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A Comprehensive Analysis to Identify the Potential of Integrating Energy-efficient Retrofit Strategies to Enhance Building Sustainability in Sri Lanka's Warm-Humid Warm-Dry Climate Condition#

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ABSTRACT

A sustainable city strategy is crucial to combat climate change, as buildings contribute significantly to carbon emissions and energy source depletion. Buildings account for 30% of greenhouse gas emissions, 40% of energy consumption, 25% of water, and 40% of resource use. A sustainable city strategy involves retrofitting existing buildings to make them green and energy-efficient by reducing carbon emissions and promoting a more sustainable future. However, developing countries like Sri Lanka are reluctant to adopt energy-efficient retrofitting solutions due to several factors, including a lack of awareness and misconceptions about the costs outweighing the benefits over the building's life cycle. To dispel these misconceptions, this paper aims to establish a comprehensive analysis framework to guide stakeholders in setting an optimal technical combination of energy-efficient retrofit measures for a selected commercial building in Sri Lanka. DesignBuilder software is used to simulate energy performance by analyzing technical features such as insulation, shading, and lighting. The optimal configuration for assessing its environmental and economic impact is determined through life cycle analysis, energy performance assessment, and cost-benefit analysis, integrated with carbon taxing and future energy price scenarios. This study reveals that the optimal retrofitting of buildings could reduce total energy consumption by around 26.79%, environmental impact by around 25% and their payback period was around 17.33 years, while LED lighting has the highest impact on energy efficiency, cost-effectiveness, and environmental impact on the building, while retrofitting the building envelope also brings considerable environmental impact and around 7% energy saving. Furthermore, this study demonstrates that insulation is less efficient in Warm-Humid and Warm-Dry environments than in other area types. This framework for sustainable-comprehensive analysis provides theoretical and practical support and can serve as a reference for future studies on different scenarios.

Keywords: Sustainable city strategy; Cost-benefit analysis; Life cycle assessment; Energy-efficient retrofitting; Carbon taxing; DesignBuilder software

NONMENCLATURE

Abbreviations	
EER	Energy Efficient Retrofitting
UHI	Urban Heat Island
GHG	Greenhouse Gas
CVRMSE	Coefficient of Variation of the Root Mean Square Error
NMBE	Normalized Mean Bias Error
NPP	Net Present Value
IPP	Investment Payback Period
IRR	Internal Return of Rate
LCA	Life Cycle Assessment
Symbols	
$\in$	Energy saving ratio

1. INTRODUCTION

Climate change is a global concern due to its significant negative impact on delicate natural resources, such as coastal lands and marine ecosystems. It has reduced the resilience, structure, and function of ecosystems and altered seasonal patterns. Additionally, climate change has caused irreversible consequences, such as glacier depletion and permafrost thawing, highlighting its status as a major global issue. Elevated global temperatures pose a primary challenge within the context of climate change. Key contributors to this environmental emergency include human-induced greenhouse gas emissions and the urban heat island effect.Since the industrial revolution, global

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temperatures have been rising by 1°C annually, with a double increase since 1981. Climate scientists urge limiting warming to 1.5°C by 2030 to prevent devastating climate change effects such as droughts, wildfires, and floods. In addition to these issues, another significant concern is the depletion of natural resources, which regenerate at a slow rate. This problem is exacerbated by the ever-growing demand for energy resources, driven by the world's population of 7 billion people. Moreover, CO_2 emissions have decreased by nearly 6% in the past three years due to the COVID-19 pandemic, resulting in a reduction of 102 million tons of emissions, a significant factor in the climate change crisis. However, according to the International Energy Agency [2], global energy-related CO_2 increased by 0.9% (321 MT) last year, with an all-time high value of 36.8 MT. World cities, despite only covering 3% of the earth's surface, which is the major contributor to global emissions of carbon dioxide, influence more than 75% of total global emissions [3]. The built environment, which is one of the leading dimensions in cities, contributes 30% of all carbon emissions and 40% of the world's energy usage [4]. Furthermore, the built environment is responsible for 50% of the world's waste production and 60% of its resource use [5], seriously damaging ecosystems and causing considerable biodiversity loss. Therefore, these statistics clearly emphasize that transforming the current building sector into a more sustainable one can enormously contribute towards tackling these ongoing global issues.

Inefficient building design and geometry contribute to energy issues, necessitating energy-efficient retrofitting for sustainable cities. Sri Lanka's energy and environmental crises, particularly in Kandy, demand a sustainable city approach to address these urgent issues. However, developing nations are often reluctant to adopt energy-efficient retrofitting solutions for several reasons, including a lack of knowledge, misconceptions that the costs will outweigh the benefits over the building's lifetime, and insufficient government support. These challenges are primarily driven by myths surrounding the concept of energy-efficient retrofitting in the built environment. This study addresses misconceptions about energy-efficient retrofitting by providing a comprehensive analysis framework for stakeholders to optimize technical measures for a commercial building in Sri Lanka.

2. METHODOLOGY

2.1 *Building modelling and simulation*

2.1.1 Case study selection

Commercial buildings are widely recognized as one of the most prominent building types in the world, playing a significant role in urban landscapes and sustaining economic activities. The existing building sector has been crucial in addressing these issues, making commercial buildings a vital component of the urban environment. This study aims to understand the impact of commercial buildings on the city's sustainability. Therefore, Kandy City Center, the largest commercial building in Kandy, Sri Lanka, has been selected as the case study due to the city's significant environmental issues related to climate change.

2.1.2 Building model development and Validation

In the initial stage of this research, data collected from stakeholders, municipal councils, and existing literature will be used for further analysis. DesignBuilder software, based on the EnergyPlus building performance tool, will serve as the primary tool for this research, focusing on building energy simulation [6]. EnergyPlus is a leading tool for dynamic energy modeling in structures. DesignBuilder facilitates construction simulation processes by enabling quick and cost-effective comparisons of various building designs. The building structure will be modeled according to Kandy's weather data, sourced from the ASHRAE database. The EnergyPlus simulation program will calculate energy usage on an hourly basis for the year 2023 (8760h).

After successfully modeling the baseline building, we proceed to a primary step in this study: validation. To validate the models, we utilize several established protocols, including ASHRAE Guideline 14-2014, the Federal Energy Measurement and Verification Protocol (IPMVP), and the Federal Energy Management Program (FEMP). During the validation process, we adhere to ASHRAE validation measures and guidelines. Two key indices are used: The Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE). The following equations 1 and 2 are applied for CVRMSE and NMBE calculations. According to ASHRAE 14-2014 guidelines [7], the acceptable values for CVRMSE and NMBE are less than 30% and 10%, respectively. A lower value indicates better accuracy, while a higher value indicates a lack of accuracy.

$$CV(RMSE) = \frac{1}{Y}\sqrt{\frac{\sum_{i=1}^{N}(M1-S1)^2}{N}} \times 100\% \qquad (1)$$

Where: *Y* is the Mean Value of consumption and *N* is number of scenarios, *M1* is measured consumption value and *S1* is simulated consumption value.

$$NMBE = \frac{1}{Y} \times \frac{\sum_{i=1}^{N}(M1 - S1)}{N - P} \times 100\% \qquad (2)$$

Where: *Y* is the Mean value of consumption*, N* is the Number of scenarios, *M1* is Measured consumption value, *S1* is Simulated consumption value and *P* is Number of modifiable model parameters, which for calibration needs is recommended to be zero.

2.1.3 Parametric simulation

The initial phase of baseline building modeling has been completed, and the simulated data has been validated against real-world observations, with a focus on the critical parametric simulation stage. The primary objective is to analyze the impact of various parameters such as wall insulation, flat roof insulation, glazing, shading, lighting, and renewable energy sources like PV panels within the context of a modeled building design. Key performance metrics, including net site energy consumption, construction costs, electricity usage, carbon emissions, and discomfort hours, are assessed in accordance with the Energy Efficient Building Code of Sri Lanka [8]. This stage serves to provide insights into how these parameters interact, guiding the development of an optimal retrofitted building design through an iterative optimization process.

2.2 Comprehensive assessment

The analytical groundwork of this study rests upon Wan. S.'s (2022) [9] sustainable development framework for building retrofits, with modifications illustrated in Figure 1. Methodologically, various paths have been used for showing economic and environmental sustainability by using net present value, payback period, energy saving ratio, and life cycle analysis, respectively.

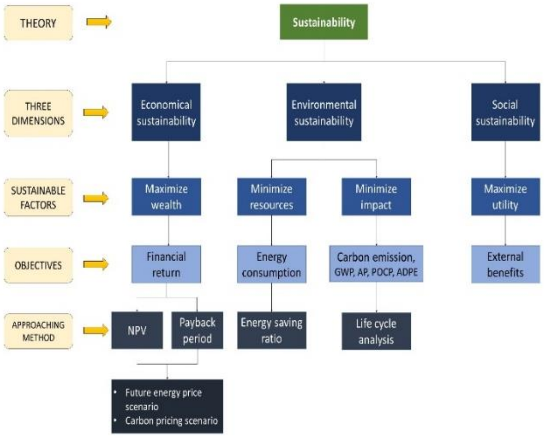

Fig.1 Modified framework of sustainable development of building retrofits with methodological approaches

2.2.1 Energy performance assessment

Energy performance assessments must consider the energy-saving capability or energy efficiency ratios (EERs) in buildings. The EER quantifies energy savings relative to a reference case or baseline building. Eq. (3) evaluates the energy-saving potential of each EER measure.

$$\in = \frac{(E - E_O)}{E_O} \times 100\% \qquad (3)$$

Where, E is Energy consumption after the energy efficient retrofitting and EO – Energy consumption before the energy efficient retrofitting.

2.2.2 Life cycle assessment

Environmental impact is also one of the significant objectives, which could evaluate the potential ecological implications of EER mainly for carbon footprint and environmental impact indicators such as; global warming potential, acidification, ozone depletion, and abiotic depletion by using life cycle analysis (LCA) of the building before and after retrofitting. Following Eq (4) is used to calculate the CO_2 emission reduction potential of EER strategies (*ENVi*).

$$ENVi = \frac{CO_{2-eq}}{\sum_{i=1}^{k} CO_{2-eq}} \qquad (4)$$

Where *CO_2-eq* is the carbon dioxide equivalent reduction per year of the ith energy retrofitting strategy and this ratio should be state between 0 to 1. higher number of ratios means better CO_2 reduction potential.

OneClick LCA software [10] has been used to execute the LCA in this study for 40 years of life span

2.2.3 Cost-Benefit analysis

The profitability of energy-efficient retrofitting strategies is assessed using net present value (NPV) and investment payback period (IPP), considering lifespan costs, retrofit expenditures, running costs, and lifecycle energy savings. Energy consumption is a key criterion and quantifying operating cost reductions is crucial. Estimating energy usage using commercial building models and simulation software can help compute these costs. Future energy price and carbon pricing scenarios highlight the positive impact of EER measures. Following Eq.5 and Eq.6 for evaluate the NPV while Eq.7 is for IPP.

$$NPV = C_I - \sum_{t=1}^{n}(C_E - C_M) \times t \times (1 + i)^{-t} \qquad (5)$$

$$C_E = \sum \Delta Q_i \times P_i \quad (6)$$

$$IPP = \sum_{t=0}^{P_t} (C_I - C_E + C_M) \times t \times (1+t)^{-t} \quad (7)$$

Where C1 is total investment of building energy efficient retrofitting, CE is Benefits of energy savings, ΔQi – savings of ith type energy in each year, Pi – market price of ith type of energy, CM is Annual maintenance cost of the building, T is life expectancy under one technological combination of EER and i is Discount rate and Pt – Dynamic investment recovery period.

3. RESULTS

3.1 Optimal building modeling

The validation results for the baseline building model were 9.20% and 2.65% for CVRMSE and NMBE, respectively. Therefore, it is acceptable to go through the optimal building modeling process. After having the parametric simulation by 137 iterations, expanded polystyrene (100mm) insulation, double reflectance C-L clear 6mm/13mm air, extruded polystyrene HFC blowing (100mm), overhang + side fins (0.5m each), LED lighting, and PV set 1 (257.19 m^2) were chosen for external wall, glazing, flat roof, shading, lighting, and renewable retrofitting, respectively.

3.2 Energy performance assessment

The energy savings are calculated in comparison to a baseline or reference building. Following Fig.2 and 3 contains the energy performance assessment results of each retrofitting strategies.

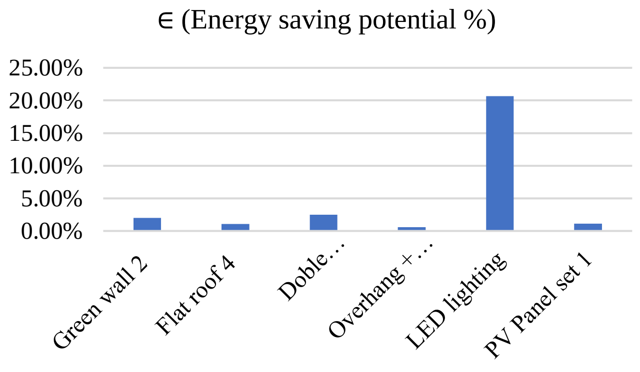

Fig.2 Optimized building strategies' energy saving potential profile

Considering the energy-saving potential across all retrofitting options, LED lighting stands out as the most significant contributor to reducing energy consumption in buildings. Moreover, the overhang+sidefins option was the least energy-saving option, while green wall 2, Dbl Ref A-L Clear 6mm/13mm, flat roof 4, and PV Panel Set 1 had some considerable impact on reducing the total energy efficiency of the building. And according to Fig.2 26.79% energy consumption is less than baseline building.

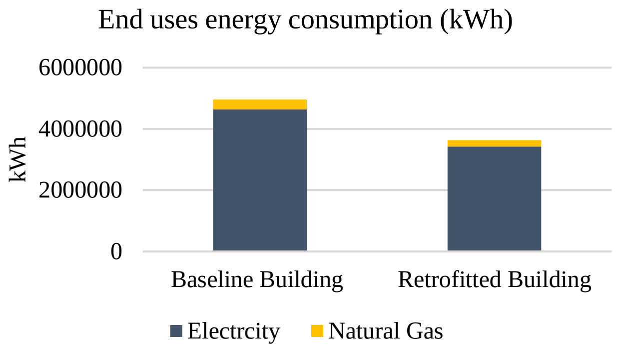

Fig.3 End use energy consumption comparison

3.3 Life cycle analysis

Following table is shown the carbon footprint calculation of each retrofitting strategies which was calculated by using ENVi (formula 4).

Table 1 ENVi of EER measures

	Annual CO_2 emission (kg)	Annual CO_2 emission saving (kg)	ENVi
Baseline model	2869794.64	0	0%
Green wall 2	2851173.40	18621.24	2.31%
Flat roof 4	2803355.91	14413.06	1.83%
Doble Reflectance-A-L Clear 6mm/13mm Air	2855381.58	66438.73	8.43%
Overhang + side fins (0.5m projection)	2852864.01	16930.63	2.14%
LED lighting	2235954.61	633840.03	80.38%
PV Panel set 1	2831590.57	38204.07	4.84%

LED lighting offers the highest annual carbon emission savings among retrofitting strategies, significantly reducing CO_2 emissions. Glazing retrofitting is the second-highest option, but the reduction difference between these two is substantial. The insulated flat roof has the least potential for CO_2 reduction, accounting for only 1.83% of the total reduction. The overall comparison of environmental impact by both the baseline model and the retrofitted model is shown in Figure 4. By retrofitting existing building structures using optimal retrofitting strategies, the most crucial environmental indicators like abiotic depletion, ozone depletion, acidification, and global warming potential impact have been reduced by 15%, 25%, 22%, and 23%, respectively.

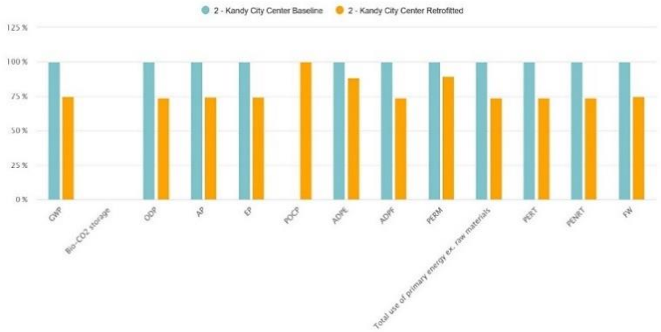

Fig.4 Overall Results of environmental impact from life cycle

3.4 Cost-Benefit analysis results

The Following table contains the NPV and Payback Period of each retrofitting strategy.

Table 2 Cost benefit results of retrofitted building model

	NPV (Net Present Value) ($)	Payback Period (years)
Green wall 2 (insulated)	-767180.70	43.95
Flat roof 4 (insulated)	-915335.32	49.20
Overhang + Side fins (0.5m)	576103.66	30.64
Doble Reflectance-A-L Clear 6mm/13mm Air	3756227.95	19.30
PV Panel	2022722.43	20.34
LED lighting	44251991.55	10.97
Whole retrofitted building	**48924529.58**	**17.33**

Regarding this table, there were only two strategies whose Net Present Value was under zero and payback period didn't satisfy (above a 40-year period), those two were external wall insulation and flat roof insulation. Moreover, the most cost-effective strategy was lighting because the NPV for lighting was the highest and the payback period was the lowest.

3.4.1 Future energy price scenario

Following are the results set for Payback Period, return rate and NPV by applied future energy scenarios (1%,1.5%, 2%) to the retrofitted building.

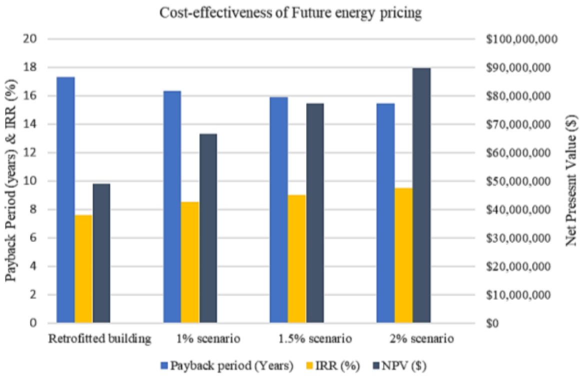

Fig.5 Cost-effectiveness of future energy pricing

By considering the Fig 6 it's clear that the building's economic feasibility has been increasing substantially by rising the future energy price annual percentage with lowering the Payback Period, increasing NPV and Internal return of rate (IRR) (which is the discount rate that NPV gets zero) simultaneously.

3.4.2 Carbon Pricing scenario

For Carbon pricing, it has been undertaken with four different scenarios (25$, 54.61$, 75$, 100$). Following are the results of fluctuation of cash flows with different carbon pricing ranges.

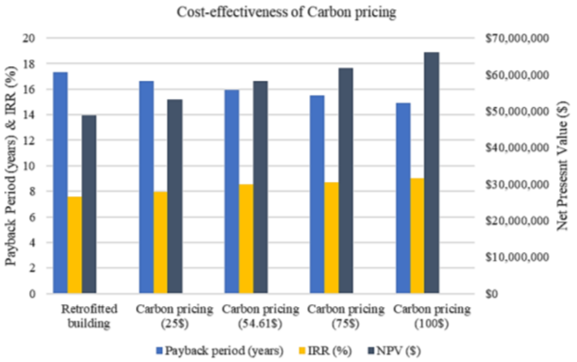

Fig.6 Cost-effectiveness of Carbon pricing

Regarding the results, the building's economic viability has been significantly raised as carbon pricing has increased, resulting in an early payback period, a higher NPV, and a higher IRR at the same time. Considering about applying the current carbon pricing scenario which is 54.61$, there was a considerable amount of increasing the cost benefit by 20% and 13% on NPV and IRR respectively while the Retrofitting expenditures payback period has been decreased by 1.42 years.

4. DISCUSSION

By referring this study it's clear that, environmental and economic feasibility of energy-efficient retrofitting was highly relied on energy saving potential. Unlikely some other recent literatures, insulation didn't affect to overall energy saving of the retrofitted building in this study. This is one of the most important aspects that needs to be highlighted in this study because, most stakeholders in retrofitting existing buildings often apply insulation for flat roofs and external walls without considering climate conditions. And this paper conveys that, it's a must needed action to consider the climate condition before applying insulation to an existing building stock. Moreover, unlike the other studies, this building's existing external wall has a quite decent U-value due to the 100-mm air gap in the wall construction. And the U-value difference between retrofitted wall structure and existing wall structure was not that substantial, and this reason might be one of the factors for lowering the insulation's energy-saving effect. The study found that flat roof insulation did not significantly reduce energy consumption in warm, humid weather conditions. The second-highest ideal strategies were glazing retrofitting, and installing PV panels. The humidity level of the atmosphere is directly affected by insulating structures, as well as other factors like glazing, PV panels, lighting retrofitting, and shading. The energy performance assessment of retrofitting strategies is influenced by the existing building's energy performance level and the climate condition of the building's location.

5. CONCLUSION

The study presents a framework for stakeholders and policymakers to plan energy-efficient retrofitting for buildings to achieve sustainable development goals by 2050. The framework considers energy efficiency, environmental impact, and cost-benefit. The study focuses on assessing the best ideal retrofitting combination for buildings in selected weather conditions in terms of environmental, economic, and energy-saving feasibility. Key findings include:

- The optimal building retrofitting combination can reduce 26.79% annual building energy demand. LED lighting is the option that has the most substantial potential for reducing energy consumption.
- Optimized retrofitting strategies reduce Carbon footprint by 25.33% and environmental indicators like abiotic depletion, ozone depletion, acidification, and GWP by 15%, 25%, 22%, and 23%, respectively.
- The payback period for retrofitting existing buildings is 17.33 years, with flat-roof insulation having the longest period and LED lighting having the shortest. Future energy price (2%) and carbon pricing scenarios (100$/tCO$_{2eq}$) made shorter payback periods of 15.45 and 14.9 years, respectively.
- Insulation (specially for Flat roof) is the only retrofitting measure which is not an ideal for Warm-Humid, Warm-dry climate condition.

For Future studies, it is recommended to focus on energy-efficient retrofitting strategies like green roofing systems, HVAC retrofitting, and advanced controls. They should also consider water consumption savings and the water-energy nexus to assess a building's energy consumption. Low-embodied carbon materials, especially in building envelope insulation, can mitigate carbon emissions. A social investigation to gather diverse perspectives on social benefits would also be beneficial for future studies.

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