# Supplementary material

Bridging India's housing gap: lowering costs and $CO_2$ emissions

*Alessio Mastrucci and Narasimha D.Rao*

## Content

## SM1. Input data

### *1.1 Weather data*

Weather data for the locations representative of the five climatic zones in India are reported in Table SM1.

### *1.2 Construction materials and components*

Input data for construction materials and components are reported in Table SM2-SM3. Embodied energy (EE) intensities are assumed from Indian sources. In case of values available from different sources, an average was considered similar to other authors (Sharma & Marwaha, 2015).

$CO_2$ emissions embodied in building materials were calculated based on the material type, EE intensity, fuel share for the production process and cement content. First, the fuel share for the production of different construction materials was estimated based on EXIOBASE data (Tukker et al., 2013; Wood et al., 2015) (Table SM4). Then India-specific carbon intensity coefficients (Ministry of Environment and Forests (MoEF), 2010) were applied to the different fuels used for each material (Table SM5) and weighted on the respective share and multiplied by the EE intensity of the material. Emissions for cement production, equal to 0.507 $tCO_2$ eq/t clinker production (Gibbs, Soyka, & Conneely, 2000), were added depending on the cement and clinker content (see Table SM6). The content of clinker in cement is assumed as 95%.

The cost of building materials was estimated based on the Dehli Schedule of Rates (Central Public Works Department (CPWD), 2014). Uncertainty on the price variation of materials was estimated as the 5-year variation in the wholesale price index for India (2011-12 to 2016-17) (Reserve Bank of India, 2018) and reported in Table SM7.

Building components for the different archetypes and construction systems are reported in Tables SM8.

Table SM1 - Climatic zones and monthly statistics for daily average air temperature and relative humidity.

| **Climatic zone** | **Location** | **Parameter** | **Monthly statistics*** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Warm-humid | Chennai | $T_{air}$ (°C) | 24.2 | 25.8 | 28.2 | 30.1 | 31.5 | 31.1 | 30.3 | 29.4 | 29.2 | 27.7 | 25.7 | 24.9 |
| | | *RH (%)* | *77* | *73* | *80* | *73* | *69* | *68* | *71* | *71* | *75* | *83* | *84* | *77* |
| Composite | Allahabad | $T_{air}$ (°C) | 14.7 | 18.9 | 24.0 | 30.9 | 33.0 | 33.1 | 29.5 | 29.3 | 28.2 | 25.7 | 21.3 | 16.6 |
| | | *RH (%)* | *67* | *70* | *51* | *37* | *51* | *57* | *80* | *81* | *86* | *67* | *61* | *78* |
| Hot-dry | Jodhpur | $T_{air}$ (°C) | 16.9 | 17.1 | 24.6 | 30.9 | 31.2 | 33.9 | 30.5 | 28.9 | 30.2 | 27.4 | 22.8 | 17.7 |
| | | *RH (%)* | *54* | *35* | *32* | *30* | *48* | *50* | *66* | *70* | *51* | *43* | *52* | *47* |
| Temperate | Bangalore | $T_{air}$ (°C) | 20.8 | 23.4 | 26.0 | 27.6 | 26.8 | 23.8 | 23.4 | 22.7 | 23.3 | 22.9 | 21.8 | 20.5 |
| | | *RH (%)* | *66* | *45* | *52* | *49* | *68* | *77* | *75* | *85* | *78* | *80* | *72* | *71* |
| Cold | Dehradun | $T_{air}$ (°C) | 11.2 | 14.0 | 18.9 | 24.2 | 27.3 | 28.8 | 26.1 | 25.9 | 25.0 | 20.7 | 16.7 | 13.5 |
| | | *RH (%)* | *66* | *69* | *58* | *56* | *54* | *61* | *88* | *86* | *78* | *78* | *63* | *63* |

*Source: Indian Society of Heating Refrigerating and Air-Conditioning Engineers (ISHRAE), Indian Weather Data, (2005). https://energyplus.net/weather.

Table SM2 Properties and embodied energy intensity of building materials and components assumed for India.

| **Material** | **Density[a]** | **Thermal conductivity[a]** | **Specific heat[a]** | **Embodied Energy (EE)** | | **$CO_2$ emissions[b]** | | **Cost[c]** | | **References for EE[d]** |
|---|---|---|---|---|---|---|---|---|---|---|
| | ($kg/m^3$) | (W/m K) | (J/kg K) | (GJ/unit) | (unit) | (kg $CO_2$/ unit) | (unit) | ($/unit) | (unit) | |
| 1. Fired clay bricks | 1800 | 0.81 | 1000 | 2.41 | $m^3$ | 0.122 | ton | 305.82 | $m^3$ | See Table SM3 |
| 2. Hollow concrete blocks (HCB) | 1200 | 0.63 | 1000 | 0.88 | $m^3$ | 0.067 | ton | 341.67 | $m^3$ | See Table SM3 |
| 3. Fly Ash-lime-gypsum bricks (FAB) | 1270 | 0.36 | 857 | 1.09 | $m^3$ | 0.079 | ton | 330.34 | $m^3$ | See Table SM3 |
| 4. Stabilised earth blocks (SEB) | 1920 | 0.55 | 835 | 0.79 | $m^3$ | 0.038 | ton | 176.74 | $m^3$ | See Table SM3 |
| 5. Aerated concrete blocks (ACB) | 906 | 0.24 | 750 | 0.63 | $m^3$ | 0.077 | ton | 351.28 | $m^3$ | See Table SM3 |
| 6. Brick tiles (hollow) | 1200 | 0.50 | 1000 | 3.33 | ton | 0.334 | ton | 227.44 | $m^3$ | (Ramesh, Prakash, & Shukla, 2012) |
| 7. Clay tiles (Roofing) | 2300 | 1.30 | 840 | 3.33 | ton | 0.334 | ton | 26.83 | $m^2$ | (Ramesh et al., 2012) |
| 8. Clay tiles (Flooring) | 2300 | 1.30 | 840 | 3.33 | ton | 0.334 | ton | 34.66 | $m^2$ | (Ramesh et al., 2012) |
| 9. Cement mortar | 2800 | 0.88 | 896 | 2.00 | ton | 0.183 | ton | 200.04 | $m^3$ | (Ramesh et al., 2012; Reddy, Jagadish, Venkatarama Reddy, & Jagadish, 2003) |
| 10. Plaster | 1800 | 1.00 | 1000 | 2.00 | ton | 0.183 | ton | 11.36 | $m^2$ | (Reddy et al., 2003) |
| 11. Cast concrete | 2000 | 1.35 | 1000 | 1.47 | $m^3$ | 0.067 | ton | 354.75 | $m^3$ | (Ramesh et al., 2012) |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 12. Reinforced concrete<br>a. column (2% steel) | 2400 | 2.50 | 1000 | 5.84 | $m^3$ | 0.284 | ton | 1305.84 | $m^3$ | Based on concrete and steel values |
| b. beam (2% steel) | 2400 | 2.50 | 1000 | 5.84 | $m^3$ | 0.284 | ton | 1139.78 | $m^3$ | Based on concrete and steel values |
| c. slab (1% steel) | 2300 | 2.30 | 1000 | 3.65 | $m^3$ | 0.291 | ton | 885.86 | $m^3$ | Based on concrete and steel values |
| d. foundation (0.5% steel) | - | - | - | 2.56 | $m^3$ | 0.092 | ton | 531.95 | $m^3$ | Based on concrete and steel values |
| 13. Precast reinf. concrete<br>a. wall (2% steel) | 2400 | 2.50 | 1000 | 5.84 | $m^3$ | 0.284 | ton | 1253.91 | $m^3$ | Based on concrete and steel values |
| b. slab (1% steel) | 2300 | 2.30 | 1000 | 3.65 | $m^3$ | 0.291 | ton | 742.68 | $m^3$ | Based on concrete and steel values |
| 14. Steel | 7800 | 50.00 | 450 | 20.62 | ton | 1.820 | ton | 29043.30 | $m^3$ | (Debnath, Singh, & Singh, 1995) |
| 15. Timber | 700 | 0.18 | 1600 | 5.01 | $m^3$ | 0.636 | ton | 2561.53 | $m^3$ | See Table SM3 |
| 16. Wood panel (OSB) | 650 | 0.13 | 1700 | 15.00 | ton | 1.286 | ton | 72.49 | $m^2$ | (Hammond & Jones, 2011)* |
| 17. Plasterboard | 700 | 0.21 | 1000 | 6.75 | ton | 0.579 | ton | 62.53 | $m^2$ | (Hammond & Jones, 2011)* |
| 18. Wood (Door) | 700 | 0.18 | 1600 | 0.16 | $m^2$ | 0.014 | $m^2$ | 76.09 | $m^2$ | (Debnath et al., 1995) |
| 19. Wood (Window) | - | - | - | 0.16 | $m^2$ | 0.014 | $m^2$ | 76.09 | $m^2$ | (Debnath et al., 1995) |
| 20. Single Glazing | 2500 | 1.00 | 750 | 0.54 | $m^2$ | 0.046 | $m^2$ | 119.47 | $m^2$ | (Debnath et al., 1995) |
| 21. Double Glazing (LowE) | - | - | - | 1.08 | $m^2$ | 0.093 | $m^2$ | 225.00 | $m^2$ | Based on (Deshmukh & More, 2014) |
| 22. Thermal insulation (EPS) | 25 | 0.035 | 1400 | 2.50 | $m^3$ | 6.125 | ton | 12.47 | $m^2$ | (Ramesh et al., 2012) |
| 23. Thermal insulation (Rockwool) | 30 | 0.04 | 1030 | 16.8 | ton | 1.441 | ton | 490.60 | $m^2$ | (Hammond & Jones, 2011)* |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 24. Bitumen (membrane) | 1100 | 0.23 | 1000 | 2.98 | ton | 2.980 | ton | 0.10 | $m^2$ | (Ramesh et al., 2012) |
| 25. Aggregate | 2200 | 2.0 | 1180 | 0.08 | ton | 0.080 | ton | 57.75 | $m^3$ | (Debnath et al., 1995; Sharma & Marwaha, 2015) |
| 26. Fired bricks (foundation) | - | - | - | 2.41 | $m^3$ | 0.122 | ton | 249.76 | $m^3$ | See Table SM3 |
| 27. Brick bats | - | - | - | 2.41 | $m^3$ | 0.122 | ton | 27.50 | $m^3$ | See Table SM3 |
| 28. Concrete (plinth protection) | - | - | - | 1.47 | $m^3$ | 0.067 | ton | 460.90 | $m^3$ | (Ramesh et al., 2012) |
| 29. Earth filling | - | - | - | - | | - | | 6.18 | $m^3$ | |
| 30. Earth excavation | - | - | - | - | | - | | 2.77 | $m^2$ | |

Notes: [a] Source for material properties (ISO, 2007), except 1,6 (DIN, 2007) and 2-5,7-9 (Ramesh et al., 2012).

[b] $CO_2$ emissions: own calculation (see above).

[c] Source for costs: (Central Public Works Department (CPWD), 2014). Cost for SEB estimated from (Ministry of Rural Development (MoRD), 2016). Conversion rate from Rs to $2010 PPP: 0.055

[d] All sources for EE intensities are Indian, except sources marked with *.

Table SM3 Properties and embodied energy intensity of building materials and components assumed for India.

| **Material** | **Embodied Energy (GJ/m$^3$)** | | | | | | | | | | | | **Average (GJ/m$^3$)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | |
| Fired clay bricks | 2.14 | 2.08 | 2.27 | 2.52 | 1.51 | | 4.11 | | 2.24 | | | | **2.41** |
| Hollow concrete blocks (HCB) | | | | | 0.97 | | 0.78 | 0.96 | 0.82 | | | | **0.88** |
| Fly Ash-lime-gypsum bricks (FAB) | | | 1.16 | 0.60 | 1.26 | | | | | 1.34 | | | **1.09** |
| Stabilised earth blocks (SEB) | 0.71 | | | | | | 0.59 | 0.80 | | | 1.06 | | **0.79** |
| Aerated concrete blocks (ACB) | | | 0.45 | | | | | | 0.82 | | | | **0.63** |
| Timber | | | | | 6.80 | | | | | | | 3.21 | **5.01** |

*Sources: 1. (Reddy et al., 2003); 2.(Harrison, 2013); 3.(Chani, Najamuddin, & Kaushik, 2003); 4.(Gumaste, 2008); 5.(Deshmukh & More, 2014); 6. (Singh, 2012); 7. (Reddy et al., 2003); 8. (Energy Directory of Building Materials (EDBM), 1995); 9. (Gupta, 1998); 10. (Bansal, Singh, & Sawhney, 2014); 11. (Debnath et al., 1995).

Table SM4 – Fuel share for different materials (primary energy).

| **Material** | **Coal** (%) | **Gas** (%) | **Oil** (%) |
|---|---|---|---|
| Cement | 83 | 4 | 13 |
| Steel | 83 | 6 | 11 |
| Others | 63 | 10 | 27 |

Note: Estimated based on EXIOBASE data (Tukker et al., 2013; Wood et al., 2015)

Table SM5 – Carbon intensity for different fuels in India.

| **Material** | **Carbon intensity** ($tCO_2/TJ$) |
|---|---|
| Coal | 95.8 |
| Gas | 56.1 |
| Oil | 74.1 |

Source: (Ministry of Environment and Forests (MoEF), 2010)

Table SM6 – Cement content assumed for different materials.

| **Material** | **Cement content** (%) |
|---|---|
| Concrete | 25 |
| Cement mortar | 20 |
| Plaster, Cement screed | 14 |
| Cement-based blocks | 10 |
| Stabilised-Earth blocks | 7 |

Table SM7 – Cost variation assumed for different materials.

| **Material** | **Cost variation*** (%) |
|---|---|
| Wood and wood-based products | 29.8 |
| Rubber and plastic products | 7.5 |
| Non-metallic mineral products | 9.8 |
| Metal products | 5.1 |

* Based on the 5-year (2011-12 to 2016-17) variation of the Wholesale Index price for India 2016-17 compared with the base year 2011-12 (Reserve Bank of India, 2018).

Table SM8 Construction systems for single-storey and multi-storey housing.

| **Construction element** | **Construction system (thickness in cm)** | | | |
|---|---|---|---|---|
| | **Masonry** | **RCC framing**[1,2] | **Prefab**[2] | **Steel**[1,2] |
| External walls | Plaster (1.2), Fired bricks (30.0), Plaster (1.2) | Plaster (1.2), Fired bricks (25.0), Plaster (1.2) | Plaster (1.2), RCC prefab panels (SFH 15.0; MFH 20.0), Plaster (1.2) | Plasterboard (2.0), Rockwool (5.0), air (5.0) ext. finishing (2.0) |
| Internal non load-bearing walls | Plaster (1.2), Fired bricks (8.0), Plaster (1.2) | Plaster (1.2), Fired bricks (8.0), Plaster (1.2) | Plaster (1.2), RCC prefab panels (15.0), Plaster (1.2) | Plasterboard (2.0), Rockwool (5.0), air (5.0), Plasterboard (2.0) |
| Roof | Plaster (1.2), RCC (12.0), cement screed (3.0), bitumen (0.5), ceramic tiles (1.0) | Plaster (1.2), RCC (12.0), cement screed (3.0), bitumen (0.5), ceramic tiles (1.0) | Plaster (1.2), RCC prefab slab (14.0), cement screed (3.0), bitumen (0.5), ceramic tiles (1.0) | Plaster (1.2), RCC prefab slab (14.0), cement screed (3.0), bitumen (0.5), ceramic tiles (1.0) |
| Standard floor | Plaster (1.2), RCC (12.0) | Plaster (1.2), RCC (12.0) | Plaster (1.2), RCC prefab slab (12.0) | Plaster (1.2), RCC prefab slab (12.0) |
| Ground floor | Brick bats (15.0), concrete (4.0), ceramic tiles (1.0) | Brick bats (15.0), concrete (4.0), ceramic tiles (1.0) | Brick bats (15.0), concrete (4.0), ceramic tiles (1.0) | Brick bats (15.0), concrete (4.0), ceramic tiles (1.0) |
| Foundation | Fired bricks | RCC | RCC | RCC |
| Doors | Wooden doors | Wooden doors | Wooden doors | Wooden doors |
| Windows | Single-glazing, wood framing | Single-glazing, wood framing | Single-glazing, wood framing | Single-glazing, wood framing |

Notes: [1] Structural elements such as beams and columns were computed separately.

[2] For MFH, materials for staircases and additional structures were computed separately.

### *1.3 Building geometry*

The input data for building geometry of reference archetypes is reported in Table SM9.

Table SM9 – Input geometry for the reference building archetypes.

| **Archetype** | **SFH** | | | **MFH**[1] | | |
|---|---|---|---|---|---|---|
| **Structure** | Masonry | RCC | Prefab | RCC | Prefab | Steel |
| N. dwellings | 1 | 1 | 1 | 4 | 4 | 4 |
| Floor surface per dwelling ($m^2$) | 40.00 | 40.00 | 40.00 | 40.00 | 40.00 | 40.00 |
| Floor surface total ($m^2$) | 40.00 | 40.00 | 40.00 | 160.00 | 160.00 | 160.00 |
| Storey height (m) | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Surface ext. walls ($m^2$) | 72.18 | 57.72 | 72.18 | 111.54 | 148.85 | 148.85 |
| Surface ext. RCC framing[2] ($m^2$) | - | 14.46 | - | 37.32 | - | - |
| Surface int. walls ($m^2$) | 41.88 | 35.76 | 41.88 | 266.88 | 317.40 | 317.40 |
| Surface int. RCC framing[2] ($m^2$) | - | 6.12 | - | 50.52 | - | - |
| Surface additional RCC structure[3] ($m^2$) | - | - | - | 6.39 | 6.39 | - |
| Steel framing structure ($m^3$) | - | - | - | - | - | 3.05 |
| Surface roof ($m^2$) | 43.76 | 43.27 | 42.82 | 56.53 | 57.25 | 54.89 |
| Surface ground floor ($m^2$) | 43.76 | 43.27 | 42.82 | 56.53 | 57.25 | 54.89 |
| Surface standard floor ($m^2$) | - | - | - | 169.58 | 171.74 | 164.67 |
| Surface vert. foundation ($m^2$) | 15.23 | 15.23 | 15.23 | 26.10 | 26.10 | 26.10 |
| Surface windows[4] ($m^2$) | 4.44 | 4.44 | 4.44 | 14.23 | 14.23 | 14.23 |
| Surface external doors ($m^2$) | 1.68 | 1.68 | 1.68 | - | - | - |
| Surface internal doors ($m^2$) | 6.72 | 6.72 | 6.72 | 33.60 | 33.60 | 33.60 |

[1] For MFH the quantities refer to a portion of building consisting of four stacked dwellings. A quota of common stairs and corridors is considered.

[2] RCC structure including beams and pillars.

[3] Additional structure for the quota of common stairs and corridors.

[4] Window frame assumed as 25% of total window surface.

### *1.4 Building operation*

Space heating, cooling and dehumidification were considered in this study and modelled on the basis of previous work (Mastrucci & Rao, 2017). Space cooling and dehumidification are provided by a single speed air conditioners with coefficient of performance (COP) 3.26, corresponding to average performance of air conditioning systems in India (Bureau of Energy Efficiency, 2006). For the reference case, operative temperatures (Top) was set at 26°C and relative humidity (RH) at 60%, corresponding to optimal thermal comfort settings for tropical countries suggested by other studies (Kwong, Adam, & Sahari, 2014; Wan, Yang, Zhang, & Zhang, 2009; Yamtraipat, Khedari, & Hirunlabh, 2005). Under the assumption of indoor air velocity at 0.1 m/s, housing metabolic activity (MET = 1.1) and summer clothes (CLO = 0.5), this leads to Predicted Mean Vote (PMV) values in the range of ±0.5, in agreement with the comfort level for new buildings recommended by the standard ISO 7730 (ISO, 2005). In the parametric analysis, setpoints were varied to account for different thermal comfort levels:

- Top = 25°C; RH = 55%: more stringent set-points (comfort category “A” in ISO 7730), accounting for potential overuse of A/C when available;

- Top = 27°C; RH = 65%: less stringent set-points, accounting for adaptability and cost-conscious behaviour. The Top (27◦C) represents the upper limit in the European standard EN 15232 and the upper limit for RH (65%) recommended by ASHRAE [65].

An electric heater with efficiency 0.9 is assumed for space heating, in agreement with other studies (Ramesh, Prakash, & Kumar Shukla, 2013). Electric heaters, although not efficient, are common in India due to short winter seasons and mild temperatures in most of the regions. Set-point temperature for heating is set at 20°C and setback at 18°C (night and non-occupied periods).

Occupation and availability schedules for A/C and electric heater are reported in Table SM10. Activity schedules were adapted from other Indian studies (Rawal & Shukla, 2014). Internal heat gains: 5 W/m$^2$. The influence of varying operation times for A/C was analysed by testing two schedules: a reference schedule where A/C is used only in bedrooms for 8 hours at night-time and an extended schedule where A/C is used at in bedrooms for 10 hours at night-time and in the living room in the evening (entire day) for weekdays (weekend). Schedules were not varied for heating due to its low demand.

Table SM10 Activity schedules.

| Space type | Activity schedules<br>Occupation (% occupied) | Heating | Cooling |
|---|---|---|---|
| Living room | W: 8:00-18:00 (50%); 18:00-22:00 (100%)<br>WE: 8:00-22:00 (100%) | W: 18:00-22:00<br>WE: 13:00-22:00 | No cooling (R)<br>W: 18:00-22:00 (E);<br>WE: 13:00-22:00 (E) |
| Bedrooms | 22:00-08:00 (100%) | W-WE: 22:00-8:00 * | W-WE: 22:00-6:00 (R)<br>W-WE: 22:00-8:00 (E) |
| Non-conditioned spaces | - | - | - |

Note: W = weekdays; WE = weekends; (R) = Reference schedule; (E) = Extended schedule; *at night-time the setback temperature is applied for heating.

### *1.5 Housing gap data*

Table SM11 reports the housing gap data and main climatic zone assumptions used for the aggregation of results at the state level.

Table SM11 – Main climatic zone and housing gap by State in India.

| **State** | **Climatic zone** | **Housing gap** (Million units) | |
|---|---|---|---|
| | | Rural [a] | Urban [b] |
| Andaman and Nicobar | Warm-Humid | 0.00 | 0.00 |
| Andhra Pradesh | Warm-Humid | 1.07 | 1.27 |
| Arunachal Pradesh | Cold | 0.05 | 0.03 |
| Assam | Warm-Humid | 1.68 | 0.28 |
| Bihar | Composite | 6.90 | 1.19 |
| Chandigarh | Composite | 0.00 | 0.02 |
| Chhattisgarh | Composite | 1.54 | 0.35 |
| Dadra and Nagar Haveli | Warm-Humid | 0.01 | 0.05 |
| Daman and Diu | Warm-Humid | 0.00 | 0.01 |
| Delhi | Composite | 0.00 | 0.49 |
| Goa | Warm-Humid | 0.00 | 0.06 |
| Gujarat | Hot-Dry | 1.43 | 0.99 |
| Haryana | Composite | 0.36 | 0.42 |
| Himachal Pradesh | Cold | 0.17 | 0.04 |
| Jammu and Kashmir | Cold | 0.24 | 0.13 |
| Jharkhand | Composite | 1.81 | 0.63 |
| Karnataka | Warm-Humid | 1.64 | 1.02 |
| Kerala | Warm-Humid | 0.15 | 0.54 |
| Lakshadweep | Warm-Humid | 0.00 | 0.01 |
| Madhya Pradesh | Composite | 4.04 | 1.10 |
| Maharashtra | Composite | 1.85 | 1.94 |
| Manipur | Warm-Humid | 0.09 | 0.08 |
| Meghalaya | Warm-Humid | 0.06 | 0.03 |

| | | | |
|---|---|---|---|
| Mizoram | Warm-Humid | 0.02 | 0.02 |
| Nagaland | Temperate | 0.02 | 0.21 |
| Orissa | Warm-Humid | 2.38 | 0.41 |
| Puducherry | Warm-Humid | 0.00 | 0.07 |
| Punjab | Composite | 0.15 | 0.39 |
| Rajasthan | Hot-Dry | 2.16 | 1.15 |
| Sikkim | Cold | 0.02 | 0.01 |
| Tamil Nadu | Warm-Humid | 1.04 | 1.25 |
| Tripura | Warm-Humid | 0.12 | 0.03 |
| Uttar Pradesh | Composite | 11.19 | 3.07 |
| Uttarakhand | Cold | 0.29 | 0.16 |
| West Bengal | Warm-Humid | 2.63 | 1.33 |
| **Total** | | **43.12** | **18.78** |

Notes: [a] Gap for rural housing estimated based on aggregated national estimation (Ministry of Rural Development (MoRD), 2011) and weighted on low-income population data for disaggregation at the state level. [b] Source for urban housing gap at the state level: (National Buildings Organisation (NBO), 2013).

## SM2. Methods

### *2.1 EE, costs and $CO_2$ emissions of building materials*

This section describes in detail the procedure used to calculate total quantity of individual materials and aggregate results (energy, costs and $CO_2$ emissions) to the building level for each model run (Fig. SM1). All analyses were carried out using dedicated scripts developed in R (R Development Core Team, 2012).

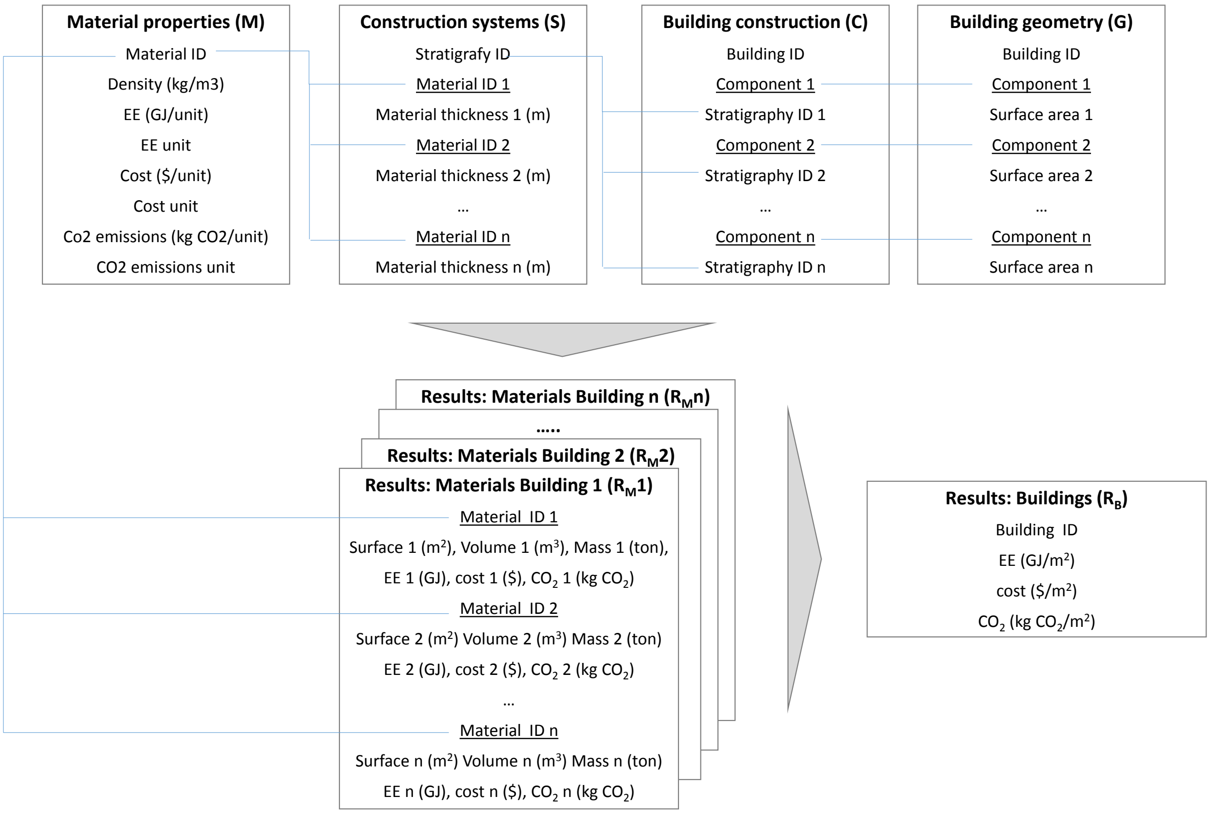



Figure SM1 – Overview of the methodology to calculate EE, cost and $CO_2$ emissions of buildings.

The above described input data have been processed into four tables:

- Material properties (*M*): each line represents a building material, identified by a unique ID. Data for each single material include material properties and intensities for EE, costs and $CO_2$ emissions per material unit (see Table SM2). Allowed units include surface ($m^2$), volume ($m^3$), and mass (ton).
- Construction systems (*S*): each line represents a construction systems, identified by a unique ID and constituted by a series of material layers (based on the data in Table SM8). Material layers are identified by a material ID (consistent with the table *M*) and an optional thickness. Thickness is mandatory if the material unit is volume or mass.

- Building construction (*C*): each line represents a single building, corresponding to a single model run. Each run is identified by a unique building ID. For each of the building components (e.g. external walls, roof, ground floor, etc.) a unique stratigraphy of materials is assigned, identified by its respective ID, consistent with table *S*.
- Building geometry (*G*): each line represents a single building, corresponding to a single model run and identified by a unique building ID. For each of the building components (e.g. external walls, roof, ground floor, etc.) a unique surface value ($m^2$) is assigned (see Table SM9). Components in table *C* are consistent with table *G*.

The four tables are used as inputs to calculate EE, costs and $CO_2$ emissions, and aggregate them to the building level for every model run. First a series of m tables, being m the number of model runs, is generated. Each of the table refers to a single building (model run) and contains results propagated through the model. As an example equations for EE calculation are reported (costs and CO2 emissions follow the same procedure). Three different equations are used, depending on the way the EE intensity for the material *m* is expressed: per unit of surface ($EE_{int,m(S)}$), per unit of volume ($EE_{int,m(S)}$) or per unit of mass ($EE_{int,m(M)}$).

$$EE_{tot,m,b} = EE_{int,m(S)} \cdot \sum_{c} s_{c,b}$$

$$EE_{tot,m,b} = EE_{int,m(V)} \cdot \sum_{c} (s_{c,b} \cdot t_{m,c,b})$$

$$EE_{tot,m,b} = EE_{int,m(M)} \cdot \rho_m \cdot \sum_{c} (s_{c,b} \cdot t_{m,c,b})$$

where, $s_{m,c,b}$ is the surface of the component c (containing the material m) for the building b (from the table *G*), $t_{m,c,b}$ is the thickness of the material m in component c (from table S) and $\rho_m$ is the density of material m (from table D). Surface values are summed up for all components containing material m in a given building.

Once total EE, cost and $CO_2$ emissions are calculated for every material contained in each of the buildings analysed, they are stored in a series of tables $R_M1$, $R_M2$,… $R_Mn$, where n is the number of building analysed. Finally, a table $R_B$ is generated and contains total results for each of the buildings, obtained by summing up total results for individual materials in the building.

### *2.2 Operational energy requirements*

The final energy for space heating and cooling was simulated in dynamic state using the software EnergyPlus (U.S. Department of Energy's (DOE), 2016) and the user interface of the OpenStudio suite (National Renewable Energy Laboratory (NREL), 2016). Simulations were launched via the software jEplus (Zhang, 2012) for multiple runs. A representative location was assumed for each of the five Indian climatic zones (Bureau of Indian Standards, 2005) – warm-humid, composite, hot-dry, temperate and cold – (Table SM1) using the EnergyPlus weather data (Indian Society of Heating Refrigerating and Air-Conditioning Engineers (ISHRAE), 2005). Simulations were run using a multi-zonal approach, distinguishing living room, bedrooms, and unconditioned spaces.

A primary energy conversion factor of 3.4 was assumed for electricity in India (Ramesh et al., 2013, 2012). $CO_2$ emissions associated to electricity were calculated using an emission factor of 0.82 $tCO_2$/MWh of electricity (Ministry of Power (MoP), 2011).

The price of electricity was set to an average of 0.164 $/kWh (IHSN - International Household Survey Network, 2013), using a conversion factor of 0.0595 from Rupees 2010 to $ 2010 PPP (Purchasing Power Parity). Uncertainty was assumed as 16%, corresponding to the difference between electricity price paid by A/C owners and the average, according to the survey data.

## SM3. Detailed results

### *3.1 Material intensity of housing archetypes*

Table SM12 shows the result of the material intensity calculation for the difference archetypes in the reference case. Values were compared with another study in literature estimating the material intensity of Indian buildings (Praseeda, Reddy, & Mani, 2016), finding a good correspondence for building with similar characteristics.

Table SM12 – Material intensity per floor surface area unit.

| **Archetype** | **Structure** | **Material intensity** (ton/m$^2$) | |
|---|---|---|---|
| | | This study | (Praseeda et al., 2016) |
| SFH | Masonry | 2.71 | 2.23; 2.72 |
| | RCC | 2.82 | |
| | Prefab | 2.89 | |
| MFH | RCC | 2.09 | 2.29 |
| | Prefab | 2.62 | |
| | Steel | 1.18 | |

### *3.2 Results for different dwelling size*

Figure SM2 shows the results of analysis of Life-Cycle Energy (LCE) and Life-Cycle Cost (LCC) analysis for different housing size, assuming reference case and composite climate.

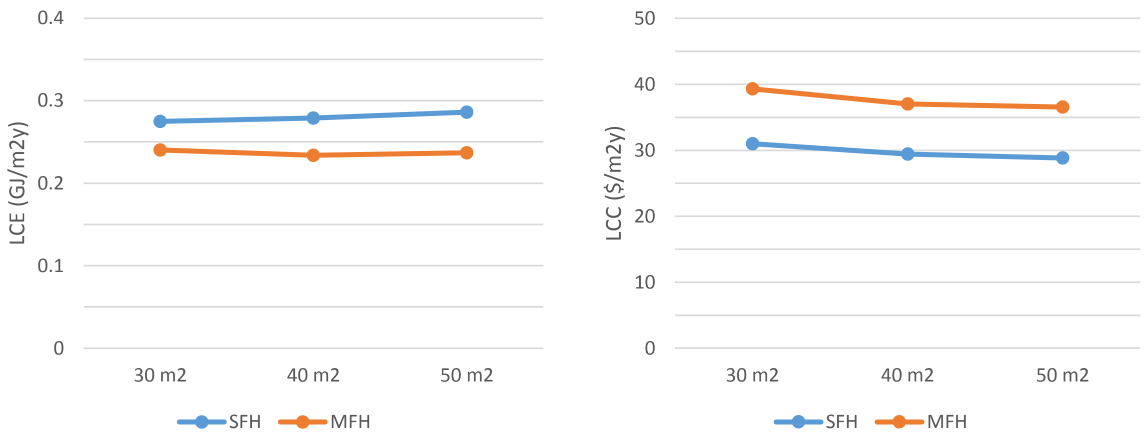



Figure SM2 - LCE and LCC (social discount rate) for different housing size (reference case, composite climate). Note: SFH = Single-Family House, MFH = Multi-Family House.

### *3.3 Results for different climatic zones*

Table SM7-9 show the results of the LCE, LCC and $CO_2$ emissions analysis for SFH and MFH in different climates for three cases: reference, minimum LCE and minimum LCC.

Table SM13 – Results of calculation for different climatic zones, assuming dwelling floor surface of 40m$^2$. Reference case.

| **Archetype** | **Climate** | **LCE** (GJ/m$^2$y) | | | **LCC*** ($/m$^2$y) | | | **$CO_2$ Emissions** (kg$CO_2$/m$^2$y) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | E | O (% space heating ) | **TOT** | I | O | **TOT** | E | O | **TOT** |
| SFH | Warm-Humid | 0.079 | 0.224 (0%) | **0.303** | 26.76 | 3.00 | **29.76** | 6.34 | 14.99 | **21.33** |
| | Composite | 0.079 | 0.200 (4%) | **0.279** | 26.76 | 2.68 | **29.44** | 6.34 | 13.37 | **19.71** |
| | Hot-Dry | 0.079 | 0.179 (1%) | **0.258** | 26.76 | 2.40 | **29.16** | 6.34 | 11.98 | **18.32** |
| | Temperate | 0.079 | 0.098 (0%) | **0.177** | 26.76 | 1.31 | **28.08** | 6.34 | 6.56 | **12.90** |
| | Cold | 0.079 | 0.149 (41%) | **0.229** | 26.76 | 2.00 | **28.76** | 6.34 | 10.00 | **16.34** |
| MFH | Warm-Humid | 0.080 | 0.179 (0%) | **0.259** | 34.98 | 2.40 | **37.38** | 7.17 | 11.98 | **19.15** |
| | Composite | 0.080 | 0.153 (3%) | **0.234** | 34.98 | 2.06 | **37.04** | 7.17 | 10.27 | **17.44** |
| | Hot-Dry | 0.080 | 0.137 (0%) | **0.217** | 34.98 | 1.84 | **36.82** | 7.17 | 9.18 | **16.35** |
| | Temperate | 0.080 | 0.092 (0%) | **0.172** | 34.98 | 1.24 | **36.21** | 7.17 | 6.17 | **13.34** |
| | Cold | 0.080 | 0.107 (27%) | **0.187** | 34.98 | 1.44 | **36.41** | 7.17 | 7.18 | **14.34** |

Notes: E = Embodied; O = Operational; I = Investment; *Social discount rate used for LCC calculation.

Table SM14 – Results of calculation for different climatic zones, assuming dwelling floor surface of 40m². Minimum LCE.

| Archetype | Climate | Energy/Cost savings measures | LCE ($GJ/m^2y$) E | LCE O | LCE TOTAL (difference with REF %) | LCC* ($\$/m^2y$) I | LCC O | LCC TOTAL (difference with REF %) | $CO_2$ Emissions ($kgCO_2/m^2y$) E | $CO_2$ O | $CO_2$ TOTAL (difference with REF %) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SFH | Warm-Humid | ACB, Filler slab | 0.056 | 0.202 | **0.258** (-15%) | 26.07 | 2.72 | **28.79** (-3%) | 4.85 | 13.55 | **18.41** (-14%) |
| | Composite | ACB, Filler slab, Roof ins | 0.058 | 0.126 | **0.185** (-34%) | 26.71 | 1.70 | **28.41** (-4%) | 5.03 | 8.47 | **13.50** (-32%) |
| | Hot-Dry | ACB, Filler slab, Wall ins, Roof ins, DG | 0.065 | 0.064 | **0.130** (-50%) | 28.89 | 0.86 | **29.75** (+2%) | 5.48 | 4.31 | **9.79** (-47%) |
| | Temperate | ACB, Filler slab, DG | 0.058 | 0.080 | **0.138** (-22%) | 27.10 | 1.08 | **28.18** (0%) | 5.00 | 5.38 | **10.37** (-20%) |
| | Cold | ACB, Filler slab, Roof insul, DG | 0.061 | 0.091 | **0.152** (-33%) | 27.74 | 1.23 | **28.97** (+1%) | 5.17 | 6.13 | **11.30** (-31%) |
| MFH | Warm-Humid | SEB, Filler slab, Wall ins, Roof ins, DG | 0.074 | 0.156 | **0.230** (-11%) | 32.40 | 2.10 | **34.50** (-8%) | 6.83 | 10.48 | **17.31** (-10%) |
| | Composite | ACB, Filler slab, Wall ins, Roof ins, DG | 0.072 | 0.088 | **0.160** (-31%) | 34.90 | 1.19 | **36.09** (-3%) | 6.48 | 5.92 | **12.41** (-29%) |
| | Hot-Dry | ACB, Filler slab, Wall ins, Roof ins, DG | 0.072 | 0.066 | **0.138** (-36%) | 34.90 | 0.89 | **35.79** (-3%) | 6.48 | 4.44 | **10.93** (-33%) |
| | Temperate | ACB, Filler slab., Roof ins, DG | 0.069 | 0.069 | **0.139** (-20%) | 34.27 | 0.93 | **35.20** (-3%) | 6.32 | 4.65 | **10.96** (-18%) |
| | Cold | ACB, Filler slab, Wall ins, Roof ins, DG | 0.072 | 0.068 | **0.140** (-26%) | 34.90 | 0.91 | **35.81** (-2%) | 6.48 | 4.53 | **11.02** (-23%) |

Notes: E = Embodied; O = Operational; I = Investment; ACB = Aerated concrete blocks; SEB = stabilised-earth blocks; ins = insulation; DG = High-performance double-glazing window. *Social discount rate used for LCC calculation.

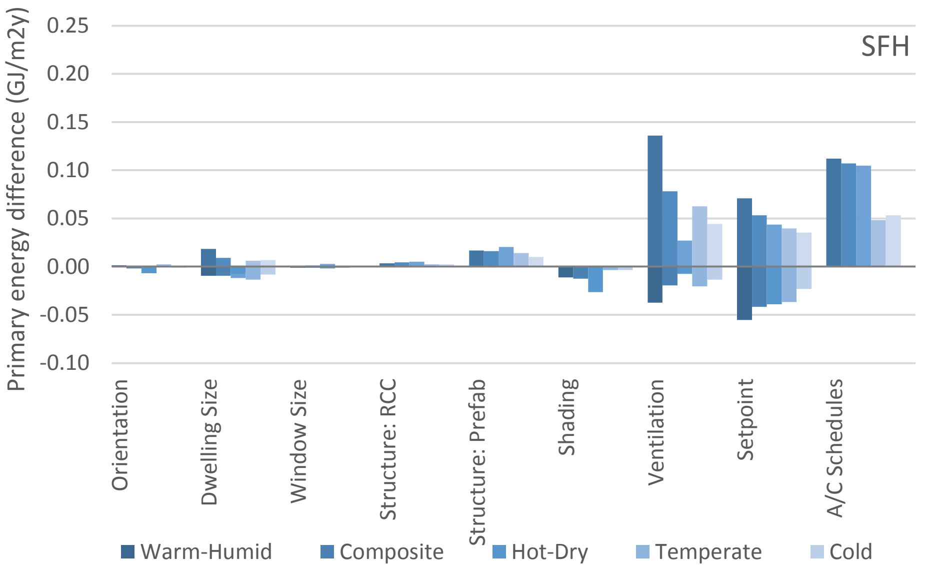
Table SM15 – Results of calculation for different climatic zones, assuming dwelling floor surface of 40m$^2$. Minimum LCC.

| **Archetype** | **Climate** | **Energy/Cost savings measures** | **LCE** (GJ/m$^2$y) | | | **LCC*** ($/m$^2$y) | | | **$CO_2$ Emissions** (kg$CO_2$/m$^2$y) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | E | O | **TOTAL** (difference with REF %) | I | O | **TOTAL** (difference with REF %) | E | O | **TOTAL** (difference with REF %) |
| SFH | Warm-Humid | SEB, Filler slab | 0.060 | 0.204 | **0.264** (-13%) | 20.99 | 2.74 | **23.73** (-20%) | 5.55 | 13.67 | **19.22** (-10%) |
| | Composite | SEB, Filler slab | 0.060 | 0.174 | **0.234** (-16%) | 20.99 | 2.33 | **23.33** (-21%) | 5.55 | 11.64 | **17.19** (-13%) |
| | Hot-Dry | SEB, Filler slab, Roof ins | 0.063 | 0.091 | **0.153** (-41%) | 21.63 | 1.22 | **22.85** (-22%) | 5.72 | 6.08 | **11.81** (-36%) |
| | Temperate | SEB, Filler slab | 0.060 | 0.088 | **0.148** (-17%) | 20.99 | 1.18 | **22.17** (-21%) | 5.55 | 5.88 | **11.43** (-11%) |
| | Cold | SEB, Filler slab | 0.060 | 0.132 | **0.192** (-16%) | 20.99 | 1.78 | **22.77** (-21%) | 5.55 | 8.86 | **14.41** (-12%) |
| MFH | Warm-Humid | SEB, Filler slab | 0.068 | 0.174 | **0.243** (-6%) | 30.53 | 2.34 | **32.87** (-12%) | 6.46 | 11.69 | **18.15** (-5%) |
| | Composite | SEB, Filler slab, Roof ins | 0.069 | 0.119 | **0.188** (-19%) | 30.73 | 1.60 | **32.33** (-13%) | 6.52 | 7.97 | **14.49** (-17%) |
| | Hot-Dry | SEB, Filler slab, Roof ins | 0.069 | 0.088 | **0.157** (-28%) | 30.73 | 1.18 | **31.91** (-13%) | 6.52 | 5.88 | **12.39** (-24%) |
| | Temperate | SEB, Filler slab | 0.068 | 0.085 | **0.153** (-11%) | 30.53 | 1.14 | **31.67** (-13%) | 6.46 | 5.67 | **12.13** (-9%) |
| | Cold | SEB, Filler slab, Roof ins | 0.069 | 0.081 | **0.150** (-20%) | 30.73 | 1.09 | **31.82** (-13%) | 6.52 | 5.42 | **11.94** (-17%) |

Notes: E = Embodied; O = Operational; I = Investment; SEB = stabilised-earth blocks; ins = insulation; DG = High-performance double-glazing window. *Social discount rate used for LCC calculation.

### *3.4 Sensitivity of contextual conditions for different climatic zones*

Figure SM3 shows the results of varying contextual conditions on cooling/dehumidification energy requirements, as compared to the reference case. Sensitivity is shown for different housing archetypes and climatic zones.



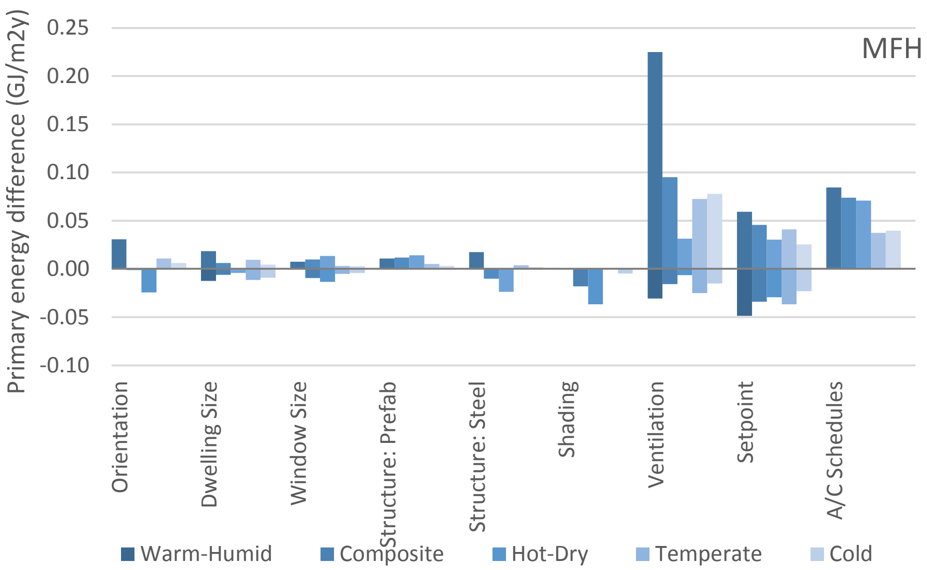




Figure SM3 – Sensitivity of contextual parameters on cooling/dehumidification energy requirements for SFH (above) and MFH (below), under different climatic zones.

### *3.5 Sensitivity of energy saving measures for different climatic zones*

Figures SM4a-e shows the effect of energy saving measures on cooling/dehumidification and heating energy requirements, as compared to the reference case. Sensitivity is shown for different housing archetypes and climatic zones.

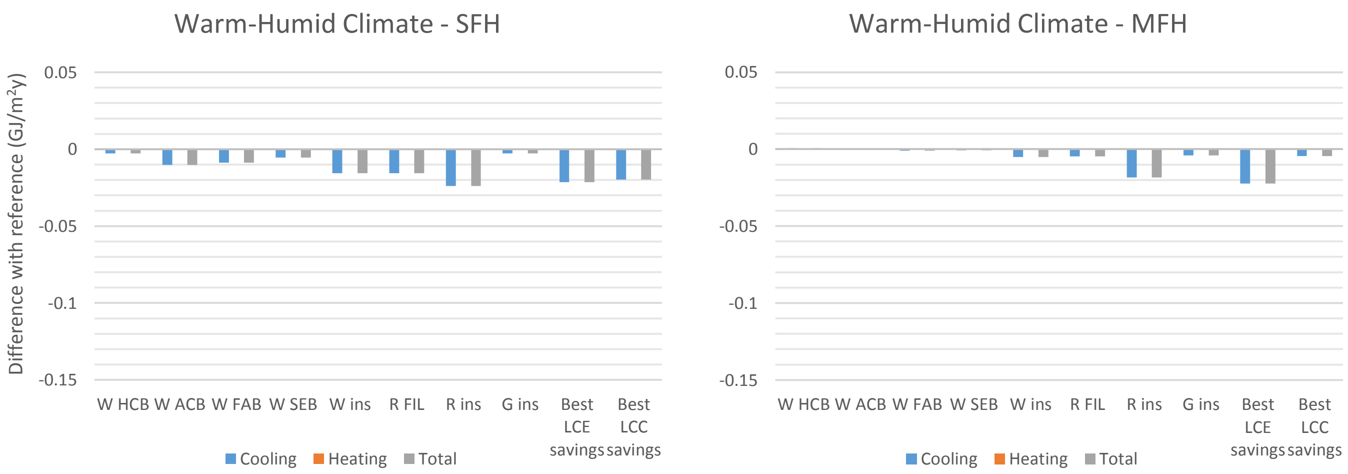



Figure SM4a – Sensitivity of energy savings measures on energy requirements for space cooling/ dehumidification and heating for SFH (left side) and MFH (right side) - Warm-Humid climate.

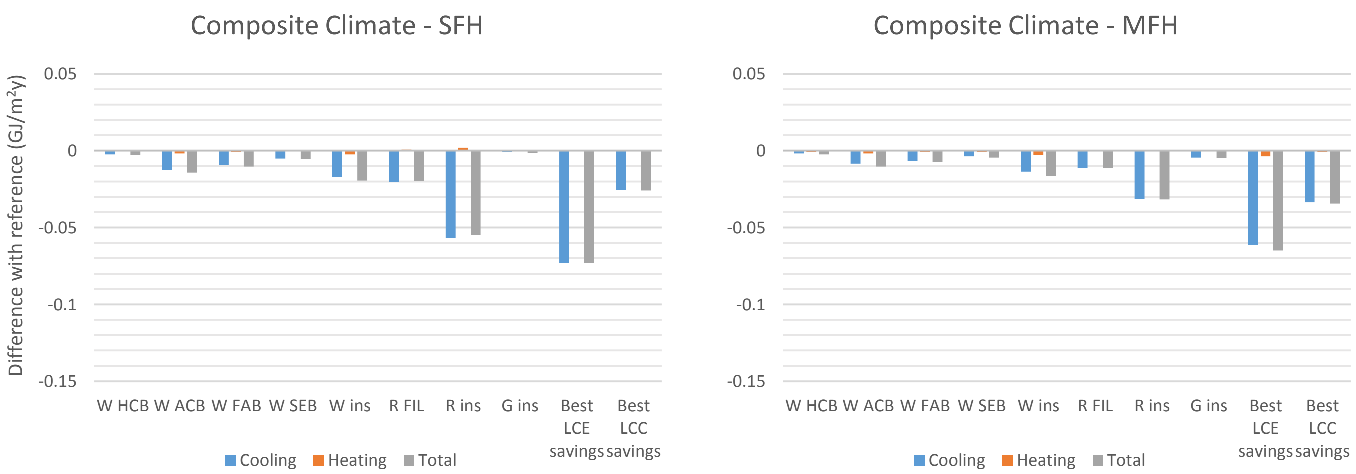



Figure SM4b – Sensitivity of energy savings measures on energy requirements for space cooling/ dehumidification and heating for SFH (left side) and MFH (right side) - Composite climate.

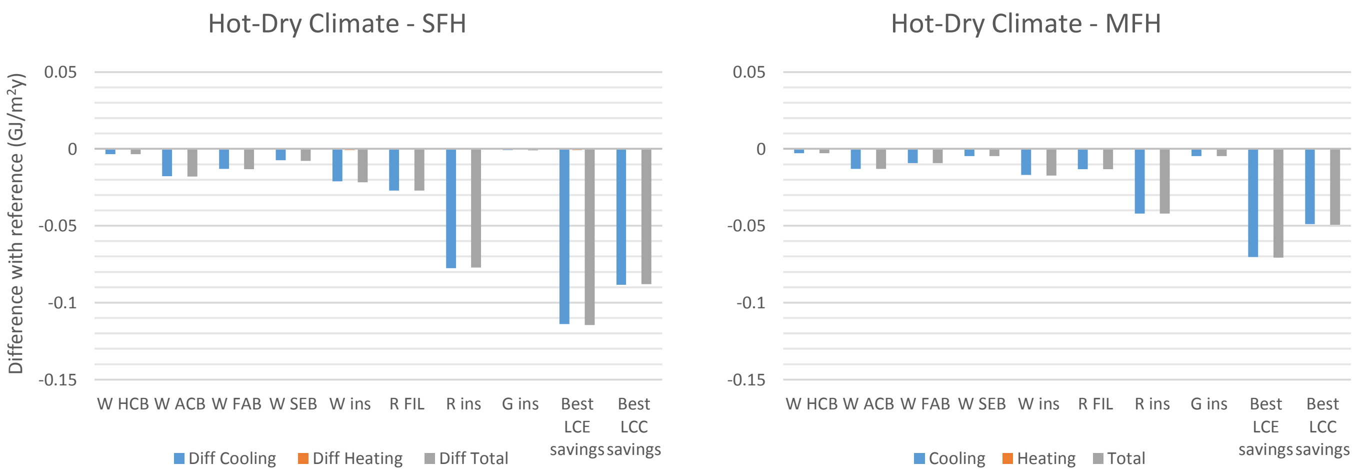



Figure SM4c – Sensitivity of energy savings measures on energy requirements for space cooling/ dehumidification and heating for SFH (left side) and MFH (right side) – Hot-Dry climate.

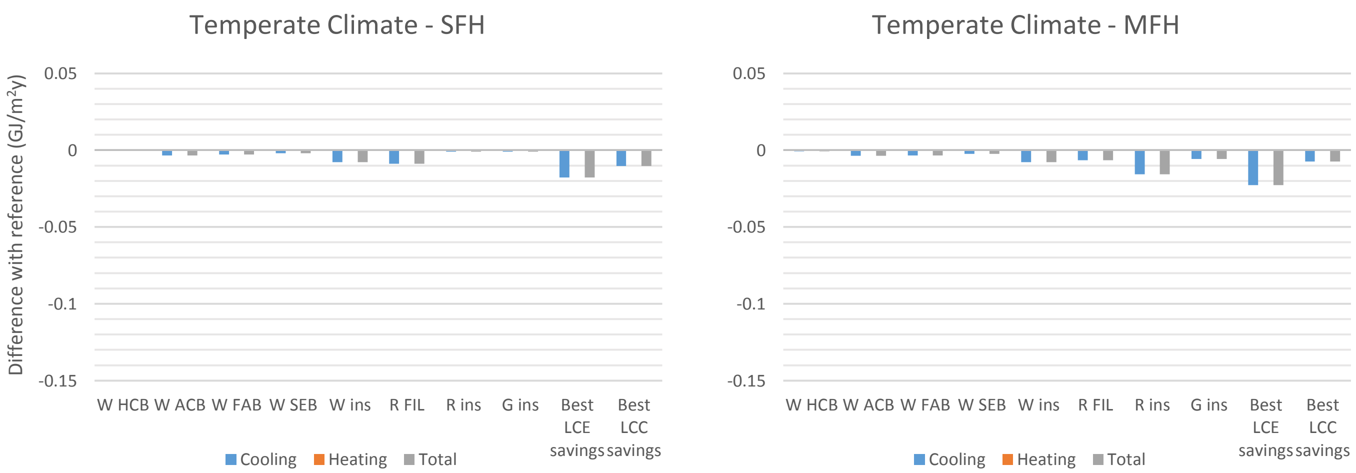



Figure SM4d – Sensitivity of energy savings measures on energy requirements for space cooling/ dehumidification and heating for SFH (left side) and MFH (right side) – Temperate climate.

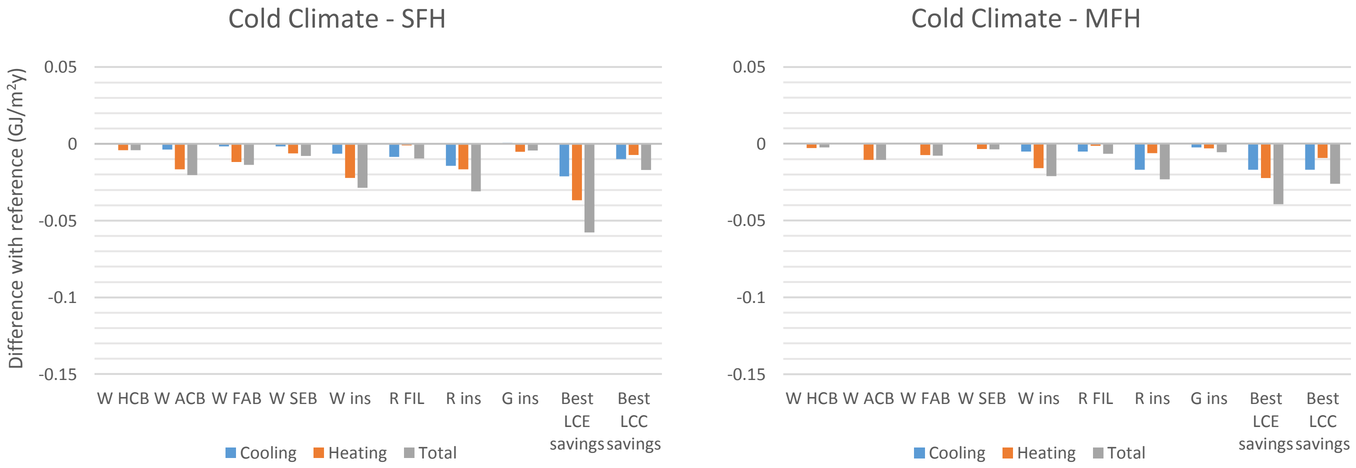



Figure SM4e – Sensitivity of energy savings measures on energy requirements for space cooling/ dehumidification and heating for SFH (left side) and MFH (right side) – Cold climate.

### *3.6 Pareto optimal solutions*

Pareto optimal solutions for different archetypes and climatic zones are reported in Figs. SM5a-j. Results were obtained by running simulations for all possible combinations of energy saving measures for each archetype (SFH and MFH) and climatic zone. Pareto optimal solutions for minimum LCE and LCC were computed using the R package *rPref* [1], functions *psel* and *plot_front*.

[1] R package "rPref" available at https://CRAN.R-project.org/package=rPref (last consulted: April 2018).

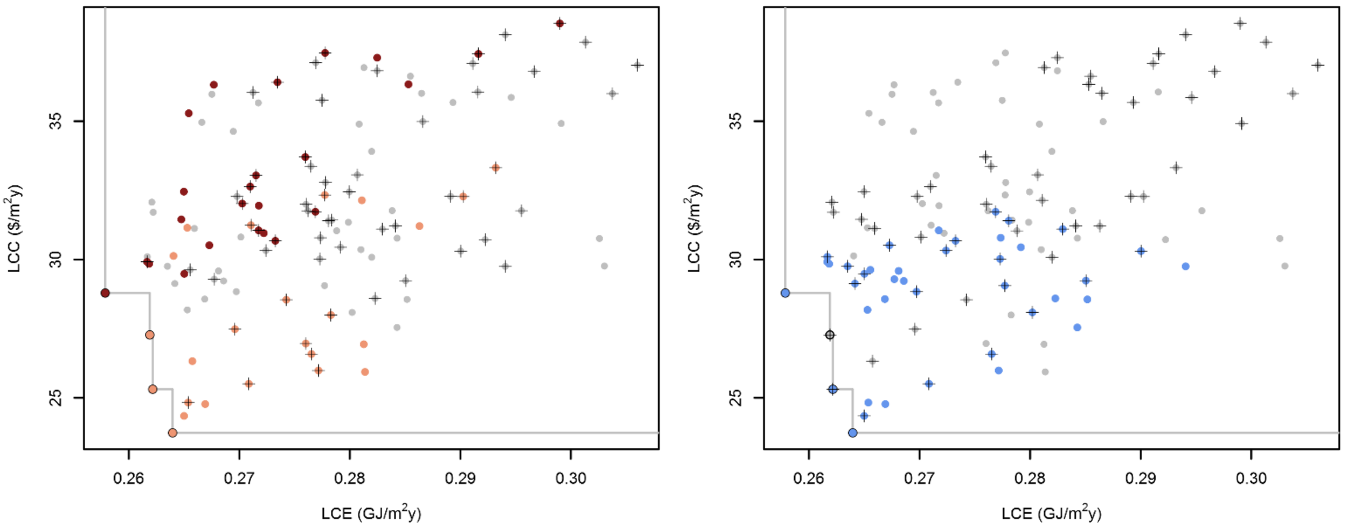



Figure SM5a – Pareto-optimal solutions for walls (left) and roof (right) * – SFH – Warm-humid climate.

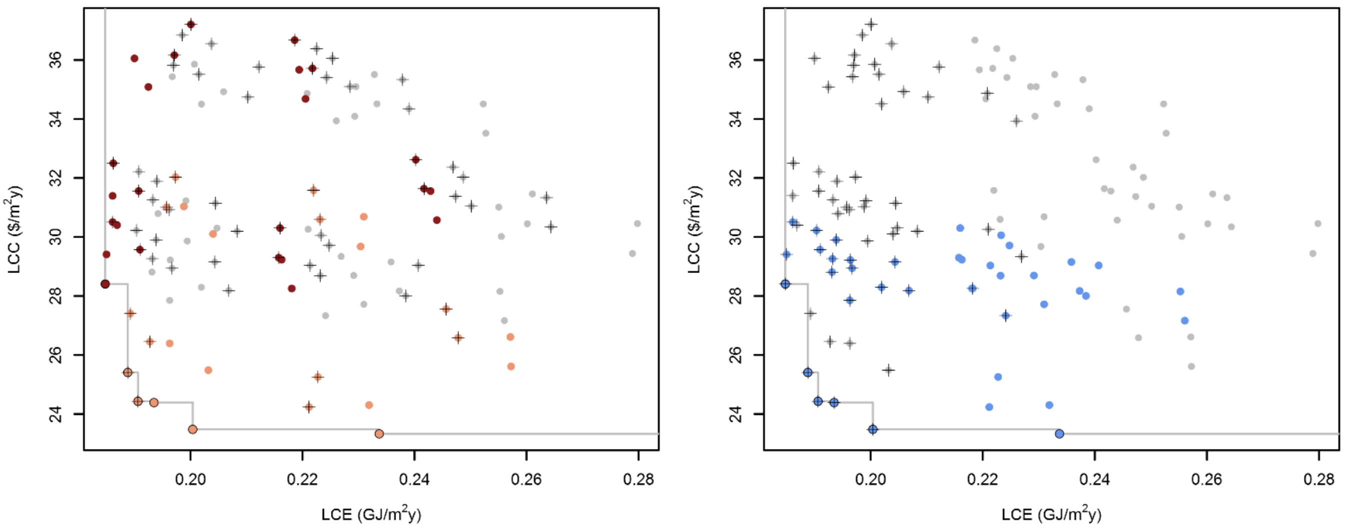



Figure SM5b – Pareto-optimal solutions for walls (left) and roof (right) * – SFH – Composite climate.

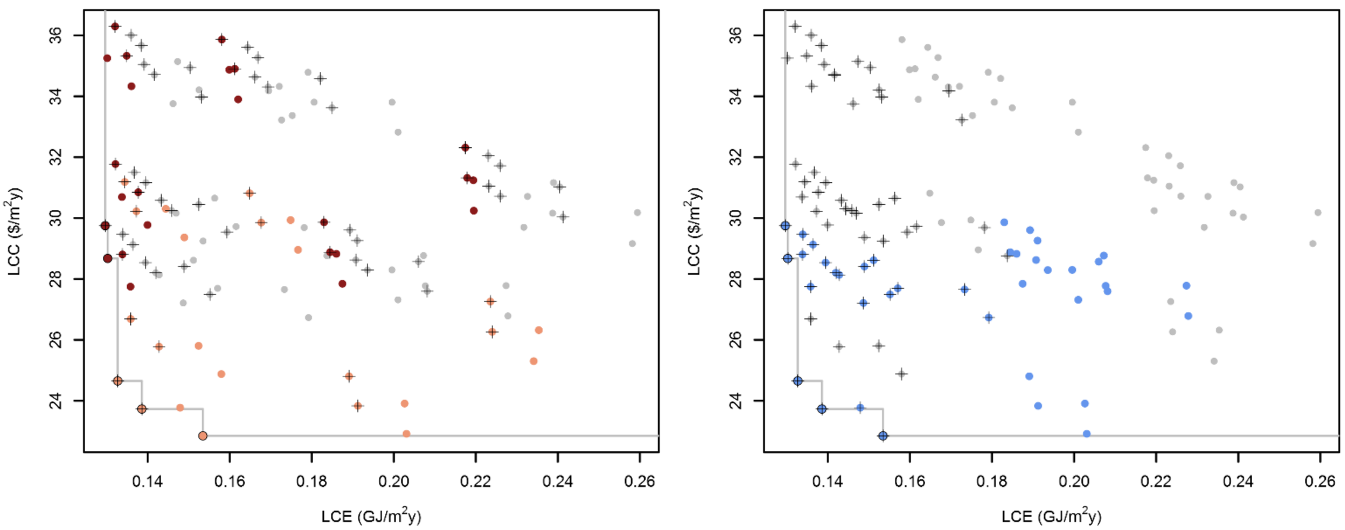



Figure SM5c – Pareto-optimal solutions for walls (left) and roof (right) * – SFH – Hot-Dry climate.

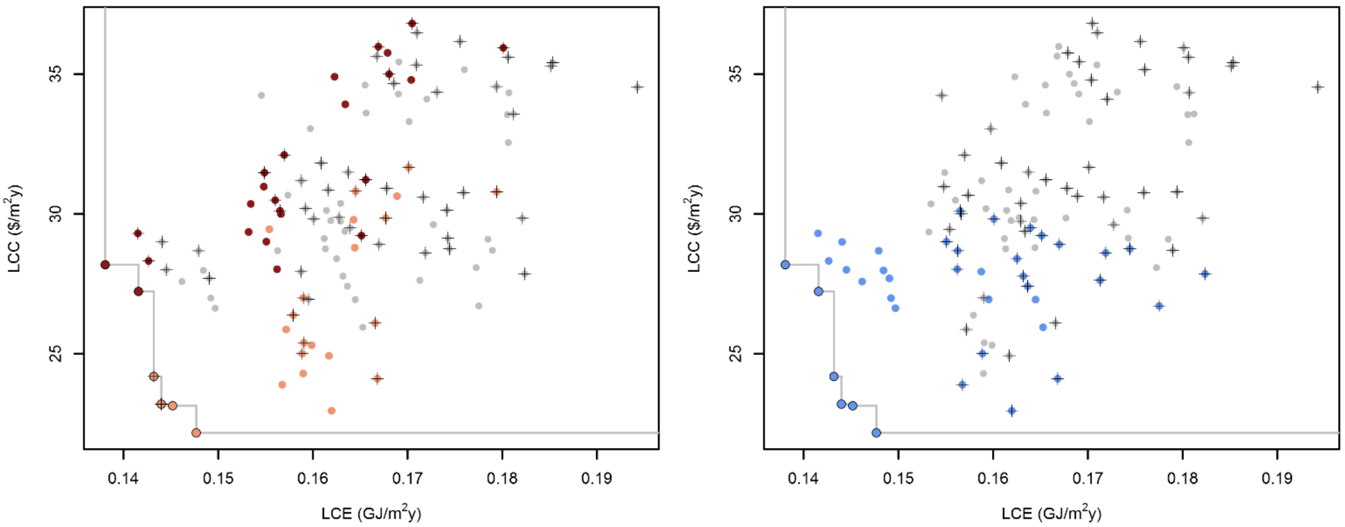



Figure SM5d – Pareto-optimal solutions for walls (left) and roof (right) * – SFH – Temperate climate.

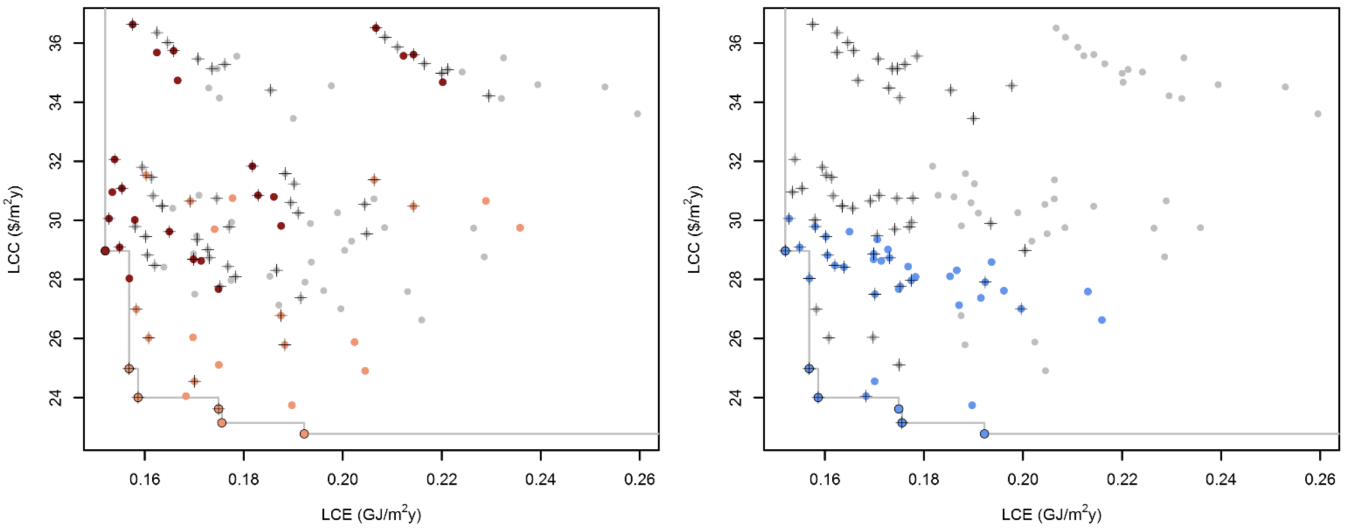



Figure SM5e – Pareto-optimal solutions for walls (left) and roof (right) * – SFH – Cold climate.

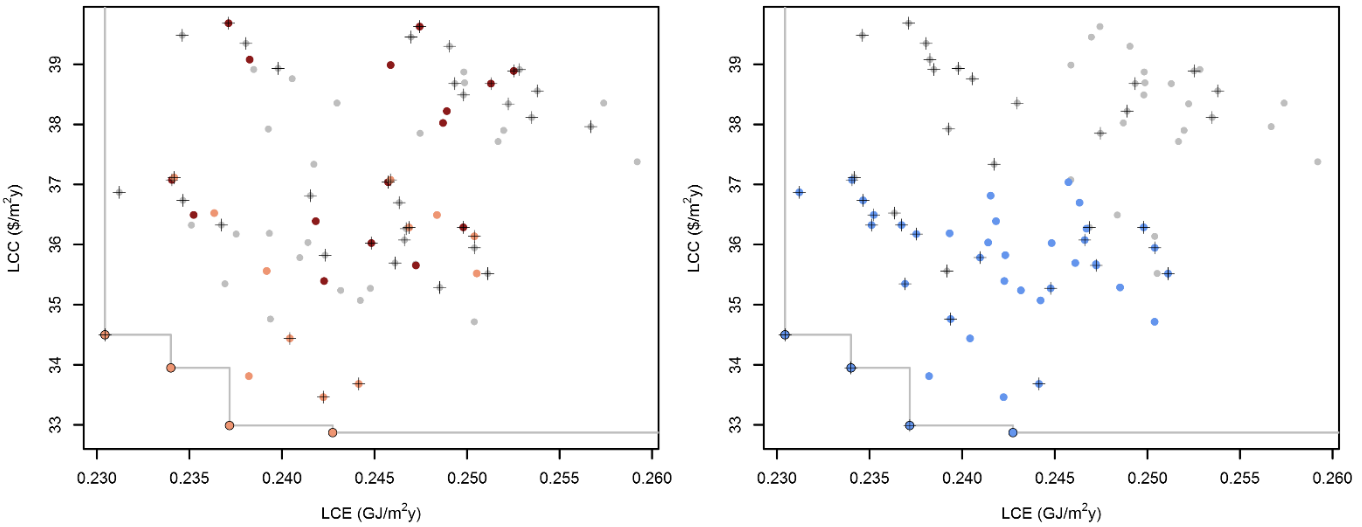



Figure SM5f – Pareto-optimal solutions for walls (left) and roof (right) * – MFH – Warm-Humid climate.

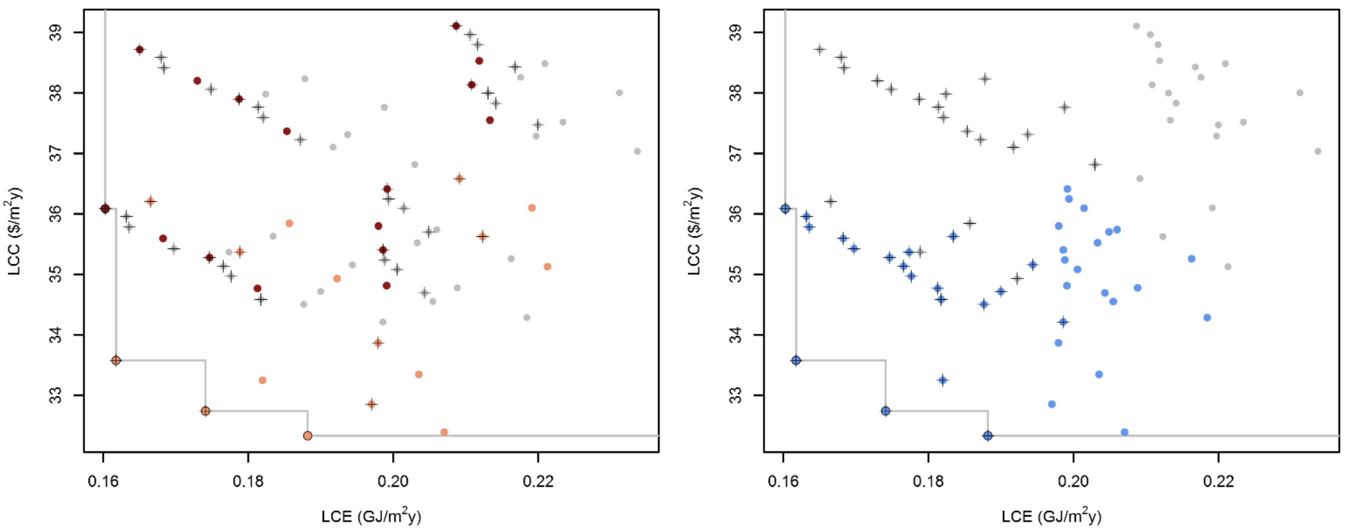



Figure SM5g – Pareto-optimal solutions for walls (left) and roof (right) * – MFH – Composite climate.

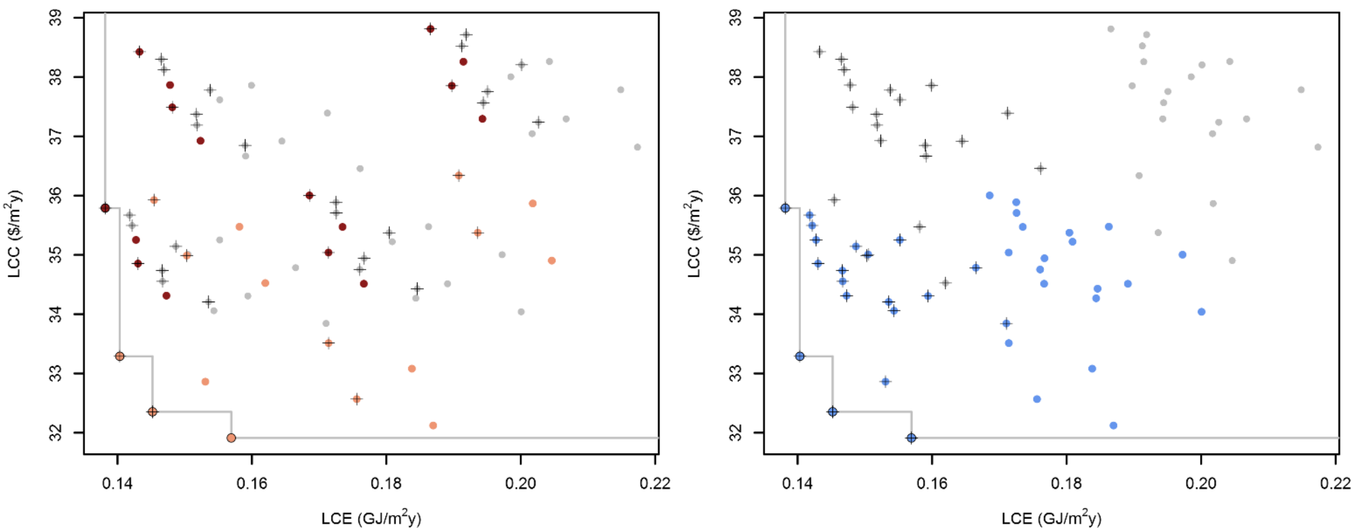



Figure SM5h – Pareto-optimal solutions for walls (left) and roof (right) * – MFH – Hot-Dry climate.

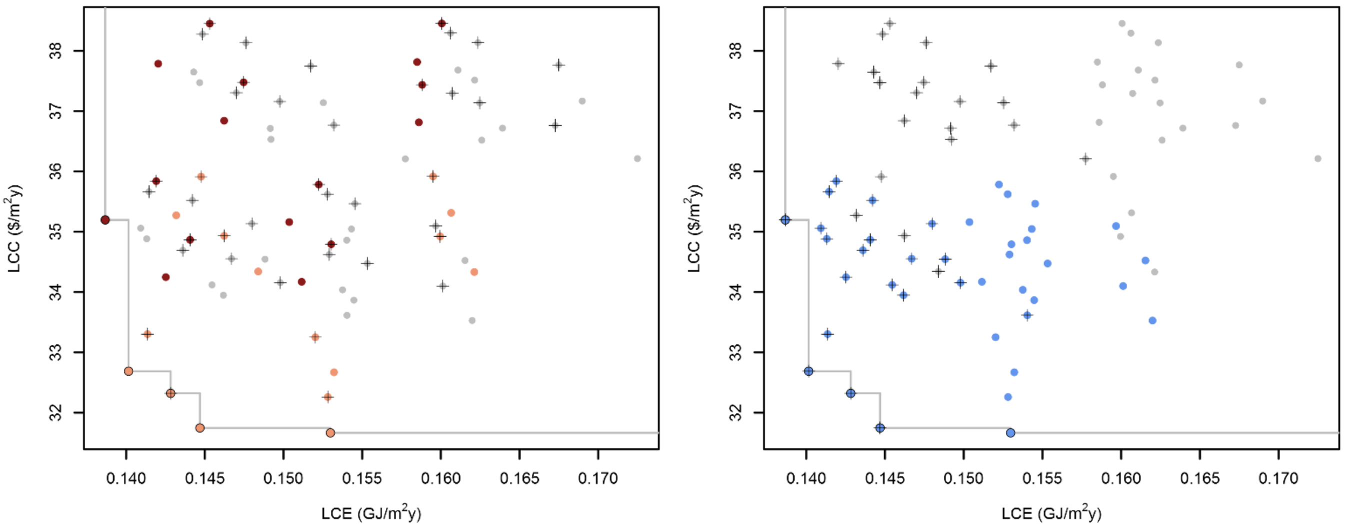



Figure SM5i – Pareto-optimal solutions for walls (left) and roof (right) * – MFH – Temperate climate.

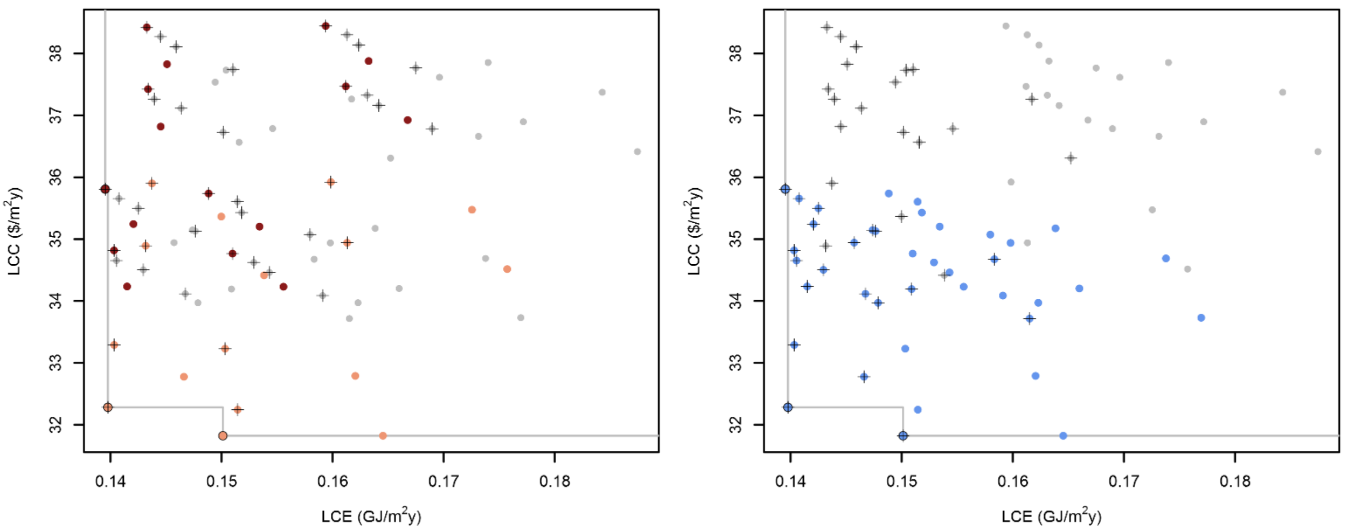



Figure SM5j – Pareto-optimal solutions for walls (left) and roof (right) * – MFH – Cold climate.

Notes: * Pareto frontier indicated by points with dark border linked by a grey continuous line. Each set of left and right figures reports the results of the full set of simulations for a given archetype (SFH and MFH) and climatic zone. Adopted solutions for walls are marked on the left side: dark red indicates ACB, light orange indicates SEB, light grey other wall technologies, a plus (+) indicates wall insulation. Adopted solutions for roofs are marked on the right side: blue indicates filler slab roofing, light grey RCC slab, a plus (+) indicates roof insulation.

### *3.7 Comparison of operational energy results with other studies*

Operational energy results for the SFH and MFH archetypes (reference case) in different climatic zones were compared with measured consumption obtained from other studies for India (Praseeda et al., 2016), mostly showing a good agreement (Figure SM6).

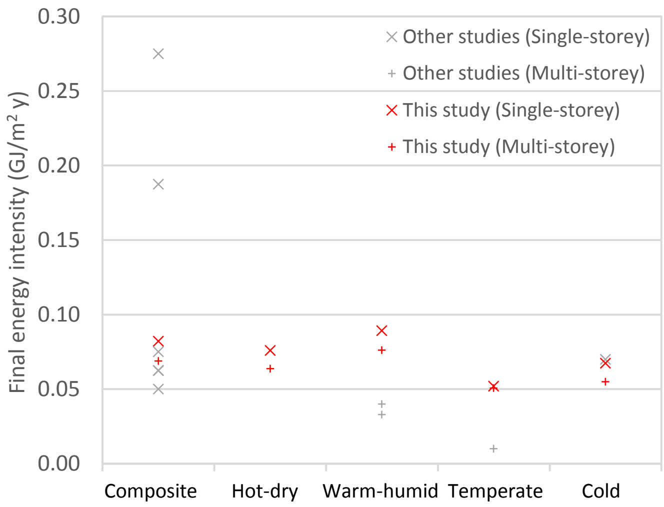



Figure SM6 – Comparison of final energy results with values from other studies (Praseeda et al., 2016) for different climatic zones in India.

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