Proceedings of the 2023 Winter Simulation Conference
C. G. Corlu, S. R. Hunter, H. Lam, B. S. Onggo, J. Shortle, and B. Biller, eds.

A CUSTOMIZABLE COMMUNITY-BUILDING-ENERGY-MODELING DECISION SUPPORT SYSTEM (CCBEM-DSS) FOR NET-ZERO PLANNING IN DEVELOPING COUNTRIES

Omprakash Ramalingam Rethnam
Albert Thomas

Department of Civil Engineering
Indian Institute of Technology Bombay
Powai
Mumbai – 400 076, Maharashtra, INDIA

ABSTRACT

Buildings contribute to about 40% of global energy-related CO_2 emissions, and reducing energy demand in buildings has become one of the vital components of the current climate change mitigation strategies. Optimizing energy for the urban building stock by energy-efficient retrofits is becoming increasingly popular in developed countries where the functional and construction elements of the stock are uniform, along with the updated stock database already built in desirable standard formats for energy simulation exchange. However, a decision support system to arrive at energy-efficient retrofits for developing countries where the building stock is highly diverse, with varying construction and operational philosophies, and has no readily available datasets of existing stock is highly challenging. To close this gap, this study suggests an adaptable decentralized community building energy simulation and modeling schema using free and open-source tools for retrofit decision-making.

1 INTRODUCTION

Buildings and construction accounted for about 36% of global final energy consumption and 37% of energy-related CO_2 emissions in 2020, which is high compared to other end-use sectors (United Nations Environment Programme 2021). The observed trend is statistically similar in developing countries such as India, where the building sector contributes about one-third of the country's total energy consumption (Tarkar 2022). Further, more recently, India reiterated some significant targets at the COP27 summit in Egypt, which include reducing the emissions intensity of India's GDP by 45 percent by 2030, extracting half of the country's energy contribution from renewable resources by 2030, aiming to achieve net zero emissions by the year 2070. A radical intervention of efficient building technologies is thus necessary to satisfy the current national-level demand for sustainability.

The national building stock of many developing countries, including India, is a rich mixture of buildings with different construction dates, materials, heating, ventilation, air-conditioning (HVAC) strategies, and functional properties. For instance, a study surveying 800 households in four climate zones of India to map the current penetration rate of appliances and electricity consumption patterns reveals the diverse energy consumption patterns of occupants ranging between energy performance index (EPI) of 27-54 $kWh/m^2/year$ (Shukla et al. 2015). Hence, a universal approach to energy retrofitting of the existing building stock of India using contemporary energy codes such as the energy conservation building code may not be appropriate for the entire spectrum of building households with different EPIs.

However, on the other hand, building parameters and the occupants' behavior are increasingly similar depending on the type of communities they reside in. To illustrate, a community approach to determining the energy use intensity of the residential community with 14 buildings in India indicate that the average cooling energy consumption of the building community is only close to 4% of the total energy consumption

(Ramalingam Rethnam and Thomas 2022). The results contrast with some residential building stock, with air conditioners alone contributing to 39% of the total household consumption in summer (Ramapragada et al. 2022). Some reasons for such differences are the household residents' diverse income groups that affect the frequency of usage of air conditioners and the different building envelope thermal conductivities that generally increase over the age of the building within a community. Building maintenance also plays a vital role in the energy use intensity of the building stock. A poorly maintained building with many cracks, typically similar to other community buildings, can significantly increase air infiltration levels, which invariably affects the heating and cooling. A unified urban building energy modeling framework cannot cater to such varied energy use distributions ranging from commonly observed naturally ventilated to mechanically ventilated building stock in developing tropical countries. Hence, there is a critical need for clustering the entire building stock of India into reasonable parcels of building communities for decision-making related to net-zero planning or any immediate energy conservation measures rather than one single energy code regulation system. The proposed study explores the viability of a customizable, focused, community-based energy simulation and modeling framework using open-source tools and geospatial techniques in the context of developing countries, decentralizing the theme of improving the energy efficiency of the current national residential building stock in parcels for energy-efficient retrofit decision-making.

2 RESEARCH BACKGROUND AND MOTIVATION

This section establishes some existing frameworks available, their rudiments, along with their limitations to help achieve community-wide energy retrofitting strategies. Building Energy Modeling (BEM) is the most popular and widely accepted technique for simulating and analyzing a building's energy performance by creating a digital replica of the building and running a physics-based simulation to determine its energy and resource consumption (Rajput and Thomas 2022). However, the limitations of such individual building energy models are their inability to handle the urban context of the building under study and consecutively discount the shading effects of neighboring buildings (Ali et al. 2021; Reinhart and Cerezo Davila 2016). However, the thermal performance of the building is significantly impacted by nearby structures and vegetation (Yu and Pan 2018). For instance, a study used numerical simulations to compare the effect of shading from neighboring buildings on energy consumption in three American cities under various climatic conditions. According to the study's findings, the shading effect causes a significant variation in a building's annual heating or cooling energy consumption, ranging from 16.7 to 63.4% (Han et al. 2017). Therefore, considering nearby structures appropriately during the energy assessment stage helps improve the efficacy of strategies and reduce uncertainties in the energy assessment.

Urban building energy modeling (UBEM) approaches are slowly evolving to understand urban-level energy consumption patterns and interactions to overcome this limitation of single-building physics-based models (Johari et al. 2020; Ramalingam Rethnam and Thomas 2023a; b). The existing frameworks, nevertheless, mainly cater to the need of developed countries whose city models are already coded in the specific standards suitable for energy simulation exchange. For instance, CitySim considers a simplified electrical circuit model that uses the default CityGML standard (Kämpf and Robinson 2009). Another tool, SimStadt, also works with the Energy Application Domain Extension (ADE), again an extension of CityGML to represent the building envelope and other technical properties (Agugiaro et al. 2018). Other frameworks include default templates for geometric and semantic data (non-geometric), which are difficult to apply for countries with no standardized templates ratified nationwide. In addition, the simulation tools such as City Energy Analyst and CityBES are specifically designed for use mainly in the US, Europe, and South-East Asia regions. Further, most of these frameworks are not flexible enough to customize the building envelope features such as Window-Wall-Ratio for facades in every direction and offer limited control over cooling and heating equipment schedules since they are designed more towards mechanically ventilated building scenarios appropriate for developed countries.

A custom-formatted, quickly implementable automated simulation and modeling framework that can dynamically consider the urban context of the building community, along with the flexibility for the users to change the templates as demanded, is the need of the hour for especially developing countries. The proposed study envisages developing a customizable community-building-energy-modeling decision support system (CCBEM-DSS) for net-zero planning using open-source tools available. The established framework is further demonstrated with the help of a case study building community to investigate the significance of energy-retrofitting strategies for building envelopes.

3 METHODS

The various workflow stages towards developing the CCBEM-DSS are delineated as part of the study. A quick summary of the same is given in Figure 1. Each stage of the workflow is explained in detail in the coming section, and a case study on a residential building community adopting the decision support system is also demonstrated. All the phases discussed are developed as separate modules through the visual programming language in the Grasshopper environment within the Rhinoceros 3D computer-aided design application for user interaction.

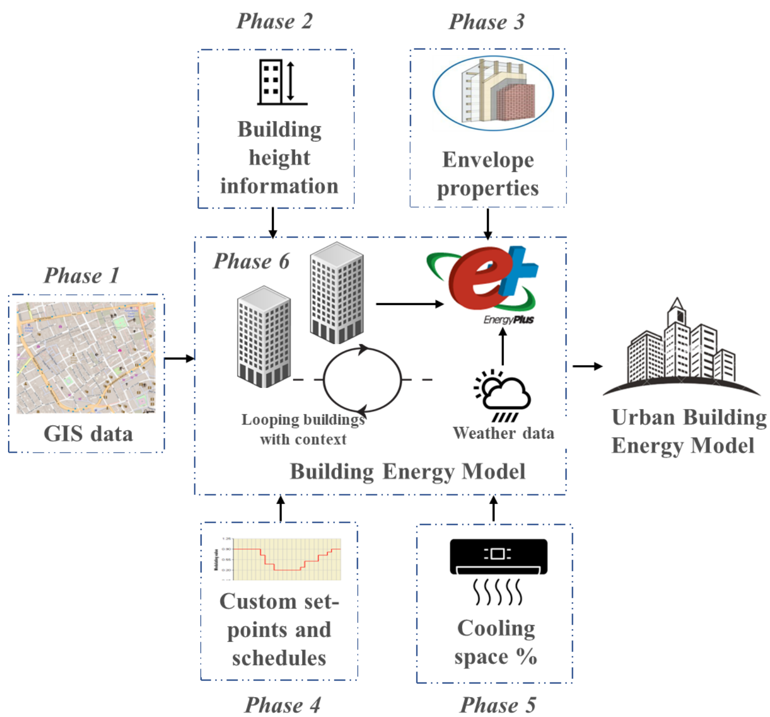

Figure 1: Schematic representation of the community-building-energy-modeling decision support system for net-zero planning.

Phase-1: Building footprint extraction using geospatial analysis

The first phase involves extracting the footprint information of the building community under study into the energy modeling interface. A free and open-source geographic database, OpenStreetMap (OSM), is used to initially collect the required building community's footprint (Klinkhardt et al. 2021). Again, a free and open-source geospatial platform called Quantum GIS (QGIS) is used to process the extracted footprint from OSM to create the footprint shapefile along with relevant features required, such as the name of the building and year of construction added to the attribute table. The buildings are georeferenced appropriately, and QGIS automatically computes the footprint area of the buildings. This georeferenced building footprint dataset is exported in the shape file format and then imported into the Rhino-Grasshopper interface through the 'Import SHP' module. The boundary edge curves from the shape file are then converted into planar surfaces ready for extrusion.

Phase-2: Building elevation information extraction using LiDAR or site-survey

The Digital Elevation Model (DEM) and Digital Surface Model (DSM) of the community under investigation can be collected using airborne Light Detection and Ranging (LiDAR) datasets collected by LiDAR drones. The elevation of the earth's surface is obtained from the DEM with reference to a particular datum. On the other hand, the elevation of various things on the ground, such as buildings and vegetation, is contained in the DSM about the same datum. A new model that only incorporates the object's height above the earth can be generated when the elevations of the DEM and DSM are subtracted from each other. Where such a LiDAR survey is not possible, a simple site survey and contacting required government agencies can fetch some of the critical details of the building stock, including the year of construction, number of floors, and building height. The latter method is used in this study because of the limited scope of the building community. The building height information collected is annexed to the attribute table of the previous footprint shapefile generated by performing a geospatial join operation in the QGIS interface. The attribute table is extracted from QGIS as an Excel file which is then imported into Rhino-Grasshopper, from which the respective heights of the buildings within a community are connected as the respective vector directions for the extrusion of the planar curves created in the earlier phase to create shoebox 2.5D model of the building community.

Phase-3: Assignment of building envelope properties

The next phase involves assigning non-geometric parameters to the building community. Since a building community typically does not differ much in its construction materials and operational schedules, deterministic characterization is adopted. Building construction materials, Window-Wall Ratio (WWR), occupancy schedule, lighting, and equipment density are the typical non-geometric values essential for the analysis. Suitable country-specific database manuals or references for such building communities are adopted for parameter definition. Opaque materials are assigned properties using the 'HB Opaque Material' component. Some of the inputs assigned for the building envelopes include thickness, thermal conductivity, density, specific heat capacity, roughness, thermal absorption fraction, solar absorption fraction, and visible light absorption fraction. The transparent element of the building envelope is assigned properties using the 'HB Window Material' component accepting critical inputs that include the overall heat transmission coefficient, solar heat gain coefficient, and the visible light transmission fraction.

Phase-4: Creating custom setpoints and schedules

Post assigning the building envelope properties, the next step is to create custom templates for assigning the electrical load to the building community under study. Most developing countries do not follow default ASHRAE standards for running air-conditioning loads. Hence, creating custom schedules that suit the country's occupant behavior is essential for accurate building energy demand estimation. For example, the statistical results from the survey conducted in India found that the average household typically switches 'ON' the AC between 22:00 and 06:00 hours (Shukla et al. 2015). The custom set points and schedules are fed into the simulation workflow through the 'HB Apply Room Schedules' component in the Rhino-Grasshopper interface.

Phase-5: Cooling space fraction investigation

Unlike developed countries, most developing countries do not have fully conditioned space. In addition to creating custom set points and schedules, one of the crucial features for arriving at accurate community-building energy consumption is to estimate the close to the real cooling space of the building stock. A straightforward method of site inspection is used in the proposed decision support system to determine the number of AC outdoor units fixed at each building inside the community. The carpet area of the bedrooms, the only airconditioned rooms in a typical housing unit, is obtained from government agencies (or) a survey and used to calculate the building's cooling energy consumption of the neighborhood. Based on the minimal efficiency advised by the energy efficiency requirements, the seasonal energy efficiency ratio (SEER), particular to the country, is considered.

Phase-6: Building energy modeling and automated looping with context

The final phase is to create building energy models. The energy model of each building in the stock is created using EnergyPlus, an open-source program created by the United States (US) Department of Energy (DOE) after all necessary input data has been acquired or calculated. Creating 3D models, defining thermal zones, assigning envelope attributes, and assigning non-geometric parameters to zones are all performed in the multi-step model production process. The shoebox model is used as the form of calculation for the proposed framework. This method clusters the building façade into simple representative zones based on the building footprint, which is of the regular geometry throughout. Shoebox is preferred for quick decision-making and the least computational effort compared to detailed multi-floor multi-zone 3D models (Monteiro et al. 2017). Further, through scripting in the open-source Rhino-Grasshopper interface, buildings within the community are looped automatically along with the neighborhood shading context, and the energy simulations of individual buildings are accumulated consecutively to fully develop the community building energy model ready for deploying with different energy-efficient retrofits (Roudsari and Pak 2013). The inputs of the CCBEM-DSS are finally further refined based on the energy consumption results obtained from a thorough sensitivity and uncertainty analysis summary.

4 CASE STUDY

The case study is based on a group of 14 separate apartment-type buildings that are part of an educational institution in Mumbai, India. Step-by-step implementation of the methodology section is followed consecutively. The critical information to be gathered from the residential building community includes the year that various buildings within the community were built, the materials used in building the building envelope, the size of the structures' footprints, and the corresponding heights of the buildings. A description of the baseline building envelope materials from the site survey and a list of the materials' associated thermal transmittances derived from appropriate reference codes (Ministry of Power 2017) are given in Table 1. Further, in the proposed study, the baseline building community's building envelope characteristics are modified per the ECBC's (BEE, 2017) recommendations to analyze the effects of various energy-efficient scenarios on energy consumption. The corresponding thermal transmittance factors are given in Table 1. The study considers a scheduled mixed-mode operation of ACs, where the AC runs continuously from 22:00 to 06:00 hours, maintaining space set points of 24^{o}C with windows closed during that time (Shukla et al. 2015).

Table 1: Building envelope baseline and ECBC-compliant characteristics.

Building fabric	Baseline description	Baseline U value (W/m^2-K)	ECBC compliant U value (W/m^2-K)
Roof	100 mm RCC + 50 mm foam concrete + waterproofing	1.08	0.33
External wall	1.25 cm cement plaster + 22.5 cm brick + 1.25 cm cement plaster	2.13	0.40
External window	Single clear glass	5.8 with SHGC 0.8	3 with SHGC-0.23

The visual interface of the developed CCBEM-DSS for the simulation in the Rhino-Grasshopper interface, with EnergyPlus, as the thermal engine, is given in Figure 2. All the buildings within the community are looped automatically along with the neighborhood shading context, and the energy simulations of individual buildings are accumulated consecutively to fully develop the community building energy model, both with baseline envelope and ECBC-compliant characteristics.

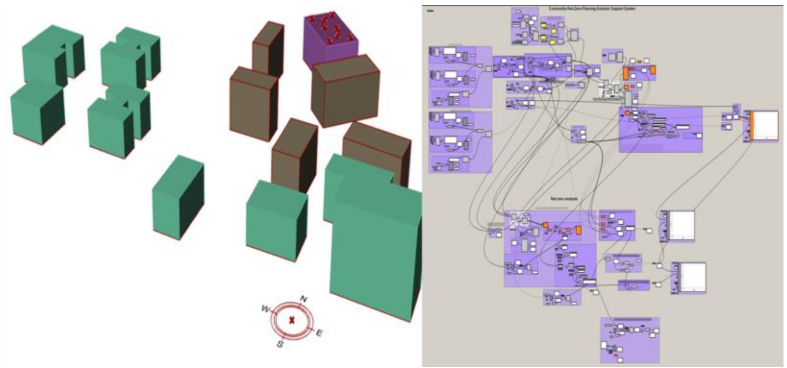

Figure 2: CBEM decision support system set up in Rhino-Grasshopper interface.

5 RESULTS

The archetype building with the mean building footprint and height was selected within the community. It was supplied with different critical inputs of the energy model to test the effect of those inputs on the cooling load through a sensitivity analysis approach. The critical inputs that were selected include the roof material, wall material, the type of glazing, the orientation of the site, the window wall ratio, and the cooling set point. The The uncertainty analysis yields a mean of 108,716 kWh per year as shown in Figure 3.

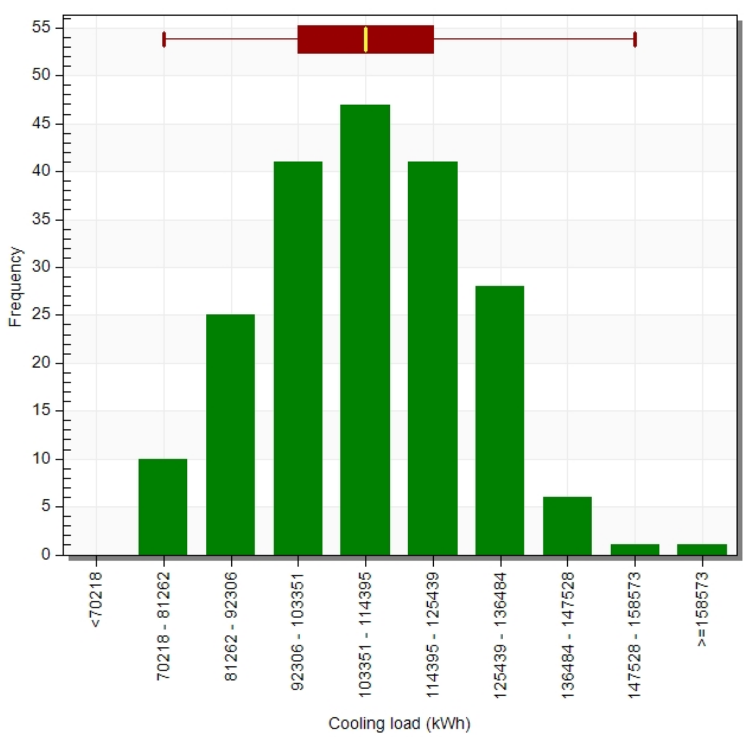

Figure 3: Uncertainty analysis results showing the spread of the cooling load output

The sensitivity analysis results found the key critical parameters responsible for this diverse uncertainty, as shown in Figure 4. For setting up the analysis, a random sampling method is used. Multiple linear regression is used as the statistical method for estimating the relationships among input variables. The most and least significant variables are determined by the Standardized Regression Coefficient (SRC), which outputs the sensitivity of each input variable. Assuming that the input variables are independent of one another, SRC aids in understanding how the typical value of the output changes when any one of the input variables is changed. Cooling setpoint temperature and window-to-wall ratio strongly influence cooling load, with an inverse relationship and a significant impact, respectively.

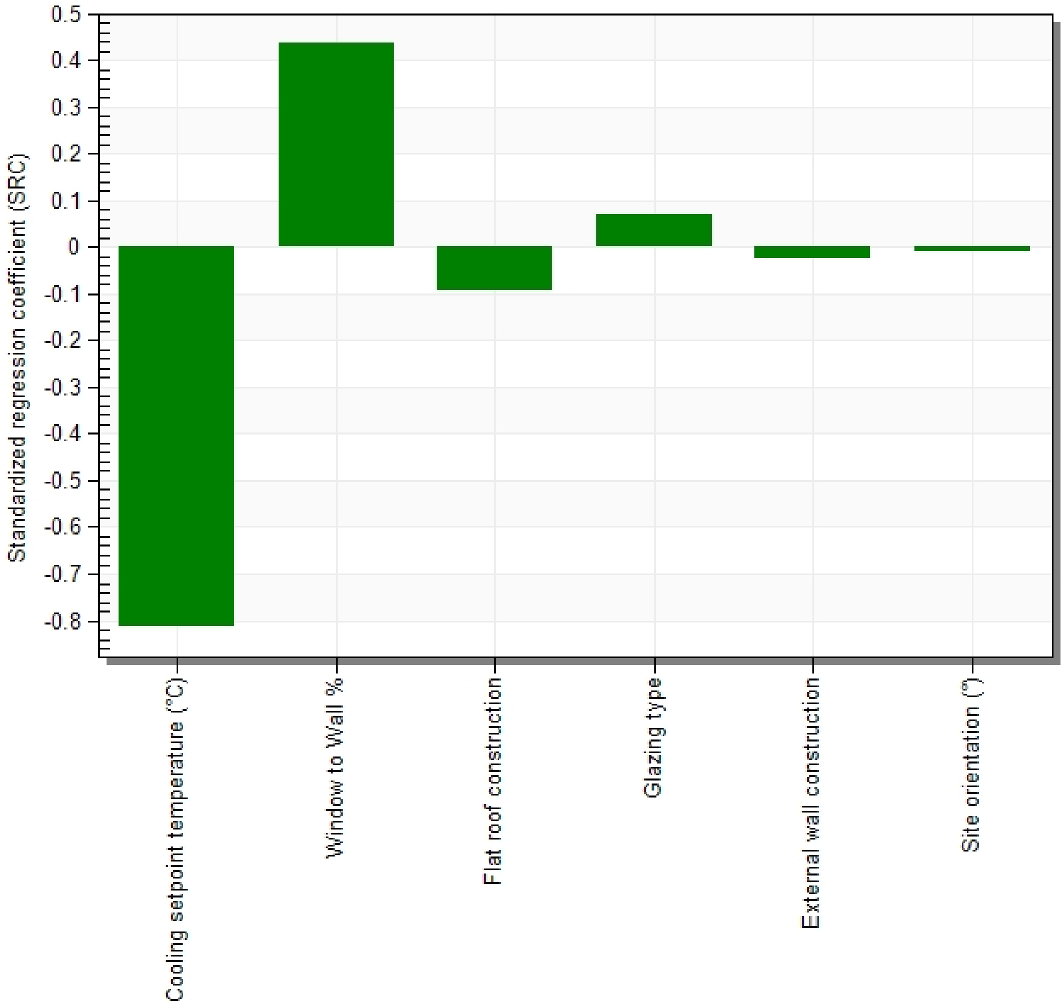

Figure 4: Sensitivity analysis results showing the significant factors responsible for the changes in the cooling load.

Glazing type, external wall construction, and site orientation have negligible effects on cooling load. Hence, the cooling set point and the window wall rato inputs were refined close to the actual for further running the simulation. The simulation results indicated that the average Energy Use Intensity (EUI) of the building stock with baseline building envelope characteristics is 27.80 kWh/m^2, and the total site annual energy consumption is 384.67 MWh. The cooling energy consumption of the building stock summed up to 29.8 MWh, which is around 8% of the total energy consumption against the cooling space fraction of 4%.

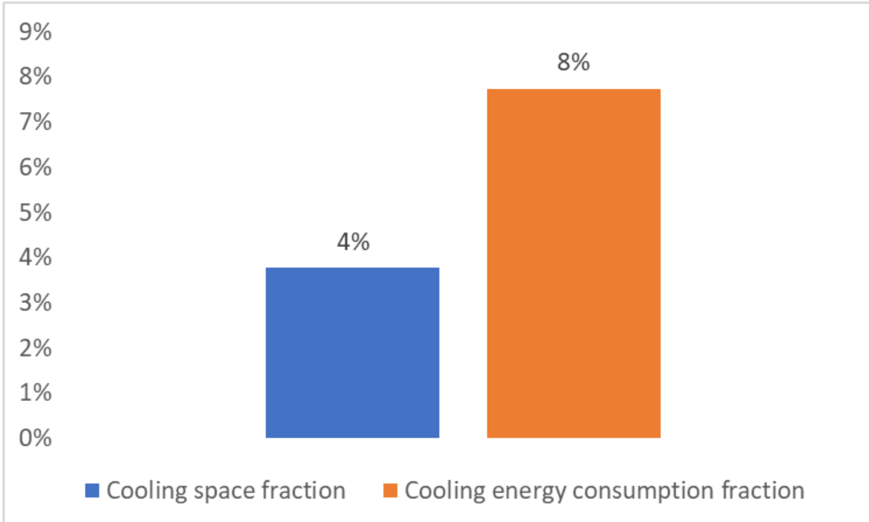

Figure 5: Comparison between cooling space fraction and cooling energy fraction.

The mean EUI based on the actual energy consumption from the building community is observed to be 29.51 kWh/m^2, and the actual total site annual energy consumption is 396.85 MWh. In the energy-efficient scenario where the building envelopes that include wall and roof insulation, glazing, and solar heat gain coefficient (SHGC) are ECBC compliant, the annual average EUI of the building community drops to 27.01 kWh/m^2. The energy consumption spread of the baseline and energy-retrofitted building community is given in Figure 6, and the comparison of EUI with energy-efficient envelopes with that of the baseline EUI for different buildings is given in Figure 7.

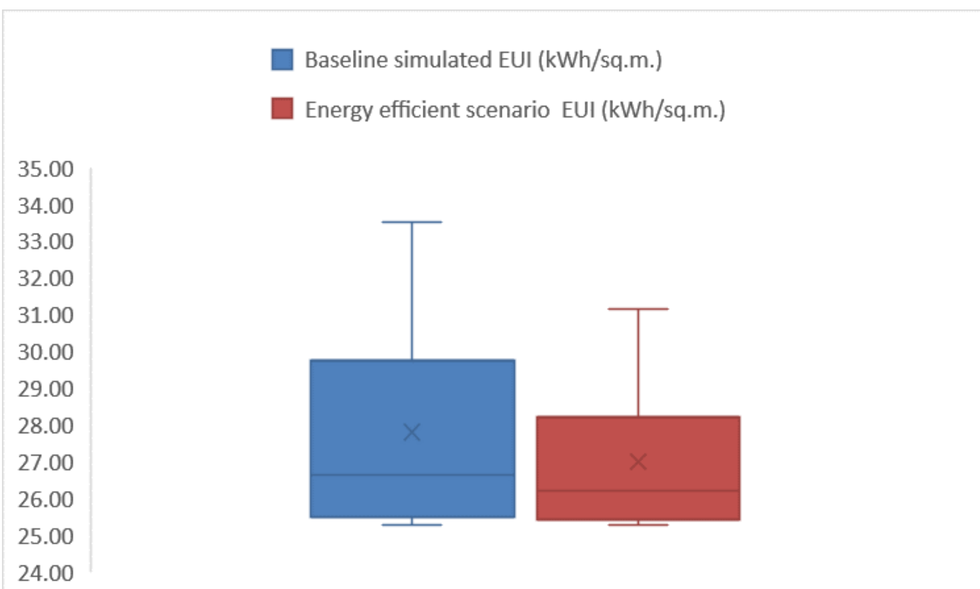

Figure 6: Annual average EUI (kWh/m^2) spread of the baseline and energy-retrofitted building community.

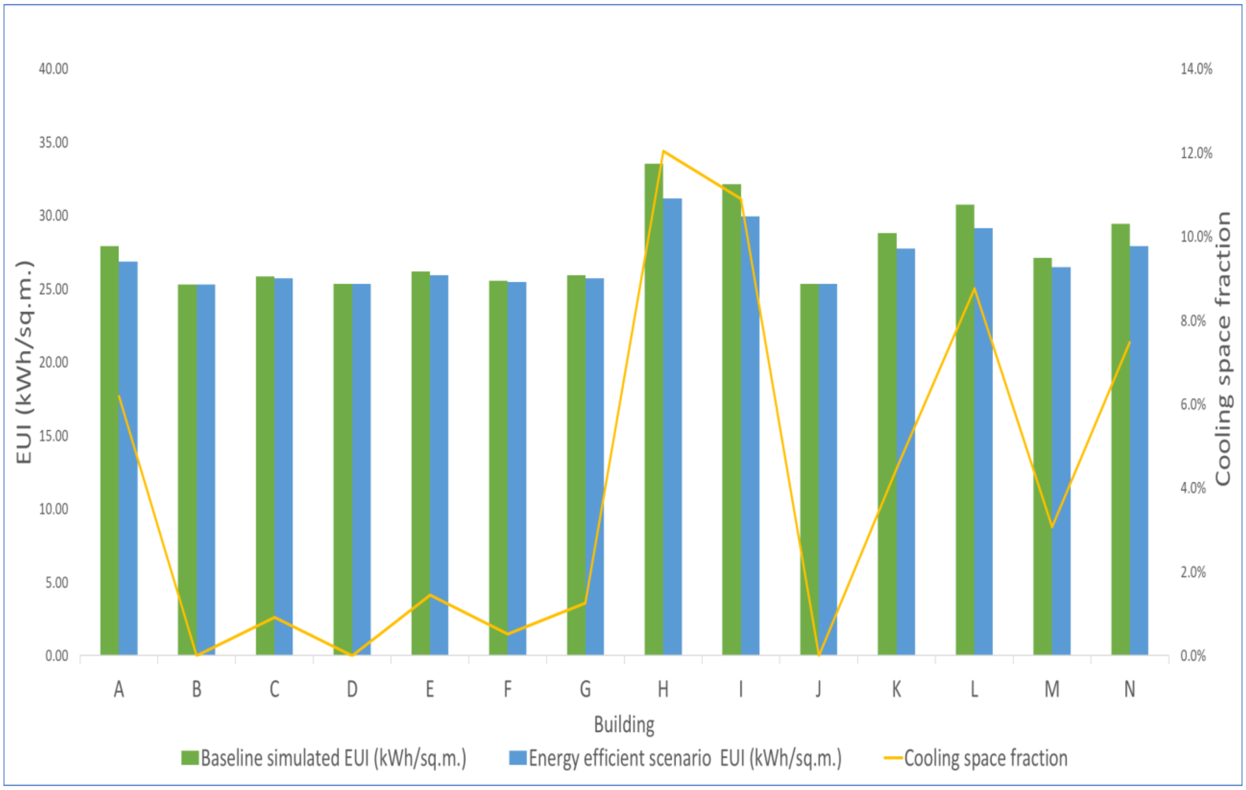

Figure 7: Annual average EUI (kWh/m^2) comparison between the baseline and energy-retrofitted buildings within the community.

6 DISCUSSION

The component of validating the urban building energy models with real-time energy consumption of the buildings is one of the missing components because of the deficiency of appropriate datasets (Sharma et al. 2020). However, such models' reliability and precise accuracy have to be studied in detail for using them in essential areas such as policy-making. The real-time energy consumption data of the building stock obtained from the government agency is extensively used to validate this study. Percent Error (PE) is one of the most often used validation paths to estimate the deviation between simulated and actual energy consumption (Huerto-Cardenas et al. 2020). The inaccuracies may arise for various causes, including the model's operational load assumptions, the geometrical simplicity of the shoebox model, or any unpredictability in the input configuration. In this study, the cumulative yearly EUI of the residential building stock is used to determine the PE. The calculation of PE used in the study is given below in Equation (1).

$$\text{Mean PE} = \frac{|\text{Mean simulated EUI} - \text{Mean actual EUI}|}{\text{Mean actual EUI}} \times 100\% \qquad (1)$$

The percent error is estimated to be 3 %, well within the acceptable range of 1% - 15% (Cerezo Davila et al. 2016). Deploying the building community energy model with the energy efficient envelope scenario gives the energy reduction of about 22.13 MWh, a 3% drop from the baseline EUI. It is observed that the annual energy reduction of 5% - 10% is achieved when the cooling space fraction of the building is greater than 10%. In all other cases, where the cooling space fraction is negligible, the corresponding energy drop due to the energy-efficient building envelope is also meager. This effect of cooling space fraction on how adequate the energy reduction potential of energy-efficient building envelopes is given in Figure 8.

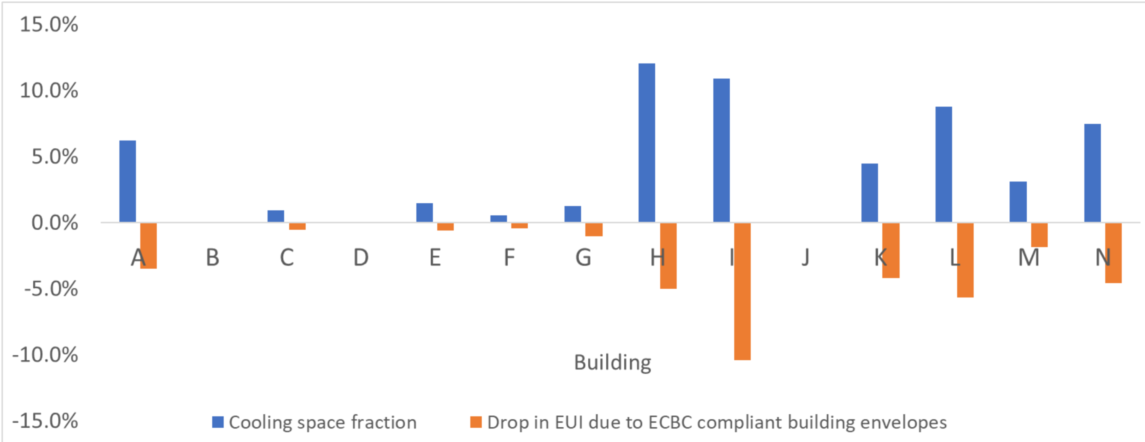

Figure 8: Influence of cooling space fraction on the energy reduction potential of ECBC-compliant building envelopes.

To summarise, in addition to the finding that, in the current building stock context, employing a retrofit strategy does not appear to provide a significant amount of energy (or) financial advantage with only a 4% cooling space fraction, one of the critical implication is that the merits of ECBC compliance should not be disregarded when only taking the current building stock context into account. To ensure the code's effectiveness, it is necessary to consider the likelihood of adding cooling space and any potential future severe weather. The framework's application is tested with a 14-building residential community because of data availability of the building envelope properties and energy consumption details. However, the framework can be applied to other residential building communities in different geographical locations in the future to validate the framework's flexibility further and for decision-making.

Some of the existing UBEM frameworks, such as CitySim, SimStadt, and IES-ICD, work with dominantly a fully conditioned residential building stock with limited flexibility to change the inputs of the building stock energy model. For example, IES recently released the IES -Intelligent Communities Lifecycle (ICL) package to incorporate the digital twin technology at the city scale. The platform can incorporate GIS features like shapefiles, assess the potential for renewable energy across the building stock, and handle country-specific building parameters. The simulation interface's primary engine is one of the most widely used and validated thermal engines, the IES-VE (Oleiwi et al. 2019). However, IES-ICL does not support flexibly changing the cooling set points schedules of the building stock based on a new dataset relevant to developing countries. In addition, the metric, cooling space fraction, within the building stock is not commonly used in many of the existing UBEM frameworks. In addition, most of such tools need considerable human intervention for modeling without being a completely automated workflow. All of the above places the developed framework in a more executable front compared to other frameworks, especially favoring the system conditions of developing countries with significantly less air-conditioned workspace and varying building envelope properties. Although this study does not incorporate the energy supply portion of the building community, such informed decision-making on the amount of energy reduction achieved by different retrofits can help plan the infrastructure and required electrical energy transmission more efficiently. The study can be extended further to include the occupant behavior factors such as usage patterns, thermostat settings, and lifestyle choices that can significantly affect energy models and retrofit strategies. In addition, other socioeconomic factors, such as income levels, building occupancy, and demographics, can impact energy modeling, and retrofit decision-making can be considered in the future for the simulation. Finally, energy policies and regulations directly impact energy modeling and retrofit decision-making. Government incentives, building codes, and energy efficiency standards can drive or hinder retrofit initiatives, affecting the feasibility and cost-effectiveness of different strategies. Integrating such policy implications within the framework can be a future research direction.

7 CONCLUSION

This study presented a holistic customizable decentralized framework of the developed community-building energy-modeling decision support system from scratch, which can be quickly adopted from any other developing country's perspective. This study provided a method and means for utilizing the created and validated community building energy model to comprehend the impact of energy conservation compliance on the energy consumption of the residential building stock after incorporating the regional-level relevance. The energy use intensity of the case study building community is found to be 29.51 kWh/$m^{2,}$ with a very low percent error of 3% when validated by the actual energy consumption readings. Further, the energy use intensity drops to 27.01 kWh/m^2 when the building envelopes comply with the energy conservation building code. The results also indicated that the cooling space fraction significantly impacts the energy reduction potential of the energy-efficient building envelopes. Any inaccuracy in the cooling load investigation can thus lead to uneconomical retrofit policies.

Policymakers can directly implement the developed CCBEM-DSS for quickly checking any building retrofit schemes with slight tweaking on the inputs, such as the building community shapefiles, thermal transmittance of the building envelopes, and cooling space fractions. All other modules are connected and scripted to facilitate a completely automated workflow to ease the system's replicability for beginners and non-technical staff to handle the support system efficiently with minimum effort. At the same time, the tool is versatile for expert users to delve deep, if required, into the different modules since it is developed on an open-source visual programming platform. At this stage, further refinement is happening on the code and data documentation to ensure that they meet the highest standards of quality and clarity. Some of the resources and datasets will be shared with the scientific community through dedicated GitHub repositories in the near future. The likelihood of utilizing geospatial photogrammetry techniques for data collection rather than labor-intensive manual site investigation, which can significantly lower the computational cost, can be addressed in the future scope of work.

REFERENCES

Agugiaro, G., J. Benner, P. Cipriano, and R. Nouvel. 2018. "The Energy Application Domain Extension for CityGML: Enhancing Interoperability for Urban Energy Simulations." *Open Geospatial Data, Software and Standards*, 3 (1): 1–30.

Ali, U., M. H. Shamsi, C. Hoare, E. Mangina, and J. O'Donnell. 2021. "Review Of Urban Building Energy Modeling (UBEM) Approaches, Methods and Tools Using Qualitative And Quantitative Analysis." *Energy and Buildings*, 246: 111073.

Cerezo Davila, C., C. F. Reinhart, and J. L. Bemis. 2016. "Modeling Boston: A Workflow for the Efficient Generation and Maintenance of Urban Building Energy Models from Existing Geospatial Datasets." *Energy*, 117: 237–250.

Han, Y., J. E. Taylor, and A. L. Pisello. 2017. "Exploring Mutual Shading and Mutual Reflection Inter-Building Effects on Building Energy Performance." *Applied Energy*, 185: 1556–1564..

Huerto-Cardenas, H. E., F. Leonforte, N. Aste, C. Del Pero, G. Evola, V. Costanzo, and E. Lucchi. 2020. "Validation of Dynamic Hygrothermal Simulation Models for Historical Buildings: State of the Art, Research Challenges and Recommendations." *Building and Environment*, 180 (June): 107081.

Johari, F., G. Peronato, P. Sadeghian, X. Zhao, and J. Widén. 2020. "Urban Building Energy Modeling: State of the Art and Future Prospects." *Renewable and Sustainable Energy Reviews*, 128 (May): 109902.

Kämpf, J. H., and D. Robinson. 2009. "Optimisation of Urban Energy Demand using an Evolutionary Algorithm." *Proc. International Building Performance Simulation Association Conference. July 27-30, Glas. Scotl.*, 668–673.

Klinkhardt, C., T. Woerle, L. Briem, M. Heilig, M. Kagerbauer, and P. Vortisch. 2021. "Using Openstreetmap as a Data Source for Attractiveness in Travel Demand Models." *Journal of the Transportation Research Board*, 2675 (8): 294–303.

Ministry of Power, G. of I. 2017. *Energy Conservation Building Code for Residential Buildings (Part I: Building Envelope Design)*. *Bur. Energy Effic.*

Monteiro, C. S., A. Pina, C. Cerezo, C. Reinhart, and P. Ferrão. 2017. "The Use of Multi-detail Building Archetypes in Urban

Energy Modelling." *Energy Procedia*, 111 (September 2016): 817–825.

Oleiwi, M. Q., M. F. Mohamed, M. K. A. M. Sulaiman, A. I. Che-Ani, and S. N. Raman. 2019. "Thermal Environment Accuracy Investigation of Integrated Environmental Solutions-Virtual Environment (IES-VE) Software for Double-Story House Simulation in Malaysia." *Journal of Engineering and Applied Sciences*, 14 (11): 3659–3665.

Rajput, T. S., and A. Thomas. 2022. "Optimizing Passive Design Strategies for Energy Efficient Buildings using Hybrid Artificial Neural Network (ANN) and Multi-Objective Evolutionary Algorithm through a Case Study Approach." *Optimizing Passive Design Strategies for Energy Efficient Buildings using Hybrid Artificial Neural Network (ANN) and Multi-Objective Evolutionary Algorithm through a Case Study Approach*, 23 (13): 2320–2332. Taylor & Francis.

Ramalingam Rethnam, O., and A. Thomas. 2022. "A Community-Based Urban Building Energy Modeling Framework for Transitioning towards Zero Energy Building Communities in Developing Countries." *Proc. uSim 2022 International Building Performance Simulation Association Conference. Novemb. 25th, Scotland, United Kingdom*, 1–9.

Ramalingam Rethnam, O., and A. Thomas. 2023a. "A Community Building Energy Modelling – Life Cycle Cost Analysis Framework To Design and Operate Net Zero Energy Communities." *Sustainable Production and Consumption*, 39 (May): 382–398.

Ramalingam Rethnam, O., and A. Thomas. 2023b. "Urban Building Energy Modelling-Based Framework To Analyze The Effectiveness of the Community-Wide Implementation of National Energy Conservation Codes." *Smart and Sustainable Built Environment*, 2030.

Ramapragada, P., D. Tejaswini, V. Garg, J. Mathur, and R. Gupta. 2022. "Investigation on Air Conditioning Load Patterns and Electricity Consumption of Typical Residential Buildingsin Tropical Wet and Dry Climate in India." *Energy Informatics*, 5 (4): 1–21. Springer International Publishing.

Reinhart, C. F., and C. Cerezo Davila. 2016. "Urban Building Energy Modeling - A Review of a Nascent Field." *Building and Environment*, 97: 196–202.

Roudsari, M. S., and M. Pak. 2013. "Ladybug: A Parametric Environmental Plugin for Grasshopper to help Designers Create an Environmentally-Conscious Design." *Proc. 13th International Building Performance Simulation Association Conference, August 26th-28th, Chambery, Fr.*, 3128–3135.

Sharma, K., R. Rawal, P. Fennell, A. Mathur, P. Russyvelt, D. Crawley, and I. Korolija. 2020. "Developing a 3D geometry for Urban energy modelling of Indian Cities." *Proc. uSim 2020 International Building Performance Simulation Association Conference. Novemb. 12th, Scotland, United Kingdom*, 1–8.

Shukla, Y., K. L. Campus, R. Rawal, S. Shnapp, G. Buildings, and P. Network. 2015. "Residential Buildings in India : Energy Use Projections and Savings Potentials." *European Council for an Energy Efficient Economy Summer Study Proc.*

Tarkar, P. 2022. "Energy Efficient Buildings in India: Key Area and Challenges." *Proc. IOP Conference Series: Earth and Environmental Science. June 24th-25th, Rajasthan, India*, 1–5.

United Nations Environment Programme. 2021. *Global Status report for Buildings and Construction 2021. Global Alliance for Buildings and Construction*.

Yu, C., and W. Pan. 2018. "Effects of Shading on the Energy Consumption of High-Rise Office Buildings in Hong Kong." *Proc. ASHRAE International Building Performance Simulation Association -USA Building Simulation Conference. Sept. 26th-28th, Chicago, U.S.A.*, 486–493.

AUTHOR BIOGRAPHIES

OMPRAKASH RAMALINGAM RETHNAM is a Prime Minister Research Fellow, doing his Ph.D. in the Civil Engineering Department of the Indian Institute of Technology Bombay. His primary research interest is in the area of urban building energy modeling, urban micro-climate modeling, urban thermal comfort assessment, agent-based modeling, and life cycle cost analysis of different energy-efficient strategies. He also utilizes simulation to address problems in net-zero planning of building communities. His email address is 204040004@iitb.ac.in, and his homepage is https://omprakashrr.owlstown.net/

ALBERT THOMAS is an Assistant Professor in the Civil Engineering Department of the Indian Institute of Technology Bombay. His research interests include system dynamics, agent-based modeling, discrete event simulation, distributed simulation, life cycle analysis, energy simulation, and various lean construction-based techniques. His primary focus is developing frameworks and tools that help adopt sustainable and lean practices in construction projects and infrastructure systems, thereby reducing waste and environmental impacts. He is also a guest editor for the Sustainable Production and Consumption journal. His email address is albert@iitb.ac.in, and his website is https://www.civil.iitb.ac.in/~albert/.