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Life cycle greenhouse gas emissions of energy retrofitting strategies for residential buildings in India: A case study

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Abstract: Significant research and regulatory efforts have focused on reducing operational emissions in new residential buildings. However, the consideration of broader life cycle greenhouse gas (GHG) emissions of these buildings has been limited in the context of India, due to insufficient publicly available data. Energy retrofitting is a conventional approach for reducing the operational emissions of building, however, the impacts of embodied and life cycle GHG emissions are rarely considered. In this research, a low-rise reinforced concrete residential building located in the temperate climatic zone of India is assessed to analyse the net life cycle GHG emission implications of 216 retrofitting scenarios, each resulting in a distinct retrofitted building model. Streamlined life cycle assessment, along with DesignBuilder for dynamic energy simulation, are used to quantify the life cycle GHG emission impacts of the adopted scenarios. A total of 213 retrofitting scenarios resulted in a net life cycle benefit, whereas 3 scenarios associated with combined strategies of fenestration weatherstripping, and roof insulation did not yield any life cycle GHG benefits when compared to the base building. This may help inform the development of targeted policies, and actions to more consciously improve India's existing residential stock.

Keywords: Greenhouse gas emissions; energy retrofitting; residential buildings; India.

1. Introduction

Climate change caused by global warming has impacted everyone beyond national and socio-economic barriers. Currently, the built environment is one of the major anthropogenic emitters, generating approximately 42% of the total greenhouse gas emissions (GHGE), producing around 14 metric GtCO$_2$e of GHGE yearly (Boland et al., 2023). Residential buildings alone contributed to 75% of the operational greenhouse gas emissions (OGHGE), whereas the embodied greenhouse gas emissions (EGHGE) are uniformly shared among residential, non-residential, and other built environment elements (Boland et al., 2023). This emphasises the need for improving the building stock to reduce GHGE.

It is critical to acknowledge that OGHGE of any building is also highly dependent on the quality of building, especially in terms of the building envelope properties, as it is one of the primary contributing factors in indicating the heat gain, loss, and thermal comfort of the occupants (GBPN, 2014). Since the building energy consumption and demand are deeply influenced by the envelope characteristics, it is critical to focus on the retrofitting strategies of the existing building stock by upgrading insulation, and façade elements for improved performance. It is of utmost importance to emphasise the life cycle perspective instead of solely targeting the energy and building OGHGE (Schmidt *et al.*, 2020). EGHGE are often disregarded in the environmental performance measures, and hence, it is yet to be determined if the existing residential buildings, when retrofitted, will encounter any LCGHGE benefits across a 50-year period. A considerable amount of research has been performed in terms of exploring the life cycle energy of the residential buildings in India under varying climatic conditions and utilising alternative building materials as substitutes for concrete. However, none of these studies evaluated the life cycle GHGE of adopting energy retrofitting strategies in the context of multi-storey residential buildings. Therefore, the aim of this study is to assess the LCGHGE performance of energy retrofitting a residential building in India.

2. Research approach

2.1 Assessing life cycle embodied greenhouse gas emissions

Streamlined life cycle assessment (LCA) is adopted in this study as it is primarily used to assess one or multiple environmental impacts such as global warming, acidification, etc (Crawford, 2011). Process analysis has been selected as the most appropriate method to assess the life cycle embodied greenhouse gas emissions (LCEGHGE) for the Indian building industry due to availability of comprehensive life cycle inventory (LCI) databases by IFC (2017). When data is unavailable, alternative databases such as Inventory of Carbon and Energy (ICE) and Ecoinvent by Hammond and Jones (2008) and Wernet *et al.* (2016), respectively, are adopted. The LCEGHGE is calculated by using Equation (1), which includes initial and recurring EGHGE.

$$\mathrm{LCEGHGE} = \sum \mathrm{m_i EGHGEC_i} + \sum \mathrm{m_i EGHGEC_i}\left(\frac{\mathrm{L_b}}{\mathrm{L_m}} - 1\right) \tag{1}$$

Where LCEGHGE = Life cycle embodied GHGE of the building (tCO_2e); m_i = quantity of building material (i) in functional unit kg, m, m^2, m^3, tonne or L; $EGHGEC_i$ = embodied GHGE coefficient of building material (i) per unit quantity ($kgCO_2e/kg$ or $kgCO_2e/m^3$); L_b = building service life; L_m = material service life.

2.2 Assessing life cycle operational greenhouse gas emissions

The OGHGE of a building is based on the climatic zone, building envelope properties, orientation, building geometry, usage of appliances, occupancy count, operating hours, and occupant behaviour. It is important to note that liquid petroleum gas (LPG) is used in all Indian urban residential buildings as the form of cooking fuel and the entire operational energy is based on usage of appliances, air conditioners, mechanical ventilation, lighting, household hot water heating, along with the factors dependent on the building characteristics and users' habits (MoSPI, 2012; Ramesh *et al.*, 2012). In this study, a dynamic energy simulation is performed for assessing the annual operational energy of the base building using DesignBuilder due to its extensive material library. The weather files are derived from ISHRAE (2014), whereas, the model of the base building is developed based on the architectural drawings. The occupancy is considered to be 5 based on the average household size per the MoHUA (2013). Additionally, bedrooms are assumed to be the only conditioned area during 10 PM – 1 AM and 1 PM – 4 PM based on findings by

Khosla *et al.* (2021). The operational energy use is converted to primary energy (PE) by using 3.72 as the factor, to consider transmission and distribution losses (McNeil and Sathaye, 2009). Once the primary operational energy use is assessed, LCOGHGE can be calculated using Equation (2). The GHGE factors for Indian electricity grid and primary energy are 0.83 $kgCO_2e/kWh$ and 58 tCO_2e/TJ, respectively (IEA, 2017; CEA, 2019).

$$\mathrm{LCOGHGE} = \mathrm{POPE} \times \mathrm{EF} \times \mathrm{L_B} \tag{2}$$

Where, LCOGHGE = Life cycle operational greenhouse gas emissions (tCO_2e); POPE = annual primary operational energy (MJ); EF = greenhouse gas emission factor of primary energy (tCO_2e/TJ); L_B = building service life.

2.3 Assessing life cycle greenhouse gas emissions

The LCGHGE of the base and retrofitted buildings is assessed by adding the LCEGHGE and LCOGHGE as shown in Equation (3).

$$\mathrm{LCGHGE} = \mathrm{LCEGHGE} + \mathrm{LCOGHGE} \tag{3}$$

Where, LCGHGE = Life cycle greenhouse gas emissions of building archetype (tCO_2e); LCEGHGE = life cycle embodied greenhouse gas emissions (tCO_2e); LCOGHGE = life cycle operational greenhouse gas emissions (tCO_2e). The net life cycle greenhouse gas emissions ($LCGHGE_{net}$) which determine the GHG benefits of retrofitting the base building, is determined by subtracting the total $LCGHGE_{RT}$ of retrofitted buildings from the $LCGHGE_B$ of the base building, as indicated in Equation (4). A positive value from this equation results in a benefit.

$$\mathrm{LCGHGE_{net}} = \mathrm{LCGHGE_B} - \mathrm{LCGHGE_{RT}} \tag{4}$$

2.4 A case study approach

The low-rise building considered for this case study is a reinforced concrete (RC) structure composed of three storeys and is currently located in Bengaluru, India in Figure 1.

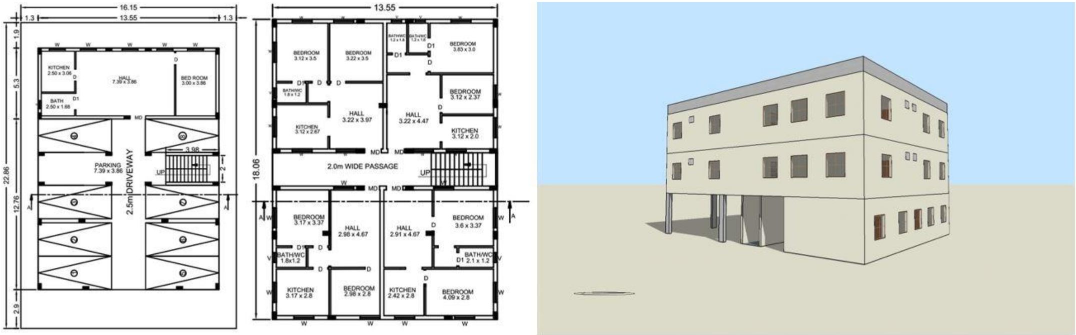

Figure 1: Floor plan and elevation of case study

The building envelope comprises of cement plastered burnt clay modular bricks as wall elements with 21 single glazed clear glass wooden framed windows. There are no balconies in this building and hence there exists one exterior door for each apartment, which results in a total of 13 exterior doors. The roof is a reinforced concrete slab with no reflective surface, thereby increasing heat absorption. There is neither any insulation nor weather stripping with respect to the existing building envelope. Furthermore, there is no external shading on the windows to prevent heat gain. An overview of the base building envelope elements is provided in Table 1, Section 2.5.

2.5 Building envelope retrofitting strategies and scenarios

In this study, retrofitting strategies (RS) are upgrades to the building envelope (BE) as it plays a vital role in energy consumption due to its thermal efficiency and air tightness attributes. The retrofitting scenarios (LT) are developed by combining one RS with another. Therefore, each scenario has either the base element of the base building or an RS from Table 1. The base elements roof, wall, etc, are labelled as R_0, W_0, respectively, in Table 1. Combining each strategy resulted in a total of 216 LTs, which excludes the base building. The high thermal mass properties of existing RC roof of the base buildings have high emittance, low reflectance, and high absorption, due to absence of any exterior insulation, reflective coating, or both (Shafigh et al., 2018). Therefore, a 20 mm acrylic reflective coating and 100 mm glass-fiber insulation have been selected as RS aiming to lower heat absorption and cooling transfer from conduction. The external insulation of 50 mm glass-fiber batt insulation on external walls has been coupled with autoclaved aerated concrete (AAC) or aerated cellular concrete (ACC) due to its humidity resistance, lower embodied energy, thermal and sound insulation, than the existing burnt clay bricks (BMTPC, 2021). The exterior windows and doors are susceptible of air leakage which in return leads to extensive energy loss. Therefore, weather stripping the exterior doors and windows promotes effective usage of existing HVAC system. This strategy has been combined with sun control film applied to the existing single glazing along with overhang shading on all windows. Passive measures like shading are added to restrict the heat gain from outside. The existing single glazing has been replaced by 3 mm and 6 mm grey glass with low-emissivity films respectively with insulated uPVC frames. These uPVC window frames are insulated with 20 mm elastomeric foam to reduce cooling energy loss from indoors. The tinted glazing has been added due to its lower solar heat gain co-efficient (SHGC) which aids in maintaining the indoor temperatures by avoiding heat gain through windows, especially in the summer periods in India.

Table 1: Retrofitting strategies for temperate climatic zone

	Retrofitting strategies	ID
Roof	127 mm cast in place concrete U-Value (W/m^2-K) = 4.334	R_0
	20 mm acrylic reflective coating U-Value (W/m^2-K) = 3.024	R_{RC}
	100 mm Glass-fiber batt insulation U-Value (W/m^2-K) = 0.391	R_{I2}
Exterior wall	Burnt brick wall of 101 mm thickness with 15 mm and 12 mm outside and inside plaster respectively U-Value (W/m^2-K) = 3.058	W_0
	50 mm Glass-fiber batt insulation U-Value (W/m^2-K) = 0.671	W_{I2}
	50 mm Glass-fiber batt insulation with AAC U-Value (W/m^2-K) = 0.436	$W_{I2\text{-}M1}$
	50 mm Glass-fiber batt insulation with ACC U-Value (W/m^2-K) = 0.552	$W_{I2\text{-}M2}$
Exterior door	Hardwood door U-Value (W/m^2-K) = 1.149	D_0

	20 mm Polyurethane foam U-Value (W/m^2-K) = 0.79	D_{WS}
Window	3 mm single glazed window with hardwood frames SHGC = 0.861 and U-Value (W/m^2-K) = 5.894	Wn_0
	3M Corporation scotch tint sun control film SHGC = 0.236 U-Value (W/m^2-K) = 2.439	Wn_{SC}-Wn_{ws}
	1 m overhang steel shading	Wn_S-Wn_{ws}
	3 mm grey glass with 3M Corporation low-emissivity film SHGC = 0.261 and U-Value (W/m^2-K) = 2.650 20 mm elastomeric foam on frame U-Value (W/m^2-K) = 1.481	Wn_{G1}-Wn_{ws}
	6 mm grey glass with 3M Corporation low-emissivity film SHGC = 0.238 and U-Value (W/m^2-K) = 2.307 20 mm elastomeric foam on frame U-Value (W/m^2-K) = 1.481	Wn_{G2}-Wn_{ws}
	3 mm grey glass with 3M Corporation low-emissivity film SHGC = 0.261 and U-Value (W/m^2-K) = 2.650 uPVC window frame with 20 mm elastomeric foam U-Value (W/m^2-K) = 1.454	$Wn_{G1\text{-}F1}$-Wn_{ws}
	6 mm grey glass with 3M Corporation low-emissivity film SHGC = 0.238 and U-Value (W/m^2-K) = 2.307 uPVC window frame with 20 mm elastomeric foam U-Value (W/m^2-K) = 1.454	$Wn_{G2\text{-}F1}$-Wn_{ws}
	3 mm grey glass with 3M Corporation low-emissivity film and 1 m steel overhang shading SHGC = 0.261 and U-Value (W/m^2-K) = 2.650 uPVC window frame with 20 mm elastomeric foam U-Value (W/m^2-K) = 1.454	$Wn_{G1\text{-}F1\text{-}S}$-$Wn_{ws}$
	6 mm grey glass with 3M Corporation low-emissivity film and 1 m steel overhang shading SHGC = 0.238 and U-Value (W/m^2-K) = 2.307 uPVC window frame with 20 mm elastomeric foam U-Value (W/m^2-K) = 1.454	$Wn_{G2\text{-}F1\text{-}S}$-$Wn_{ws}$
	20 mm elastomeric foam U-Value (W/m^2-K) = 1.481	Wn_0-Wn_{WS}

3. Results and discussion

The building life cycle is 50 years per the National Building Code of India and the first year of analysis is considered as 2022. Each retrofitting scenario (RS) has resulted in a new retrofitted building (LT) which has been denoted as LT1 to LT216 and is shared in Figshare. The LCEGHGE of the base building LT0 resulted in 335.78 tCO_2e, and 36 retrofitted buildings, namely, LT55 – 72 and LT199 – 216, have lower LCEGHGE than the base building as highlighted in Figure 2. Common strategies have been observed in these 18 buildings LT55 - 72, namely, no roof related RS has been adopted, whereas the external walls have been replaced with 50 mm glass-fiber batt insulation with ACC, along with weather stripping on windows. The variations are observed due to weather stripping in doors in LT64 – 72 and upgrades on windows per strategies mentioned in Table 1. Details on all LTs can be viewed in Figshare. The lowest LCEGHGE results in LT55 equating to 302.81 tCO_2e. This is around 10% less than LT0 and this is caused by the lower EGHGC of AACs as compared to common building materials as burnt clay bricks. In case of LT199 – 216, 100 mm glass-fiber batt insulation has been added to the existing roof along with the same wall strategy as LT55 – 72. This is the only strategy that is same across these 36 buildings that account for lower LCEGHGE than L0. Hence, it is important to note that adopting comparatively more building materials than the base building may not necessarily yield a higher GHGE as shown by 16% of the retrofitted buildings in this study. 84% of the retrofitted buildings have projected more LCEGHGE than the base building. The highest LCEGHGE accounted to be 403.52 tCO_2e in L126 retrofitted building with reflective coating on the existing roof, and AAC as exterior wall material along with 50 mm glass-fiber batt insulation. The windows and exterior doors are weather stripped, and single glazed are replaced by 6 mm grey glass with low-emissivity film along with the 1 m steel overhang shading. The EGHGE with respect to the external walls of LT216 is lower than LT0 due to adoption of AAC, however, the windows and exterior doors result in more than double of the emissions due to the higher volume of material quantities involved.

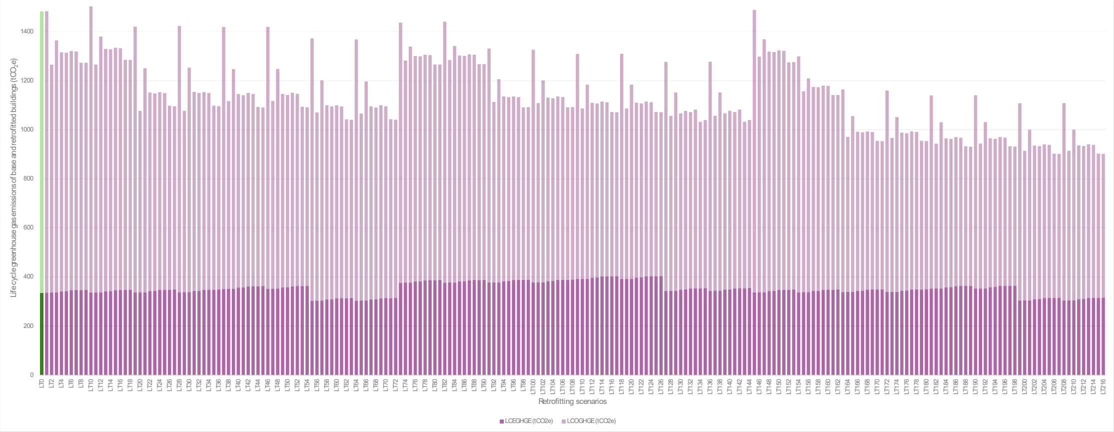

Figure 2: Life cycle embodied and operation GHG of base and retrofitted buildings across 50 years

The LCOGHGE is conventionally expected to decrease as energy retrofitting scenarios are applied. However, 3 buildings LT1, LT10, and LT145 resulted in higher LCOGHGE than the base building L0, as shown in Figure 2. Only weather stripping of windows is adopted in LT1, which has resulted in an increase of 1.58 tCO_2e when compared to the base building which emits 1145.30 tCO_2 during its 50 years life cycle. This can be explained by the increase in end use energy required for cooling as the dry bulb (indoor) temperature must have surpassed the cooling set back temperatures. Heat gain through windows and other opaque surfaces along with infiltration heat are some of the key determining factors for the increase in OGHGE. Similarly, the retrofitted building LT145 has weather stripped windows and 100 mm glass-fiber batt insulation on the existing roof, which also resulted in a higher LCOGHGE of 6.19 tCO_2e than the base building indicating an increase of 1% of GHGE. Therefore, this shows that the combination of window weather stripping and roof insulation has instead contributed to more operational emissions due to increased consumption of electricity for cooling. Furthermore, L10 with weather stripped doors and windows projects 21.05 tCO_2e more LCOGHGE than the base.

3.3. Net life cycle greenhouse gas emissions

The net LCGHGE determines if there are any LCGHGE benefits of applying the 216 retrofitting scenarios in comparison to the base building, as shown in Figure 3. Buildings LT1, LT10, and LT145 are the only 3 retrofitted buildings that do not result in emissions benefits. These buildings are the very same buildings that also exceeded the LCOGHGE in comparison to the base buildings as discussed in Section 3.2. However, it is critical to mention that retrofitted building L10 with the simplest weather stripping applied to external doors and windows has led to the least beneficial building resulting in a net negative benefit of 21.53 tCO_2e, due to its higher operational and embodied emissions than L0. This is caused due to the increased LCOGHGE as discussed in Section 3.2 as the LCEGHGE for L10 is only 0.48 tCO_2e more than L0 due to EGHGE of weather stripping. On the other hand, the highest amount of benefit has been witnessed in 72 retrofitted buildings which has resulted in more than 400 tCO_2e savings across 50 years of building life, when compared to the base building. The maximum benefit is seen in LT216, in which all the building envelope elements are retrofitted with 100 mm glass-fiber batt insulation on existing roof, replace the wall with 50 mm glass-fiber batt insulation with aerated cellular concrete, weather stripped the external doors and windows, and, replaced existing single glazing with 6 mm grey glass with low-emissivity film and 1 m steel overhang shading, which accounts for 579.61 tCO_2e.

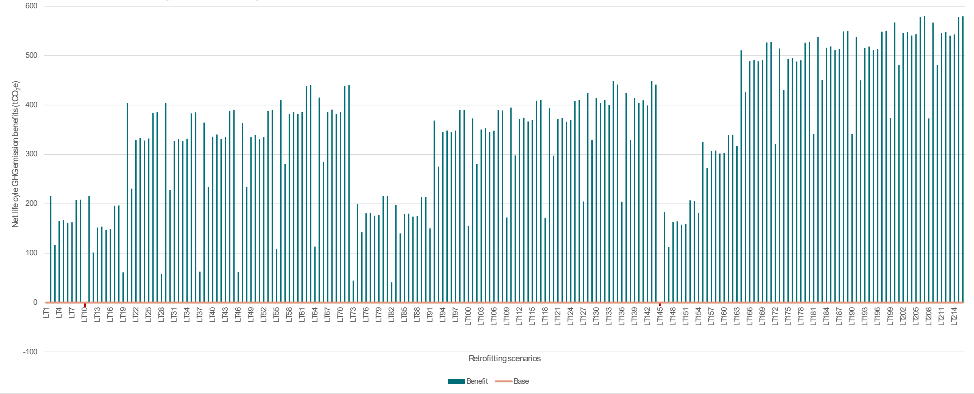

Figure 3: Net life cycle GHG benefits of retrofitted buildings

4. Conclusion

The building energy policies and regulations only focus on the operational emissions of the new buildings, without the holistic life cycle perspective of reducing emissions of existing stock by retrofitting strategies. Therefore, it is key to determine if there are any net LCGHGE benefits prior to the decision-making process. After assessing 216 retrofitting scenarios and each scenario representing a sole retrofitted building, it was found that 213 buildings projected net LCGHGE benefits and the highest GHG savings accounted for 579.61 tCO_2e from retrofitted building LT216. The retrofitting strategies associated with this building are 100 mm and 50 mm glass-fiber batt insulation on the existing roof and external walls, respectively. The burnt clay brick walls and single glazed windows of the base building are replaced by aerated cellular concrete and 6 mm grey glass low-emissivity film. Additionally, weather stripping to the external doors and windows is added, along with 1 m of overhang shading. However, 3 retrofitted buildings didn’t showcase any net GHGE benefits, leading to the conclusion that thermal and solar heat gain properties of building materials cannot be the only consideration parameters when it’s about selection of retrofitting strategies. Other factors like heat trapping especially in the tropical climatic zones and dynamic relations

hips between the building service elements must be assessed. It is also important to mention that availability of building material quantities, architectural drawings, occupancy schedules, etc is key in terms of implementation of further research that can explore financial implications on these results. Additionally, cost-benefit analysis can be performed to compare the GHGE impacts with economic benefits.

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