Chapter 5
Calibrating the Carbon Problem

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This section consists of two essays: *Evaluating the Hidden Carbon in SDE 1 & 3* by Wolfgang Kessling investigates the value of preserving embodied carbon through Life Cycle Analysis (LCA) undertaken over the multiple design scenarios of the SDE renovation. *A Problem of Problems* by Nirmal Kishnani speaks to recognizing design challenges and addressing them at their scales of complexity. These essays position the SDE renovation projects as important prototypes that belong to a larger systemic whole; their authors offer, respectively, quantitative and qualitative perspectives on the carbon conversation, while underlining the challenges that professionals need to work with in order to create positive change.

Evaluating the Hidden Carbon in SDE 1 & 3

Wolfgang Kessling

In the building sector, the carbon conversation has long been centered around expectations of thermal comfort and energy performance. Reducing carbon was linked to reducing operational energy or the carbon intensity of the energy supply. Though less understood, the extraction of natural resources for construction purposes and the production of building materials are also energy-intensive processes that release significant carbon emissions, among their other negative impacts.[1] Advancing the global agenda of decarbonizing the building sector is a major challenge. To reduce the burden on future generations, building projects today need to be on a pathway for zero-carbon operational energy and they must aggressively explore new design principles to reduce embodied carbon.

This pathway is explored with the SDE 1 & 3 building carbon story, which is discussed in the following essay. The first part explores the net-zero strategies for operational energy, while the second delves into the impact of avoiding carbon emissions by retaining the base buildings' embodied carbon. These different but complementary strategies are linked together through the carbon story of the project, thereby illustrating the vision for the reduction of the project's carbon footprint.

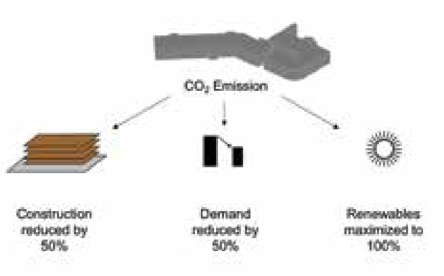


Fig 5.1.1 Original vision for reducing the carbon footprint of a tropical building. SDE 1 and SDE 3 apply a three-pronged approach to reduce CO2 emissions by addressing the construction process, energy consumption, and energy generation.

Part I: Creating Excellent Environmental Conditions for People

The goal of the renovation of the SDE 1 & 3 buildings was to create spaces of inspiring architectural quality while simultaneously designing a building that operates on a low-energy-demand basis. When SDE 1 & 3 were reviewed for refurbishment, the design team focused on the potential of the base buildings to create excellent environmental conditions for people through (i) daylight access and autonomy, (ii) thermal comfort, (iii) natural ventilation, and (iv) indoor air quality. The base buildings could deliver these qualities by reusing the building structures, upgrading the facades, and introducing innovations in designing for thermal comfort in the tropics.[2] By focusing on people's needs and the climatic and cultural context of the project, the quest to create these qualities through passive design and technical systems resulted in significantly reduced energy demand.

The Hidden Treasure

In the initial exploration of the existing base buildings, one of the most astonishing findings was the great hidden ceiling volumes. The structure for these two conjoined buildings was built in the late 1970s, when responsibility for building performance was shifted from architecture to HVAC systems. This resulted in the allocation of significant building height volumes within the suspended ceilings for the ductwork of cooling and ventilation systems, and some of these spaces were up to 1.8 m in height. All the floors had very low suspended ceilings, so the structure was not contributing to the building's performance and its spatial qualities, but it had the potential to. In order to take advantage of the existing structure and improve the spatial quality, the removal of the suspended ceilings was proposed. Such high ceilings in a new building would have been economically unfeasible.

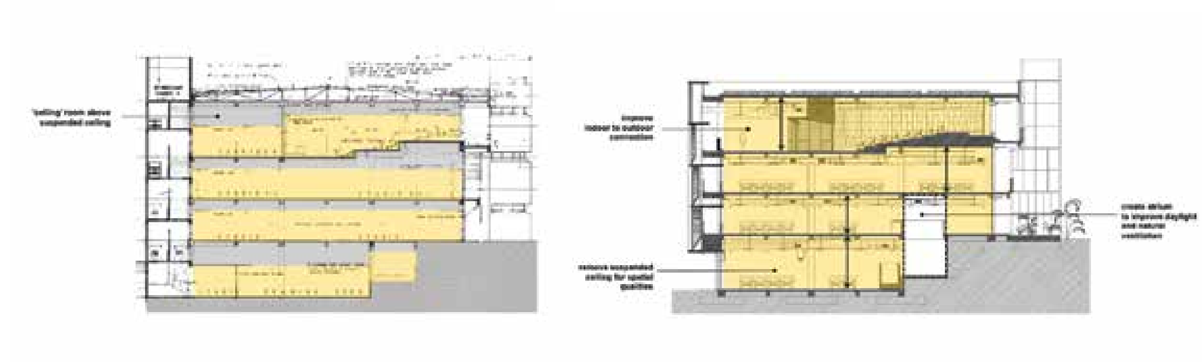


Fig 5.1.2 Indicative section with original suspended ceilings and compressed floor volumes before refurbishment (left). Proposed section showing changes improving daylight access and ceiling height (right).

Exploring Daylight Options

The original facade significantly limited the quality of daylight in the spaces. The existing brise-soleil completely shaded the transparent facade elements to protect the rooms from solar gains, but it also eliminated the possibility of using daylight in the buildings. The dark tones, high ceiling partitions, and suspended ceilings amplified this effect. It was recommended to refurbish all facades with high-selective sun-protective glazing to allow for daylight while simultaneously providing an efficient protection against solar radiation. The external shading is an essential part of the identity of the architectural ensemble. Therefore, many options for the reconfiguration of the external lamellas were studied, with the goal of reducing glare from the tropical skies while optimizing daylight and balancing solar gain. The potential of the combined effects for daylight turned out to be high, offering excellent daylit spaces and reducing the energy demand for artificial lighting.

Fig 5.1.3 Renderings with daylight impression before (top) and after inclusion of atrium and removal of suspended ceiling within the original structure (bottom).

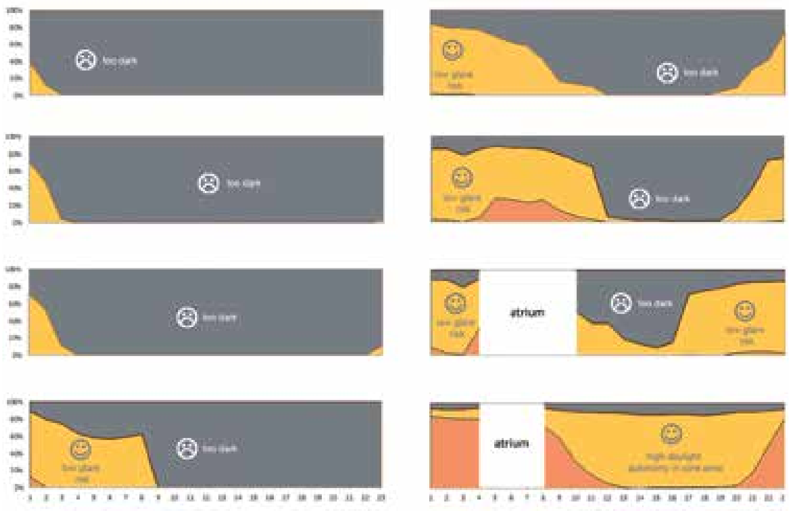


Fig 5.1.4 SDE 3 section indicating improvement in Useful Daylight Illuminance (UDI). Range: 300–2000 lux at 0.8 m FFL between 08:00–18:00 due to improvement of facade and inclusion of atrium.

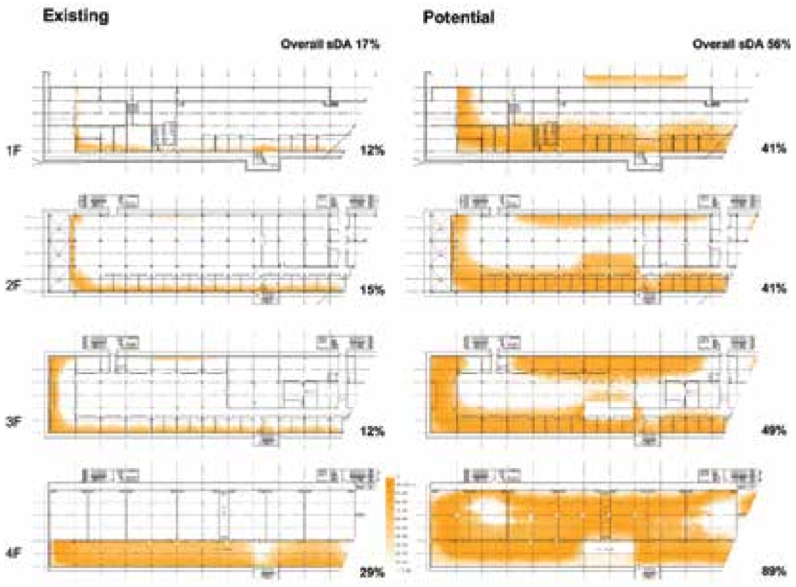


Fig 5.1.5 SDE 3 floor plans indicating improvement in Spatial Daylight Autonomy (sDA). Range: 300–2000 lux at 0.8 m FFL between 08:00–18:00 hours.

Numbers represent Spatial Daylight Autonomy, sDA range: 300–2000 Lux at 0.8m level, 8am to 6pm.

Improving the Indoor Environment with Hybrid Ventilation and Cooling Systems

Besides the lack of functionality for daylight performance, the facades were outdated in technical terms for solar gain control, U-values, air tightness, and operability for natural ventilation. Originally, the buildings were fully sealed and operated with air-conditioning and mechanical ventilation systems in almost all areas. When these systems were switched off after working hours, the buildings overheated and the indoor air quality became very poor for the students and faculty members who were still working in the studios.

To improve and optimize these environmental conditions, the design team studied innovative concepts to create a sequence of outdoor, transitional, and indoor spaces. The layout of thermal zones in the different program areas was organized as per their environmental requirements. Many areas were purposefully designed as outdoor areas, protected against wind and rain, but were also nicely daylit and provided with excellent natural ventilation. Major program areas now operate with a wider temperature and humidity range with hybrid cooling; that is, a combination of ceiling fans and mixed-mode mechanical and natural ventilation. Only where strictly required are indoor spaces fully air-conditioned.

The improvement of the indoor environment quality with hybrid ventilation and cooling systems had already been successfully explored in the SDE 4 building.[3] A hybrid cooling system delivers air temperature and humidity at higher set points than conventional air-conditioning systems. To offset this, the rooms are fitted with ceiling fans that increase air speed to improve the thermal sensation of the occupants.

As a single-pass system design with excellent air supply rates, there is no recirculating air; more fresh air is healthier for the building's occupants.[4] This means that there is no return air ducting, and the supplied air spills over into adjacent outdoor spaces, thereby enhancing the thermal comfort in these areas. Compared to conventionally cooled spaces, the slightly increased room temperatures result in smaller differences between indoor and outdoor spaces. This allows for a gentle switch from a tempered mechanical air supply to natural ventilation and significantly increases the value of designing facades and thermal zoning of tropical buildings for natural ventilation. Furthermore, there are significant implications for energy and carbon savings.

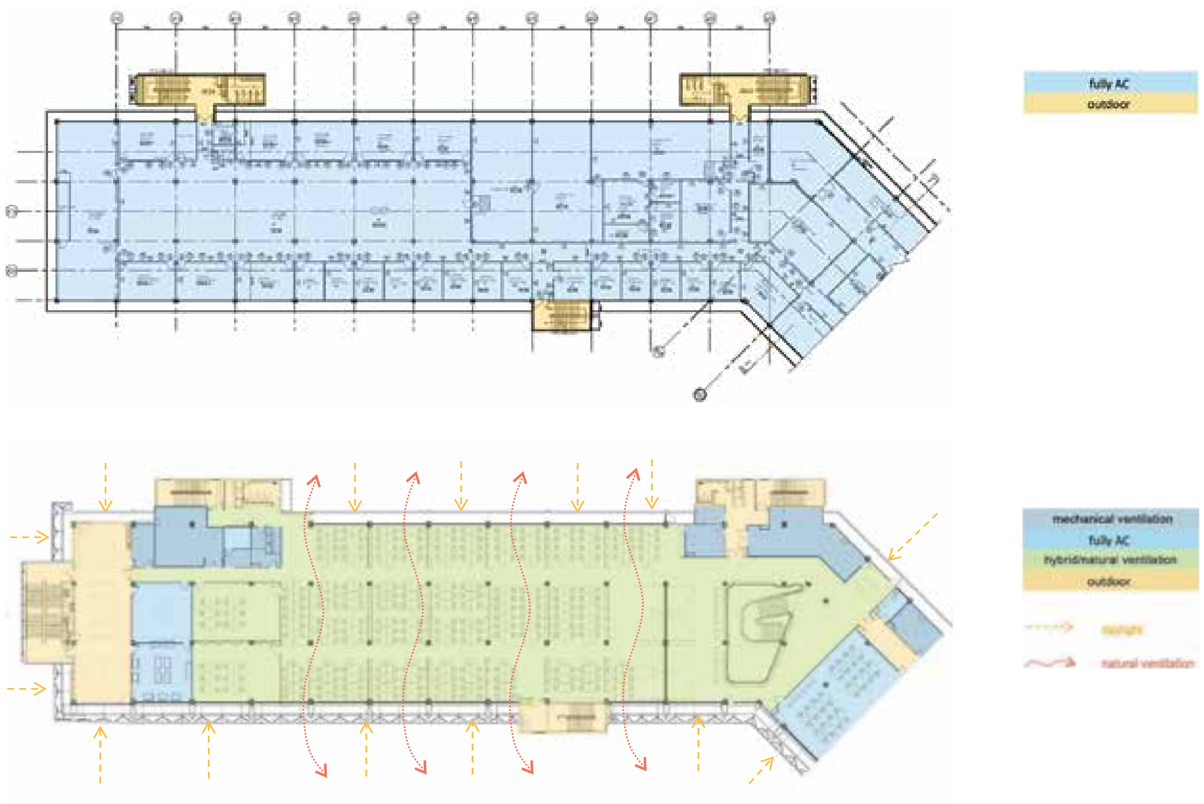


Fig 5.1.6 SDE 3 floor plans with original fully air-conditioned layout (top) and with improved thermal zoning with refurbished facade (bottom). Significant areas can be operated in hybrid ventilation mode: mechanical ventilation with supply of tempered air.

Low Energy by Design

The combined effects of the proposed interventions on energy demand are significant. The average energy use intensity (EUI) of the SDE 1 & 3 buildings across all program areas was estimated to be around 90 kWh/m²/yr (kilowatt-hour per square meter per year), significantly less than the 300 kWh/m²/yr average EUI for university buildings in Singapore.[5] Given the site constraints, about 50% of the total energy demand could be produced with an array of photovoltaic panels on the roof.[6]

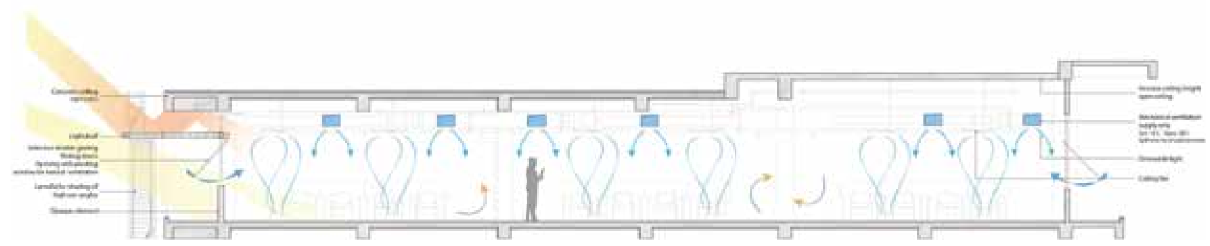


Fig 5.1.7 Typical section showcasing hybrid cooling concept elements such as the building facade working in conjunction with the MVAC system.

Part II: The Value of Embodied Carbon

As the base buildings were to be retained, the team estimated the embodied carbon in the original structures to put the emissions of operation and construction into perspective and complete the holistic carbon story.[7]

The production of buildings, from the extraction of natural resources to the construction, releases significant carbon emissions. To summarize the impact of the materials in the structures, the team performed a Life Cycle Assessment (LCA). This allowed us to estimate the "embodied carbon" of the buildings, a measure for their carbon intensity. The lower these emissions are, the lesser the carbon impact of the buildings is on the environment.

There are few studies on embodied carbon available for Singapore's building stock, and there is no available regional database on carbon emissions factors for building materials. The design team therefore adapted a methodology following the modular Life Cycle Models of the EN 15804 in a "cradle to gate" analysis. This included the three steps of production of building materials: raw material supply (A1), transport (A2), and manufacturing (A3). In the absence of a comprehensive source for regional emissions factors, emissions factors from the Inventory of Carbon and Energy (ICE) and the Oekobaudat (OKO) Sustainable Construction Information Portal were used.[8] In addition, the emissions factors for cement and concrete were adapted from a LCA study on imported concrete for Singapore.[9] To estimate the masses of the building materials, a 3D model of the main building structure and facade was used. The model was developed by the architects out of the historic plans and sections and updated to the status of refurbishment. For the estimation, the buildings were deconstructed into twelve major building elements for the base buildings, facades, and mechanical ventilation and air-conditioning (MVAC) systems. Each element was matched to the most appropriate material definition available in the databases, and the related emissions factors were assigned.

The limitations to this methodology include the following: The building model, particularly the original 1970s foundation elements, could be incomplete. The material compositions (for example, for the concrete and steel) are based on solely on conjectures and on-site observations. Available emissions factors haven't been developed for Singapore, nor are historic carbon factors for construction materials used in the seventies available. With the acknowledgement of the methodological limitations, the estimation of embodied carbon puts the reuse of the existing building structures into perspective vis-à-vis rebuilding the same structures at the same location. From this point of view, the value of reusing the base buildings lies in avoiding the environmental impacts that result from constructing a new building.[10]

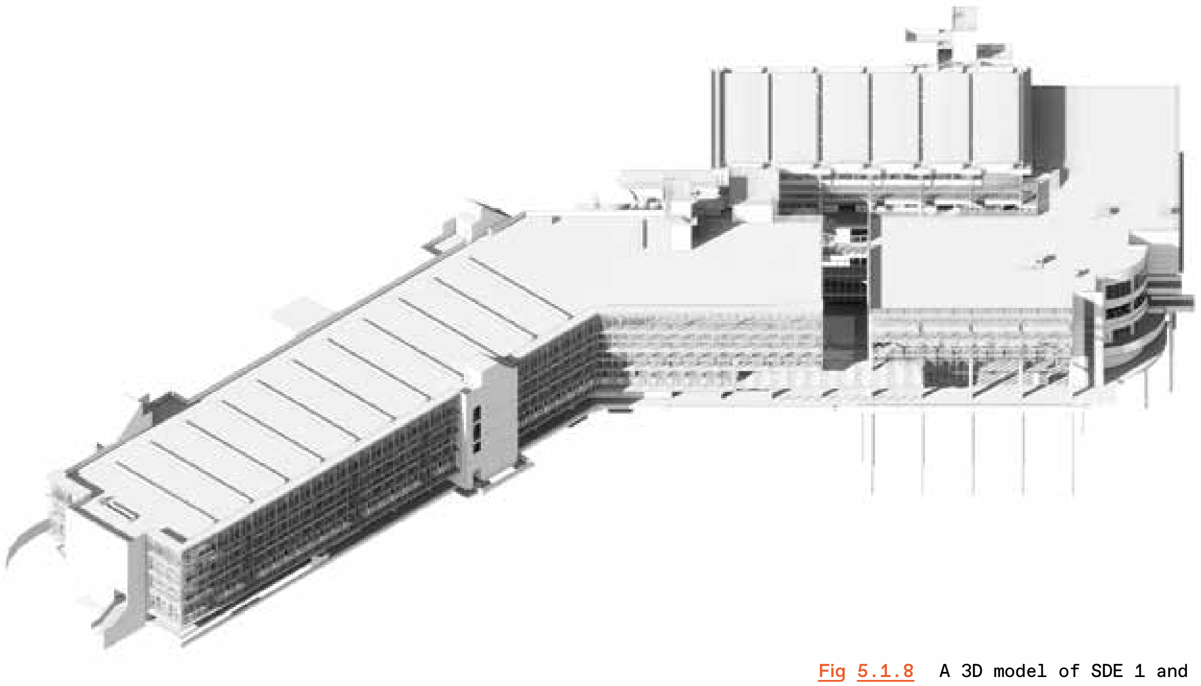
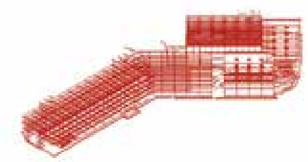
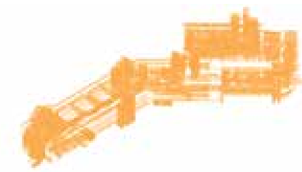


Fig 5.1.8 A 3D model of SDE 1 and SDE 3 was used for the Life Cycle Analysis (LCA) to estimate the masses of the main construction components to be retained and refurbished (top).

Fig 5.1.9 Detailed breakdown of the model by construction materials. Base building elements were retained (right).

No.	Construction Component Name	Construction Component Location	Material	Mass (tons)	Notes
01	Foundation		Concrete C30/37	5018	The estimated mass of the foundations was tripled as the 3D model only indicated foundations for 1/3 of the building.
02	Columns		Concrete with 4.5% reinforcing steel	2118	C30/37 concrete
03	Beams		Concrete with 4% reinforcing steel	7218	
04	Walls		Concrete with 1% reinforcing steel	8067	
05	Floor		Concrete with 1% reinforcing steel	15200	
06	Stairs		Concrete with 1.5% reinforcing steel	1095	
07	Ceiling		Plasterboard (false ceiling)	376	
08	Windows		Double glazing, aluminum frame	121	
09	Shading		Aluminum, not recycled	53	The reuse of the existing shading material was considered as an option.

Five different scenarios were compared: (i) a totally new construction, rated with local concrete emissions factors; (ii) a totally new construction, rated with ICE emissions factors; (iii) a totally new construction, rated with Okobaudat emissions factors for 2019; (iv) the existing buildings (taking the refurbishment into account); and an optional scenario, (v), considering the reuse the aluminium for shading elements and a lean MEP (hybrid cooling) system.

Assuming a new building constructed at the site with the same size and functionality, the total specific embodied carbon emissions would be approximately in the range of 255 to 512 kg CO2-eq/m² (kilogram of carbon dioxide equivalent per square meter)of ground-floor area (GFA), which indicates a wide range of possible emissions.[11] The higher estimate is most likely the closest to the actual carbon emissions embodied in the existing structure. The lower estimate would represent a new construction made with greener material. The adaptive reuse of the base buildings and replacement of the elements in need of upgrade, such as the facades and the MVAC system, would reduce the carbon emissions. The so-called "recurring embodied carbon" would be approximately 95 kg CO2-eq/m² of GFA. This scenario most likely represents the best estimate for the refurbished base building. As an additional possibility, reusing the material of the shade systems and consequently implementing a lean hybrid cooling system would further reduce carbon emissions to approximately 60 kg CO2-eq/m² of GFA. The last option, pushing the limits to lower the embodied carbon, was not realized.

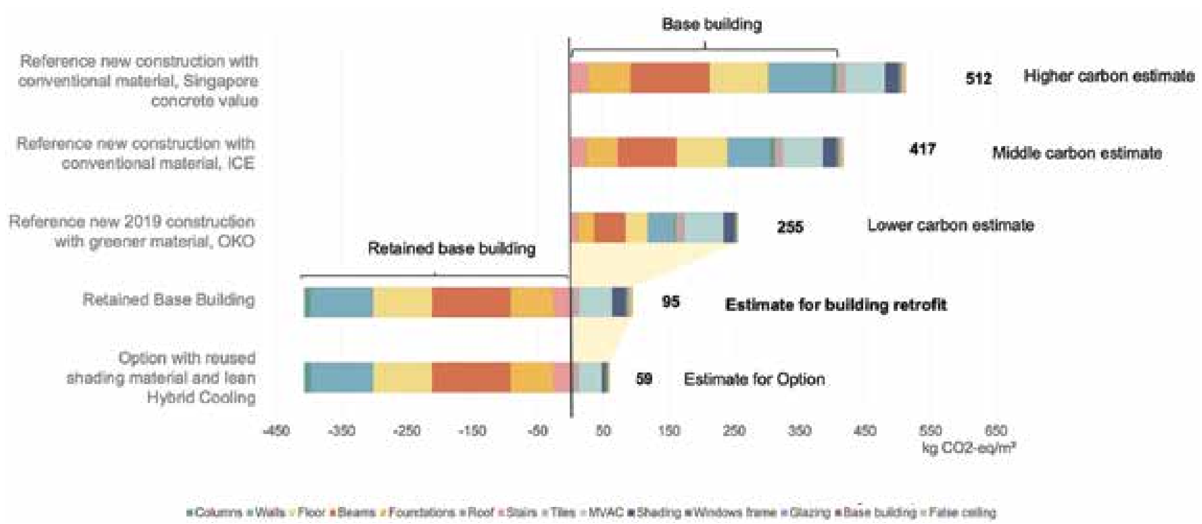


Fig 5.1.10 Estimation of embodied carbon.

The Carbon Story: Putting Carbon Emissions in Perspective

The net-zero design strategies for energy demand, energy generation, and retainment of embodied carbon tell the carbon story of the SDE 1 & 3 buildings from different perspectives that, in the end, merge into a holistic framework. Its final purpose is to be a tangible example of two things: a pathway to follow in order to lower carbon emissions and the establishment of accountable goals to be agreed upon with stakeholders.

The adaptive reuse and conservation of the base buildings gives value to past construction emissions. The retrofit emissions are estimated to be only 20% of what would hypothetically be emitted for a newly constructed building; these occur at the time of refurbishment. In the future, there will be operating emissions as the SDE 1 & 3 buildings host many generations of architects. Reducing the buildings' energy demand by 60% directly avoids those future carbon emissions. The savings will not only be related to the energy-efficient design, but also to the user's conscious operation. The shift of energy sources from fossil fuels to renewables contributes directly to the reduction of the emissions as well, but data on the use of the latter is limited.

While absolute carbon emissions remain abstract, when carbon emissions are outlined in per capita terms, the urgency of acting now — with every new building — becomes very clear. The sustainable world goal for the year 2030 is around 2.5 t CO2-eq/yr (tons of carbon dioxide equivalent per year) per capita.[12] The average per capita emissions of a Singaporean person in 2018 were about 8.4 t CO2-eq/yr. A part of this number is attributed to the construction and operation of buildings used for education and work. For a user of the SDE 1 & 3 buildings, the scenarios in this carbon story allocate per capita emissions of 1.7 t CO2-eq/yr (conventional new construction scenario) to 0.5 t CO2-eq/yr (adaptive reuse and hybrid cooling system scenario) to about 0.03 t CO2-eq/yr (all-renewable energy supply scenario).[13] The numbers highlight the relevance of restorative building practices and circular material economy models to transform the global and local building practices.

The SDE projects are earnestly exploring relevant options for low carbon / high comfort in buildings in the tropics. The university can be thought of as a living test bed where future professionals can experience firsthand how context-sensitive tropical design works and feels. It is our hope that they leave with the confidence and knowledge required to deliver it in practice.

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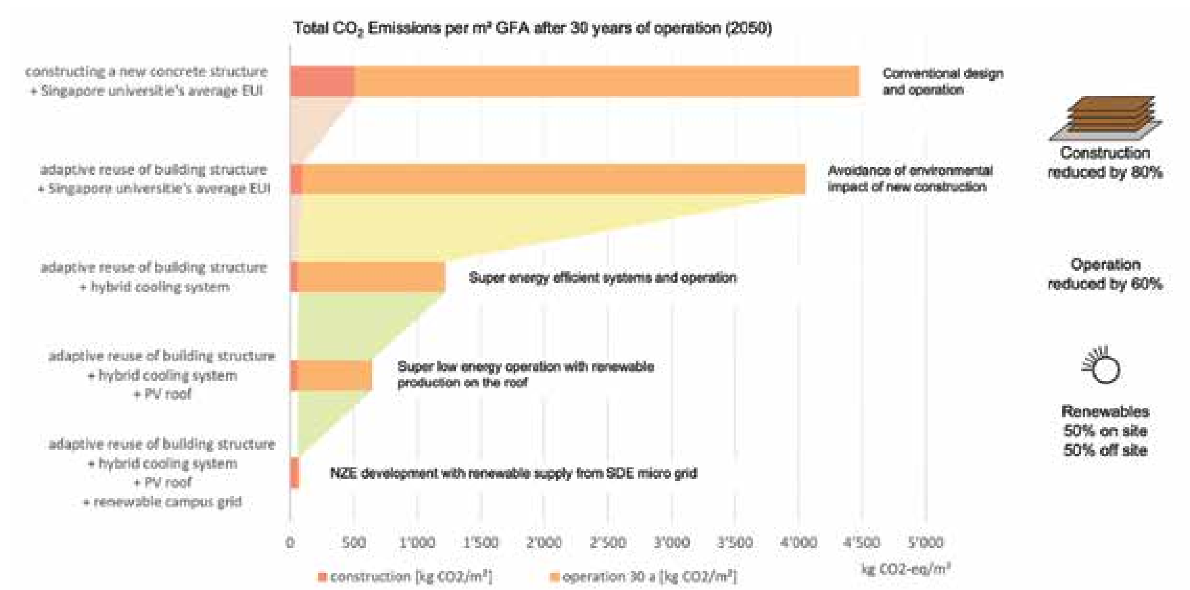

Fig 5.1.11 SDE 1 & 3's carbon story.