are limited. Soils support the plant life and in turn the entire ecosystem on the earth is dependent on plant life. Fertile soil when used for the manufacture of burnt clay products gets transformed into a nearly a rock form. Recovering clay minerals from the burnt clay product again needs millions of years of natural weathering. Therefore, depletion of soil resources can threaten the plant and animal life on earth.

4.1 *Raw materials extraction/ management*

Utilization of mined raw materials from the earth for construction, can never lead to the construction sector becoming sustainable. Over exploitation of raw material resources and widespread use of energy-intensive materials can drain the energy and material resources and can adversely affect the environment. Some of the possible options for addressing issues on depleting materials wealth due to the manufacture of construction materials are as follows.

4.1.1 Effect minimum changes to natural materials during production processes: Discarded materials should go back to their native state with minimum environmental costs. Simple example is the use of soil based materials like rammed earth, cement stabilized soil blocks, laterite bricks, etc. where the soil is not fired/burnt, thereby conserving the natural clay minerals in the soil. Such products when discarded after the end of life of the product can easily be recycled as natural soil.

4.1.2 Recycle non-organic solid wastes into building products: Recovering and recycling of non-organic solid wastes may not be attractive and essential due to the assumption that raw materials (to produce construction materials) are abundantly available. Depletion of raw materials is imminent as the raw materials are mined to produce construction materials. The value of the raw materials shoots up as they become scarcer. Therefore, it becomes essential to explore alternative resources to satisfy the demand for raw materials. In this context recovery and recycling of non-organic solid wastes becomes absolutely essential.

Industrial and mining activities generate huge quantities of non-organic solid wastes. Global production of solid wastes is 12 billion tonnes per annum.[50] Investigations of Asokan et al.,[51] reveal that 390 million tonnes of non-organic solid wastes are generated annually in India. These include pulverized fuel ash, mine tailings, coal mine wastes, slag, marble dust, kiln dust, red mud, construction and demolition wastes, etc. Apart from the annual production of wastes, there are huge quantities of wastes accumulated over several decades (wastes from thermal power plants, coal mine wastes, ore tailings of several mines, etc.). Recycling of non-organic solid wastes into construction products can mitigate the pressure on depleting raw materials resources due to mining. Investigations by Ullas and Reddy,[52] Xuping Li,[53] Robinson et al.,[54] Padmini et al.,[55] Khalaf and DeVenny[56] are some attempts in this direction. Non-organic solid wastes can become the resources in future for the manufacture of construction materials across the globe.

4.1.3 Construction products from renewable materials: Biomass is a renewable and carbon neutral resource. Biomass is available in woody and non-woody forms. Bamboo, timber, poles, twigs, etc fall under the category of woody biomass. Agro residues, variety of grasses, leaves, straw, etc come under the category of non-woody biomass. Apart from timber and fodder value, biomass is mainly a source for energy. Sheshagiri et al.,[57] estimate the annual biomass production (in India) to be about 700 million tonnes, out of which the agro biomass is about 500 million tonnes. Traditionally, biomass in various forms have been successfully used for the construction of buildings. Processed timber, glue laminated timber, glue laminated bamboo, plywood panels, wood based composite panels, bamboo mat, bamboo and wooden poles, etc. represent different forms of woody biomass used in the construction sector. Except thatch and straw bale construction, there is hardly any application for non-woody biomass in construction. There is a great challenge in developing structural materials using non-woody biomass as well as agro residues. Biomass based construction materials are the real renewable and green materials. Such materials can be grown without threatening food security. There is an urgent need for rigorous R&D efforts to utilize biomass for the manufacture of construction materials for both structural and non-structural applications.

4.2 *Energy, emissions and pollution*

Energy is expended in all stages of the production chain in manufacturing construction materials. Various stages in the life cycle of construction materials include raw material extraction, transportation, processing and production, carting to the point of usage, construction, dismantling and safe disposal. Apart from embodied energy (EE) in the materials, energy is spent for the assembling of materials and construction. It is difficult to accurately assess the EE of buildings. EE of residential and commercial buildings compiled by Ding[58] from several sources indicate 3.6–8.76 GJ/m^2 for residential buildings and 3.4–19.0 GJ/m^2 for commercial buildings.

Energy expenditure incurred in the built environment has two components: (a) embodied energy and (b) maintenance energy. EE is the primary energy incurred for the material manufacture, transportation and construction of buildings. It is a one time investment with minor maintenance-energy expenditure during the life-cycle of the building and infrastructure. Maintenance energy is required to cater to the lighting, ventilation, space conditioning, repairs and refurbishment, etc., during the life cycle of a building. Quantum of maintenance energy spent is greatly dependent upon the climatic conditions of the region. Figure 2 represents the trends of EE and maintenance energy spent over the lifecycle of the buildings. EE can be either less than or greater than the maintenance energy during the life cycle of a building. If the building spaces are highly conditioned through artificial means, the maintenance energy during the buildings life cycle can be more than EE.

Energy expenditure is always associated with unwanted emissions and pollution. Carbon emissions can be estimated from the energy data and the type of energy source. Total carbon emissions from the built environment are 140 million tons and 10 billion tons of CO_2 eq. in India and the world respectively.[59,60] It has been estimated that 30% of GHG emissions is contributed by the construction sector in India.[39]

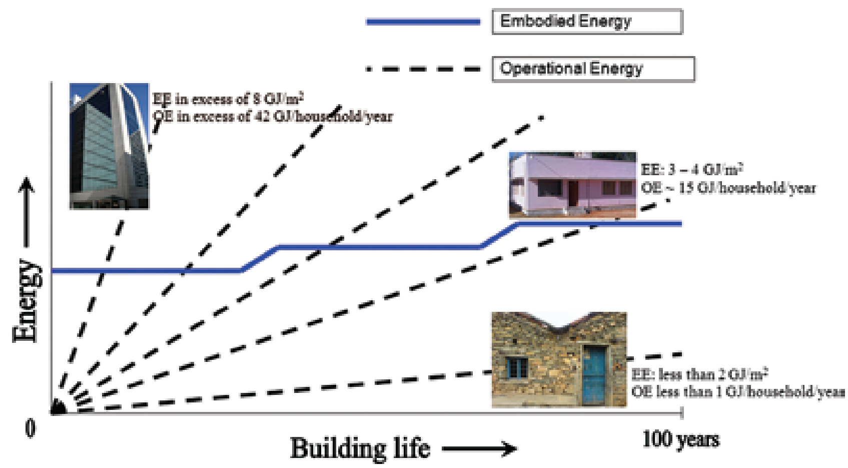

Figure 2: Varying embodied and operational energy scale in rural and urban buildings (Adapted from Yohanis and Norton,[61] Nakagami et al.,[38] Reddy and Jagadish[62]).

4.3 *Energy impact of transitions in rural (vernacular) dwellings*

According to a UN report, with world population expected to reach 9 billion by 2040 the 3 billion increase in middle-class consumers would put an unprecedented demand for energy and material resources.[63] A significant impetus to this would be the rural transitions to middle and upper middle-class lifestyles with consequent alteration in the built environment, a trend which has yet not been accounted for in global energy/material demand estimates. This transition is inevitable in India given the fact that 50% of its population is below the age of 25, and more than 65% below 35 (expected average age in India in 2020 is 29).[64] The interpretation one needs to appreciate is that this age group represents the most productive and aspiring with their expectations matching those of modernism and development. India's average annual income has also increased (doubled) from Rs. 27,131 in 2005–06 to Rs. 53,331 in 2010–11.[65] Economic growth of the most developed countries is based on technologies and consequently resource exhaustion.[36] With lesser developed regions (and economies in transition) following suit in developing *improved* lifestyles, resource scarcity brings in special significance as it directly threatens its sustained availability for the already developed regions. A disaggregated study involving thirty thousand household on the elasticity of electricity demand in urban Indian households reveals that electricity demand is income and price inelastic in all three seasons, indicating that energy consumption patterns are unlikely to be influenced by pricing policies.[66]

To reiterate, 20–25% of India's total national energy demand is attributable to material manufacturing for the building sector, with an additional 15% towards running the buildings.[67] Globally, approximately 29% of projected baseline GHG emissions by 2020 can be avoided cost-effectively through mitigation measures in the residential and commercial sectors. Further studies suggest a global cost-effective mitigation potential of 31% by 2030 in the building sector. Estimates reveal a reduction of 3.2, 3.6 and 4.0 billion tonnes of CO_2-eq in 2020 at zero, 20US$/t$CO_2$ and 100 US$/t$CO_2$, respectively. While occupant behavior, culture and consumer choice as well as use of technologies are also major determinants of energy consumption (and CO_2 emissions) in buildings, the potential reduction through non-technology options are yet to be assessed.[10] This includes strategies for regulating rural transitions and reinterpreting vernacular passive designs adopting local resources and skill for modern lifestyles.

In India, the effective household energy consumption (and consequent CO_2 emission) per capita (between 1990–2003) was found to have increased by a factor of 1.4 in urban areas and 1.2 in rural areas.[38] Current penetration of appliance use in developing countries is still comparatively low. However with a dynamic and rapid increase in GDP the consequent steep rise in appliance saturation, particularly in urban areas, would demonstrate their importance in the developing world.[68] This in conjunction with *rebound effect*[37] would further exacerbate global GHG levels, with the possible consequence of the North blaming the South for pursuing development models of the North.

Measures to reduce GHG emissions from buildings fall into three categories, viz., reducing energy consumption and embodied energy in buildings, switching to low-carbon fuels including renewables, and reduction of non-CO_2 GHG gases.[10] A fourth unrecognized category would to review and preserve low-energy vernacular buildings adopting local building materials and skills. Towards this end it is crucial to regulate the ongoing transition in rural habitations.[28] Among the not widely adopted avenues for abating GHG emissions in buildings includes passive solar-design, high-efficiency lighting and appliances, natural ventilation and cooling systems, solar water heaters, high-reflectivity building materials and multiple glazing. Amongst the existing building stock the largest portion of carbon saving by 2030 is in retrofitting buildings and replacing energy-using equipment.[10] However, the impact of a reverse trend of solar-passive designs giving way to modern (climate *unresponsive*) structures has neither been explicitly acknowledged nor assessed.

5 Rural transitions

Rural habitations account for nearly 70% of India's population, with an estimated rural housing shortage of 47.43 million units by end of 2012.[69] Rural habitations have predominantly evolved over time adopting local-materials and skills in response to prevalent climatic and environmental conditions. Most settlements are scattered and until the past few decades lacked grid-power supply and hence were sustaining on local energy sources, primarily firewood. Only 60.2% of rural households use electricity as the primary source of lighting.[70] Energy requirement for conditioning the dwelling for thermal comfort is negligible as these vernacular dwelling have evolved over time and amazingly regulate the indoor thermal environment for comfort and productivity. The building materials adopted required very little processing and the actual construction was a community-involved activity. With the booming economy, increased affordability and increasing exposure to urban lifestyles', both in India and China, the average rural household now earns for an urban-like lifestyle. This has also been reinforced by government housing programmes which specify adoption of standardised cement and steel intensive construction. Such practices dissuade the use of local materials and skills. Further, government supported schemes of subsidised (often free) power supply and widespread distribution of TV sets is, in all likelihood, reinforcing the earning for an urban-like *developed* lifestyle. In response to this, rural (and tribal) habitations are now exhibiting a strong transition towards urban-like high-process material dependent, climatically un-responsive shelters (thereby further increasing the demand for power to provide for building comfort).

The likely resulting impact of these transitions on global CO_2 contribution and resource consumption still remains unperceived. The following sections discuss salient results from two case-studies dealing with transitions in tribal/rural villages in West Bengal and Karnataka (India), including an assessment into the nature of ensuing CO_2 contributions.

5.1 *Energy impact of rural transitions*

The material-energy impact of rural transitions is based on two case-studies. The first is a tribal village Banskuti in West Bengal and the second is Suggenahalli in Karnataka (India). The former case-study involved a detailed investigation into the resource and climatic-response impact of transitions while the latter involved a detailed survey to ascertain the aspiration of the community towards adopting modern building materials and design. Conservative estimates have been established on the rate of transition (from vernacular to modern) based on population and demographic data.[37,70] Assumptions on the dwelling size, material resources required, energy demand for operation and lifestyle (appliances) have been established through house-hold surveys conducted, measurements and published literature. Both resource and energy demands attributed to modern transitions have been represented as an energy impact (embodied energy and operational energy).

Case-study—I: Banskuti, West Bengal (India)

This study is based on an integrated sustainability assessment into earthen dwellings in a tribal village *Banskuti* in West Medinipur district in West Bengal, India.[28] The earthen structures of rural West Bengal have evolved over generations (see Figure 3). Orientation, height of the building and preparation of materials all follow simple,

Figure 3: Traditional two-storied tribal shelter (earthen walls, thatch roof).

well-established rules in response to local climatic conditions. All building materials used are locally available and produced by the community itself. These include thatch, earth and bamboo.

Preliminary assessments revealed that the houses respond well to local extremes (winters reaching as low as 13°C and summers a scorching 45°C) of climate and provided adequate occupant comfort without the need for modern amenities like fans and heaters. Figure 4 illustrates a typical building climatic-response typology rendered feasible through the adoption of local building materials and passive solar architecture. Despite external diurnal temperature variation ranging between 10–15°C indoor temperatures are maintained within a range of 3°C, with this range occurring well within physiological resilience of the community. This resilience is typically characteristic to tribal/rural dwellers and in recent days subject to extensive research. Urban dwellers are physiologically unable to exhibit such resilience.

Over the past decade transitions in their dwellings facilitated through improved economic viability is apparent, primarily in the building materials adopted (building form still remaining the same). The transitions can be observed in three progressive phases, (see Figure 5) viz., Phase-I involves the replacement of traditional thatch roof by either a corrugated asbestos/cement (AC) or tin sheet roof; Phase-II involves adoption of burnt clay brick (procured from nearby town) wall with mud mortar replacing traditional earthen walls; Phase-III, though less pronounces, involves a total transition to burnt clay brick walls with cement mortar and corrugated tin sheet roof. A recent satellite image of the village reveals the extent of transition with the adoption of corrugated asbestos/cement (AC) sheet roofs distinctly disenable from the others (see Figure 6). Thus far significant alterations in the basic form of the shelter have not been observed, though this is expected to be the next significant phase. Besides, a unanimous response of increasing discomfort in the *altered* dwellings, both during winters and summers, the tribal community is still inclined towards further adopting these *modernising* transitions.

Not only did these modern transitions make the dwelling less responsive to regulate climatic extremes, they also vitiated a closed-loop (cradle to cradle) local resource cycle that was sustainable (see Figures 7). All resources required for the dwelling is procured within a mile of the locality, with crop varieties chosen such as to provide thatch for the roof, adopting locally honed skill and wisdom. With modern transitions, the role of external market and alien skill becomes pronounced which not only vitiates (see dotted lines Figure 8) the earlier close-looped resource cycle

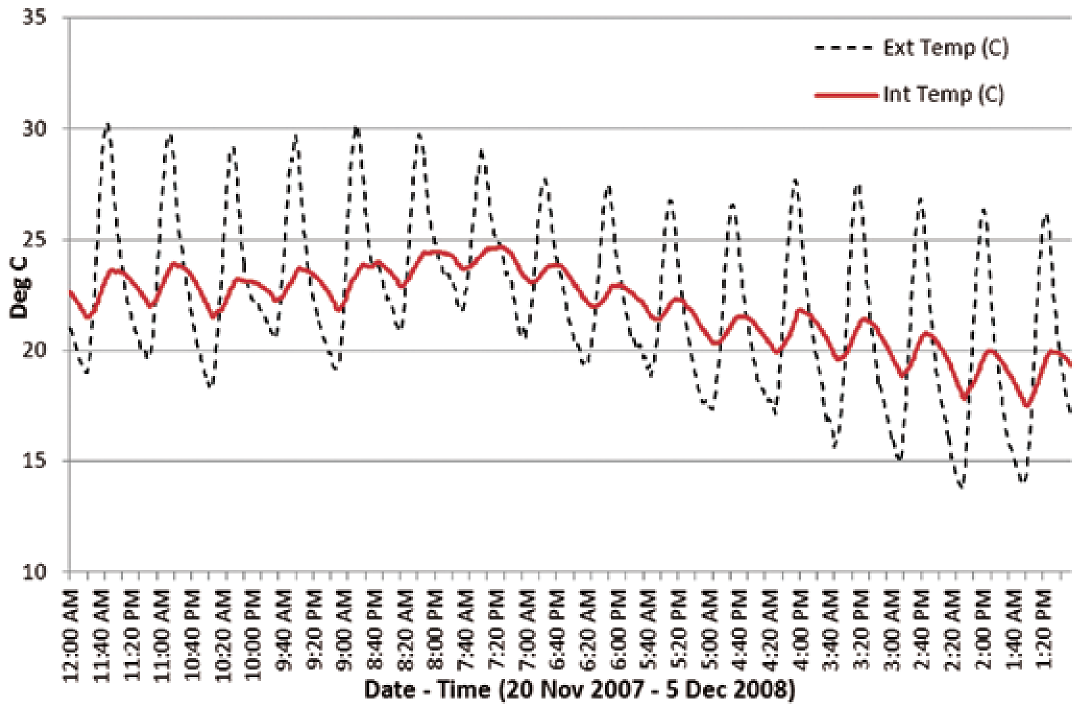

Figure 4: Typical building-climatic response (external vs internal temperature variations).

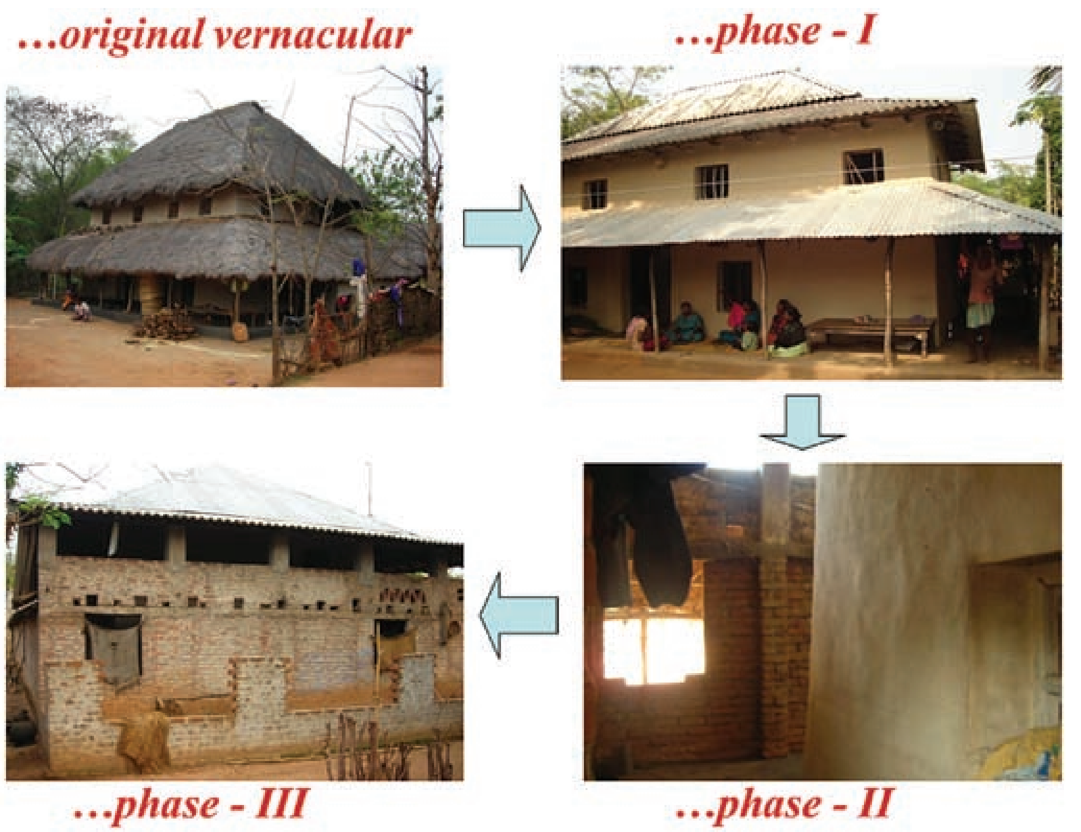

Figure 5: Transitions in vernacular architecture—Phase—I → Phase—II → Phase—III.

Figure 6: Satellite image revealing modern transitions—Banskuti, West Bengal (courtesy Google maps).

but also disrupts practices that foster community integrity. Further, the integration of alien materials into vernacular designs, results in the dwellings becoming increasingly unequipped to maintain comfortable indoor conditions. This leads to the community either spending time outdoors (under the tree) during extreme summer months and/or demanding for electricity connection to power and install fans. A detailed LCA study also revealed an increase in Ecological Footprint from 0.5 gha (primarily attributed to the agricultural field owned by the dwellers) to 1.5 gha.[28] Further study including embodied energy values[62] revealed a 6 T CO_2-eq contribution attributed to transition Phase-III.

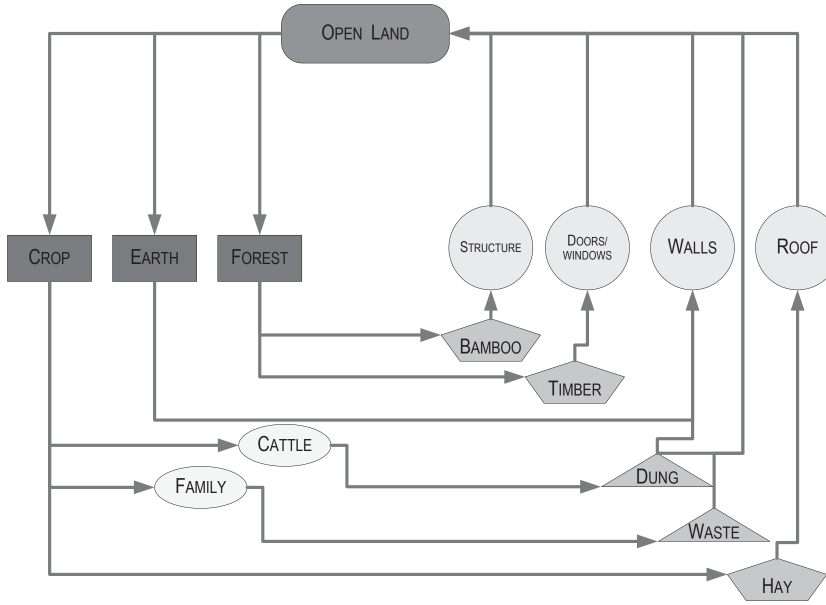

Figure 7: The closed-loop (cradle to cradle) resource cycle for vernacular dwellings.[28]

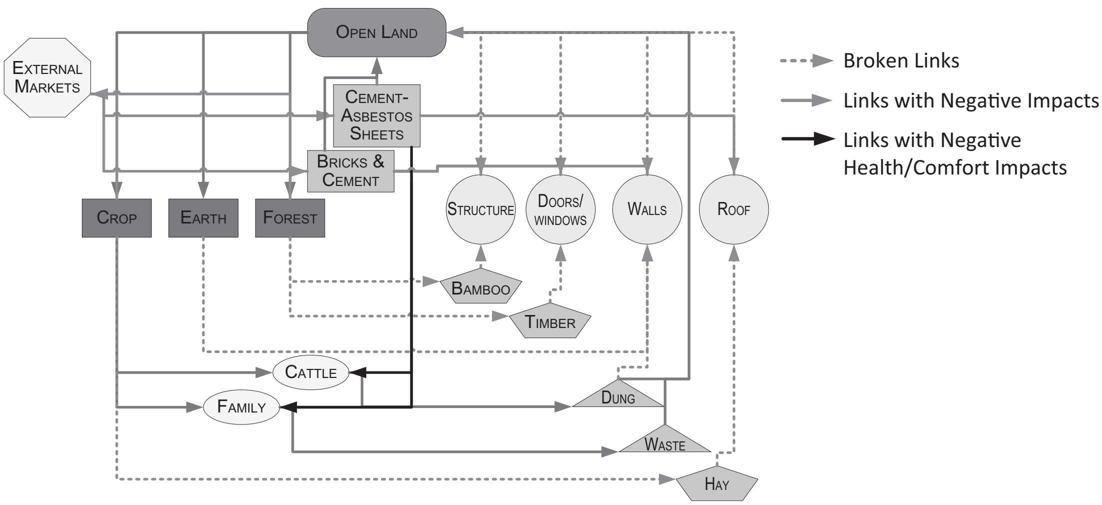

Figure 8: Altered (vitiated) resource cycle involving adoption of modern building materials.[28]

Case-study—II: Suggenahalli, Karnataka

Suggenahalli, is an agricultural settlement situated 90 km north-west of Bangalore, Karnataka, and comprises vernacular dwellings that have evolved over centuries and carries a characteristic pattern in terms of spatial layout, orientation, natural ventilation, courtyard and roof, and material use. The local geology has a strong influence on the building materials adopted, as most external walls comprise stones collected from nearby hillocks (see Figure 9). While a few dwellings are in dilapidated condition, most of them are still well-maintained and lived-in as vernacular lifestyle, barring minimal intrusion of electricity for TV and lighting.

Modern transitions akin to Case-study-I are clearly visible in adopting conventional/modern building materials, viz., cement, brick and concrete. A detailed survey of 155 dwelling (of various ages) revealed strong preference of the community towards adopting modern building materials. Figure 10 illustrates the actual transitions observed in the adoption of modern building materials with reference to the actual age of current dwellings. What is evident is that more recent dwellings are clearly exhibiting preference (around 60%) to adopt *modern* building materials, as this is perceived (through access to televisions) as a move towards a developed society and shunning the *stigma* of being called tribal/rural. A detailed investigation

Figure 9: Traditional single-storied dwelling (stone walls, clay-tile roofs).

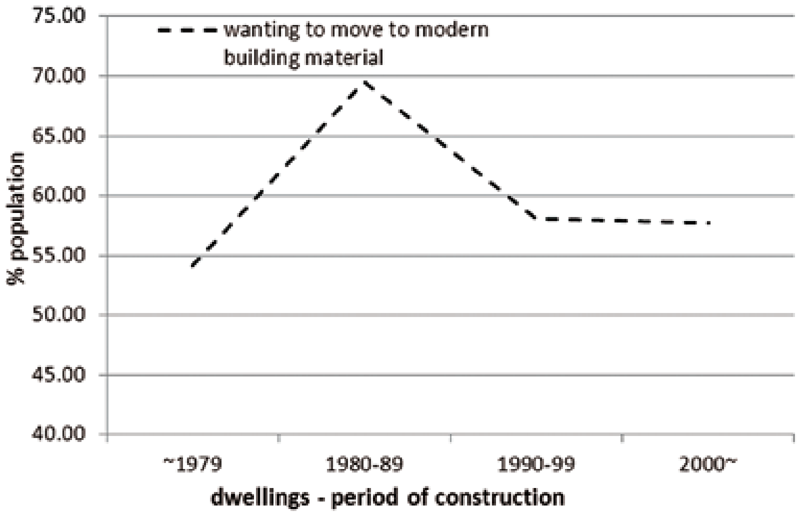

Figure 10: Community preference to adopting modern building materials.

into the transitions in adopting modern materials for various components of these dwellings (Figure 11) clearly reveals an increasing trend, viz., 80% adoption of cement based flooring and roof; 50% adoption of burnt clay bricks, 10% and rising adoption of reinforced cement concrete.

5.2 *Likely impact of modern rural transitions*

Based on the insights gathered from transition studies in two different rural/vernacular case-studies in India a conservative rate of transition of 2.5% has been estimated. There is also a natural increase in the number of rural households,[70] which invariably are built adopting conventional or modern building materials. An average of 40 m^2 has been considered as the built-up area for rural dwellings.[71,72] Based on this an estimate of 15 T CO_2-eq was arrived at as the embodied energy contribution per dwelling attributed to new rural constructions and 6 T CO_2-eq for transitions per vernacular dwelling. An extremely conservative figure (11.16 kWh/month/capita—50% of that in urban areas[70]) has been assigned as electricity consumption (attributed to operational energy for maintaining comfort in buildings and minimum lifestyle appliances—viz., TV, refrigerator, computer) in these (new and in-transition) rural households. As per MoEF,[12] projected GHG emission figures for India in 2031 is estimated between 4.0–7.3 billion tonnes of CO_2-eq. Figure 12 illustrates the likely CO_2 contributions (2011–2031) attributed to rural building transitions and new rural dwellings combined. These emissions have a

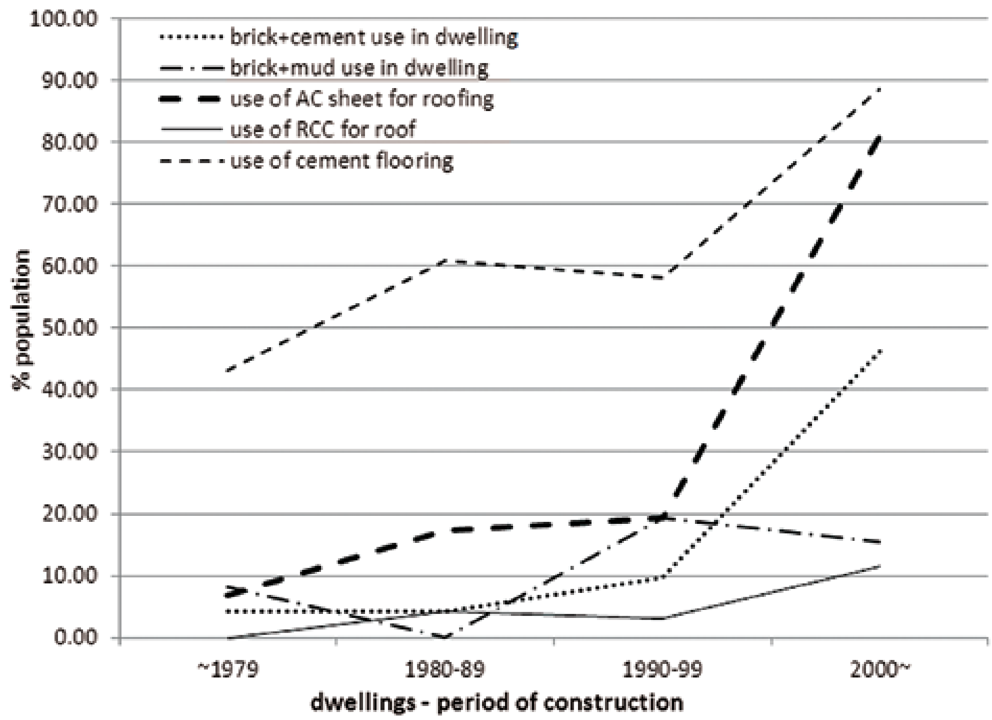

Figure 11: Actual transition-trends in adoption of conventional building materials.

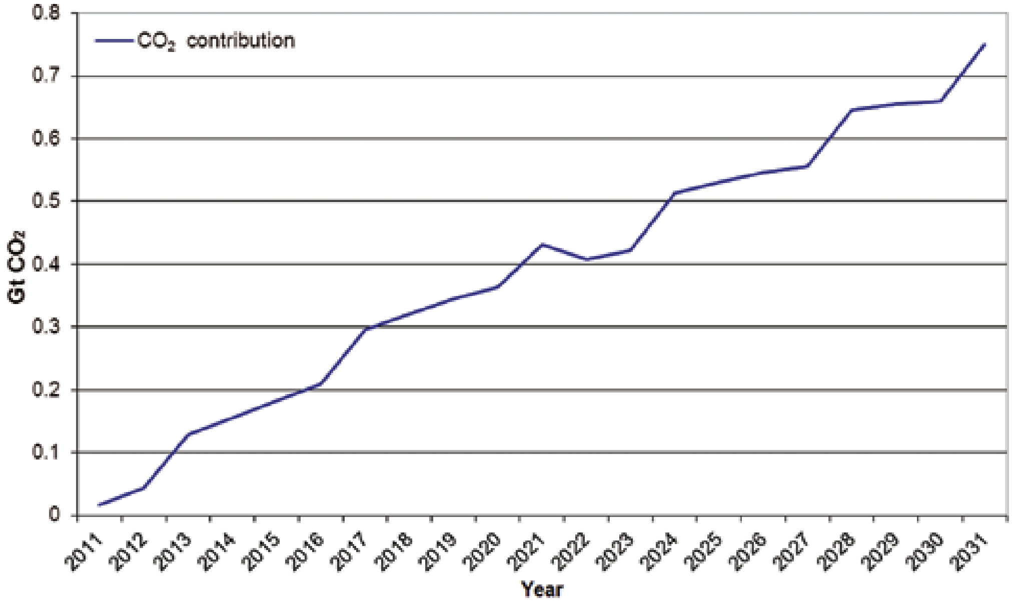

Figure 12: Likely contribution (2011–2031) in CO_2 emissions attributed to new and rural building transitions.

clear potential to increase projected MoEF[12] GHG emission estimates by 8.5–10%. Figure 13 illustrates the expected increase in electricity demand towards operational energy (comfort and minimum lifestyle) attributed to these transitions and lifestyle aspirations of the community.

It is important to state that the authors view is not to criticize the aspirations of rural households in pursuing and effecting such transitions, but to bring-forth the imminent significance attributed to these unperceived transitions. These transitions are a reality and amongst other imminent challenges,

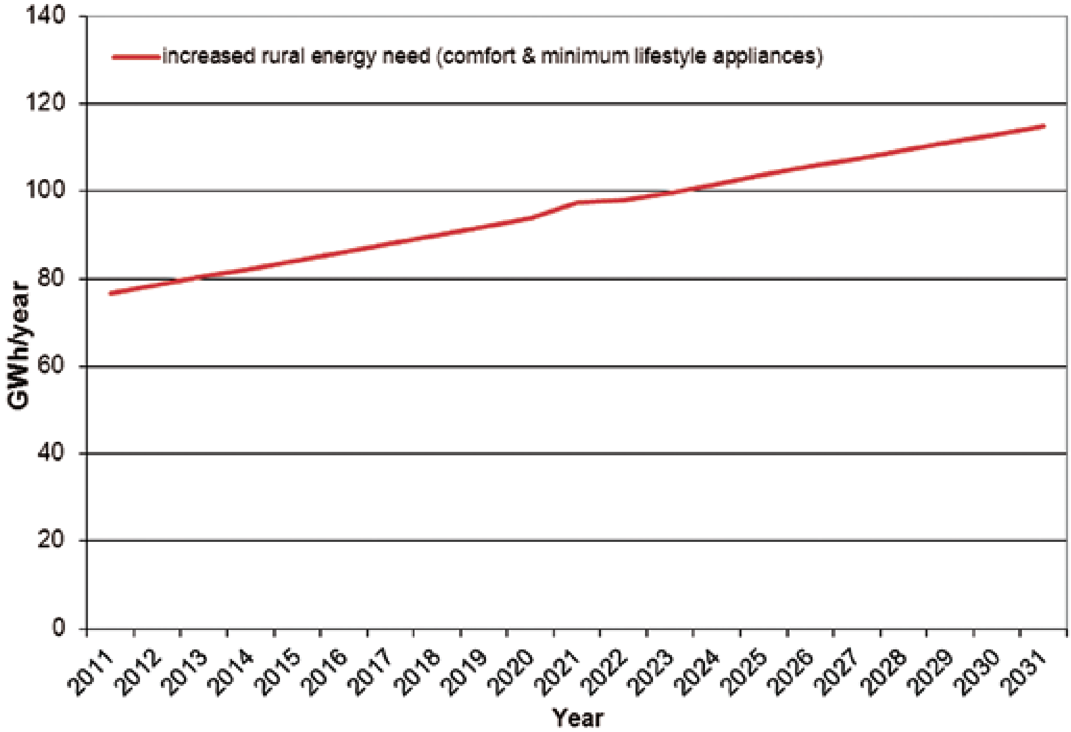

Figure 13: Likely electricity demand in rural habitations (2011–2031).

society must be also prepared to appropriately address these challenges if sustainability of human-settlements at large is to be realized.

6 Concluding Remarks

The current paper provides an overview of sustainability in the context of human settlements, with specific emphasis on a hitherto unaddressed dimension of rural transitions imminent in India, an economy in transition. While, the built-environment is responsible for the single largest share of resource and energy consumption and demand, this impact may not represent the entire spectrum of buildings, viz., *urban and rural*, but would be more representative of urban (and industrial) settlements. Construction materials and the built environment are always associated with the use of mined materials from the earth and a lion's share of energy resources. Anything mined is unsustainable and energy expenditure causes pollution. Hence, immediate attention is required to find renewable alternative materials for construction and minimizing energy expenditure in the construction sector in general and built environment in particular. The challenge is to develop techniques to convert solid wastes and biomass (both woody and non-woody) into construction products with minimum energy expenditure.

Sustainability of rural settlements is important especially in a fast growing economy like India due to modern/urban influences and consequent transitions in the built-environment and lifestyle aspirations. Further, modern transitions in rural habitations is a slow and steady *unrecognized* phenomenon which can potentially amplify current energy and resource demands attributed to buildings/construction. Estimates for these have been assessed based on two rural case-studies, one in West Bengal and the other in Karnataka (India). GHG emission increase attributed to modern transitions in the rural built-environment could range between 8.5–10% of projected 2031 national emissions. Since majority of India's the population is rural, as in most other economies in transition, any transition in these communities is likely to have a pronounced impact. While these transitions are inevitable, modern society must be prepared to also appropriately address these challenges if sustainability in human-settlements is to be realized. Further, unrestrained trends towards adopting green buildings based on energy efficiency alone, may fail to address the complex issues pertaining to the living environment, and carries the risk of amplifying the envisaged boomerang effect. It must also be realized that the highest energy-efficient lifestyle (such as in Japan) would still not be feasible, from a resource and energy point of view, to equitably provide for every household on the planet. Judicious (effective) use of material and energy resources is crucial and underlies Mahatma Gandhi's most quoted statement '...the earth provides for every man's needs...'. Modern building designs need to understand and learn from the passive climatic-response exhibited in vernacular designs and appropriately integrate measures (energy efficient lighting and cooking devices, low-carbon building materials, local water security, etc.) to substitute drudgery (characteristic of rural/tribal habitations) and set forth a perception of development that is truly amenable to both urban and rural aspirations.

Received 16 March 2012.

References

1. Dixon, J.A.; Fallon, L.A.: 'The concept of sustainability: origins, extensions and usefulness for policy', *Society and Natural Resources*, 2(2), pp. 73–84, (1989).
2. Kumarappa, J.C.: 'Economy of Permanance', Sarva Seva Sangh Prakashan, Varanasi, (1957).
3. Mani, M.; Ganesh L.S.; Varghese, K.: 'Sustainability and Human Settlements—Fundamental Issues, Modeling and Simulations', Sage Publications, New Delhi, Thousand Oaks, London, (2005).
4. Atkinson, A.: 'Introduction—The Contribution of Cities to Sustainability', Third World Planning Review, 16(2), pp. 97–101, (1994).
5. Pulselli, R.M.; Simoncini, E.; Pulselli, F.M.; Bastianoni, S.: 'Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability', *Energy and Buildings*, 39 (2007), pp. 620–628, (2007).
6. Sanyal, S.; Nagrath, S.; Singla, G.: 'The alternative urban futures report—Urbanisation & Sustainability in India: An interdependent agenda', Thomson Press, (2009).
7. Olivier, G.J.Jos.; Janssens-Maenhout, G.; Peters, J.A.H.W.; Wilson, J.: 'Long-term trend in global CO_2 emissions—2011 report', PBL Netherlands Environmental Assessment Agency, The Hague, (2011).
8. Greenpeace: 'Hiding behind the poor—a report by greenpeace on climate injustice', Greenpeace India Society, (2007).
9. WBCSD: 'Energy Efficiency in Building—Business realities and opportunities', World Business Council for Sustainable Development Publication, Geneva, (2008).
10. Levine, M.D. Ürge-Vorsatz; Blok, K.; Geng, L.; Harvey, D.; Lang, S.; Levermore, G.; Mongameli Mehlwana, A.; Mirasgedis, S.; Novikova, A.; Rilling, J.; Yoshino, H.: 'Residential and commercial buildings. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change' [Metz, B.; Davidson, O.R.; Bosch, P.R.; Dave, R.; Meyer, L.A.: (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, (2007).
11. Mani, M.; Dayal, A.: 'An unperceived unsustainable predicament: zero-energy to high-energy rural habitat transitions', Proceedings SET2008—7th International Conference on Sustainable Energy Technologies, Seoul, 24–27 August 2008, pp. 1490–1495, (2008).
12. MoEF: 'India's GHG Emissions Profile: Results of Five Climate Modeling Studies', Ministry of Environment and Forests, Government of India, (2009).
13. UNCHS: 'People, Settlements, Environment and Development: Improving the living environment for a sustainable future', Intergovernmental meeting on Human Settlements and Sustainable Development, The Hague, (1990).
14. UNCHS: Habitat II: The Habitat Agenda: Goals and Principles, Commitments and Global Plan of Action, United Nations Centre for Human Settlements (Habitat II), UNCHS Publication, New York, (1996).
15. UN-GA: 'General Assembly Resolution 44/228', Supplement No. 8, Official records of the General Assembly, The Hague, (1990).
16. Steemers, K.; Manchanda, S.: 'Energy efficient design and occupant well-being: Case studies in the UK and India', *Building and Environment*, 45, pp. 270–278, (2010).
17. Ipsos Global: 'Indians among world's happiest', Ipsos Global, www.hindustantimes.com/StoryPage/Print/809841.aspx, (2011).
18. Dunster, B.; Craig, S.; Gilbert, B.: 'The ZEDbook—Solutions for a shrinking world', Taylor & Francis, New York, (2008).
19. IEA: 'Worldwide trends in energy use and efficiency', International Energy Agency, http://www.iea.org, (2008).
20. WB: 'World Development Indicators 2009', Washington, DC: World Bank, (2009).
21. Vinayak, G.K.: 'India and World Culture', Delhi, Sahitya Akademi Press, (1989).
22. Sant, G.: 'Handling the energy crisis', Business Line: Opinion, Jan 2012, (2012).
23. Richard, K.: 'How Less can be More', Span, 48: pp. 3–5, (1999).
24. Marcotullio, P.J.: 'Asian Urban Sustainability in the Era of Globalization', *Habitat International*, 25(4), pp. 577–598, (2001).
25. O'Meara: 'Reinventing Cities for People and the Planet', Washington, D.C.: Paper #147, Worldwatch Institute, (1999).
26. Zhang, F.; Cooke, P.: 'Green Buildings and Energy Efficiency', Centre for Advanced Studies, Cardiff University, (2010).
27. Roosevelt, M.: 'The Lure of the 100-Mile Diet', TIME-CNN News, www.time.com, (2006).
28. Mani, M.; Dayal, A.; Chattopadhyay, R.N.: 'An Assessment into the Sustainability of Earthen Structures and Modern Transitions', International Symposium of Earthen Structures. 22nd–24th August, pp. 154–166, (2007).
29. Noe, F.P.; Snow, R.: 'The New Environmental Paradigm and Further Scale Analysis', *Journal of Environmental Education*, 21(4), pp. 20–26, (1990).

30. Button, K.J.: 'Transport Regulation and the Environment in Low Income Countries', *Utilities Policy*, 2(5), pp. 248–257, (1992).
31. Camagnia, R.; Capello, R.; Nijkamp, P.: 'Towards Sustainable City Policy: An economy-environment technology nexus', *Ecological Economics*, 24(1), pp. 103–118, (1998).
32. Todorovic, M.S.: 'E-Proceedings of the International Conference on Advances in Infrastructure for Electronic Business', Science, and Education on Internet, Scuola Superiore G. Reiss Romoli, L'Aquila, F 3–6, paper No. 161, pp. 1–10, (2000).
33. Baker, N.; Standeven, M.: 'Thermal comfort in free-running buildings', *Energy and Buildings*, 23, pp. 175–82, (1996).
34. WBCSD: 'Energy Efficiency in Buildings', World Business Council for Sustainable Development Publication, Geneva, (2007).
35. Sengupta, N.: 'Use of cost-effective construction technologies in India to mitigate climate change', *Current Science*, 94(1), pp. 38–43, (2008).
36. Todorović, M.S.: 'Energy efficiency and renewable energy sources for buildings greening and zero energy cities planning: Harmony and ethics of sustainability', *Energy and Buildings*, in press, (2012).
37. WB: 'Residential Consumption of Electricity in India: Documentation of Data and Methodology', Background Paper on India: Strategies for Low Carbon Growth (Draft), The World Bank, (2008).
38. Nakagami, H.; Murakoshi, C.; Iwafune, Y.: 'International Comparison of Household Energy Consumption and its Indicators', 2008 ACEEE Summer Study on Energy Efficiency in Buildings, Jyukankyo Research Institute, (2008).
39. Reddy, B.V.V.: 'Sustainable building technologies', *Current Science*, 87(7), pp. 899–907, (2004).
40. Ellen B.: 'Black Carbon from Brick Kilns', Presentation for Clear Air Task Force, slide 5 of 24, (2010).
41. USGS: 'Mineral Commodity Summaries: Cement', U.S. Geological Survey, http://minerals.usgs.gov/minerals/pubs/commodity/cement/mcs-2012-cemen.pdf, (2012).
42. Roberts, B.: 'Global cement consumption up 9.9% last year', www.constructionweekonline.com/article-11772-global-cement-consumption-up-99-last-year/, (1999).
43. WSA: 'World crude steel output increases by 6.8% in 2011', World Steel Association, www.worldsteel.org/media-centre/press-releases/2012/2011-world-crude-steel-production.html, (2012).
44. IFI: 'Global demand for plywood and OSB increasing', International Forest Industries, England, www.internationalforestindustries.com/2011/04/27/global-demand-for-plywood-and-osb-increasing, (2011).
45. MoEF: 'India Forestry Outlook Study, Asia-Pacific Forestry Sector Outlook Study II: Working Paper No. APFSOS II/WP/2009/06', Ministry of Environment and Forests, Government of India, www.scribd.com/doc/52574933/41/Growth-pattern-in-demand-for-wood, (2009).
46. NSG: 'NSG group and flat glass industry 2011', pg no 5, Hindustan National Glass and Industries Ltd, 2011, 'Corporate Presentation', slide # 41, (2011).
47. USGS: 'Mineral Commodity Summaries: Aluminum', U.S. Geological Survey, http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/mcs-2012-alumi.pdf, (2012).
48. Abhay K.: 'Lead in New Decorative Paints', Toxics Link, New Delhi, www.ipen.org, (2009).
49. IBEF: 'Glass and Ceramics: Markets and Opportunities', India Brand Equity Foundation, pp. 5–6, (2007).
50. Asokan P.; Saxena, M.; Shyam, R.; Asolekar, S.; Anusha S.: 'Cross sector recycling opportunities', Proceedings of the International seminar on waste to wealth, No. 12–13, 2009, New Delhi, India, (2009).
51. Asokan P.; Saxena, M.; Asolekar, S.R.: 'Solid wastes generation in India and their recycling potential in building materials', *Building and Environment*, 42 (2007), pp. 2311–2320, (2007).
52. Ullas, S.N.; Reddy B.V.V.: 'Iron ore tailings as sand substitute in masonry mortar', Proceedings International Seminar on Waste to Wealth, Nov. 12–13, 2009, New Delhi India, pp. 151–155, (2009).
53. Xuping, Li: 'Recycling and reuse of waste concrete in China, Part I. Material behaviour of recycled aggregate concrete', *Resources Conservation and Recycling*, 53(2008), pp. 36–44, (2008).
54. Robinson Jr. G.R.; David, M.; Helen H.: 'Recycling of construction debris as aggregate in the mid-Atlantic region, USA', *Resources Conservation and Recycling*, 42(2004), pp. 275–294, (2004).
55. Padmini, A.K.; Ramamurthy, K.; Mathews, M.S.: 'Influence of parent concrete on the properties of recycled aggregate concrete', *Construction and Building Materials*, 23, pp. 829–836, (2009).
56. Khalaf, F.M.; Alan, S.DeVenny: 'Recycling of demolished masonry rubble as coarse aggregate in concrete: Review', *Journal of Materials in Civil Engineering*, 16(4), pp. 331–340, (2004).
57. Seshagiri, G.S.; Rajan, N.K.S.; Paul, P.J.; Dasappa,S.: 'Biomass mapping and assessment, Akshaya Urja', CGPL Report, Indian Institute of Science, Bangalore, India, (2011).
58. Ding, G.: 'The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities', Ph. D. thesis, University of Technology, Sydney, Australia, (2004).
59. CCW: 'Creating climate wealth: North America', Carbon War Room Research Group, Washington, DC, www.carbonwarroom.com/sites/default/files/reports/CCW%20Pre%20Read%20G7.pdf, (2011).
60. INCCA: 'India: Greenhouse Gas Emissions 2007', Indian Network for Climate Change Assessment, Ministry of Environment and Forests, Government of India, http://moef.nic.in/downloads/public-information/Report_INCCA.pdf, (2007).

61. Yohanis, Y.G.; Norton, B.: 'Life-cycle operational and embodied energy for a generic single-storey office building in the UK', *Energy*, 27(2002), pp. 77–92, (2002).
62. Reddy B.V.V.; Jagadish K.S.: 'Embodied energy of common and alternative building materials and technologies', *Energy Buildings*, 35, pp. 129–137, (2003).
63. Nightingale, L.: 'World cannot sustain increasing population growth: UN report', People & Planet, 21 February 2012, www.peopleandplanet.net, (2012).
64. CIA: 'Demographics of India', World Factbook Demographics, Central Intelligence Agency, (2011).
65. BS: 'Per capita income tops Rs. 50,000 for first time in FY11', Business Standard, PTI, New Delhi, 31 January 2012, (2012).
66. Filippini, M.; Pachauri, S.: 'Elasticities of Electricity Demand in Urban Indian Households (CEPE Working Paper Nr. 16)', Centre for Energy Policy and Economics, Swiss Federal Institutes of Technology, (2002).
67. Sanyal, S.; Nagrath, S.; Singla, G.: 'The alternative urban futures report—Urbanisation & Sustainability in India: An interdependent agenda', Thomson Press, (2009).
68. LBNL: '2004—China Energy Databook', Version 6, 2006, Lawrence Berkeley National Laboratory, (2006).
69. NHB: '*Report on trend and progress of housing in India—2010*', National Housing Bank, (2011).
70. NSSO: 'Unit level data, household consumer expenditure round 64', National Sample Survey Organization, Ministry of Statistics and Programme Implementation, Government of India, (2010).
71. Somashekhar, H.I.; Dasappa, S.; and Ravindranath, N.H.: 'Rural bioenergy centres based on biomass gasifiers for decentralized power generation: case study of two villages in southern India', *Energy for Sustainable Development*, IV(3), pp. 55–63, (2000).
72. WBCSD: 'Energy efficiency in buildings: Transforming the market', World Business Council for Sustainable Development Publication, www.wbcsd.org, (2009).

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