Journal of Sub
ISSN: 1998-3778 (Print); 1998-3786 (Online)
VOL 14 NO 1 (2024)
Available online at https://sub.edu.bd
Journal homepage: https://sub.edu.bd/journal/index.php/jsub

ASSESSING THE BENEFITS OF LOW-CARBON RETROFIT DESIGN: A CASE STUDY ON OPTIMIZED BUILDING PERFORMANCE OF A RETROFITTED BUILDING

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A R T I C L E I N F O

Article history:

Received: 25th July 2024
Reviewed & Revised: 25th July to 19th December 2024
Accepted: 19th December 2024
Published: 30th December 2024

Keywords:

Retrofitting, Low Carbon Design, Building Envelop, Energy Performance, Commercial Building, Melbourne

JEL Classification Code:

Q01, Q41

A B S T R A C T

The built environment is a major contributor to global CO_2 emissions, with existing building stocks accounting for a significant share throughout their life cycle stages. In response, there is growing global attention to retrofitting existing buildings to reduce energy consumption and carbon emissions. A well-structured retrofitting strategy can offer a practical solution, providing reductions in emissions as well as cost, comfort, and environmental benefits. This paper focuses on a commercially initiated retrofit project in Melbourne, Australia, demonstrating its process and presenting appropriate recommendations for retrofits in a similar context. It evaluates the effectiveness of a low-carbon retrofit by comparing the retrofitted performance with the actual performance of the building. The case study is 182 Capel Street, a 1,600-square-meter commercial office building in North Melbourne, Australia, known for its retrofitted low-carbon design (LCD) strategies. Key retrofitted features include a solar-responsive building envelop, insulation, glazing, HVAC systems, and recycled materials. This paper provides a systematic approach to assessing how the retrofitted building envelop features affect energy conservation, with a detailed energy distribution analysis. The study is carried out by simulating the implemented retrofit scenarios using DesignBuilder® software, focusing on improved daylighting, and thermal comfort. Based on a summary of the implemented strategies and post-occupancy evaluation data, a comparative analysis demonstrates how the building benefits from low-carbon retrofitting in terms of energy consumption and overall performance. The findings reveal that the implemented retrofitting strategies have significantly improved the building's energy performance, leading to a 30% reduction in annual mechanical energy consumption and a 40% decrease in lighting energy use.

FINTRODUCTION

In the building sector, the majority of energy consumption occurs within existing structures, resulting the retrofitting of these buildings essential for achieving substantial reductions in energy usage (Ma et al., 2012). Retrofit solutions, encompassing energy reduction strategies and the adoption of LCD principles, play a crucial role in enhancing the energy performance of existing buildings (Marzouk et al., 2023). In response to global climate change, the transition toward low-carbon development has become a fundamental aspect of the built environment, leading to the widespread implementation of LCB worldwide (Liu et al., 2023). In recent times, extensive research has been conducted on how to retrofit existing buildings into zero-carbon. Energy retrofit clearly has the potential to deliver significant emission reductions, but in practice, the success of retrofitting existing building stock to low carbon standards is often overlooked. Furthermore, there is a lack of data on post-retrofit energy efficiency and the specific benefits of low-carbon technologies in completed projects. This study aims to bridge the gaps for designers and owners by providing a strategic guide for LCD retrofits, using a case study and assessing its effectiveness with an energy simulation tool. Additionally, it seeks to equip building researchers and practitioners with a clearer understanding of effective retrofit practices by analyzing the key steps of the selected building's low-carbon retrofit strategy, while enabling them to differentiate between as-built and intended retrofitted performance.

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https://doi.org/10.63773/.v1i1.3

To cite this article: Nitu, M. A., & Dey, T. (2024). ASSESSING THE BENEFITS OF LOW-CARBON RETROFIT DESIGN: A CASE STUDY ON OPTIMIZED BUILDING PERFORMANCE OF A RETROFITTED BUILDING. *Journal of SUB, 14*(1), 10-26. https://doi.org/10.63773/.v1i1.3

An office building in West Melbourne, Australia is selected as a case study as offices are one of the largest energy consumers (Marzouk et al., 2023). LCD retrofit strategies are applied to this building, resulting in significant improvements to its energy efficiency.

This paper begins with a literature review that establishes the context and significance of the research problem, followed by a discussion of the materials and methodology, demonstrating how they were tailored to meet the specific objectives of this study. A detailed case study is presented, outlining the retrofitting process and design considerations implemented by the consultancy firm. To assess the effectiveness of the retrofit, pre- and post-retrofit building performance was compared using computational simulations conducted in DesignBuilder®, alongside post-occupancy evaluation data. The results are analyzed, highlighting both the successes and limitations of the retrofitting strategies, with recommendations for further developments in the field.

LITERATURE REVIEW

The growing emphasis on enhancing energy conservation in existing buildings calls for the development and implementation of strategic approaches to optimize energy conservation. The building stock is regarded as a significant contribution to over one-third of CO2 emissions and overall energy consumption in both industrialised and developing countries (Xu et al., 2020) and in the commercial and residential sectors, the consumption has increased by roughly 20%–40% (Marzouk et al., 2023). Commercial buildings, in particular, typically consume more energy per square meter of floor area compared to residential buildings (Pomponi et al., 2015). To address this alarming point, in-depth research has been performed by experts in collaboration with building design and operating systems so that new buildings can be designed and constructed to ensure lower levels of energy demand (Xu et al., 2023). But at the same time the number of existing buildings exceeds that of planned new buildings in most of the developed countries (Owen et al., 2014). According to studies operation phase is the most energy consuming and existing buildings typically consume more energy due to issues like outdated construction standards (Liu et al., 2022). The age of a building can theoretically affect energy usage, as older structures generally exhibit inefficiencies in insulation and HVAC performance (Lee et al., 2019). Additionally, The International Energy Agency (IEA) highlights that by 2030, all new buildings and 20% of the existing building stock must be highly energy efficient to support the goal of reaching net zero emissions by 2050 (IEA, 2021). As a result, designers and constructors are now required to execute energy retrofits to upgrade the energy performance of existing structure, thereby decreasing global energy demand (Ferreira & Almeida, 2015).

Retrofit solutions ranging from reducing energy usage to adopting lo carbon technologies can play a significant role in enhancing the performance of existing buildings (D'Alpaos & Bragolusi, 2019). Low carbon retrofits in the construction industry aim to enhance the energy efficiency of buildings, by improving building fabrics and systems to reduce emissions and optimize performance. To deal with global climate change low carbon transition has become an integral part of the built environment and low-carbon buildings (LCB) have been introduced worldwide (Liu et al., 2023). In recent times, significant research has been conducted to assess the performance of retrofitted buildings and their compliance with evolving standards and policies (Marzouk et al., 2023). Despite the substantial potential of LCD retrofits to mitigate emissions, their practical application and the number of building retrofits are limited due to initial costs, lack of interest, insufficient information and/or credible guidance, and unpredictable consequences (Lee et al., 2019). A contributing factor is that retrofitting old structures encounters more limitations than new construction, in addition to insufficient understanding regarding effective low-carbon upgrades (Lee et al., 2019). Additionally, the success of upgrading existing building stock to comply with low-carbon standards is often overlooked. This results in gaps between building regulations and owner engagement, especially in developed countries that require retrofits to improve energy efficiency and durability. Moreover, there is an absence of information regarding post-retrofit energy efficiency and the particular advantages of low-carbon technologies of completed projects.

MATERIALS AND METHODS

The methodologies of this study focus on the effectiveness of LCD retrofits in an office building. The study utilized two sources of data: 1. publicly available sources for collecting and analyzing information on building retrofits, such as webpages and reports released by the Ministry of Melbourne. 2. Energy modeling tool: Analyze and retrofit building energy usage using building envelop analysis.

Finding low carbon measures is quite challenging among the wide range of retrofitting design strategies available today. This paper provides a systematic approach to find out the retrofitting features of the selected existing building and how those features are effective to energy conservation. The study is carried out by analyzing considered LCD strategy to reduce the energy demand through building envelop and evaluating the post-installation energy and environmental performance data.

The initial stage is to do a detailed examination of the current situation through the information gathering and site analysis of the chosen context. This step leads the way to figure out if there is an opportunity for energy improvements. The next phase follows a retrofit scenario where LCD strategies are identified and investigated to understand their implementation on the existing building. After the implementation, a thorough study has been performed to understand the improvement in energy consumption for pre- and post-retrofit scenarios. Major retrofit activities such as building performance in terms of building envelop, insulation, glazing, HAVC, and material considerations are discussed at length, all of which are essential to the success of a building retrofit project followed by a post-occupancy evaluation. The paper concluded by focusing on the learning outcome of the retrofitting design process toward an energy-efficient building. The methodology incorporates an exercise to offer guidelines on how carefully thought-out design approaches might contribute to lowering a building's energy usage. In order to further explore the concept of linking different techniques, we adopted the methods shown in Figure 1

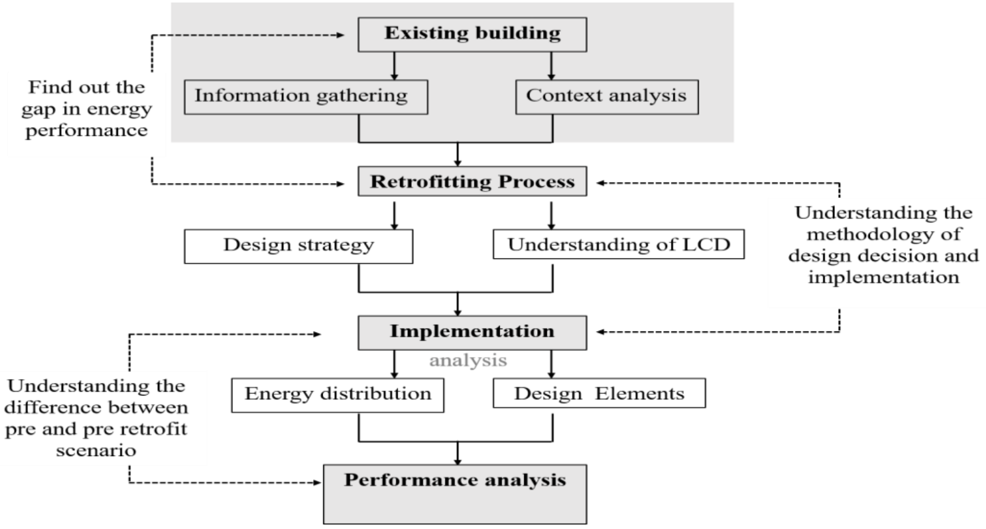


Figure 1. Methodology for low carbon retrofitted building analysis

RESULTS AND DISCUSSIONS

Case Study: Existing Building

General Information

Project Description

Constructed in 1988, the building at 182 Capel Street underwent a significant green refurbishment program between 2008 and 2011, which included the addition of a new office floor, as highlighted in image 05. The concrete flooring is supported by a lightweight steel frame, integrated with the building's pre-cast concrete structure. This west-facing, three-story building spans a total area of 1,600 sqm and includes a basement car park. The owner, FMSA, occupies the first and second floors and spearheaded the retrofitting upgrades to enhance operational efficiency, user experience, and energy performance. The ground floor is leased to a separate tenant.

Table 1. General Information of the building

Project Name:	**182 Capel Street**
Building Type:	Commercial Building
Net Land Area:	1600 sqm/ 3 floors
Location:	North Melbourne, VIC 3051, Australia
Construction date:	1984
Refurbishment date:	2008-2011
Building Owner:	Fooks Martin Sandow Anson (FMSA) / Bellatrix Holdings
Property Manager:	FMSA
Architects and ESD	FMSA Architecture
Project costs:	$416,012 plus $1.4 million additional floor
Annual saving:	$22,206

Table 2. Energy saving targets

Sector	**Existing**	**Target**
NABERS rating	1.5 star	5.0 star
NABERS water	1.5 star	4.0 star
Electricity Usage	309 kWh/day per floor	159 kWh/day per floor
Water Usage	1600 L of water / day.	900 L of water / day
Greenhouse Saving	190 – 109 tonnes CO2 floor	81 tons CO2 / floor

Tables 1 and 2 present the buildings general information and the energy savings targets achieved through retrofitting, respectively. The accompanying images illustrate the progression from the initial state to the construction and retrofit phases, showcasing the systematic approach undertaken throughout the retrofit journey.

Figure 2, 3, 4, 5 and 6 sequentially depict the transformation of the case study building through its different stages. Figure 2 captures the existing structure before any modifications, showcasing its original architectural form and condition. Figure 3 and 4 illustrate the construction phase, highlighting the ongoing retrofitting process, including structural enhancements and the integration of low-carbon design strategies. Finally, Figure 5 and 6 present the post-retrofit phase, demonstrating the completed transformation with implemented energy-efficient features and low carbon design improvements.

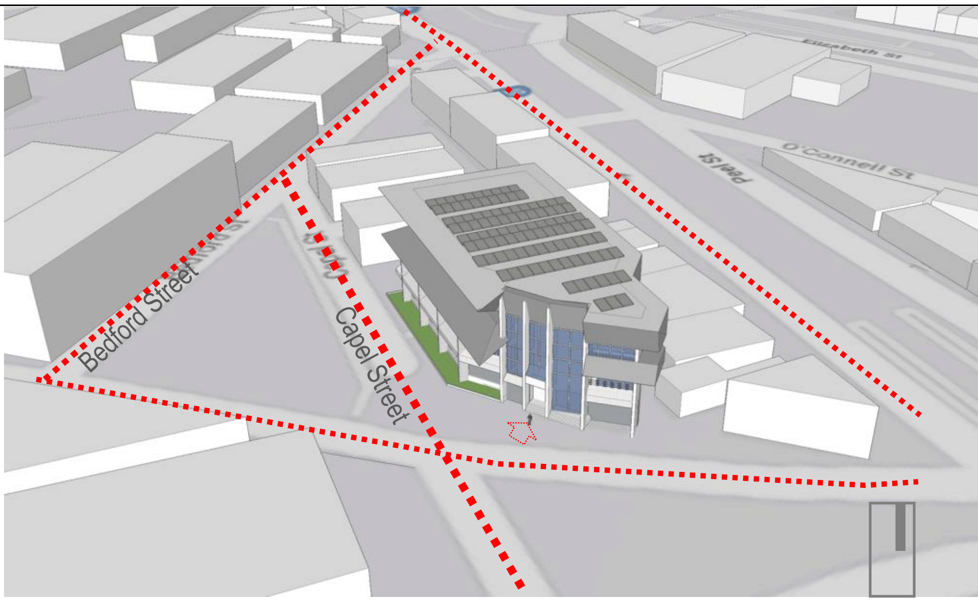
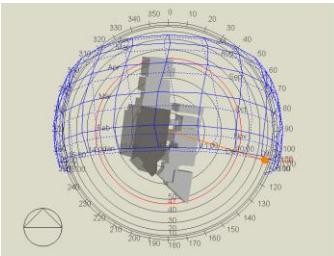
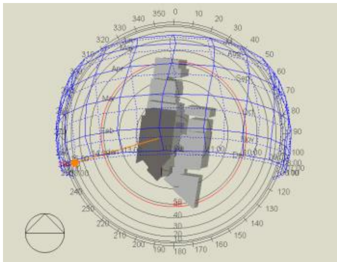
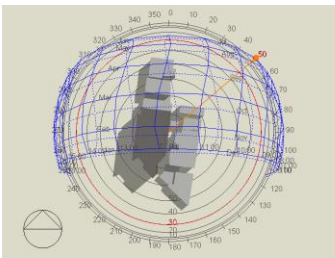
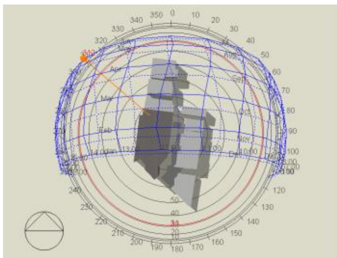
Figure 2. Existing building (FMSA Architecture Office - FMSA Architecture) Existing Phase

Figure 3 & 4. During retrofitting construction Construction Phase

Figure 5 & 6. Final image of retrofitted building Retrofitted Phase

Analysis of Existing Scenario

Table 3. Information gathering and context analysis for existing building

Site location	 *The building and site (Author in Sketchup with Geolocation)* The site at 182 Capel Street, North Melbourne, Victoria (37°48'11.6"S, 144°57'21.0"E), features a unique west and southwest-facing glazed facade aligned with the road, offering street views. The north and east facades lack openings due to adjoining buildings. The nearest weather station is Melbourne Olympic Park.
Over-Shadow Cast	With green land to the south and a landscaped road to the west, the building does not overshadow any structures in these directions during the morning. In the afternoon, shadows are cast to the east, but the building's relatively low height results in only mild overshadowing of neighboring structures. Additionally, the new floor's setback design minimizes shadow impact on adjacent buildings.  January 9am  January 3pm  July 9am  July 3pm *Sun Path diagrams with shadows (Author in Design Builder)*

<table>
<tr>
<td>Solar Heat Gain</td>
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Existing Condition on the building (FMSA Architecture Office)

According to the Bureau of Meteorology (BOM), January records the highest mean temperature at 26°C, while July sees the lowest at 6°C. The building, situated at a street corner with west and southwest facades, faces significant solar heat gain. As per Australian Institution of Refrigeration, Air-conditioning and Heating (AIRAH) data, the west facade receives up to 550 W/m² on January 21 at 4 PM, and the southwest 430 W/m² at 5 PM. This solar impact necessitates shading and insulation for the west and southeast facades. Above image shows the original building featured an outer structure and overhangs for shading, though the first floor lacks adequate protection from direct sunlight.
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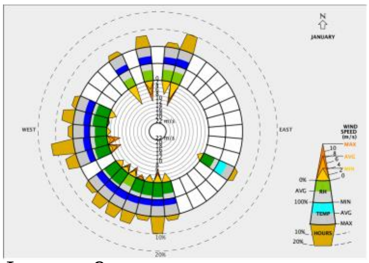
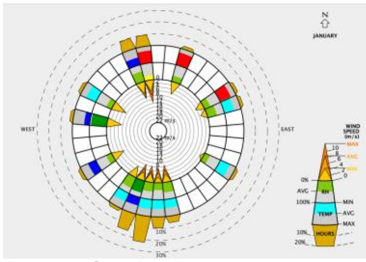
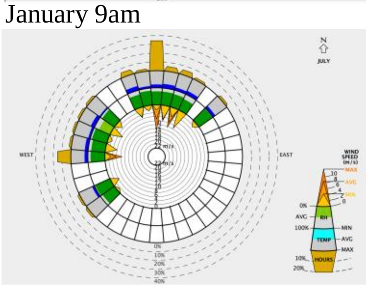
<tr>
<td>Wind Analysis</td>
<td>
In January, hot winds predominantly flow from the north, west, and south in the morning (8 m/s) and from the north and south in the afternoon (6 m/s). In July, cold winds flow from the north and west in the morning (8 m/s) and from the north, west, and south in the afternoon (12 m/s).


January 9am


January 3pm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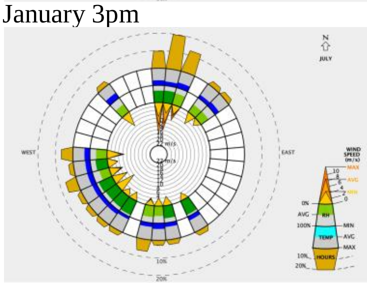
July 3pm

Wind rose diagrams (Author via Climate Consultant)
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Retrofitting Process and Design Considerations

Solar Responsive Design Strategy

Existing buildings are considered a significant source of greenhouse gas emissions, particularly amidst the growing threat of global climate change (Nitu et al., 2022). Optimizing the energy systems of the built environment is therefore critical. A key objective of LCB design is to enhance efficiency through optimized orientation, structure, window and glazing placement, and the careful selection of materials for the building envelop (Kalaiselvam & Parameshwaran, 2014). Among various strategies, researchers have identified climate-responsive design—often referred to as solar-responsive design—as the most effective approach for reducing embodied carbon (Nygaard Rasmussen et al., 2020).

The FMSA team conducted a comprehensive solar performance analysis of the existing building to integrate a climate-responsive design approach. Based on the building's geographic location and the sun's position, it was determined that the summer sun enters the building at an angle of 65°, while the winter sun enters at an angle of 22°, corresponding to the months of January and July, respectively (SunCalc Sun Position and Sun Phases Calculator). The analysis focused on 3:00 PM, as the west façade, which features the primary openings, is directly exposed to sunlight during this period (Figure 7). This exposure resulted in excessive solar heat gain, contributing to increased indoor temperatures. The lack of adequate shading on the upper floors further exacerbated overheating, leading to greater reliance on air conditioning and higher energy consumption. Given that the west and southwest façades served as the primary sources of daylight, ventilation, and views for the building, the solar-responsive design approach centered on re-evaluating the treatment of the existing west façade.

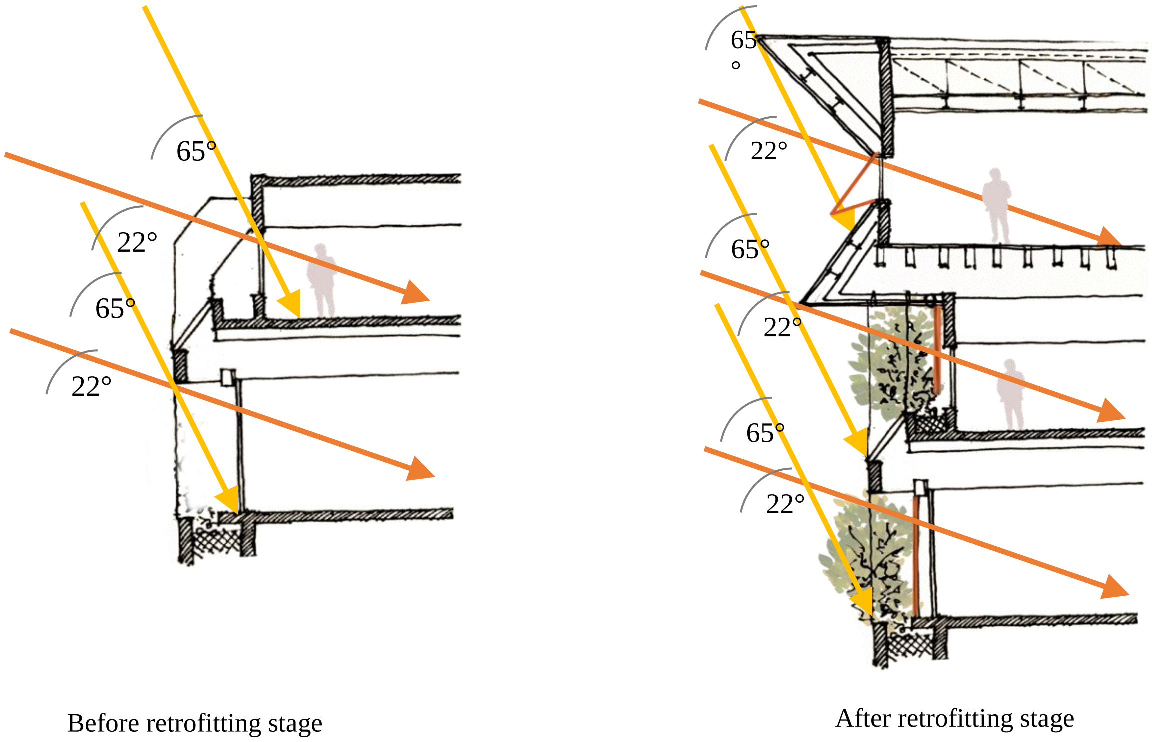


Figure 7. Solar responsive shading design (Source: Author)

The retrofitting strategies adopted by FMSA (FMSA Office Sustainable Renovation + Retrofitting Project, 2011):

- **Inclined Façade:** The sun angle guided the design of an inclined façade to act as a shading device, reducing excess heat on the new and middle floors, the latter being most affected in the previous design.
- **Operable Windows:** These were incorporated to allow cross-ventilation when required.
- **Clerestory Windows:** A sawtooth roof design introduced clerestory windows, permitting diffused daylight to enter while minimizing interior overheating.
- **Vertical Fins:** Installed on the new floor, these provide enhanced shading and facilitate better airflow.

These solar-responsive strategies enabled the building to adopt mixed-mode ventilation instead of relying solely on air conditioning, significantly lowering operational costs.

Understanding the Concept of LCD Retrofit Strategy

Before initiating the primary retrofit implementation for the selected case study, it is essential to first focus on strategies for reducing embodied carbon rather than solely aiming for a low-carbon retrofit. Embodied carbon refers to the total greenhouse gas emissions generated throughout the building's life cycle, including the manufacture and supply of construction materials, as well as the construction process itself. The goal of this LCD approach is to promote the adoption of design measures that minimize building energy consumption and the associated carbon footprint (Kalaiselvam & Parameshwaran, 2014).

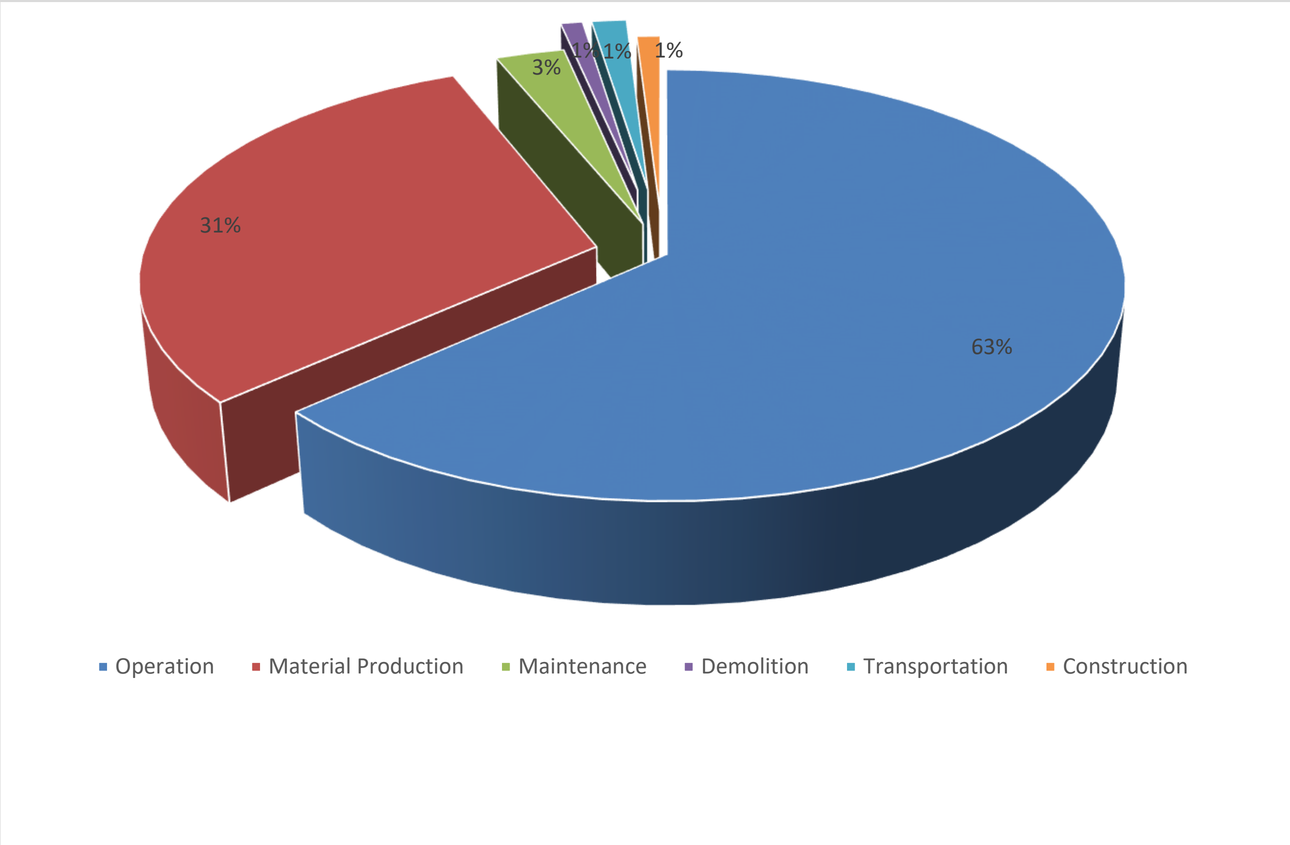


Figure 8. Carbon emissions from the various building life cycle stages

Figure 8 shows that building operation and material production contribute the most carbon emissions, with 63% and 31% respectively (Ramya Kumanayake, 2018). Therefore, any strategies implemented should prioritize these areas, as reducing emissions from these sources will significantly help minimize the overall carbon footprint.

When evaluating a LCD retrofit strategy, it is essential to consider the carbon footprint and other environmental impacts through a life-cycle approach, rather than focusing solely on energy efficiency. A combined effort of improving energy efficiency and reducing embodied carbon is crucial to achieving the ultimate goal of a low-carbon retrofit.

Upon reviewing the resources related to the case study, it is evident that the primary objective behind the architects' design decisions for this retrofit was to significantly reduce the building's carbon footprint, with an aim for at least a 50% reduction (City of Melbourne, 2023). The initiative undertaken by the consultancy and the building's owner, FMSA, has instilled confidence in their ability to exceed this target.

Methodology and Implementation of Retrofit Design

Retrofitting existing buildings requires a strategic and well-planned approach. This process is essential for understanding energy distribution within the building and for integrating necessary building services while minimizing carbon emissions. Without a comprehensive understanding of energy distribution, it becomes challenging to mitigate undesirable heat loss and gain during the retrofit, which can lead to inefficiencies in building operation management. The energy distribution for this case study will be further explored in this Section. A sustainable building retrofit program typically consists of five key phases (Ma et al., 2012). Following the program structure, the journey of 182 Capel Street low carbon retrofitting is illustrated in this flow chart (figure 9):

Project Setup and Pre retrofit Survey

(2008-2009)

- Retrofitting was commenced in 2008. The building was bought by FMSA in 2003 with an intention to sustainable adaptation.
- Initially FMSA started the retrofitting with their own finance. But the fund provided by the Australian Government's Green Building Fund added an important contribution in the overall costs (City of Melbourne, 2023).
- They set for a target to reach 5 NABERS rating from 1.5.

Energy Audit and Performance assessment

(2008-2009)

- Energy auditing was performed by analyzing building's monthly energy consumption from bills and understanding the type of energy use according to the classification of activities and types of services.
- Originally the building had its own generator, but all the previously installed mechanical equipment were already at the end of their life cycle.
- The building is west facing which is an excellent source of daylight but at the same time cause excessive solar gain during summer.
- The building is well insulated so additional adaptation was required

Identification of Retrofit Options

(2009-2010)

- FMSA, in collaboration with Cundall and Umow Lai Engineers, assessed energy estimates and developed retrofit options. Due to cost constraints, the project was divided into two stages:
  i) **Stage 01** focused on completing the 2nd floor, installing mechanical equipment, lighting, water systems, external blinds, and other environmental initiatives.
  ii) **Stage 02** included further water initiatives like rainwater collection, a green wall, and an on-site power generator.
  During retrofitting, the building remained operational, and lack of detailed programming led to disturbances, particularly during mechanical equipment and window installations.

Site Implementation and Commissioning

(2010-2011)

- By July 2011**,** almost 80% of the work was completed including the base building works and the mechanical equipment and window installation of the occupied floors.
- The consultancy team along with the engineer and lighting designers started implementing detail design decisions.
- Once the HVAC was selected, a separate mechanical company was engaged to design and install the system. (City of Melbourne, 2023).

Validation and Verification of energy Savings

(2012-

- After the completion of the work, energy consumption was monitored monthly to track the progress. Detail is going to be provided in post occupancy evaluation section.
- Compared to pre- refurbishment level, they investigated that total energy consumption (electricity and gas) was reduced by approximately 30%, from around 28,000 MJ prior to refurbishment down to an average of around 19,000 MJ after refurbishment. (City of Melbourne, 2023).
- It is estimated that lighting and mechanical system maintenance costs will be reduced by about 40% and 70%, respectively (City of Melbourne, 2023).

Figure 9. Retrofitting methodology for 182 Capel Street by FMSA (Source: Author)

Floor to Floor Energy Distribution in the Retrofit Design:

- The retrofitting strategy and features are finalized after a detail energy auditing based on two main components:

i. Types of activities
ii. Energy service

- For this paper an assumption-based approach was adopted based on the available data.

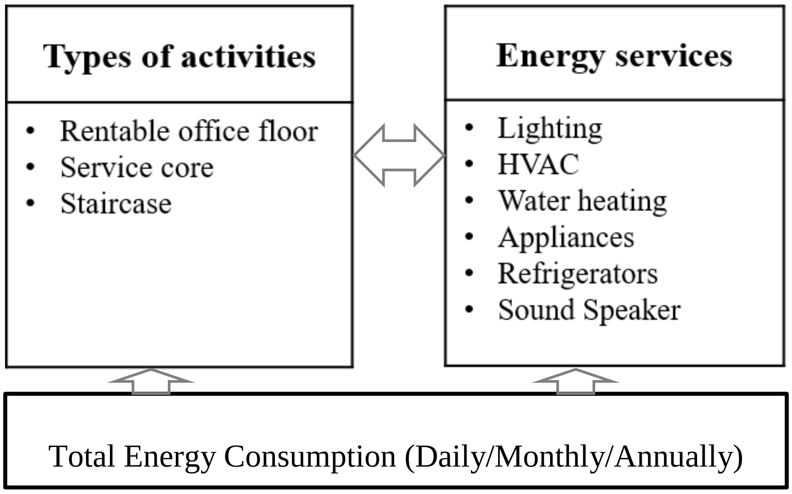


Figure 10. Energy Audit Methodology (Source: Author)

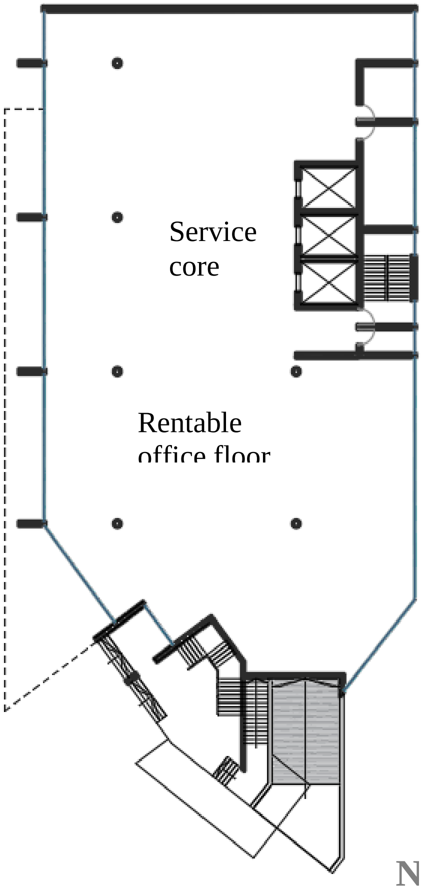


Figure 11. Floor layout for 182 Capel Street by FMSA

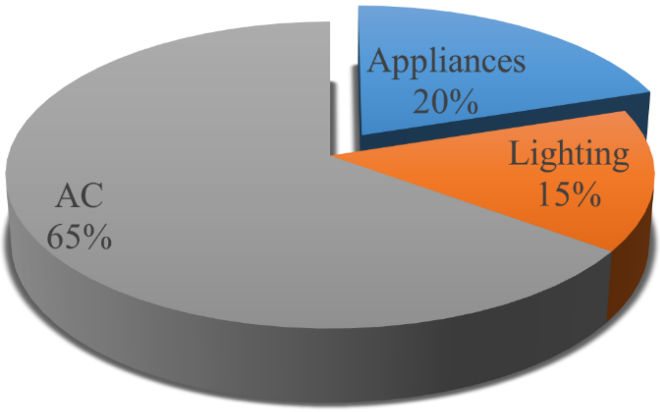


Figure 12. Energy Consumption by Service: existing scenario

Description of Building's Energy Used by Services

- Figure 12 illustrates the energy consumption pattern of the existing building based on the services installed.
- Due to the unavailability of detailed data from the building's authority, the percentages presented in the pie diagram are derived from a comparable study conducted by a team at the University of Cairo, which examined the energy performance of one of their buildings for a retrofitting study. Both buildings share similarities, including being fully air-conditioned and occupied during daytime hours (Sayigh, 2016).
- The pie diagram reveals that the largest contributor to energy consumption is air conditioning, which is part of the HVAC system.
- With targeted measures to minimize air conditioning usage and reduce the overall electricity demand, significant reductions in annual energy consumption and CO2 emissions can be achieved, as outlined in the introduction.

Retrofit Design Elements

Retrofit research primarily focuses on two areas: building services and assessments of building envelop systems (Edeisy & Cecere, 2017). Building services, as discussed in the previous section, contribute to 63% of the total carbon emissions throughout their lifetime (Figure 8). Research indicates that retrofit measures for the building envelop, such as solar shading, window glazing, air tightness, and the addition of vegetation, can reduce energy consumption by an average of 33% (El-Darwish & Gomaa, 2017).

Below is a table outlining the major design elements taken into account for the retrofitting program for the existing buildings. Only the building envelop system is going to be covered in depth in this journal due to its length constraints.

Table 4. Major Design Elements for Retrofitting the Existing Building

NO.	ELEMENT		EXISTING BUILDING	RETROFITTED BUILDING
1	**Building Envelop**		The building's largest façade, the west façade, lacked a specialized shading system to minimize solar gain. Building was mechanically ventilated Single glazed windows Well insulated pre-cast concrete structure Uninsulated roof top	Installed vegetation on the west facade Introduced mixed mode ventilation system connected to a weather station to operate the windows automatically according to the temperature fluctuation. Installed automated external blinds on the existing windows. Introduced a solar photovoltaic roof cladding. Introduced light weight structure for the new additional floor level
2	**Building Services**	HVAC	Electrical powered AC units	Gas powered constant air volume (CAV) system
3		Lighting	Unevenly distributed lighting layout North and east side of the building is overshadowed by surrounding buildings	Distributed evenly with a combination of fluorescent and LED lights Installed clerestory on the additional floor
4		Water	No water sustainability measures were considered	Installed rainwater tank in the basement. Introduced water efficient fixtures
5		Waste management	No consideration for waste disposal	Introduced ecofriendly waste disposal bags
6		Building Management System (BMS)	No BMS was installed	Installed BMS to monitor the combination of HVAC and mixed mode ventilation
7		Material	No considerations for recyclable materials.	Used recyclable materials

Building Envelop Design Strategies

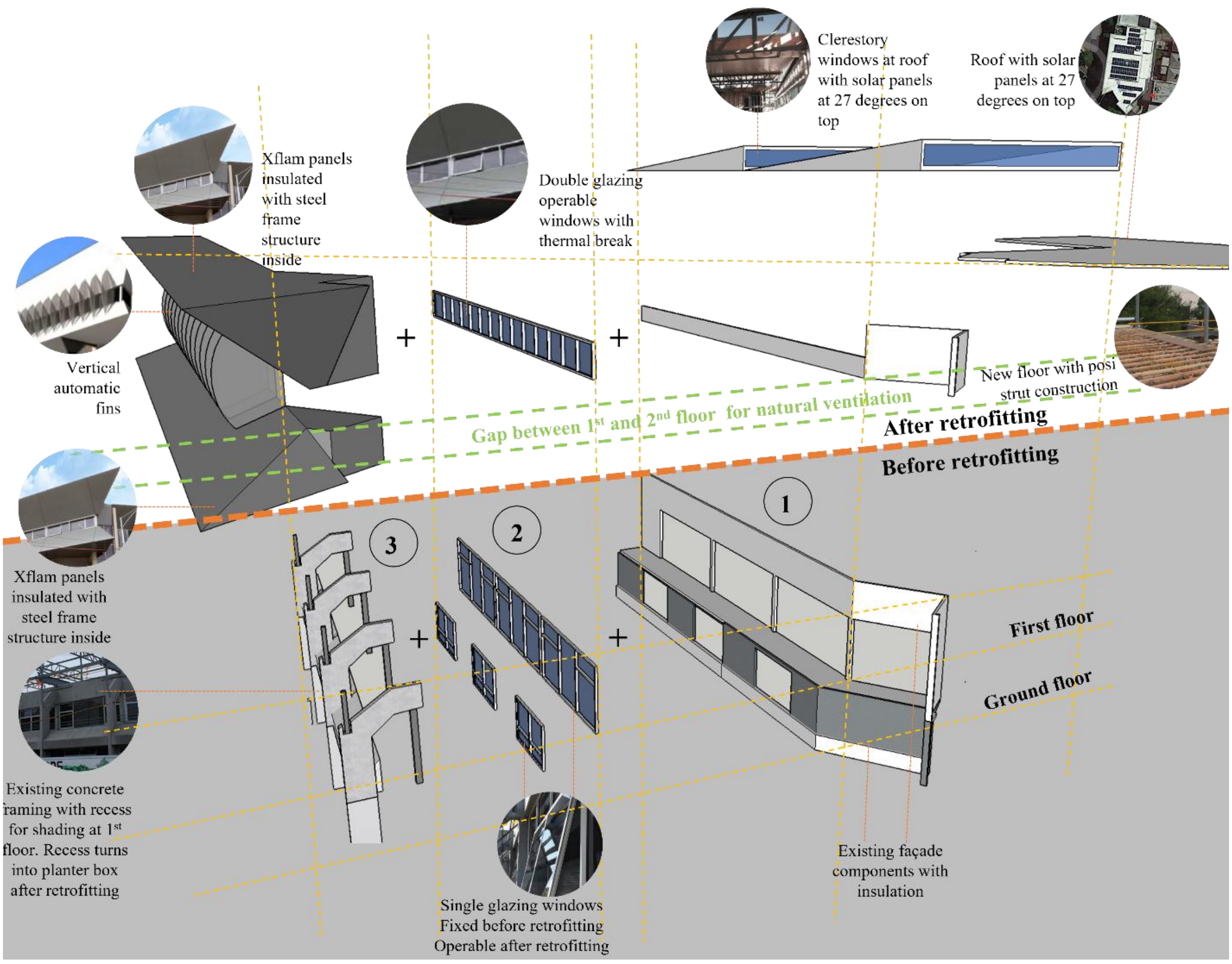
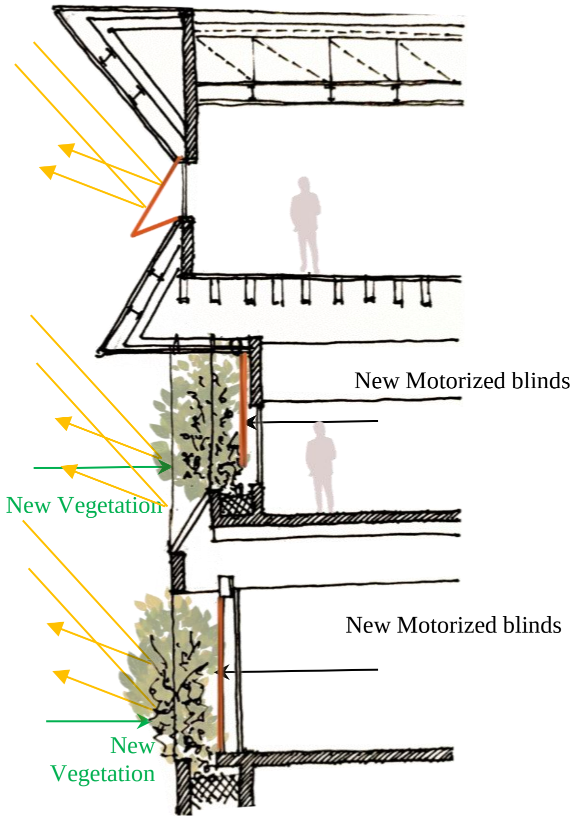


Figure 13. Building envelop strategies: Before and after retrofitting

Design strategies for the building envelop (floor+ west façade+ roof)

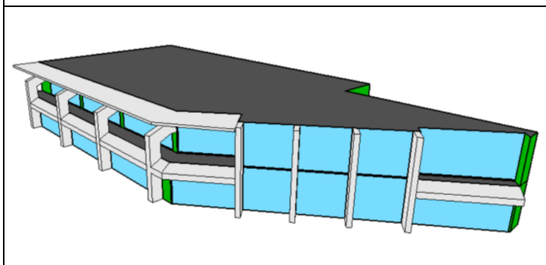
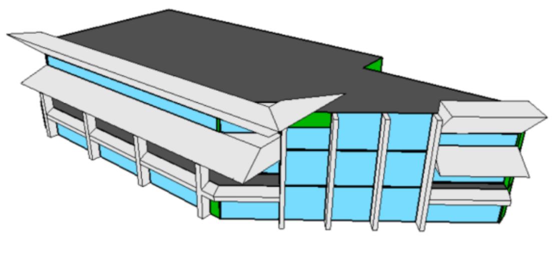


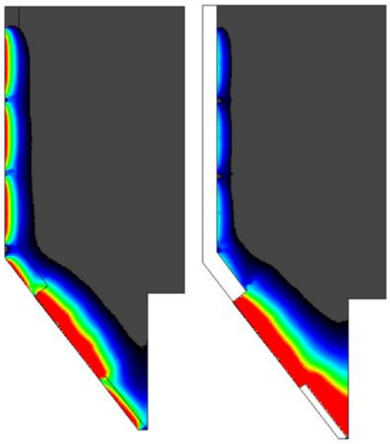
After retrofitting Façade Design:
• Contemporary lightweight structure and floor
• Good quality insulation in walls from previous design
• Double glazing operable windows with added automatic vertical fins as shading • Motorized blinds on all windows
• Sawtooth roof with clerestory lighting with a good number of new solar panels

Figure 14. Building envelope strategies: after retrofitting

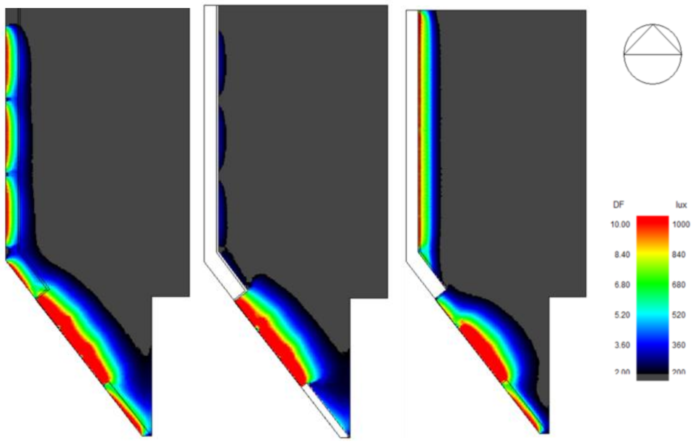
Building Envelop Performance Analysis
Design Builder simulations for daylighting and zone mean air temperature were conducted to assess the performance differences between the west and southwest façades of the building in both the initial and final stages of retrofitting. The analysis revealed that, in the initial stage, daylight availability was higher on the first floor, contributing to increased overheating and a corresponding rise in cooling load. This condition hindered the implementation of natural ventilation. In contrast, during the final stage, the integration of appropriate shading design and vegetation systems effectively filtered daylight penetration, resulting in a reduced cooling load.

Table 5. Existing Building and Retrofitted Building modelling and daylight factor simulation result

EXISTING BUILDING	RETROFITTED BUILDING
	



Ground floor. Height: 0.75m — *First floor: Height: 4.35m*



Ground floor. Height: 0.75m — *First floor. Height: 4.35m* — *Second floor. Height: 7.85m*

The Daylight Factor (DF) and direct illuminance in lux were calculated solely for the façade glazing, with diffused daylight from the clerestory windows at the new roof excluded from the simulation in order to focus on evaluating the façade performance. The initial upper floor of the southwest façade experienced excessive and uneven daylight, leading to overheating. Consequently, the designers opted for full air conditioning. However, in the final stage, this system was replaced with a mixed-mode ventilation strategy. Through the implementation of appropriate shading and façade treatments, the excess heat generated by the glazing was mitigated, resulting in energy savings and reduced operating and maintenance costs.

Natural Ventilation System: Final Retrofitted Building

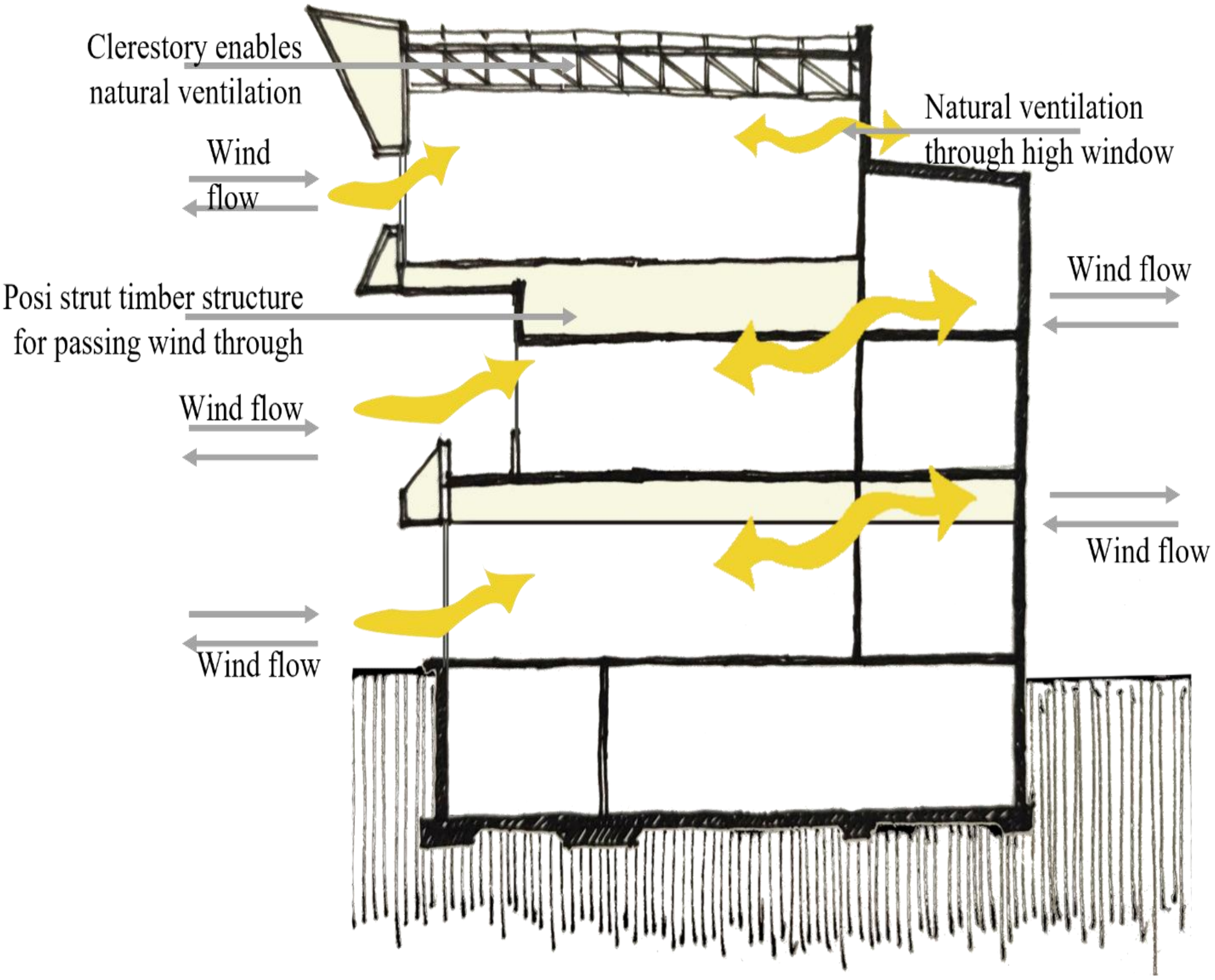


Figure 15. Natural ventilation strategy for the retrofitted building. The building can practice mixed mode ventilation to reduce cooling load and the related energy consumption

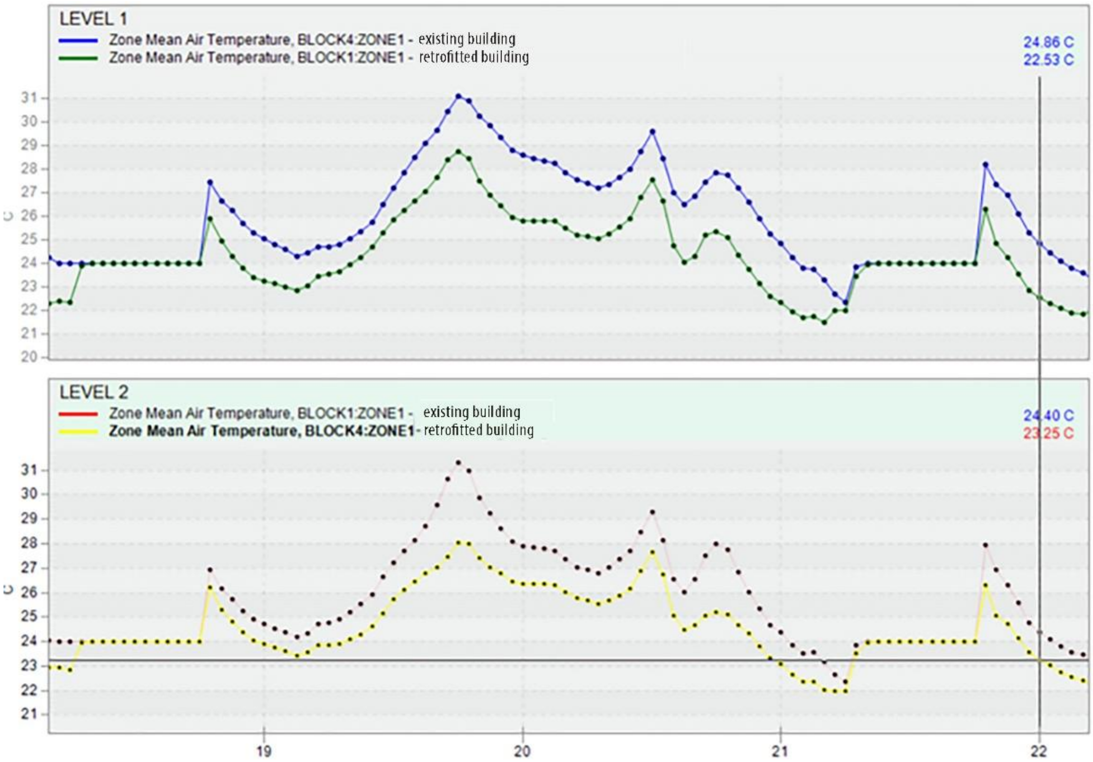


Figure 16. Mean Air Temperature in January shows the retrofitted design on west and southwest facade could reduce the mean air temperature of initial building

Mean Air Temperature: Initial vs. Final Building

Post Occupancy Evaluation

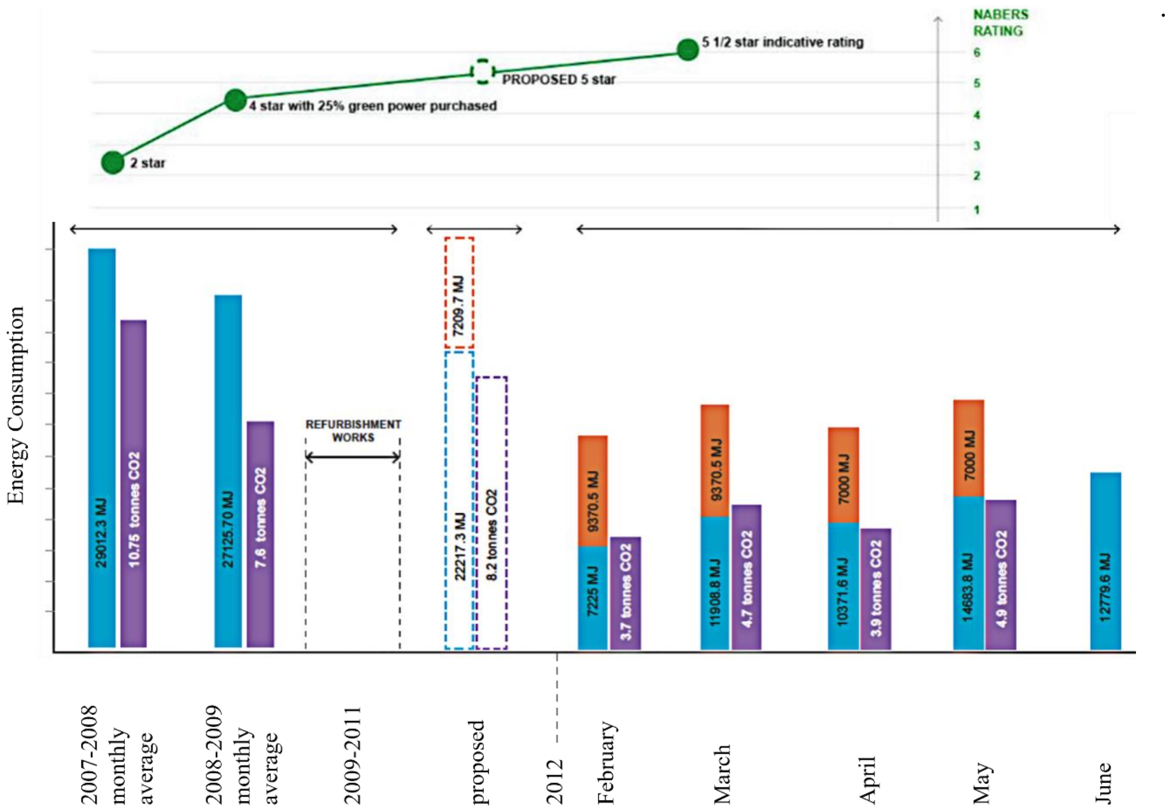


Figure 17. Preliminary energy consumption data (Source: Author with resources from City of Melbourne, 2023)

- The post-occupancy evaluation graph presented above is preliminary and may change based on monthly tracking progress for a year after the building's occupancy.
- The initial proposal aimed for a 5.0-star rating in the NABERS framework, up from the existing 1.5-star rating.
- Over time, the building's performance gradually improved, resulting in a rating increase to 5.5 stars.

Post Retrofit Design Outcome

Table 6. Post retrofit design outcome

Energy	Total energy consumption (electricity and gas) has been reduced by approximately 30 per cent compared to pre-refurbishment levels (from around 28,000 MJ prior to refurbishment down to an average of around 19,000 MJ after refurbishment).
Water	More than 50% reduction in water usage after refurbishment.
Maintenance	• Lighting maintenance cost reduced by 40 % from $1,200 per annum to $500 per annum. • Mechanical maintenance cost reduced by 30% $3,200 per annum to less than $1,000 per annum. • Carbon emission reduced by 50%
Commercial Value	Achieved 8% yield on investment.

Based on analyzing the whole retrofit system in the FMSA Building, it has several points of discussed:

- Energy-efficient Design Decisions:

FMSA successfully retrofitted the whole building through the building fabric. The retrofit design can reduce electricity consumption and create 8% of yield investment and elevate the building NABERS star from 1.5 into 5.5.
a. Building Fabric. The building has a more efficient envelop with a new insulation system for the second floor, reducing the external heat gain from the west sun by doubling the glazing, put an external motorized shading device, and lastly create mixed-mode ventilation through the windows motorized system. With the new ventilation system, the mechanical cost is reduced by 30% annually.
b. Building Daylight. The building also incorporates skylight into the second level that will later reduce electricity consumption by lighting by 40%.

- Building Management Practices:

The building conducts ongoing commissioning that later contributes to building performance improvement.

- Thoughtful Involvement:

Create targets and staff engagement in the early stage of design in energy efficiency by using program CitySwitch

- Effective Building Monitoring and Evaluation Process:

The building was also monitored and evaluated to help track the performance and contribution to the commissioning process.

- Execution within budget:

The real challenge for an architect is the budget. FMSA provides not only a good design but also securing the return of investment during the building operation.

- Organizing the high-level input:

The project ideas contribute even before the budget is committed. Therefore, letting the ideas drive the process and allowing the building to be what it should be.

- Prominent decision making:

FMSA could balance the idealism of design and budgeting the project. Sometimes, architects can push a design on building too hard, it might not really work and end up wasting money.

- Outstanding teamwork:

FMSA works closely with the inherent attributes of the building. This depends on the age, structure and fabric of the building. They are also doing workshops together called ‘ESD workshop’. This workshop includes architects, engineers, building managers and users.

CONCLUSIONS

Improving the energy efficiency of existing buildings is a critical element in addressing the challenges posed by climate change. Historically, LCD has not been developed into a systematic strategy or widely emphasized as a fundamental design principle. This study provides both theoretical and methodological guidance for the low-carbon retrofit of commercial buildings. The findings are primarily derived from analyzing the pre-retrofit conditions of the building and evaluating the enhanced energy performance post-retrofit. The design strategy includes the installation of a new building fabric system with insulation on the second floor, the addition of new glazing to reduce external heat gain from the west-facing sun, the implementation of external motorized shading devices, and the introduction of mixed-mode ventilation through motorized windows. These systems work synergistically, leading to a 30% reduction in annual mechanical costs. Additionally, the incorporation of skylights on the second level is projected to reduce electricity consumption for lighting by 40%. A well-designed building should undergo regular evaluation and monitoring to ensure sustained efficiency throughout the year, and this building incorporates a commissioning process to facilitate this. This paper focuses on the successful implementation of low-carbon design strategies that have significantly improved the building's performance. Additionally, the study highlights the importance of a commissioning process for sustained efficiency, bridging the gap between design intent and long-term building performance. However, the paper does not provide a replicable framework for broader application in diverse climatic and regulatory contexts. The next step for the research team is to develop a comprehensive framework for low-carbon retrofit strategies

Author Contributions: Conceptualization, M.A.N. and T.D.; Methodology, M.A.N.; Software, M.A.N.; Validation, M.A.N.; Formal Analysis, M.A.N. and T.D.; Investigation, M.A.N.; Resources, M.A.N.; Data Curation, M.A.N.; Writing –Original Draft Preparation, M.A.N. and T.D.; Writing –Review & Editing, M.A.N. and T.D.; Visualization, M.A.N., Supervision, M.A.N.; Project Administration, M.A.N.; Funding Acquisition, M.A.N. and T.D. Authors have read and agreed to the published version of the manuscript.
Institutional Review Board Statement: Ethical review and approval were waived for this study because the research does not involve vulnerable groups or sensitive issues.
Funding: The authors received no funding for this research.
Acknowledgments: Not applicable.
Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.
Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to restrictions.
Conflicts of Interest: The authors declare no conflict of interest.

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