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Evaluating the operational and embodied emission trade-offs of energy retrofitting two residential building typologies

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Abstract: The residential building stock has been one of the major emitters in the built environment. There are multiple guidelines and regulations on environmental performance of new residential stock, however, the lack of standards and directives for energy retrofitting the existing stock is highly concerning. Implementation of energy retrofitting configurations (RCs) in the existing stock is imperative to achieve the net zero goals, especially, in the context of developing economies as India, where there is an absence of mandatory environmental performance standards for new builds. This study addresses this gap by applying 12 energy RC to two residential building typologies (BT1 and BT2) in the warm-humid climatic zone of India. Both the base typologies are retrofitted with 12 RCs targeting the external windows of the buildings, resulting in 24 retrofitted buildings, collectively. The RCs involve upgrading the existing glazing with sun control film, alternate glazing, adoption of reflective blinds, thermal breaks and weather stripping on existing window frames. The RCs are implemented in DesignBuilder to assess the operational emissions (OE), while the embodied emissions (EE) are quantified by process-based life cycle inventory methods relevant in the Indian context. Results indicate that 6 mm grey glazing and sun control film on existing glazing are most effective RCs for BT1 and BT2, respectively, however both project a marginal emission reduction. This is only due to a maximum OE reduction of 0.03% and 0.85% for BT1 and BT2, respectively, which is not substantial to overcome the surge in corresponding EE of RCs.

Keywords: Retrofit; embodied emissions; residential building; energy simulation

1. Introduction

The emission of greenhouse gases is one of the largest contributors to climate change and global warming. The continuous increase in natural resource depletion and fossil fuel consumption from human activities have resulted in sustainable development goal (SDG) 13 for climate action, initiated by the Paris Agreement (Sachs et al., 2022). China, United States of America and India are the three largest emitters of greenhouse gases (GHG) as of 2024 and has accounted for 49% of total GHG emissions of 79,120 $MtCO_2$-eq (UNEP, 2024). A substantial amount of these GHG emissions have resulted from existing built environment, especially from the residential stock. This is specifically relevant in the context of India due to its rapid increase in population, economic growth, rapid urbanisation and high energy consumption. The Indian residential stock solely attributed to approximately 95 $MtCO_2$-eq in 2021 (BloombergNEF, 2023), and has been anticipated to be responsible for 37% of the nation's electricity consumption by 2032 (BEE, 2024). It is important to note that these are the operational emission and energy distribution of the existing residential stock, thereby, consistently dismissing the embodied emission impacts. As electricity is one of the primary energy consumption parameters for the Indian residential stock, the operational phase of new buildings has been conventionally the emission mitigation targets. This approach has excluded the life cycle perspective, thereby leading to energy building codes that focus on new residential buildings as the Eco Niwas Samhita (ENS). Additionally, the voluntary nature of this energy building code understates the demand for improving the upcoming residential stock. This also highlights the importance of reduction of energy and emissions of the existing residential stock, which has been excluded from the current

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building regulations in India. However, it is imperative to emphasise on upgrade of the existing stock to achieve the 2070 net zero goals of India. The process of energy retrofitting is traditionally associated with the operational energy and emission improvement of an existing building (Seo et al., 2018) by upgrading the building envelope elements (windows, exterior doors, envelope walls and roof), adopting energy efficient household appliances and incorporating on-site renewable energy sources. The embodied effect of implementing energy retrofits is critical to identify the holistic emission reduction of the existing residential stock. There have been multiple studies that have evaluated the embodied impacts of residential retrofits across the building service life. For example, Seo et al. (2018) highlighted that the embodied emissions of retrofit configurations (RC) of existing residential stock in Melbourne, was estimated to be 11% of total operational (heating and cooling) emissions. However, limited studies have been conducted in the context of India in terms of evaluating the operational-embodied emission trade-off, especially, focusing on the multi-storeyed buildings and windows related RC. It is essential to assess a wide range of RCs in varying climatic and geographic locations to ensure the adaptation of adequate retrofit approach. The aim of this study is to assess the operational and embodied emission trade-offs associated with energy retrofit configurations of residential buildings, across the building service life.

2. Research approach

2.1. Overview of building typologies

Two reinforced concrete residential building typologies are evaluated in this study and are referred as ‘Building Typology 1’ (BT1) and ‘Building Typology 2’ (BT2) as shown in Figure 1 (a) and (b). BT1 is a six storeyed residential building with 42,738.55 m^2 of total building area with an unoccupied area of 8,190.53 m^2. Each floor of this building comprises of 60 apartment units, resulting in a total of 360 apartments. The 5 mm thick clear glazing with PVC frames are consistent across the glass sliding doors and all sliding sash windows of BT1, accounting for approximately 3,560 m^2 of glazing area with 10 being the window to wall ratio. Each apartment unit either has 2 or 3 bedrooms, and either 1 or 2 bedrooms in both scenarios have been considered to have space cooling as a split air conditioner. For example, 2 out of 3 bedrooms are air conditioned if an apartment unit has 3 bedrooms in total. On the other hand, BT2 is a 3 storeyed building with 500.48 m^2 total building area with 439.53 m^2 unoccupied area. This building has a total of 9 apartment units, with the 2 top floors being identical to one another with 2 bedrooms in each apartment. However, the ground floor in BT2 is a stilt floor which is considered as a parking space for the building. The window to wall ratio is 10% with 3 mm thick clear glazing and wood framed casement windows.

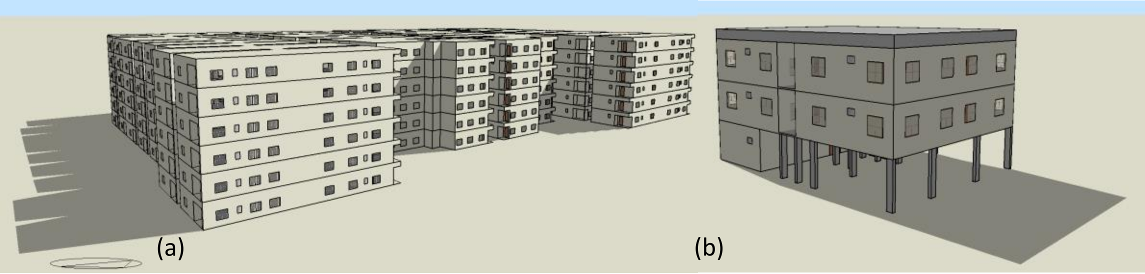


Figure 1: Base models of (a) building typology 1 (BT1) and (b) building typology 2 (BT2)

Both the buildings BT1 and BT2 neither have building envelope insulation nor shading over the windows. However, balconies are part of the building envelope in regard to BT1, which also contributes as a form of shading for any fenestration at the balconies. In case of BT2, the corridors have been considered as the part of the building envelope as the floor of level 1 is exposed to the external environment, moreover, both the top floors are partially enclosed. The building envelope walls of 229 mm thickness of BT1 is composed of fly ash bricks with 13 mm cement plaster at the interior and exterior of the building, whereas, BT2 is enveloped with burnt clay bricks with 12- and 15-mm cement plaster on the interior and exterior of the walls, respectively (Bora et al., 2024). Both the buildings are built from cast in place concrete with no reflective coating. In this study, the glazed sliding doors are also referred as windows, in case of BT1.

2.2. Energy retrofit configurations

The improvement of thermal performance by adoption of shading, upgraded glazing, integration of thermal break on frames and weather stripping have been reported to reduce approximately 15% of operational energy in residential buildings in Brazil (Sartori & Calmon, 2019). However, evaluating the embodied and operational embodied impacts of multiple windows RC have not been explored in case of residential buildings in India, yet. The baseline approach for retrofitting windows or existing glazing are upgrades to double or triple glazing. However, Nur-E-Alam et al. (2024) suggested that low emissivity films on existing glazing can be a potential retrofit configuration approach, which is further evaluated by application of RCs, as listed in Table 1. Cumulatively, 12 distinct RCs are implemented on both BT1 and BT2, resulting in a total of 24 retrofitted building (RB) typologies as shown in labels in Table 1 (12 RBs for each building typology). The base of BT1 and BT2 are represented as BT1_RC0_Base and BT2_RC0_Base, respectively, and must be noted that window system in both base typologies is not identical. The overview of the base typologies has been described in Section 2.1. The RCs implemented involve upgrading the existing glazing to low emissivity filmed double glazing with varying gaps (6 – 13 mm) either filled with air or Argon. This has been replicated in case of low emissivity filmed triple glazed RC, along with clear triple and double-glazed upgrades as different RCs. The existing glazing has been intact with respect to RC7, as a sun-control film has been applied on the exterior. Two categories of tinted single glazing are adopted in RC8-9 to assess the emission impact without opting for double glazing alternatives. Additionally, weather stripping and thermal breaks are embedded into existing window frames of BT1 and BT2 as distinct RCs in RC10-11, along with reflective blinds as presented in RC12. The objective is to systematically assess the 12 classifications of RCs in both BT1 and BT2 is to evaluate the embodied and operational emissions.

Thermal properties of glazing as Solar Heat Gain Coefficient (SHGC) defines the amount of solar radiation that is transmitted through the transparent surface and light transmission (LT) denotes the ratio between transmitted to incident light on the surface (BEE, 2018). It is essential to mention that the SHGC and LT for RC2, RC5, RC7, RC10 and RC11 vary in both BT1 and BT2, respectively as the base glazing, and frames are not similar, as already indicated previously.

Table 1: Overview of retrofit configurations

Retrofit configurations (RC1 – RC12)	Retrofit buildings typology 1	Retrofit buildings typology 2	Thermal properties of retrofit configuration
Base window properties	BT1_RC0_Base	BT2_RC0_Base	$SHGC_{BT1}$ = 0.841; LT_{BT1} = 0.884; U-$Value_{BT1}$ = 5.843 (W/(m^2·K)); $SHGC_{BT2}$ = 0.861, LT_{BT2} = 0.898, U-$Value_{BT2}$ = 5.894 (W/(m^2·K))
Double low emissivity 3 mm glazing/ 6 mm air	BT1_RC1_DG_Air6	BT2_RC1_DG_Air6	SHGC = 0.60; LT = 0.769; U-Value = 2.470 (W/(m^2·K))
Clear double 5-3 mm glazing/ 6 mm air	BT1_RC2_DGe_Air6	BT2_RC2_DGe_Air6	$SHGC_{BT1}$ = 0.734; LT_{BT1} = 0.787; U-$Value_{BT1}$ = 3.130 (W/(m^2·K)); $SHGC_{BT2}$ = 0.762, LT_{BT2} = 0.812, U-$Value_{BT2}$ = 3.159 (W/(m^2·K))
Double low emissivity 6 mm glazing/ 13 mm Argon	BT1_RC3_DG_Arg13	BT2_RC3_DG_Arg13	SHGC = 0.568; LT = 0.745; U-Value = 1.493 (W/(m^2·K))
Triple low emissivity 3 mm glazing/ 6 mm air	BT1_RC4_TG_Air6	BT2_RC4_TG_Air6	SHGC = 0.472; LT = 0.661; U-Value = 1.573 (W/(m^2·K))
Clear triple 5-3 mm glazing/ 6 mm air	BT1_RC5_TGe_Air6	BT2_RC5_TGe_Air6	$SHGC_{BT1}$ = 0.652; LT_{BT1} = 0.704; U-$Value_{BT1}$ = 2.158 (W/(m^2·K)); $SHGC_{BT2}$ = 0.682, LT_{BT2} = 0.738, U-$Value_{BT2}$ = 2.187
Triple low emissivity 3 mm glazing/ 13 mm Argon	BT1_RC6_TG_Arg13	BT2_RC6_TG_Arg13	SHGC = 0.579; LT = 0.698; U-Value = 1.058 (W/(m^2·K))
Sun control exterior film coating	BT1_RC7_SC_Film	BT2_RC7_SC_Film	$SHGC_{BT1}$ = 0.161; LT_{BT1} = 0.148; U-$Value_{BT1}$ = 2.988 (W/(m^2·K)); $SHGC_{BT2}$ = 0.161, LT_{BT2} = 0.15, U-$Value_{BT2}$ = 3.002 (W/(m^2·K))
Single low emissivity 6 mm glazing	BT1_RC8_SG_LowEm	BT2_RC8_SG_LowEm	SHGC = 0.65; LT = 0.840; U-Value = 3.447 (W/(m^2·K))
Single 6 mm grey glazing	BT1_RC9_SG_Tinted	BT2_RC9_SG_Tinted	SHGC = 0.602; LT = 0.431; U-Value = 5.778 (W/(m^2·K))
Polyurethane thermal break 20 mm thickness	BT1_RC10_TB_Frame	BT2_RC10_TB_Frame	U-$value_{BT1}$ = 2.612 (W/(m^2·K)); U-$value_{BT2}$ = 2.699

Vapour permeable felt weather stripping	BT1_RC11_WS_Frame	BT2_RC11_WS_Frame	U-value$_{BT1}$ = 3.36 (W/(m²·K)); U-value$_{BT2}$ = 3.506 (W/(m²·K))
Aluminium reflective blinds	BT1_RC12_SH_Indoors	BT2_RC12_SH_Indoors	k-value = 0.90 (W/(m·K))

Note: The base of each building typology has been represented as BT1_RC0_Base and BT2_RC0_Base, respectively. SHGC = Solar heat gain coefficient; LT = light transmission, U-value = thermal transmittance; k = thermal conductivity

2.3. Assessment of operational and embodied emissions

This study has two categories of assessment for each of the typologies BT1 and BT2 – operational and embodied emission assessment. The process of assessing the operational emissions for both typologies involved performing dynamic energy simulations in DesignBuilder and Energyplus as the simulation engine. The end-use operational energy is derived from the annual energy simulation results for each of the base and RCs for both BT1 and BT2, thereby, resulting in 26 (2 base and 24 RCs) simulations, cumulatively. It is crucial to emphasise that even though the RCs are identical for both typologies, the methodological approaches in performing the energy simulation for BT1 differed from BT2. BT1 has been simulated under the guidelines of DesignBuilder (2025), due its extensive floor area of 42,738.55 m^2 and 360 apartment units ranging in different layouts (bedroom numbers) as discussed in Section 2.1. The classification of residential activity templates (lighting, HVAC, hot water systems in bathrooms) for BT1 was categorised into 3 types, namely, living room, bedrooms with air conditioners for each apartment, and common corridors which are the only unoccupied space in BT1. Furthermore, 'zone multiplier' approach was utilised as per DesignBuilder (2025), to simplify the simulation process as floors between top and ground floors in BT1 (floors 2-5) are identical and are considered as adiabatic components in the simulation program. On the contrary, activity templates of BT2 are composed of bedrooms (with and without space cooling), bathrooms, kitchens, and lounge areas due to its comparatively less building floor area of 500.48 m^2. In both BT1 and BT2, the space cooling was switched on only during 10 PM – 1 AM and 1 PM – 4 PM (Bora et al., 2024). The annual operational energy use results deduced from DesignBuilder, was accounted for 50 years of building service life by adopting a multiplier of 50 in both the cases, and further, derived to primary operational energy using the primary energy factor (PEF) for India, as shown in Table 2. Correspondingly, the operational emissions are calculated using the relevant Indian electricity grid GHG emission factors as listed in Table 2. A summary of operational emission assessment parameters assessed in this study is presented in Table 2. Additionally, it is to be noted that, the key is to maintain consistency of simulation settings across all RCs for one building typology, which has been done in this study. However, the emissions of BT1 and BT2 are not compared due to the methodological differences in energy simulation.

Table 2: Key parameters in assessing operational emissions

Operational emission assessment parameters	
Assessment method	Dynamic energy simulation
Tool for dynamic energy simulation	DesignBuilder - EnergyPlus
Weather files	Lawrie and Crawley (2022)
Climatic zone	Warm-humid
Representative city of climatic zone	Kolkata
Type of simulation performed	Annual simulation
End use operational energy unit	kWh
Cooling set point and set back temperatures	24° C and 26° C
Primary energy factor for Indian electricity grid	3.72[a]
Operational energy use	Electricity usage for lighting, space cooling, mechanical ventilation, household appliances
Co-efficient of performance (COP) of cooling system	2.5
Greenhouse gas emission factor for Indian electricity grid	0.74 kgCO$_2$-eq/ kWh[b]

Note: a= McNeil and Sathaye (2009), b = CEA (2024)

In this study, the embodied emissions are assessed utilising the process analysis approach due to availability of relevant embodied emission database for the Indian building industry (Bora et al., 2024). The databases, functional units, and system boundaries associated with the respective databases are listed in Table 3. It is to be highlighted that Inventory of Carbon and Energy (ICE) Industrial Ecology (2024) is adopted when relevant embodied emission coefficients are unavailable in IFC (2017), developed by the International Finance Corporation (IFC). The embodied emissions across the building service life include initial, recurring, demolition and direct emissions (Crawford, 2011). The initial, recurring and direct emissions are quantified in for both BT1 and BT2, however, the emissions related to the demolition stage is excluded due to absence of relevant data for the Indian building sector. Additionally, Bora et al. (2023) highlighted that 99% of construction waste is not recycled in India, thereby, emphasising the necessity for demolition energy related information. A summary of required parameters to assess the embodied emissions are shown in Table 3. The building service life has been considered to be 50 years for BT1 and BT2 (NBC, 2016) and the material service life that depends on the type of building materials, are adapted from Rauf and Crawford (2015).

Table 3: Key parameters in assessing embodied emissions

Embodied emission assessment parameters	
Assessment method	Process analysis
Functional unit	$kgCO_2eq$
Embodied greenhouse gas emission coefficients database	IFC, ICE and EPDs of specific products
System boundaries for ICF and ICE	Cradle to gate (A1-A3)
Building material quantities	Quantified using site-specific and bill of quantities data sourced from construction project team
Building service life	50
Material service life	10-50
Greenhouse gas emission factor for transportation fuel	3.237 $kgCO_2eq/kg^a$
Note: IFC = Internation Finance Corporation, ICE = Inventory of Carbon and Energy, EPD = Environmental Product Declaration, a = Smart Freight Center India (2025)	

The direct emissions have been quantified assuming a distance of 100 km travelled one way to the construction site per Reddy and Jagadish (2003), and the emission factors for diesel as the transportation fuel is adopted, as shown in Table 3. Furthermore, the embodied emissions are assessed using Equation 1.

$$EE=\sum m_i EC_i + \sum m_i EC_i \left(\frac{L_b}{L_m}-1\right) + \sum m_i D_i EC_t \quad (1)$$

Where, EE = Embodied emissions in $kgCO_2$-eq, L_b = building service life = 50 years; m_i = building material quantities in kg, m, m^2, m^3, tonne; EC_i = embodied emission coefficient of material (i) per unit quantity ($kgCO_2$-eq/unit quantity); L_m = material service life; D = total distance travelled to construction site; EC_t = embodied emission coefficient for transportation fuel.

3. Results and discussion

3.1. Operational emission of energy retrofitted buildings

The building typologies BT1 and BT2 are simulated 13 times each as indicated in Section 2.2 in the warm-humid climatic zone of India with RCs applied as presented in Table 1. Prior to the RCs are applied, both building typologies are verified and validated using the Energy Performance Index (EPI) for residential buildings in warm-humid climatic zone based on BEE (2016). The operational emissions (OE) in BT1 and BT2 include the emissions associated with the electricity related to space cooling, domestic hot water system (HWS), interior lighting, household appliances and mechanical ventilation (fans), as presented in Figure 2 (a) and (b). It is critical to highlight that the RCs are applied to the uninsulated base BT1 with only improvements applied on the existing glazing surfaces. In BT1, the base building (without retrofit configuration) accounts to 247,825,149 $kgCO_2eq$ across the 50 years of buildings service life. The OE reduction was demonstrated by 10 RCs, apart from 2 RCs that involved thermal breaks (BT1_RC10_TB_Frame) and weather-stripped frames (BT1_RC11_WS_Frame), indicated a minimal increase of 1,044 $kgCO_2eq$. However, the overall OE reduction was limited to a maximum of only 0.03%, exhibited by the sun control film (BT1_RC7_SC_Film) on existing glazing for BT1. Additionally, the reflective blinds (BT1_RC12_SH_Indoor) exhibited a decrease of 0.02% OE when compared to the base BT1. This performance pattern resonates with the thermal properties of the RCs, for example, the SHGC and LT of RC7 was lowest indicating minimum heat gain and light transmission, as also shown in Table 1 in Section 2.2. Despite the improved SHGC and LT thermal properties of all RCs (except the reflective blinds), in comparison to the base (BT1_RC0_Base), the reduction in OE has not been significant. In broader context, the HWS, household appliances, lighting and mechanical ventilation (fans) related OE have shown no notable variation in all RCs.

However, the decrease in space cooling OE (1-2%) has been the sole contributing factor for the gross OE reduction in the 10 RCs apart from BT1_RC10_TB_Frame and BT1_RC11_WS_Frame. It has to be kept in mind that these reductions are statistically minute, however, it does result in a 17,588 kgCO$_2$eq reduction in space cooling OE over 50 years. Additionally, as shown in Figure 2 (a), the cooling, HWS and lighting, appliances and fans, is responsible for approximately 0.46%, 35% and 64% of total OE, respectively. This reduced distribution of cooling OE is due to application of simulation settings of ‘zone multiplier’ and ‘merged zones’ due to simplification of simulation process, that potentially causes reduced cooling loads as the simulation engine analyses the diverse building spaces as a combined space (DesignBuilder, 2025). In a study by Culp and Cort (2015), it was emphasised that a distinct or substantial energy reduction (cooling and heating energy) may not necessarily incur from sun control low emissivity (Low-E) glazed windows in the warmer climatic zones in the US. The study underlined the importance of case-by-case analysis of energy performance of residential buildings in the warmer zones, specifically focusing on window retrofits. Furthermore, a retrofit window study on an uninsulated residential building in mixed-humid climate of Seoul, Korean with maximum temperatures ranging from 22-26° C in summer, indicated 8-17% cooling-heating energy decrease with windows with higher U-values (Ahn et al., 2016). However, in this climatic context, the heating demand is substantially higher than the cooling demand, unlike the study by Culp and Cort (2015), which weighs on lower SHGC as a parameter for windows in warm zones.

In BT2, the OE reduction ranged from 0.03-0.9% from the base building which emits 3,075,660.83 kgCO$_2$eq across 50 years. The highest OE savings of 0.9% in this case is also exhibited by the exterior sun control film RC (BT2_RC7_SC_Film), resulting in a reduction of 26,396 kgCO$_2$eq in comparison to the base of BT2. As presented in Figure 2 (b), household appliances, fans and lighting contribute to about 60% of the total OE in all buildings, whereas, space cooling and HWS is responsible for 39% and 3% of OE, respectively. BT2_RC11_WS_Frame and BT2_RC10_TB_Frame demonstrates no OE change when compared to the base BT2. The RC that involves upgrades to existing glazing that showed the maximum OE improvement of 0.25% is BT2_RC9_SG_Tinted, 6 mm grey tinted glazing with no alterations to the existing wooden frames. The wooden frames potentially require maintenance to sustain over long periods of time due to its susceptibility to rot, however, have better thermal performance than uPVC frames of BT1. It is worth noting that the SHGC and LT of double and triple low-E glazing RCs as shown in Table 1, is higher than the 6 mm grey tinted glazing. This is comparable to the findings of Ahn et al. (2016), who emphasises on U-value as an indicator than the SHGC of the glazing, particularly for uninsulated or poorly insulated buildings. Additionally, OE corresponding to the space cooling and household appliances, lighting and fans, have projected improvements in emissions, however, the HWS OE remains consistent throughout all RCs.

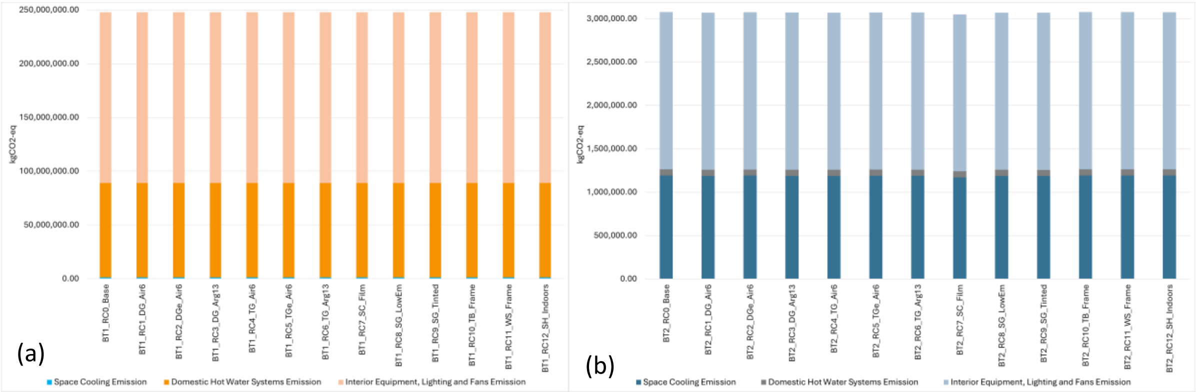
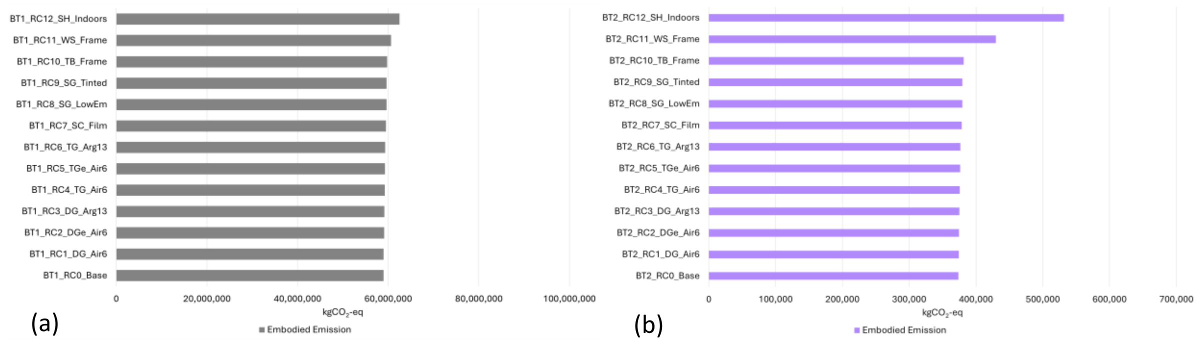


Figure 2: Distribution of operational emissions of (a) building typology 1 (BT1) and (b) building typology 2 (BT2)

It is of paramount importance to bring into attention that the studies by Ahn et al. (2016) and Culp and Cort (2015) have solely evaluated the operational energy impact of window retrofits. Both the studies have assessed the heating and cooling energy performance of RCs, thereby, presenting the necessity for emission impacts for the same. Furthermore, window system of a residential building has a substantial amount of impact on the social, aesthetic and thermal comfort of the occupants. This also emphasises on the complexity of energy retrofit configuration selection and promotes context, building and climate specific solutions.

3.2. Embodied emissions of energy retrofitted buildings

The embodied emission of both BT1 and BT2 include the initial, recurring and direct emissions across the 50 years of building service life. It is imperative to acknowledge that, conventionally, embodied emissions are expected to increase during retrofitting as additional building material quantities are introduced as a part of the RCS. In BT1_RC0_Base, 66.5%, 31.14% and 2.4% and of the total embodied emissions (EE) of 58,976,579.65 kgCO$_2$eq is attributed to initial, recurring and direct emissions, respectively. The recurring emissions are considered for aluminium louvers, uPVC window frames, wooden door frames, and paint depending on the replacement years as indicated in Rauf and Crawford (2015). The highest EE is demonstrated by RC BT1_RC12_SH_Indoors (aluminium reflective shading), with a 6% increase in comparison to the base BT1, whereas the lowest EE is found to be only 0.02% more than the base building, shown by BT1_RC9_SG_Tinted (6 mm grey tinted glazing). The EE corresponding to the RC12 of aluminium reflective shading only attributes to approximately 6% of the total EE of the entire retrofitted building BT1_RC12_SH_Indoors, while 96% of the total EE of 62,501,223.52 kgCO$_2$eq is stemmed from the base BT1 building. The maximum distribution of EE is associated with the reinforcement steel, concrete and cement, however, no recurring emissions have been considered for these building materials. The calculation of EE has been based on the retrofitted buildings as a new building, thereby, omitting the initial EE of the original building that has been replaced or upgraded by the specific RC. For example, if the RC is about upgrading the existing single glazing with a grey tinted glazing, the initial EE related to the original single glazing has not been considered while calculating the EE, however, the initial EE related to the grey tinted glazing has been utilised in the calculations. The EE in case of BT1_RC6_TG_Arg13 and BT1_RC4_TG_Air6 has been considered the same as in both the cases triple low-E glazing of 3 mm thickness have been incorporated, however, the EE associated with Argon as the air gap in the glazing panels are excluded and has been considered as negligible in this study. An overview of the EE distribution of the base and RCs of BT1 are presented in Figure 3 (a) and (b). Additionally, beyond the conventional building materials in BT1, the building materials comprised of granite, wooden laminated flooring, and substantial ceramic tiles which contributed to a substantial share of the EE. It is to be noted that, similar to the OE, the geographical implications are also associated with the EE due to the varying raw material consumption, transportation, manufacturing, construction and installation processes in India.



(a) (b)

Figure 3: Distribution of embodied emissions of (a) building typology 1 (BT1) and (b) building typology 2 (BT2)

In BT2, the base BT2_RC0_Base accounts for 373,624.88 kgCO$_2$eq with a distribution of 85%, 12.5% and 2.5% of initial, direct and recurring EE as shown in Figure 3 (b). The increase in EE ranges from 0.13% to 42% across the 12 RCs in BT2, with the highest EE of demonstrated by BT2_RC12_SH_Indoors, in comparison to the base BT2. This is due to the aluminium reflective blinds that have substantially high embodied coefficients and have a replacement year of 25 years across the building service life. The other building materials with the highest embodied coefficients such as concrete are conventionally considered to sustain across the 50 years without any replacement. In case of the BT2_RC11_WS_Frame, the weatherstripping has been added to the base BT2, which has resulted in a 15% increase in EE when compared to the base BT2, whereas, the RCs with upgrades related to triple glazing (BT2_RC4_TG_Air6 and BT2_RC6_TG_Arg13) have exhibited a negligible increase of 1.6%. It is to be noted RC11 weather stripping is an additional material added to the existing base of BT2, however, in case of RC4 and RC6, the existing glazing has been upgraded to triple glazing, therefore, the initial EE of the existing glazing has been excluded in the calculations as it quantification is performed keeping in mind that RC4 and RC6, respectively, developed 2 new retrofit buildings BT2_RC4_TG_Air6 and BT2_RC6_TG_Arg13. The minimum change in EE has been presented by BT2_RC9_SG_Tinted of single 6 mm grey glazing, with a 0.13%

higher EE than the base BT2. It is essential to emphasise on the EE difference among the retrofitted buildings with upgraded glazing and with intact window systems with improved framing. Conventionally, in studies evaluating the EE impacts of multiple RCs, the windows are upgraded to double or triple glazing depending on climatic conditions, focusing on the EE rise (Sartori & Calmon, 2019). However, it is crucial to identify the EE impacts when minor upgrades have been made to the existing building, because, as seen in this study, minor upgrades or minimal changes to the existing building do not necessarily result in embodied emissions.

3.3. Trade-off between operational and embodied emissions of energy retrofits

In this study, the operational and embodied emissions of each RCs of BT1 and BT2 are compared in order to evaluate the comprehensive emissions impact. Figure 4 (a) and (b) presents the emissions comparison of all RCs of both the buildings. The retrofit building BT1_RC9_SG_Tinted with RC9 of 6 mm grey tinted glazing solely demonstrated a favourable outcome, thereby offsetting the higher EE caused by RC9 due to OE savings. This resulted in an overall emissions reduction of 16,965 kgCO$_2$eq and a marginal decrease of 0.005% in comparison to base BT1. Despite the highest OE reduction in case of BT1_RC7_SC_Film of sun control film on existing glazing, the EE trade-off indicates a net negative impact, highlighting the importance of consideration of EE especially in the favourable OE RC outcomes. A comparable outcome is demonstrated by BT1_RC1_DG_Air6 double low-E 3 mm glazing, BT1_RC4_TG_Air6 triple low-E 3 mm glazing and BT1_RC12_SH_Indoors aluminium reflective blinds RCs, with better OE performance due to RCs, however, a net positive trade-off outcome is not observed due to significant rise in EE. In particular, BT1_RC12_SH_Indoors aluminium reflective blinds presented a 6% increase in EE, while a minor 0.02% decrease in OE is exhibited across 50 years, when compared to the base BT1. This is observed predominantly in all cases of RCs with reduction of only 0.01-0.03% in OE, while an increase of 0.02-6% in EE. It is to be also noted that the OE across 50 years in all RCs and including the base BT1, exceeds the EE by a substantial distribution as it accounts for almost 4 times of EE. It is essential to point out that the glazing area for BT1 accounts for 3,560 m^2 so an increase of 6% in EE in case of BT1_RC12_SH_Indoors results in 3,524,644 kgCO$_2$eq. Therefore, a notable amount of decrease in OE must occur to offset the EE in this building, which has not been reported by all RCs.

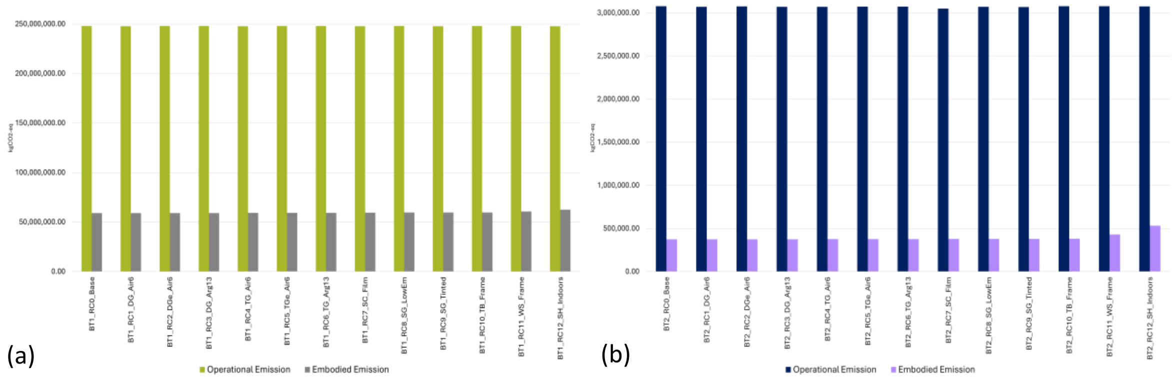


Figure 4: Distribution of operational and embodied emissions of (a) BT1 (b) BT2

The comparison of OE and EE in case of BT2 indicate that 6 out of 12 RCs present a positive trade-off impact indicating a reduction range of 46-25,512 kgCO$_2$eq, however, this represents a marginal decrease of 0-0.74% decrease in overall emissions reduction across 50 years in comparison to base BT2. The highest overall benefit among the 6 RCs has been presented by BT2_RC7_SC_Film sun control film on existing glazing that shows a reduction of approximately 0.9% in OE and increase of 0.24% in EE. The next maximum positive impact has been indicated by BT2_RC9_SG_Tinted grey single glazing with a minimal OE saving of 0.25% and increase of 0.13% in EE. It is to be noted that for BT2, the glazing area adheres to around 40 m^2, thereby, indicating the lower impacts in EE after RCs are adopted in majority of the RCs, with an exception in case of BT2_RC11_WS_Frame weather stripping in existing frame and BT2_RC12_SH_Indoors aluminium reflective blinds. This is due to the increase in overall EE of 15% and 42%, respectively. This is a substantial amount of increase due to the high embodied emissions coefficients extruded aluminium and EPDM rubber as weather sealant. The embodied coefficients of EPDM have been taken into account due to the unavailability of relevant vapour permeable felt data. With respect to all cases of BT2, including the base building, the OE across 50 years accounts to almost 8 times the

EE, thereby indicating the significantly high OE and hence, poor environmental performance of the retrofitted and base building BT2. In situations of application of thermal break and weather stripping in the existing wooden frame in BT2_RC10_TB_Frame and BT2_RC11_WS_Frame, respectively, an unfavourable emissions outcome was identified in both OE and EE. As additional material quantities are added in both RCs, the EE is projected to increase, however, in these two specific RCs, there is a minimal increase in OE.

It is crucial to acknowledge that both BT1 and BT2 are reinforced concrete residential buildings in India with notable difference in floor area, size and building materials. Furthermore, there is a distinct methodological difference OE assessment as mentioned in the research approach Section 2.3. Therefore, a comparison among the RCs and the two building typologies have not been carried out to avoid misleading interpretations. However, it is to be emphasised that both BT1 and BT2 are assessed in the warm-humid climatic conditions in India, thereby, it is key to deduce any parallels between both typologies. The RC7 sun control film on existing glazing in both BT1 and BT2 has demonstrated a favourable outcome, however, the emission reduction in both cases is not significant. On the other hand, the RC12 aluminium reflective blinds has been identified as the most unfavourable RC for both the typologies.

3.4. Limitations and further research

The assessment of EE is strictly based on availability of relevant embodied emission coefficients (EEC), and alternate EEC has been adopted if relevant Indian EEC is unavailable. Additionally, fly ash bricks are used for the building envelope in-situ BT1, however, due to absence of fly ash bricks in the material library of DesignBuilder, aerated bricks are adopted due to its identical thermal properties. It is important to acknowledge that windows predominantly contribute to thermal comfort of occupants and have aesthetic implications of the building. However, thermal comfort, air leakage and physical testing of windows have not been performed in this study and can be a scope of future research. Additionally, financial and social implications of retrofitting are critical in selection of RCs, however, in context no significant reduction in OE and EE, this could be redundant.

4. Conclusion

The present study assessed the operational and embodied emissions of two building typologies BT1 and BT2 after application of 12 retrofitting configurations (RCs) in the warm-humid climatic zone of India. The RCs involved upgrading the existing glazing by adding solar control film, or replacing it with clear triple, double, and low-E filmed glazing configurations. Furthermore, keeping the original glazing intact, the existing window frames are upgraded with thermal break, weather stripping or aluminium reflective shading RCs. It is to be noted that there is a substantial difference of glazing surface area in both building typologies, with BT1 and BT2 accounting for 3,560 m^2 and 40 m^2, respectively. In case of BT1, 10 out of 12 RCs have projected an operational emissions (OE) reduction apart from BT1_RC10_TB_Frame thermal break and BT1_RC11_WS_Frame weather stripping on existing frames. However, a marginal highest reduction rate of 0.03% has occurred among the 12 RCs that demonstrated OE savings. As anticipated, the embodied emissions (EE) increased across all RCs by 0.02-6%, and BT1_RC12_SH_Indoors aluminium reflective blinds showcased the highest distribution of EE. While comparing the OE and EE trade-off for all RCs in BT1, the sole configuration of 6 mm grey glazing BT1_RC9_SG_Tinted exhibited a reduction of 16,964.95 $kgCO_2eq$ as compared to the base BT1_RC0_Base. However, this resulted in only a 0.005% saving, which can be considered as statistically negligible. It has been indicated that both the building typologies' environmental performance have not been compared due to the differences in the methodological approaches in assessing the OE and dynamic energy simulation settings as indicated in Section 2.3. In case of BT2 as well, the only two RCs that have not projected a reduction in OE is RC10 thermal break and RC11 weather stripping on existing window frames. The remaining 10 RCs projected a reduction of 0.6-0.85% in OE, and the most favourable outcome on this basis has been presented by BT2_RC7_SC_Film with sun control on existing glazing. The EE have increased throughout all RCs from a range of 0.13-42%, with the peak EE demonstrated by BT2_RC12_SH_Indoors. There are 6 RCs that exhibited a reduction in overall emissions, primarily due to the higher OE savings than the increase in EE. Among the 6 RCs, the most favourable outcome has been indicted by the same RC that has induced highest OE reduction of 0.85% by BT2_RC7_SC_Film sun control on existing glazing. Some of the key takeaways from this study are as follows:

- Weather stripping and thermal break as retrofit configurations on uPVC and wooden frames are unfavourable for warm-humid climatic conditions of India
- 6 mm single grey tinted glazing has been beneficial after operational and embodied emission trade-off for both building typologies, however, projects marginal amount of emission reduction

- Window retrofits as individual upgrades are inadequate for the warm-humid climatic conditions of India and must be couple with other retrofit configurations to yield significant results.

It can also be concluded that RCs are significantly specific to the building and climatic conditions, as one configuration that is beneficial to a climatic zone, potentially may not yield positive results for another. This study also indicates the importance of evaluating the embodied emissions impact of RCs and even OE impacts in context of developing economies as India.

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