Sustainable Housing Construction: Reducing GHG Emissions through Process and Material Innovation

Roshan Shankar, rs2767@princeton.edu

CEE 377: Final Presentation

December 15th 2021

Rationale

- Why Net-zero pathways through construction and materials?
  - Electricity, energy and mobility receive a lot of focus and action due to direct nature of fossil fuel usage, directly seen impacts and market interest.
  - Construction has hidden and embodied emissions.
  - Changes in materials and processes requires long-term planning and regulatory action.
- Why for Portland and Coimbatore?
  - Growing cities but not megapolises yet. Mistakes of megapolises seen widely.
  - Historical sensitivity and understanding towards sustainability.
  - Progressive governance structures and relatively competent operators
  - Close to industrial clusters and natural resources

Goal

- What construction policies can contribute to net-zero pathways?
- Can process innovations reduce GHG emissions for growing cities?
- What new material can aid sustainable construction methods to build homes or parts of homes?
- What is feasible and can be mandated?
- What is desirable and can be encouraged?

Context

- Building Construction
  - Modular Construction
  - Pre-fabricated Construction

- Policy Change
  - Reduction in Cement and Steel Usage
  - Usage of lower carbon cement and steel
  - Taxation of empty properties/homes
  - Bureaucratic and technical changes to building code

- Adoption of New Materials
  - Portland
    - Mass Timber
    - Straw Bale
  - Coimbatore
    - Hempcrete
    - Bamboo
    - Sugarcane Bagasse
    - Cotton/Agri-waste

Assumptions/Data Sources

- Population, housing and square footage proxies for Coimbatore taken from Tamil Nadu Statistical Handbook, Coimbatore Smart City and Market Reports
- Industrial and commercial data assumed from Draft Coimbatore Master Plan 2031 and District Census Handbook
- Tamil Nadu Combined Development and Building Rules, 2019 for FAR/FSI and
- Building types and sizes estimated from NSS 76th Round on Drinking, Water and Sanitation 2018
- District Profile and City Corporation merged/normalized to reflect municipal data
- Data for Portland from Open Portland GIS Portal, SmartPDF Data Portal, Portland Government, academic studies or multilateral reports

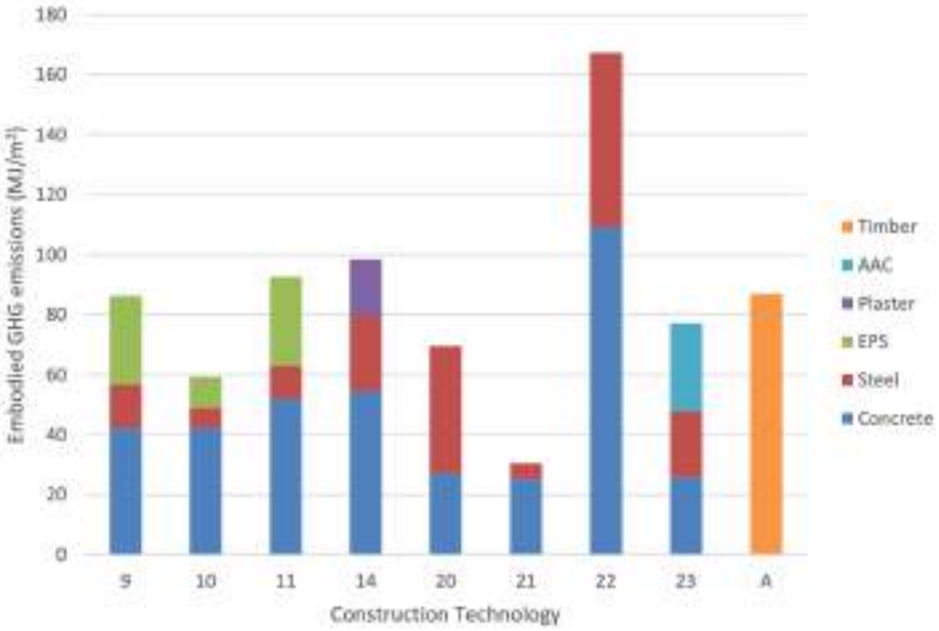
Takeaways from Baseline Emissions Footprint

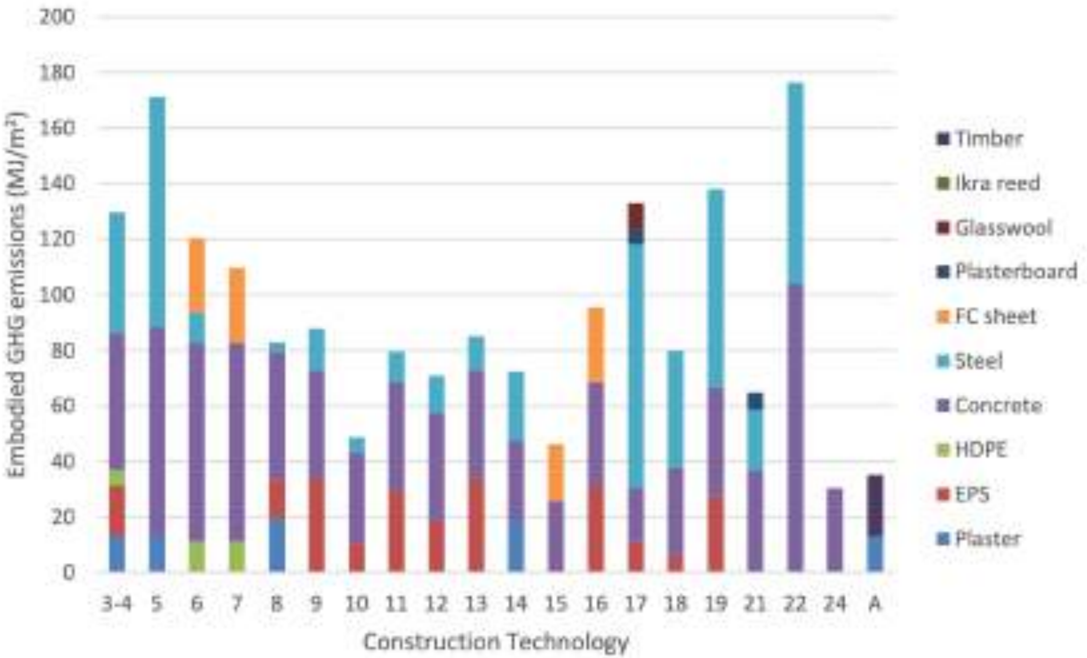
- Portland
  - 18 t/Co2 per year
  - Vehicular travel at 28%
  - Commercial and Industrial Electricity combined at 19%
  - Cement emission at 1.5%
- Coimbatore
  - 3.8 t/Co2 per year
  - Residential, Commercial and Industrial Electricity biggest contributors at 30%
  - Wood/wood chips as fuel and food contribute 10% each
  - Cement emission at 13%
  - Very little coal and lower LPG/Kerosene use makes it better than Rajkot worse than Delhi

Better building construction can reduce both cement emissions and energy useage.

More relevant for Coimbatore than Portland in relative terms. Similarly relevant in absolute terms.

Pre-fab/modular construction: Not a good idea!





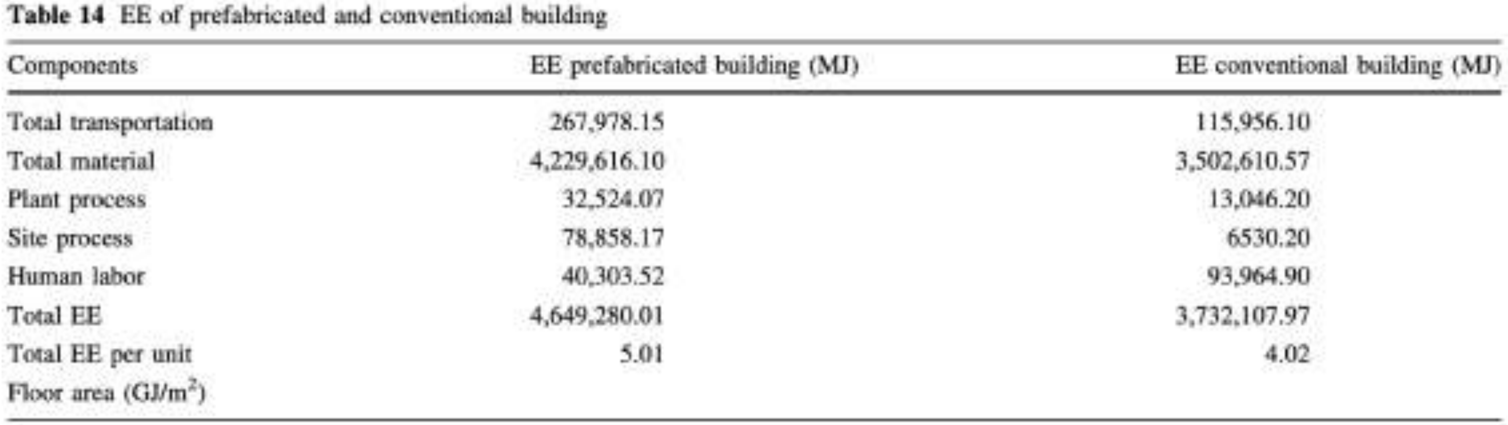


Table 14 EE of prefabricated and conventional building

Components	EE prefabricated building (MJ)	EE conventional building (MJ)
Total transportation	267,978.15	115,956.10
Total material	4,229,616.10	3,502,610.57
Plant process	32,524.07	13,046.20
Site process	78,858.17	6530.20
Human labor	40,303.52	93,964.90
Total EE	4,649,280.01	3,732,107.97
Total EE per unit Floor area (GJ/m^2)	5.01	4.02

Hemp, Sugarcane Bagasse, Cotton-waste and agri-waste products are sustainable and save emissions but still very small scale

S.P. Raut et al. / Construction and Building Materials 25 (2011) 4037–4042

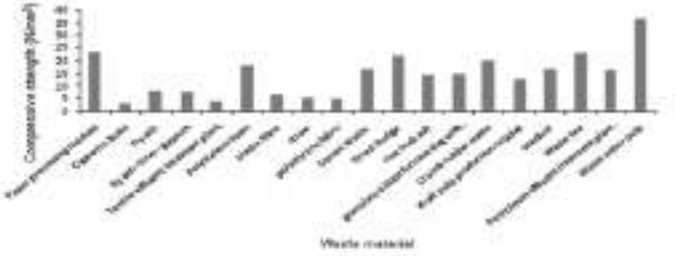


Fig. 2. Compressive strength of WCB made from various industrial solid wastes.

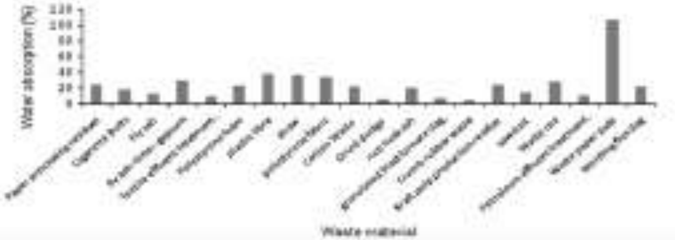


Fig. 3. Water absorption of WCB made from various industrial solid wastes.

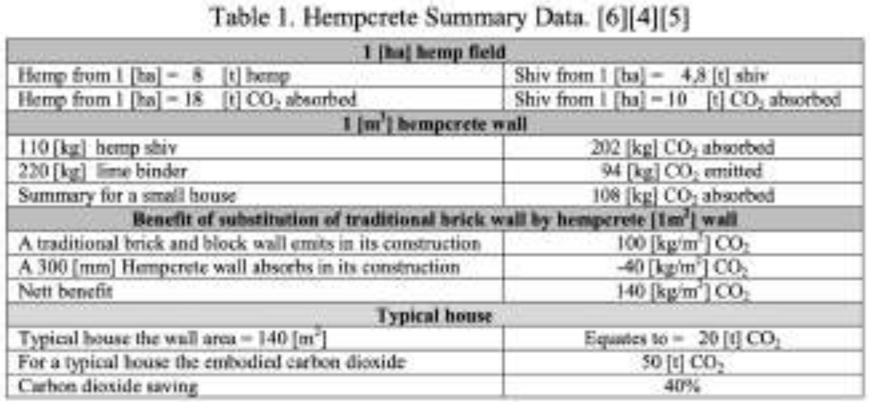


Table 1. Hempcrete Summary Data. [6][4][5]

1 [ha] hemp field	
Hemp from 1 [ha] = 8 [t] hemp	Shiv from 1 [ha] = 4,8 [t] shiv
Hemp from 1 [ha] = 18 [t] CO_2 absorbed	Shiv from 1 [ha] = 10 [t] CO_2 absorbed
1 [m³] hempcrete wall	
110 [kg] hemp shiv	202 [kg] CO_2 absorbed
220 [kg] lime binder	94 [kg] CO_2 emitted
Summary for a small house	108 [kg] CO_2 absorbed
Benefit of substitution of traditional brick wall by hempcrete [1m²] wall	
A traditional brick and block wall emits in its construction	100 [kg/m²] CO_2
A 300 [mm] Hempcrete wall absorbs in its construction	-40 [kg/m²] CO_2
Nett benefit	140 [kg/m²] CO_2
Typical house	
Typical house the wall area = 140 [m²]	Equates to = 20 [t] CO_2
For a typical house the embodied carbon dioxide	50 [t] CO_2
Carbon dioxide saving	40%

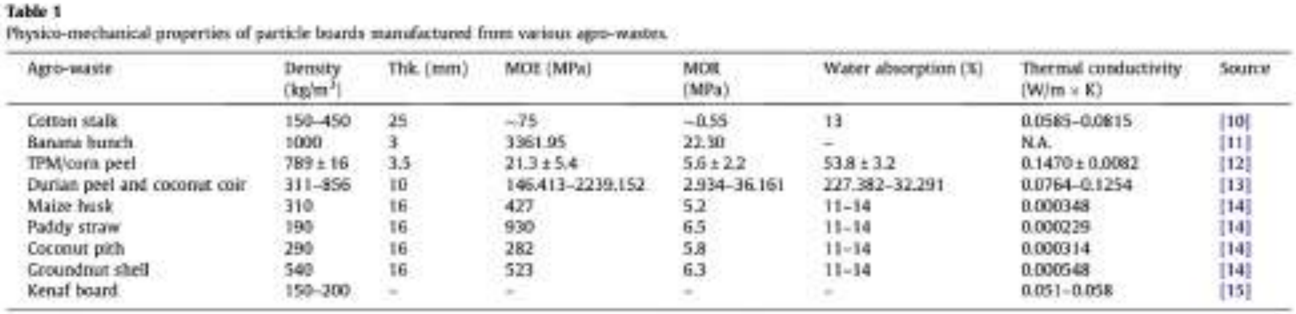


Table 1
Physico-mechanical properties of particle boards manufactured from various agro-wastes.

Agro-waste	Density (kg/m³)	Thk. (mm)	MOE (MPa)	MOR (MPa)	Water absorption (%)	Thermal conductivity (W/m × K)	Source
Cotton stalk	150–450	25	~75	~0.55	13	0.0585–0.0815	[10]
Banana bunch	1000	3	3361.95	22.30	–	N.A.	[11]
TPM/corn peel	789 ± 16	3.5	21.3 ± 5.4	5.6 ± 2.2	53.8 ± 3.2	0.1470 ± 0.0082	[12]
Durian peel and coconut coir	311–856	10	146.413–2239.152	2.934–36.161	227.382–32.291	0.0764–0.1254	[13]
Maize husk	310	16	427	5.2	11–14	0.000348	[14]
Paddy straw	190	16	930	6.5	11–14	0.000229	[14]
Coconut pith	290	16	282	5.8	11–14	0.000314	[14]
Groundnut shell	540	16	523	6.3	11–14	0.000548	[14]
Kenaf board	150–200	–	–	–	–	0.051–0.058	[15]

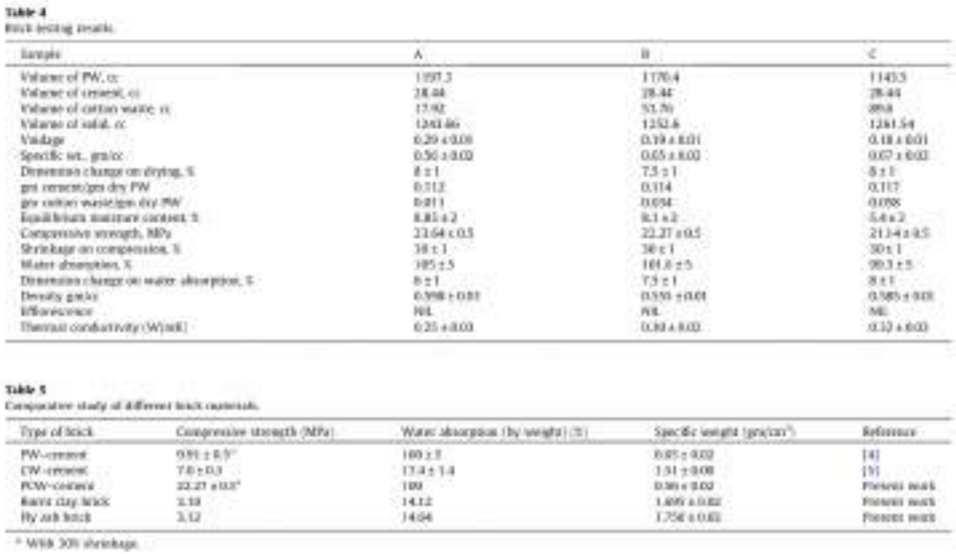


Table 4
Brick testing results.

Sample	A	B	C
Volume of PW, cc	1197.3	1170.4	1143.3
Volume of cement, cc	28.44	28.44	28.44
Volume of cotton waste, cc	17.92	53.76	89.6
Volume of solid, cc	1243.66	1252.6	1261.54
Voidage	0.29 ± 0.01	0.19 ± 0.01	0.18 ± 0.01
Specific wt., gm/cc	0.56 ± 0.02	0.65 ± 0.02	0.67 ± 0.02
Dimension change on drying, %	8 ± 1	7.5 ± 1	8 ± 1
gm cement/gm dry PW	0.112	0.114	0.117
gm cotton waste/gm dry PW	0.011	0.034	0.058
Equilibrium moisture content, %	8.85 ± 2	8.1 ± 2	5.4 ± 2
Compressive strength, MPa	23.64 ± 0.5	22.27 ± 0.5	21.34 ± 0.5
Shrinkage on compression, %	38 ± 1	30 ± 1	30 ± 1
Water absorption, %	105 ± 5	101.8 ± 5	99.3 ± 5
Dimension change on water absorption, %	8 ± 1	7.5 ± 1	8 ± 1
Density gm/cc	0.598 ± 0.01	0.550 ± 0.01	0.585 ± 0.01
Efflorescence	Nil	Nil	Nil
Thermal conductivity (W/mK)	0.25 ± 0.03	0.30 ± 0.02	0.32 ± 0.03

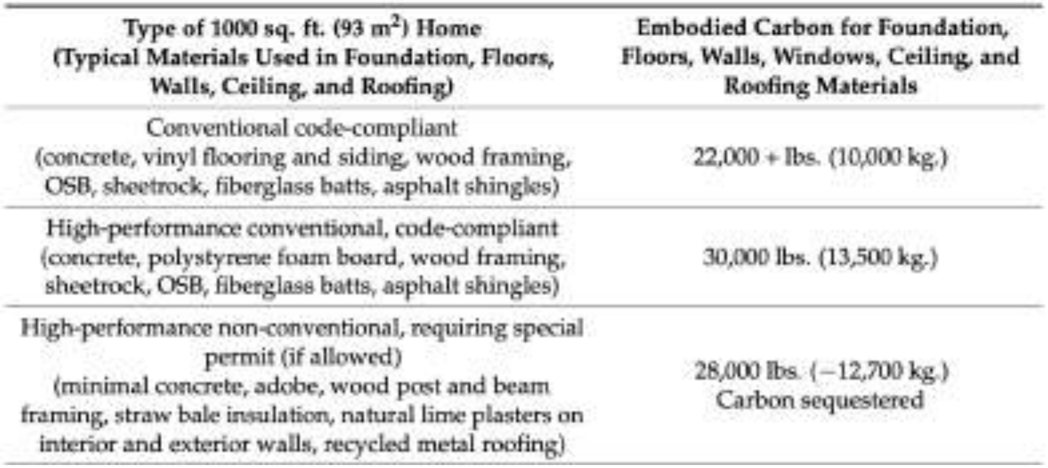
Table 5
Comparative study of different brick materials.

Type of brick	Compressive strength (MPa)	Water absorption (by weight) (%)	Specific weight (gm/cm³)	Reference
PW–cement	9.91 ± 0.5[a]	100 ± 5	0.85 ± 0.02	[4]
CW–cement	7.0 ± 0.3	17.4 ± 1.4	1.51 ± 0.08	[5]
PCW–cement	22.27 ± 0.5[a]	100	0.86 ± 0.02	Present work
Burnt clay brick	3.18	14.12	1.695 ± 0.02	Present work
Fly ash brick	3.12	14.04	1.756 ± 0.02	Present work

[a] With 30% shrinkage.

Straw-bale could be useful but doesn’t have champions

SHH Program (Estimated # Homes Built Since Founded)	Main Locations in Utah	Estimated Construction Cost (Excluding Labor)	Average Home Size (Square FootAge) (# Bedrooms and Bathrooms)	Estimated Ave. Embodied Carbon/House (Program Total)
Community Rebuilds (30 since 2010)	Moab (Grand County)	$80,000-$90,000	1000 ft^2 2 bedrm., 1 bath	Negative 28,000 lbs. (−12.7 metric tons)
Fresh Start Ventures * (no data, 2018)	Orem; Pleasant Grove (Utah County)	$30,000-$70,000	500 ft^2	11,000 lbs. (5 metric tons)
Habitat for Humanity (240 since 1986)	Cache, Salt Lake, and Utah Valleys (state-wide)	$110,000-$120,000	1200 ft^2 2–4 bedrm., 1 1/2 bath	30,000 lbs. (13.6 metric tons)
Mountainlands Community Housing Trust (198 since 2002)	Park City (Summit County)	$400,000-$600,000	1400–1800 ft^2 3–4 bedrm.s, 2 bath	50,000 lbs. (22.7 metric tons)
Neighborhood Housing Solutions (350 since 2001)	Cache Valley (Cache and Box Elder Counties)	$140,000-$160,000	1250–1700 ft^2 3–4 bedrm.s, 2 bath	45,000 lbs. (20.4 metric tons)
Self-Help Homes (400 since 2000)	St. George (Washington Co.) Orem-Provo (Utah and Wasatch Counties)	$260,000-$340,000	2300–2500 ft^2 3 bedrm., 2 bath	75,000 lbs. (34 metric tons)



Type of 1000 sq. ft. (93 m^2) Home (Typical Materials Used in Foundation, Floors, Walls, Ceiling, and Roofing)	Embodied Carbon for Foundation, Floors, Walls, Windows, Ceiling, and Roofing Materials
Conventional code-compliant (concrete, vinyl flooring and siding, wood framing, OSB, sheetrock, fiberglass batts, asphalt shingles)	22,000 + lbs. (10,000 kg.)
High-performance conventional, code-compliant (concrete, polystyrene foam board, wood framing, sheetrock, OSB, fiberglass batts, asphalt shingles)	30,000 lbs. (13,500 kg.)
High-performance non-conventional, requiring special permit (if allowed) (minimal concrete, adobe, wood post and beam framing, straw bale insulation, natural lime plasters on interior and exterior walls, recycled metal roofing)	28,000 lbs. (−12,700 kg.) Carbon sequestered

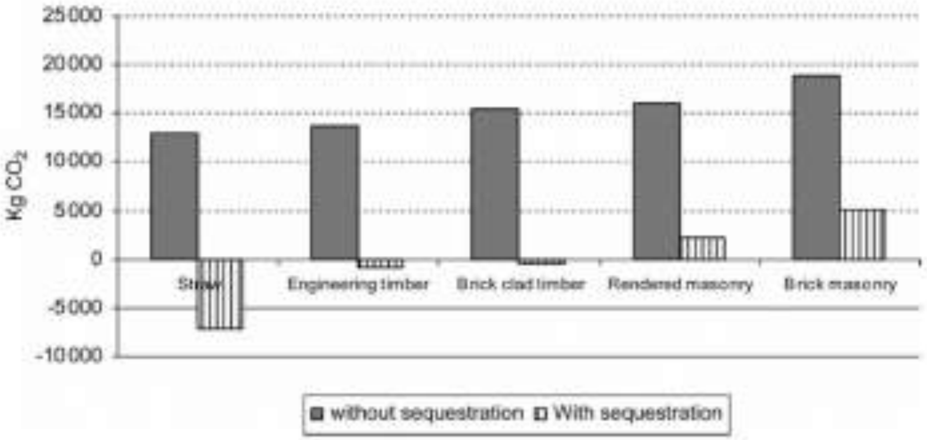
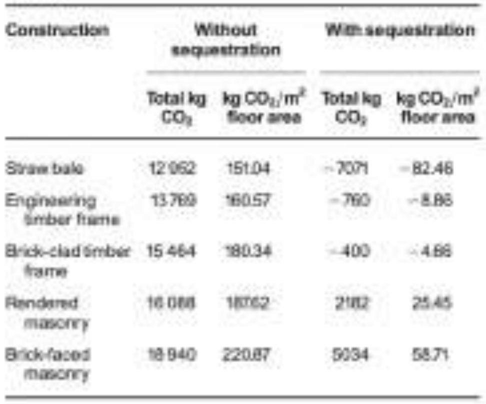


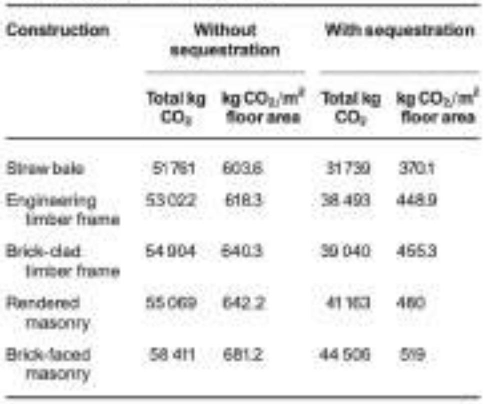
Figure 9 Total house materials CO_2 emissions of one of the houses with different external walling systems

Table 8 Comparison of the total house materials impacts per dwelling



Construction	Without sequestration		With sequestration	
	Total kg CO_2	kg CO_2/m^2 floor area	Total kg CO_2	kg CO_2/m^2 floor area
Straw bale	12 952	151.04	−7071	−82.46
Engineering timber frame	13 769	160.57	−760	−8.86
Brick-clad timber frame	15 464	180.34	−400	−4.66
Rendered masonry	16 088	187.62	2182	25.45
Brick-faced masonry	18 940	220.87	5034	58.71

Table 9 Comparison of the whole-life impact of houses with different walling systems over 60 years



Construction	Without sequestration		With sequestration	
	Total kg CO_2	kg CO_2/m^2 floor area	Total kg CO_2	kg CO_2/m^2 floor area
Straw bale	51 761	603.6	31 739	370.1
Engineering timber frame	53 022	618.3	38 493	448.9
Brick-clad timber frame	54 904	640.3	39 040	455.3
Rendered masonry	55 069	642.2	41 163	480
Brick-faced masonry	58 411	681.2	44 506	519

Bamboo Housing should be pushed

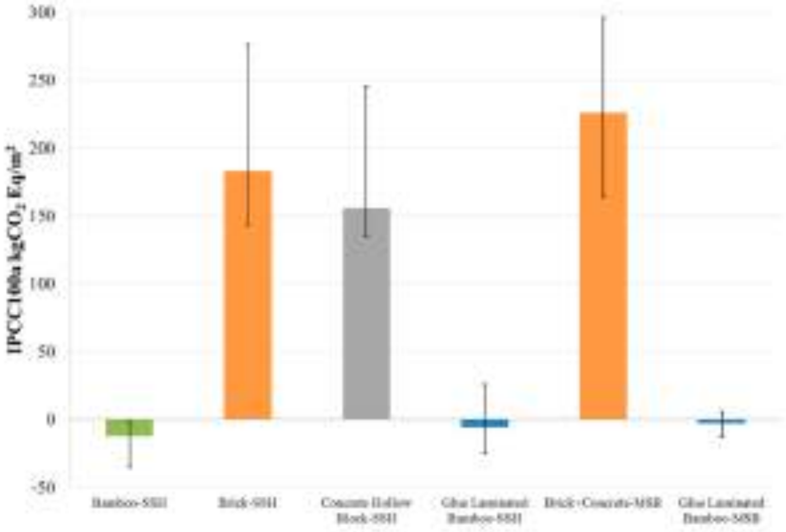


Figure 7. CO$_2$ balance. SSH: single-storey house; MSB: multi-storey building.

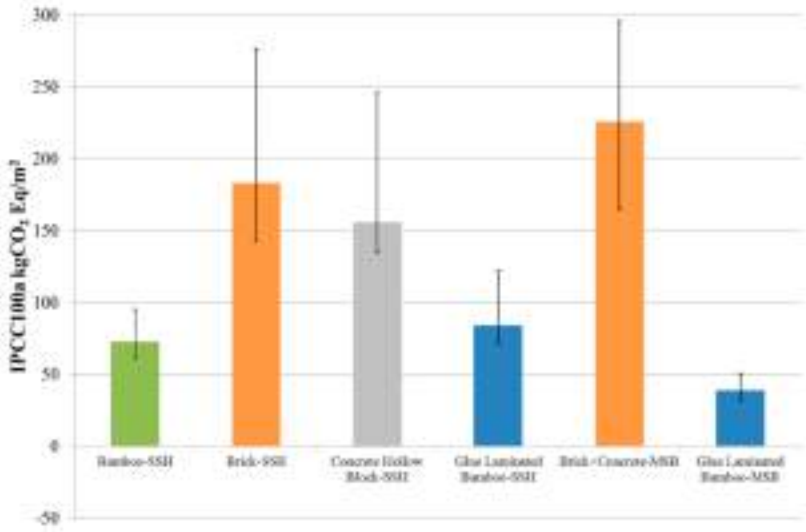


Figure 5. Environmental impact in kgCO$_2$Eq. SSH: single-storey House; MSB: multi-storey building.

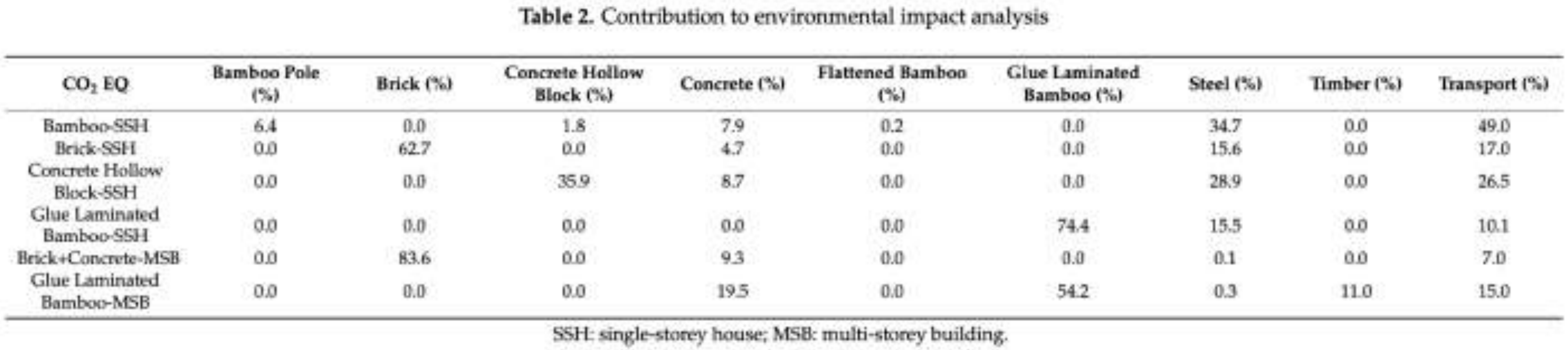


Table 2. Contribution to environmental impact analysis

CO$_2$ EQ	Bamboo Pole (%)	Brick (%)	Concrete Hollow Block (%)	Concrete (%)	Flattened Bamboo (%)	Glue Laminated Bamboo (%)	Steel (%)	Timber (%)	Transport (%)
Bamboo-SSH	6.4	0.0	1.8	7.9	0.2	0.0	34.7	0.0	49.0
Brick-SSH	0.0	62.7	0.0	4.7	0.0	0.0	15.6	0.0	17.0
Concrete Hollow Block-SSH	0.0	0.0	35.9	8.7	0.0	0.0	28.9	0.0	26.5
Glue Laminated Bamboo-SSH	0.0	0.0	0.0	0.0	0.0	74.4	15.5	0.0	10.1
Brick+Concrete-MSB	0.0	83.6	0.0	9.3	0.0	0.0	0.1	0.0	7.0
Glue Laminated Bamboo-MSB	0.0	0.0	0.0	19.5	0.0	54.2	0.3	11.0	15.0

SSH: single-storey house; MSB: multi-storey building.

Mass Timber needs scale and reforestation

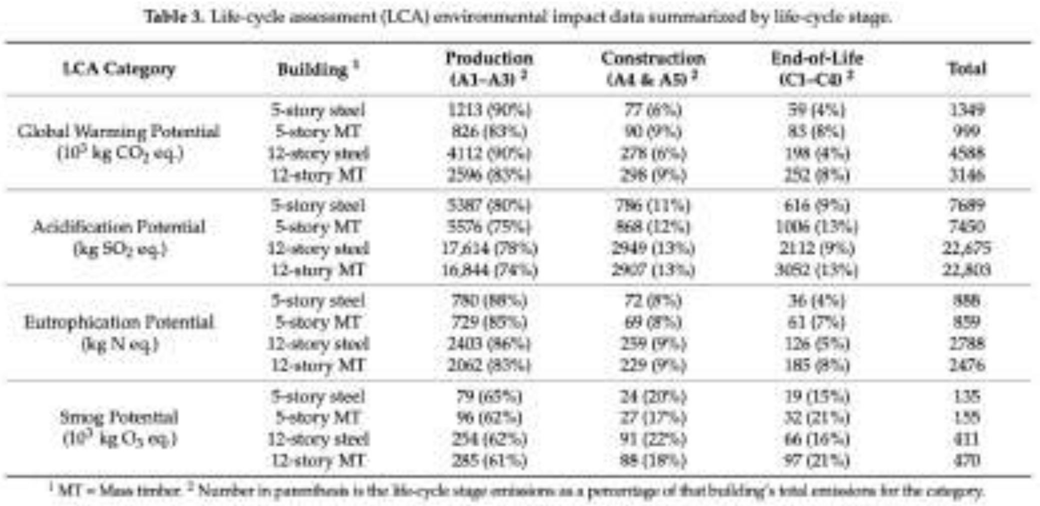
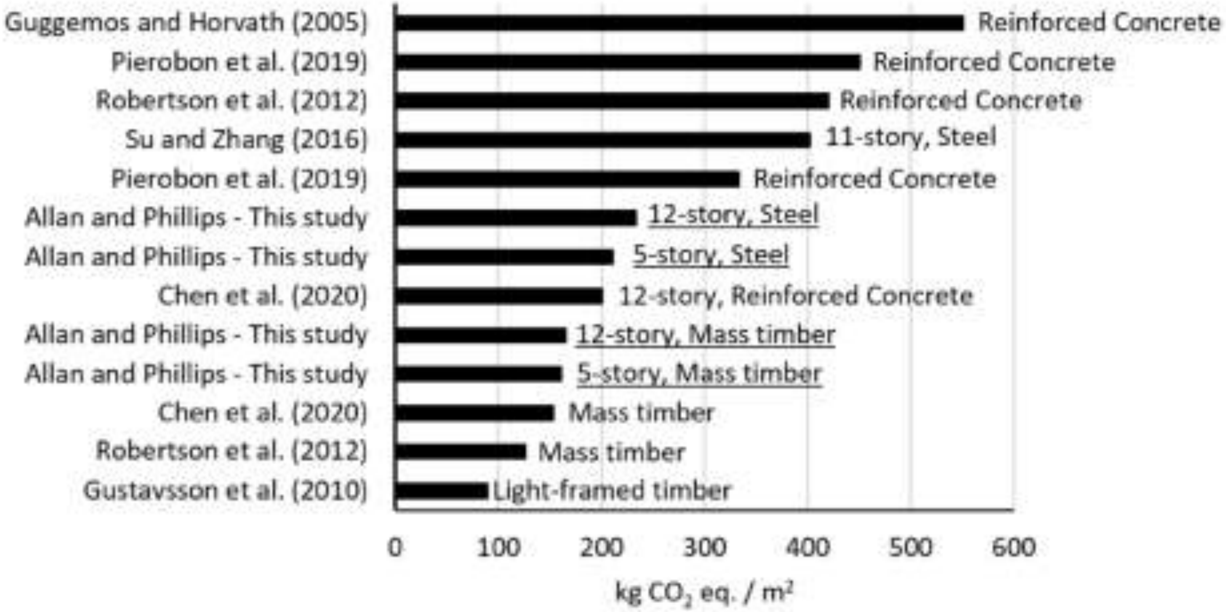


Table 3. Life-cycle assessment (LCA) environmental impact data summarized by life-cycle stage.

LCA Category	Building [1]	Production (A1–A3) [2]	Construction (A4 & A5) [2]	End-of-Life (C1–C4) [2]	Total
Global Warming Potential (10^3 kg CO_2 eq.)	5-story steel	1213 (90%)	77 (6%)	59 (4%)	1349
	5-story MT	826 (83%)	90 (9%)	83 (8%)	999
	12-story steel	4112 (90%)	278 (6%)	198 (4%)	4588
	12-story MT	2596 (83%)	298 (9%)	252 (8%)	3146
Acidification Potential (kg SO_2 eq.)	5-story steel	5387 (80%)	786 (11%)	616 (9%)	7689
	5-story MT	5576 (75%)	868 (12%)	1006 (13%)	7450
	12-story steel	17,614 (78%)	2949 (13%)	2112 (9%)	22,675
	12-story MT	16,844 (74%)	2907 (13%)	3052 (13%)	22,803
Eutrophication Potential (kg N eq.)	5-story steel	780 (88%)	72 (8%)	36 (4%)	888
	5-story MT	729 (85%)	69 (8%)	61 (7%)	859
	12-story steel	2403 (86%)	259 (9%)	126 (5%)	2788
	12-story MT	2062 (83%)	229 (9%)	185 (8%)	2476
Smog Potential (10^3 kg O_3 eq.)	5-story steel	79 (65%)	24 (20%)	19 (15%)	135
	5-story MT	96 (62%)	27 (17%)	32 (21%)	155
	12-story steel	254 (62%)	91 (22%)	66 (16%)	411
	12-story MT	285 (61%)	88 (18%)	97 (21%)	470

[1] MT = Mass timber. [2] Number in parenthesis is the life-cycle stage emissions as a percentage of that building's total emissions for the category.



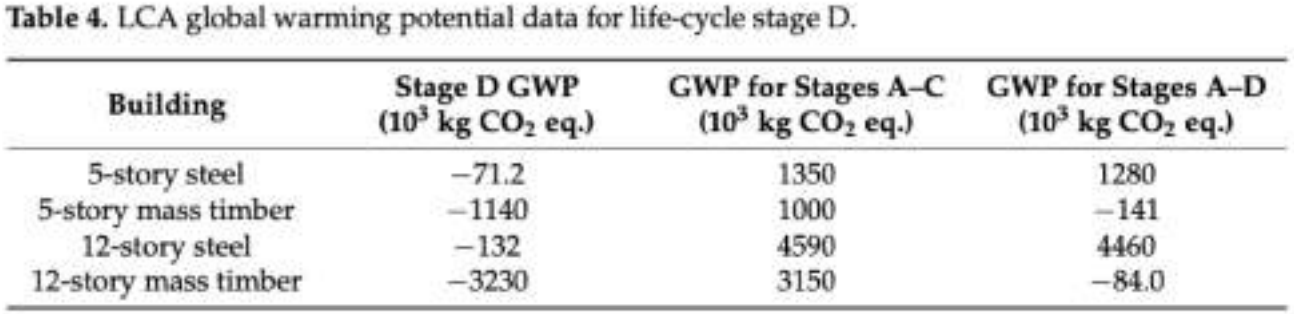


Table 4. LCA global warming potential data for life-cycle stage D.

Building	Stage D GWP (10^3 kg CO_2 eq.)	GWP for Stages A–C (10^3 kg CO_2 eq.)	GWP for Stages A–D (10^3 kg CO_2 eq.)
5-story steel	−71.2	1350	1280
5-story mass timber	−1140	1000	−141
12-story steel	−132	4590	4460
12-story mass timber	−3230	3150	−84.0

Policy Changes need to start now

- Portland has already pioneered
  - Salvage demolition waste and reduce carbon in buildings via better cement
  - Low carbon cement and concrete policy
- Ideas that have shown success and adoption
  - Life-cycle carbon limits for new buildings
  - Material efficient structural design
  - Green public procurement
  - Government leadership in procurement and leasing
  - Property taxation on empty housing can work

Conclusions

- Promote and accelerate bamboo, mass timber and straw bale housing through incentives (tax rebates, preference, permit expedition, subsidy, public procurement, government leadership)
- Encourage new materials in construction by enabling government regulation (hempcrete, agri-waste, sugarcane bagasse, cotton waste)
- Don’t artificially adopt modular and pre-fabricated construction techniques without market or GHG emission benefit
- Implement policy changes in building code to start off change in design, architecture and engineering to adopt low carbon cement and reduce carbon embodied in buildings