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Integrating Energy Efficiency in Residential Buildings: A User-Centric Web Interface Approach

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Abstract

In the global mission to achieve a net-zero carbon footprint, the contribution of buildings is substantial, accounting for over one-third of the world's carbon footprint. To re-engineer the built environment in the direction of decarbonization, the building sector's operational energy needs our special imagination. The principal aim of the following research paper is to enhance building energy management by creating a digital platform that records design stage energy performance and benchmarks annual occupant consumption. The present study attempts to evaluate Kolkata's residential high rises for their design stage energy consumption though whole building energy simulation by using design builder version 7.0.2.006. Envelope energy efficiency measures like wall, roof, and glass material changes show an annual energy performance improvement of 28.55% compared with a standard as built construction practice base case energy performance index value of 125.93 kWh/m^2/year. The web-based energy profiling and benchmarking applications has been developed using Python's Django framework. The website has been hosted on Python Anywhere. The portal features a home page, a page to add building details, and a personalised user dashboard with a building digital profile. The study shows that implementation of envelope interventions in the redesign have resulted in demonstrated improvements in annual energy performance. Integration with the web-based portal with initial design stage improvements serves to document and visualize tangible benefits in electricity bills and operational carbon emissions for the end-user, thus serving as the missing link of building operational energy performance.

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Introduction

According to several technical reports and audits worldwide, buildings contribute to over a third of the world's final energy consumption,[1] and operational energy loads are a significant contributor to the same. As per the Global ABC Roadmap for Buildings and Construction published in 2020, the building industry directly or indirectly accounts for 36% of global energy use and 39% of global GHG emission release.[2] Moreover, a study performed by the Alliance for an Energy-Efficient Economy (AEEE) revealed that India's residential building floor space will increase from 15.3 billion m^2 in 2017-18 to 21.9 billion m^2 in 2027,[3] further contextualizing and exacerbating the evolving scope of the problem.

Also, the BEE's yearly report for 2018 found that stating that 75% of India's electricity produced in 2017-18 was consumed by residential buildings.[4] Not only is this because of inefficient design practices, but it is also because of the non-compliance of design parameters in the operational stage. This is largely due to the unavailability of design parameter references upon transfer of operations to occupants. The design modification approach has been validated through studies indicating that meeting the Eco-Niwas Samhita (ENS) 2018 and Energy Conservation Building Code (ECBC) 2017 envelope standards can achieve reductions of up to 26% in operational energy use and up to 36% in cooling energy requirements for high-rise residential buildings in warm and humid regions.[9] The specific merits of implementing envelope redesign measures have been studied in Sadati *et al*. (2023) on an Iranian building, where it was found that usage of materials such as AAC blocks, LECA blocks and XPS among others resulted in annual reduction of up to 23.2% in heating loads, 26.4% in cooling loads and 18.5% in CO_2 emissions.[10]

This research seeks to answer some key questions: How can the operational energy demand of the building be reduced? How can building design parameters be effectively documented? And, how can compliance be maintained in the operational stage? Based on a survey of the most recent literature and the observed gap, a data-driven digital approach powered by comprehensive climate analysis and simulation[5-8] investigated in this study. This study utilizes Design Builder software for energy simulation running version 7.0.2.006 and climate analysis software climate consultant version 6.0.17 to develop the digital model of a high-rise residential building. A user-centric web-based interface for data capture and performance reporting will be developed using the Django 4.0.2 framework with an SQL database hosted on PythonAnywhere.

Materials and Methods

Methodology

The study zeroes in on Kolkata, India's warm, humid climate with specific interest in traditional residential high rises.[11,12] Base case and efficiency interventions were designed and simulated. Data was then fed to the digital user interface after on boarding users to generate building energy performance report and digital profile. Figure 1 demonstrates the details research methodology followed for this study.

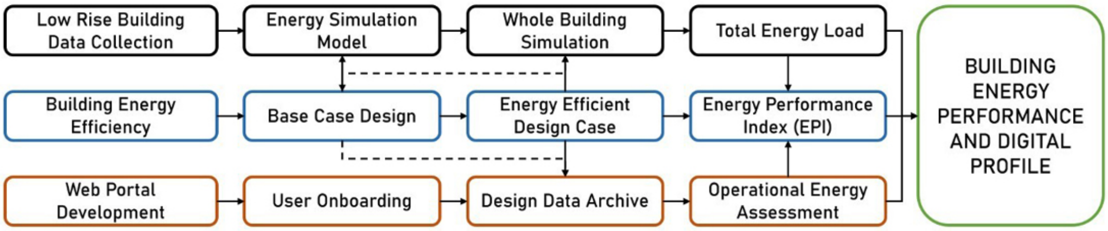


Fig. 1: Flowchart of overall methodology

Climate Analysis of Building Location

The residential building as mentioned in Table 1, located in Kolkata was designed in DesignBuilder and then climate analysis was done using Climate Consultant.[13,14] Figure 2 shows the front and top view of model. Table 1 lists the geographical parameters provided for the same.

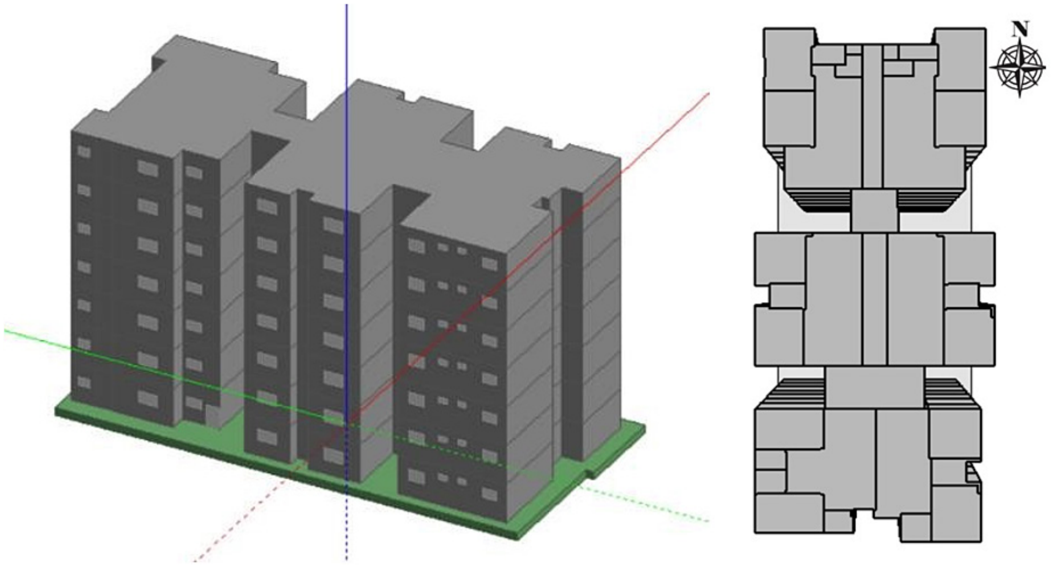


Fig. 2: Front and top view of DesignBuilder model

Table 1: Geographical parameters of studied building

Parameter	Value
Location	Kolkata, India
Building	G+7 High rise residential building
Weather File Name	IND_Kolkata.428090_ISHRAE
Climate Zone	Warm and Humid
Latitude	22.65°North
Longitude	88.45°East
Hottest Annual	43.9°C
Coldest Annual Temperature	5°C
Temperature Elevation above Sea Level	9.14m
Average Annual Temperature	26.8°C
Annual Cumulative Horizontal Solar Radiation	1521.7 kWh/m^2
Percentage of Diffuse Horizontal Solar Radiation	59.5%

Figure 3 shows the shadow analysis was done assuming summer: April 08 (12:00pm – 3:00pm)-south-east orientation. It was observed that the southern and eastern side is sufficiently shaded throughout these harsh summer hours. Eastern side is mostly shaded because of the timing and the extended roof. The southern façade till 1:00pm completely shades the window, while during 2:00pm-3:00pm there is some exposure negligible. For the winter timing it is to be seen whether these huge south sunshades blocks winter sun.[15]

The Sun Path Diagram from Figure 3 indicates that April is the hottest month. Solar altitude is high (60-90 degrees) during the peak time between 12:00pm-3:00pm. Solar Azimuth is between 120-250 degrees. December is the coldest. Solar altitude is low (4-35 degrees) during the coldest period from 7:00am-10:00am. Solar Azimuth is between 118-145 degrees. From Figure 4, the wind rose diagram shows that winds predominantly are from north and south and mostly are hot. Hence, the best orientation for this climate solely in the point of view of radiation gain would be along north-south axis.

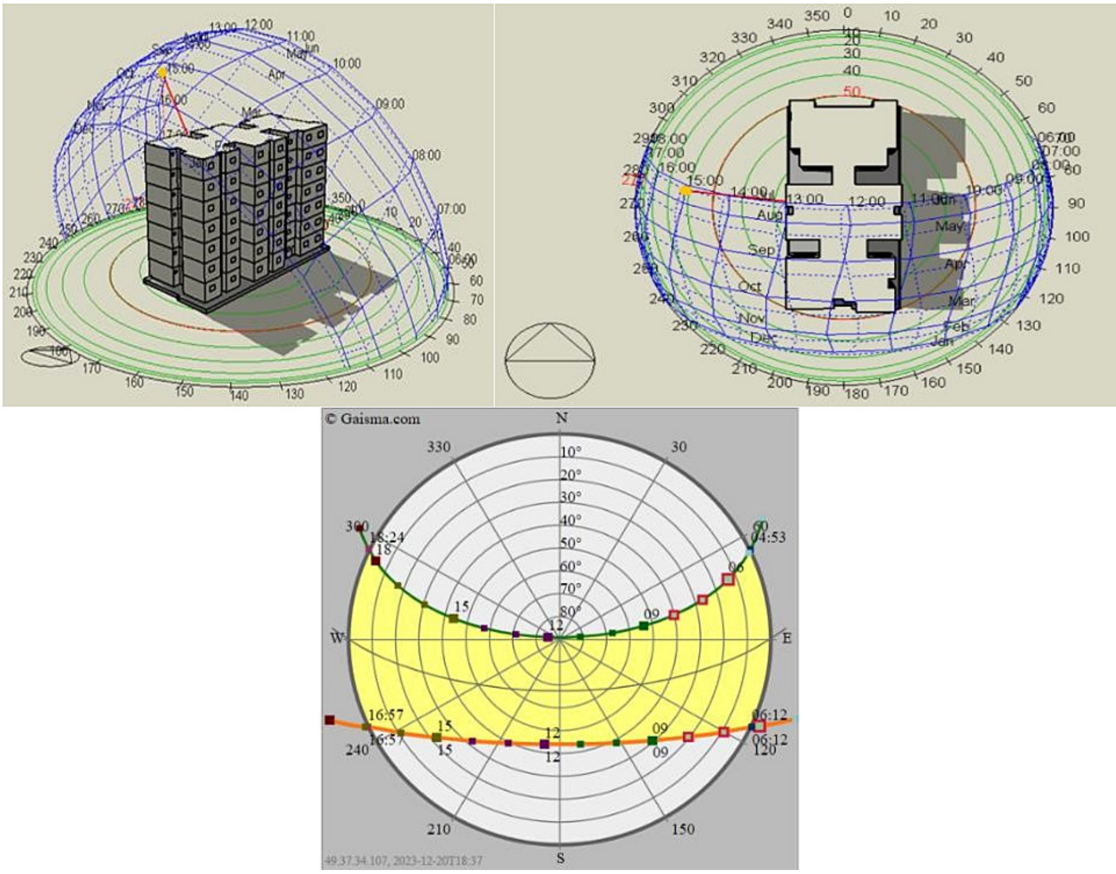


Fig. 3: Shadow analysis and sun path of building

As per Radiation Chart in Figure 4, November-April has high direct normal radiation, that is from winter to the start of summer months. May and October approximately have equal amounts of direct and diffuse radiation. June marks the beginning where diffuse radiation reaches the surface more than direct. July- Aug has more diffuse radiation than direct radiation. Sept marks the beginning of the second reversal where direct radiation is more than the diffuse radiation. Peak summers has more direct radiation. Peak rainfall coincides with the increased diffuse radiation.

Building Energy Modelling and Simulation

The initial base case was framed as per typical construction practice in the project location, consisting of Red Brick Construction (RBC) for wall and roof. The design cases have changed wall material with three other available materials, namely RCC Slab, Fly Ash Brick and Autoclaved Aerated Concrete (AAC) Blocks. Similarly, roof material has been changed with two other available materials, namely RCC Slab and AAC Blocks. Thermal transmittance for each material was calculated and presented in table 2. For glass, market survey was done and two types of Single Glazed Unit (SGU) and three types of DoubleGlazed Unit (DGU) glass typically available for residential buildings were tested. The base case utilizes a simple SGU Glass while the design cases utilize several different models of glass manufactured by Saint Gobain. The input parameters for the building simulation of various design cases are given in Table 2 and Table 3, and Table 4 has a comprehensive summary of materials selected for each case.

The energy efficiency measures as applied in terms of building envelope materials for each of the design cases with full assembly details are given in Table 4.

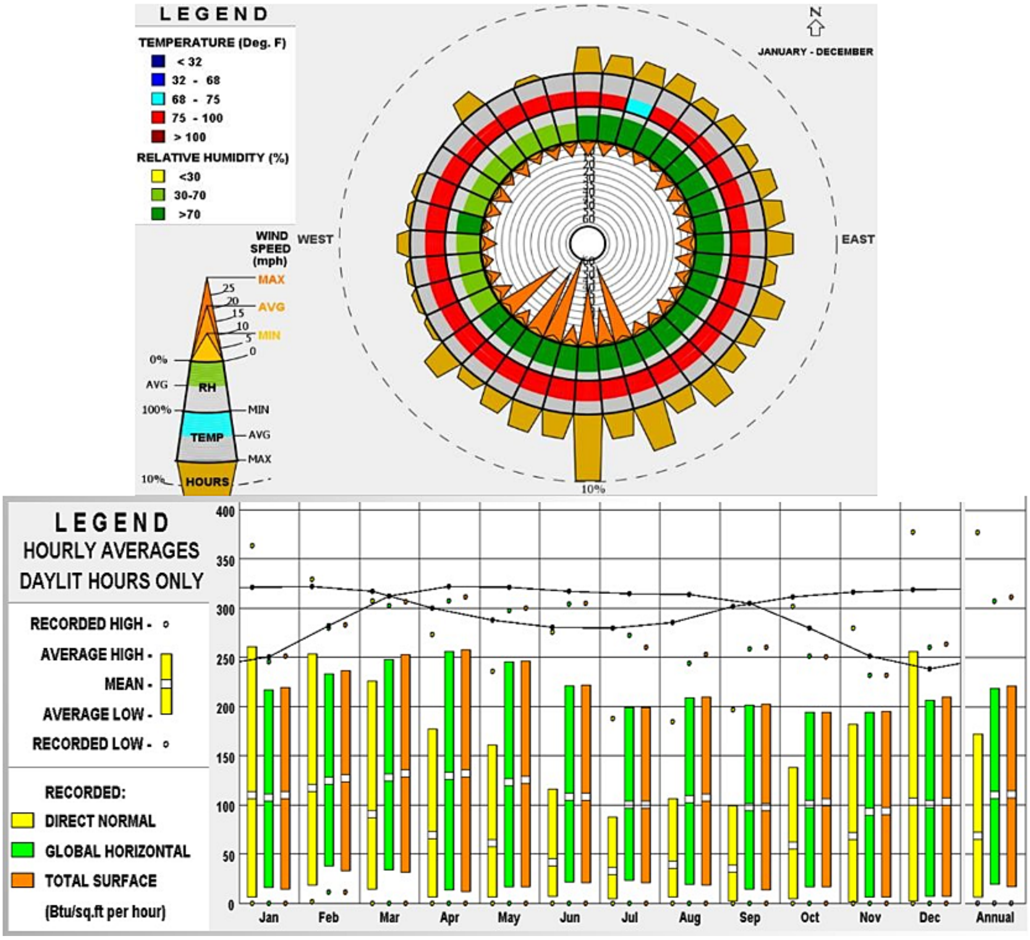


Fig. 4: Wind rose and radiation chart

Table 2: Building envelope design case[6-9]

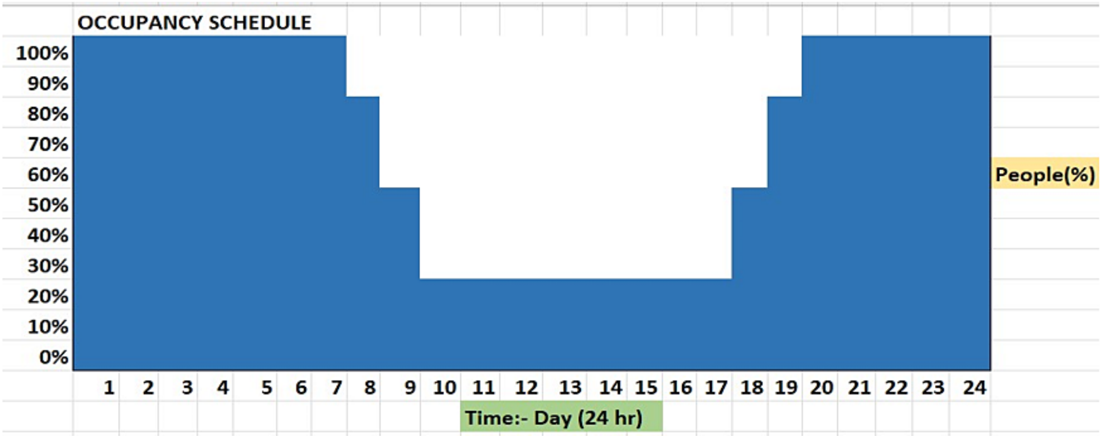
Case Unit	Wall Materials	U value (W/m²K)	Roof U value (W/m²K)	SGU/ DGU	SHGC	U value (W/m²K)	VLT (%)	Shading
Base Case	Red Brick construction	2.37	2.69	SGU	0.81	5.69	87	NO
CASE 1	RCC	3.17	3.77	SGU	0.68	5.6	67	NO
CASE 2	RCC	3.17	3.77	DGU	0.4	2.8	50	NO
CASE 3	FLY ASH	1.316	3.77	SGU	0.68	5.6	67	NO
CASE 4	FLY ASH	1.316	3.77	DGU	0.4	2.8	50	NO
CASE 5	AAC Block	0.498	3.77	DGU	0.4	2.8	50	NO
CASE 6	AAC Block	0.498	2.7	DGU	0.4	2.8	50	NO
CASE 7	AAC Block	0.498	1.2	DGU	0.4	2.8	50	NO
CASE 8	AAC Block	0.498	0.694	DGU	0.4	2.8	50	1.0 M
CASE 9	AAC Block	0.498	0.694	DGU	0.27	1.8	36	1.0 M

Table 3: Parameters for building systems [6,7,9,16,17]

Category	Building Systems		Base case	Design cases
Lighting	Light Power Density	W/m^2	7.53	4.53
Equipment	Equipment Power Density	W/m^2	10.76	10.76
HVAC Systems	HVAC	System Type	Split A.C	Split A.C
	Efficiency (COP)	EER	3.1	3.8
Ventilation	Min. Fresh Air Required	l/S Per Person	2.5	2.5
Occupancy	Occupant Densities	m^2/Person	12.50	12.50

Table 4: Building materials for each simulation case[6,7,9,18,19]

Case	Building materials Wall, Roof, Glass
Base Case	**Wall-** Red Brick Construction, U-Value: 2.37 W/m^{2}k, **Roof-** Red Brick Construction, U Value: 2.67 W/m^{2}k, **Glass-** SGU- U Value-5.69, SHGC-0.81, VLT-87
Case 1	**Wall-**RCC Slab (235mm incl. 35mm Internal + External Cement Work), **Roof-** RCC Slab (177mm incl. 27mm Internal + External Cement Work), **Glass-** Saint Gobain Glass -ST 167 (SGU)- U Value5.6, SHGC-0.68, VLT-67
Case 2	**Wall-** RCC Slab (235mm incl. 35mm Internal + External Cement Work), **Roof-** RCC Slab (177mm incl. 27mm Internal + External Cement Work), **Glass-** Saint Gobain Glass -ST 467 (DGU)- U Value2.8, SHGC- 0.4, VLT- 50
Case 3	**Wall-** Fly Ash Brick (235mm incl. 35mm Internal + External Cement Work), **Roof-** RCC Slab (177mm incl. 27mm Internal + External Cement Work), Glass- Saint Gobain **Glass** -ST 167(SGU)- U Value-5.6, SHGC-0.68, VLT-67
Case 4	**Wall-** Fly Ash Brick (235mm incl. 35mm Internal + External Cement Work), **Roof-** RCC Slab (177mm incl. 27mm Internal + External Cement Work), Glass- Saint Gobain **Glass -**ST 467(DGU)- U Value-2.8, SHGC- 0.4, VLT- 50
Case 5	**Wall-** AAC Block (235mm incl. 35mm Internal + External Cement Work), **Roof-** RCC Slab (177mm incl. 27mm Internal + External Cement Work), Glass- Saint Gobain **Glass -**ST 467 (DGU)- U Value2.8, SHGC- 0.4, VLT- 50
Case 6	**Wall-** AAC Block (235mm incl. 35mm Internal + External Cement Work), **Roof-**RCC With Ceramic Tile (206.4mm incl. 54mm Internal + External Cement Work and Insulation), **Glass-** Saint Gobain Glass -ST 467(DGU)- U Value-2.8, SHGC- 0.4, VLT- 50
Case 7	**Wall-** AAC Block (235mm incl. 35mm Internal + External Cement Work), **Roof-** RCC With Ceramic Tile (206.4mm incl. 54mm Internal + External Cement Work and Insulation), **Glass-** Saint Gobain Glass -ST 467(DGU)- U Value-2.8, SHGC- 0.4, VLT- 50
Case 8	**Wall-** AAC Block (235mm incl. 35mm Internal + External Cement Work), **Roof-** RCC Slab (227mm incl. 27mm Internal + External Cement Work), **Glass-** Saint Gobain Glass -ST 467 (DGU)- U Value- 2.8, SHGC- 0.4, VLT- 50
Case 9	**Wall-** AAC Block (235mm incl. 35mm Internal + External Cement Work), **Roof-** Aerated Concrete Slab (227mm incl. 27mm Internal + External Cement Work), **Glass-** Saint Gobain Glass -KT 140(DGU)- U Value-1.8, SHGC- 0.27, VLT- 36 (12mm air gap)



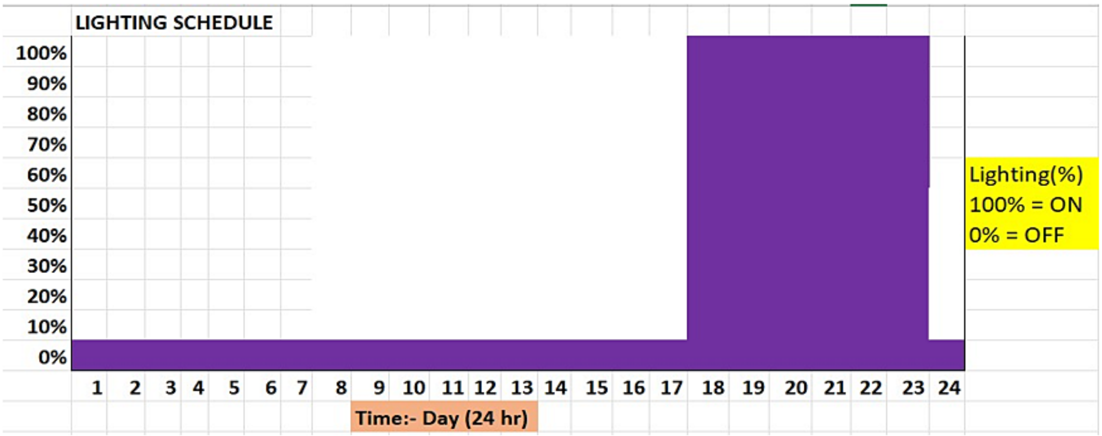


Fig. 5: Occupancy schedule and lighting schedule

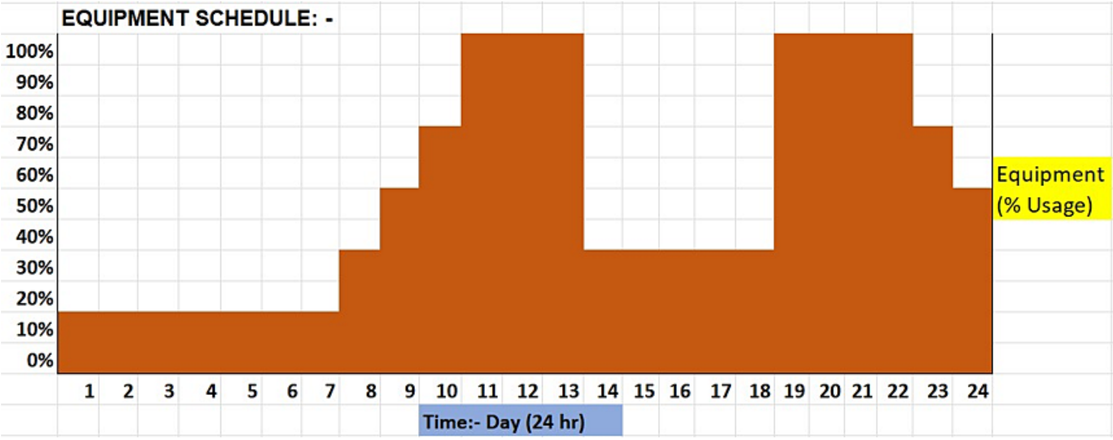


Fig. 6: Equipment schedule

Figures 5 and 6 graphically represent the building operation, lighting, and equipment schedule throughout the day respectively.

Web – Based Digital User Interface

The web portal has used Django, a Python-based backend framework alongside HTML and JavaScript, with CSS and Bootstrap for styling and an SQL database. The website and database have been hosted on PythonAnywhere. The static files have been hosted on AWS. Table 5 notes the data required for user onboarding and verification.

Table 5: Data required for user onboarding & verification

Parameter	Purpose
Username	Onboarding
Password	Onboarding
Name	Identification
Email	Verification and Communication
Location	Benchmarking and Verification
ID Proof Selection (e.g., Aadhaar Card)	Verification
ID Proof Number (e.g., Aadhaar Card No.)	Verification
Address Proof Selection (e.g., Voter ID Card)	Verification
Address Proof Number (e.g., Voter ID Card No.)	Verification

The website encompasses a range of features designed to provide a comprehensive and userfriendly experience. A secure login and registration system allow users to register their properties without divulging personal data, ensuring privacy. The implementation of an email system facilitates communication for registration, password resets, and benchmark results, enhancing user engagement. Each user is granted a personalized dashboard, fostering a tailored experience and easy management of their property-related information. Additionally, a dedicated admin dashboard provides specialized tools for efficient administration. Table 6 notes the operational energy input parameters.[20,21]

Table 6: Data and inputs collected for operational energy benchmarking and report

Parameter	Unit/Data
Category	BHK
Name	N/A
Area	Sq. Ft.
Rooms	Number
Occupants	Number
Appliances	Number, Type, Make, Model & Rating
Annual Consumption	Units
Annual Bill	INR
Month – wise Consumption for Last 3 Years	Units

The database functionality enables the listing of flats, creating a structured repository of property information. The benchmarking feature enhances user insights by comparing properties against others in the same category and historical data. Detailed data collection, including appliance data, ensures a thorough understanding of consumption patterns. A dedicated benchmark page for each flat presents a comprehensive overview, featuring past consumption metrics, Energy Performance Index(EPI),and per-occupant consumption data.

Figure 7 shows the user experience for onboarded users in the form of a flowchart.

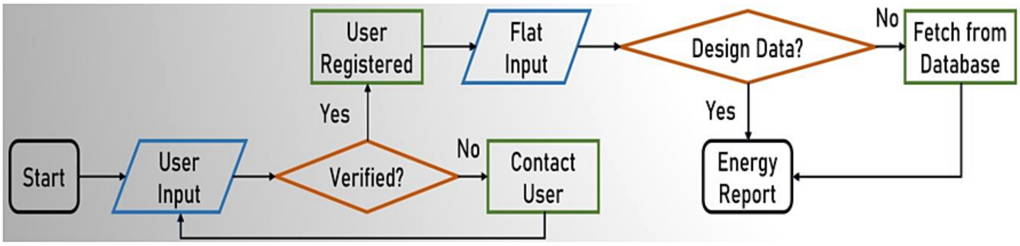


Fig. 7: User experience flowchart

Results and Discussion

Operational Energy Performance of Base Case

A digital model of a G+7 residential building located in Kolkata, India, using DesignBuilder software was successfully created. The comprehensive climate analysis was performed to narrow down the factors that must be accounted for occupant comfort throughout the year and to size HVAC, lighting, equipment, and other loads accordingly. Shadow analysis, sun path, wind rose, and comfort analysis were performed with climate consultant software. The base case of the building envelope was constructed with commonly used, low-cost building materials. Both the wall and roof are made of red brick, and the glass is a commonly available single-glazed unit (SGU). This yielded a base-case EPI of 125.93 kWh/m^2/year.

Table 7: Annual energy performance index (EPI) for base and design Cases

Simulation Case	Energy Performance Index (kWh/m^2/Year)
Base case	125.93
Design case_1	113.30
Design case_2	111.13
Design case_3	103.85
Design case_4	101.15
Design case_5	95.10
Design case_6	94.12
Design case_7	91.95
Design case_8	91.28
Design case_9	90.01

Table 7 shows annual EPI values for the base case and all design cases.

Operational Energy Reduction Through Envelops Energy Efficiency Measures

The first design case swapped the red bricks in both the wall and roof for RCC Slab construction, and the glass was changed to slightly more efficient ST 167 SGU. This immediately resulted in a 10.05% improvement over the baseline. In Cases 3 and 4, fly ash bricks were used for the wall assembly. Henceforth, all wall assemblies will have 20mm external and 15mm internal cement plaster. In case 4, Saint Gobain ST 467 Double Glazed Unit (DGU) glass was used. This yielded a 17.50% and 19.64% improvement over baseline in cases 3 and 4, respectively. Case 5 represents a significant improvement in the design's operational energy performance, with a 24.45% improvement over the baseline. This is made possible by swapping fly ash bricks in the wall assembly with AAC blocks.Case 6 changes the roof assembly to a 12mm ceramic tile exterior, 30mm cement mortar, 152.4mm RCC, and 12mm cement plaster, giving a 25.22% improvement over the baseline. Case 7 adds insulation to it and further improves energy performance up to 27.96%. In Case 8, wall assemblies were kept fixed with ACC blocks, and energy efficiency measures were applied to the roof assembly with an improved construction layer that utilises 15mm external cement plaster, 200mm of aerated concrete Slab, and 12mm internal cement plaster, yielding a 27.56% improvement over baseline. In the most improved proposed design case 9, the wall and roof construction were kept from the previous improved design case and efficient glass material changed with specification KT 140 DGU with a 12mm air gap, giving us our best EPI of 90.01 kWh/m^2/year, which is a 28.55% improvement over baseline. Figure 8 represents this progressive energy performance improvement as a bar chart.

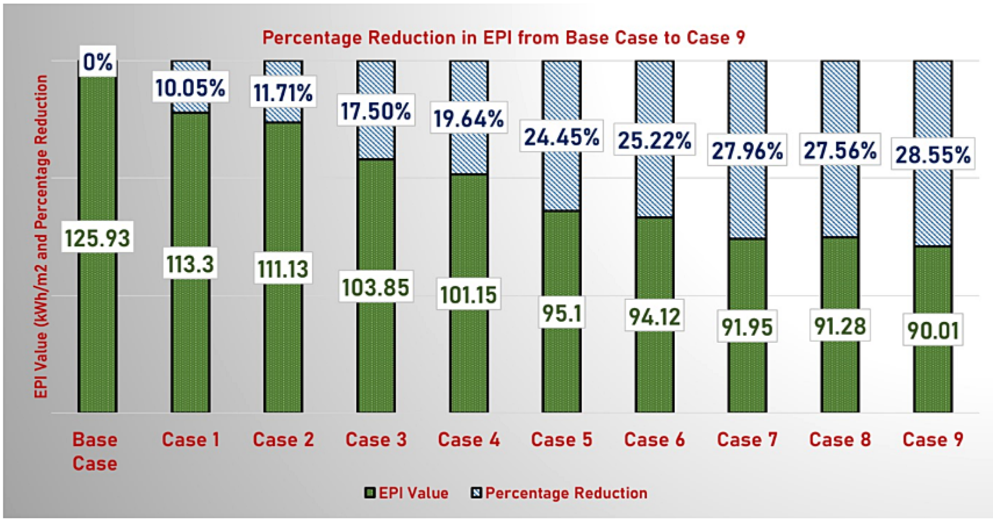


Fig. 8: Percentage reduction in EPI from base case to design case 9

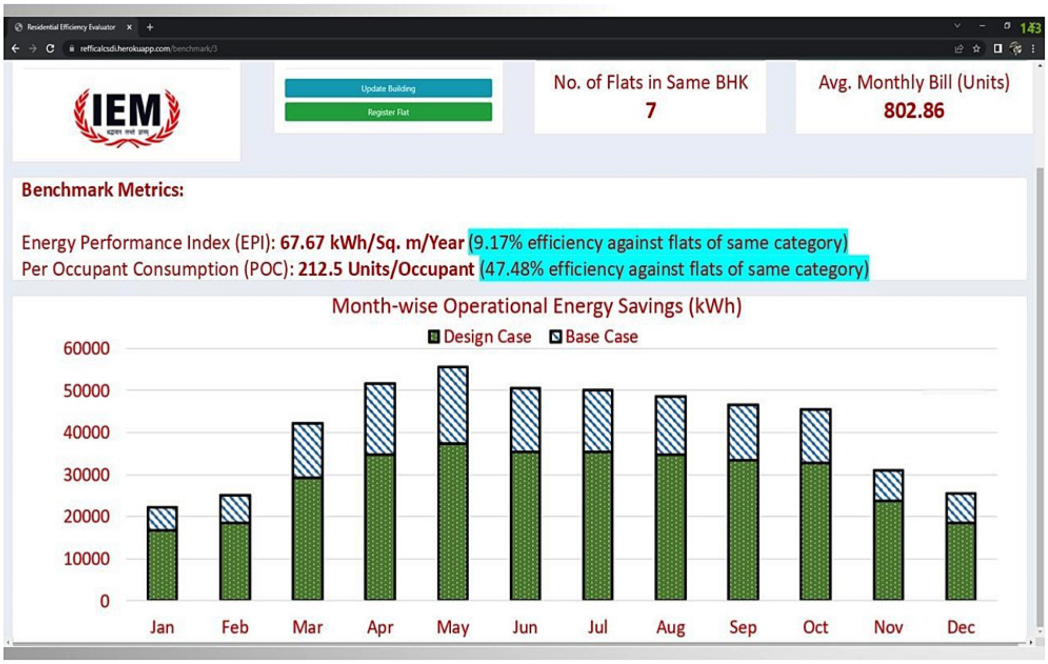


Fig. 9: User dashboard with energy load graph

Web – Based Digital Interface with Performance Report

Figure 9 is a screenshot from the web portal highlighting the difference in energy load between the optimum presented Design Case and the presented Base Case. The developed portal [Link: refficalc.pythonanywhere.com] is successfully taking user input, onboarding them, and capturing the design input parameters as intended. The portal has been hosted on PythonAnywhere. It is capable of giving a detailed performance report, from energy performance compliance to per-occupant consumption, energy performance index, and building performance against flats in the same category. The user manual provided by this portal will help to achieve energy efficiency and control the behavioural impact of operational energy demand.

Conclusion

In this study, various building envelope material's effect on a building's operational energy is evaluated. The web portal has been developed using Python's Django framework and SQL. The energy efficiency measures proposed have achieved a significant improvement in energy efficiency, and the developed web portal has enabled a seamless transition of the building from the design stage to operation. Proposed design Case 9, with the combination of AAC block walls, an aerated concrete Slab roof, and highly efficient double-glazed glass, achieved an EPI of 90.01 kWh/m^2/Year, which is 28.55% better than the base case. The web portal successfully onboarded users and captured design data input and month-wise energy load data. However, the results reported in this paper are only applicable to the city of Kolkata and the warm and humid climate zones, but the methodology applied is generic and applicable irrespective of location and climate zone. Also, as any redesign or retrofit for the purpose of improving energy efficiency comes with a significant cost component, a detailed cost-benefit analysis of the initial capital expenditure and return-on-investment for any such redesign will be addressed as part of the future scope of this work.

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Conflict of Interest

The author(s) do not have any conflict of interest.

Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research study are available on request from the corresponding author.

Ethics Statement

The study doesn't involve experiments on human and animals.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Author Contributions

Gunjan Kumar: Conceptualization, Result analysis, Review & Editing, Formal analysis

- **Kausar De:** 1st Draft Writing, Web development, Flowcharts, Graphics
- **Ayan Guha Roy:** Energy Simulation
- **Subhajit Bag:** Data Collection and Building Modelling.

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