A COMMUNITY-BASED URBAN BUILDING ENERGY MODELING FRAMEWORK FOR TRANSITIONING TOWARDS ZERO ENERGY BUILDING COMMUNITIES IN DEVELOPING COUNTRIES

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ABSTRACT:

The target of achieving net-zero emissions by the mid-century set in the recent COP26 climate summit in Glasgow demands the formulation of many innovative policies related to sustainability worldwide. In developing countries such as India, 74% of the country's greenhouse emissions is is accounted to the energy sector. A significant recipient of the supplied energy is the building sector consuming more than one-third of the country's total energy consumption. Although there are many existing policies such as the India Integrated Energy policy, building codes such as the energy conservation building code, and other rating manuals such as the Indian Green Building rating system, the focus of these existing standards is mainly on accomplishing energy efficiency in individual buildings. To achieve the stringent net zero targets for the building sector, exploring the energy dynamics of community-based renewable energy adoption is essential, especially in a developing country perspective, where space availability is a concern. Therefore, there is a strong need to implement various policies and recommendations from standards on a community/city scale to support the journey towards net-zero emissions in the coming decades. This study develops a framework with focus on a community-based energy analysis approach, where the theme of net-zero energy consumption is decentralized in parcels by focusing on residential building communities. The framework developed is then used to explore the feasibility of community-solar rooftops where the solar energy generated on the rooftop of one building is shared with other buildings within the same premises, thus offsetting the inadequacy of some existing buildings to cater to the renewable energy installations on-site due to space and other implementation issues.

An urban building energy modelling framework is developed for a residential building community with a set of 14 individual apartment-type buildings in the city of Mumbai, India. Further, a solar photovoltaic (P.V.) assessment is carried out, and the results are validated using geospatial analysis. The study results demonstrate that out of the 14 buildings selected, not every building can meet its energy demand using rooftop solar P.V. panels. However, the rooftop potential across the building community varies between as low as 68% to as high as 236% of the individual building's total energy demand. By integrating the solar rooftops across different buildings within the building community, the effect of net-zero energy consumption as a community is achieved in this proposed study.

Keywords: Building stock, Energy modelling, Simulation, Urban building energy modelling, Renewable, Solar assessment, Photovoltaics, Energy forecasting.

INTRODUCTION

The building sector is one of the significant global contributors to energy consumption along with its associated greenhouse gas (GHG) emissions. It contributed 55% of the world's total energy use, with 28% of energy-related carbon dioxide (CO_2) emissions in 2019 (Hamilton and Rapf 2020). It is also projected that the cumulative effect of population increase and urbanization across the globe will lead to 50% growth in the urban population by the year 2050 (Ritchie and Roser 2018). All of the above calls for crucial attention toward building energy optimization, especially in the urban community.

In India, the building sector contributes more than one-third of the total energy use (Ruparathna, Hewage, and Sadiq 2016). In addition to energy consumption, the building sector accounts for about 32% of the country's total GHG emissions stand-alone (Javadekar et al. 2021). One of the vital promising directions to achieve the intended energy optimization across the building stocks is to transition towards net-zero energy consumption buildings. A building structure built to meet at least its own energy demand by energy generation through a renewable energy resource, either on-site or offsite, is termed a net-zero energy consumption building (nZECB) (Crawley and Torcellini 2006). Many policies are already formulated to improve the energy efficiency of buildings by the Government of India (GOI), encouraging the building occupants to switch to renewable energy alternatives, heading gradually towards the goal of net-zero energy consumption buildings.

Achieving net zero energy consumption is comparatively easy in a building to be constructed, given the flexibility to optimize the building parameters in the early design phase. However, it is essential to devise mechanisms to retrofit the existing buildings to realize the stringent net-zero targets. The proposed study decentralizes the theme of improving the energy efficiency of the current national residential building stock in parcels by exploring the feasibility of a focused community-based energy modelling framework using Urban Building Energy Modeling (UBEM) and geospatial techniques in an Indian context.

RESEARCH BACKGROUND AND MOTIVATION

Achieving nZECB status for existing buildings is a highly challenging mission as most renewable energy projects are dependent on the type, location, and operational characteristics of the building. Especially, rooftop solar panel installation may be an infeasible option for quite some buildings due to inadequate roof size, orientation, and shading effects. Lack of motivation observed among consumers is one of the other critical reasons why renewable energy projects are not highly successful in many countries. Studies show that the community interaction effect is the vital factor that biases the consumer's decision towards adoption or non-adoption of rooftop solar P.V. (Rai and Robinson 2015). In India, although many existing standards focus on accomplishing energy efficiency in individual buildings, there is a strong need to implement various policies and recommendations to offset the inadequacy of some existing buildings to cater to the renewable energy installations on-site by moving in the direction of Zero Energy Communities (ZEC). According to the U.S. Department of Energy (DOE), ZEC is defined as an energy-efficient community where the actual delivered annual energy is at least equal to the on-site exported renewable energy on a source energy basis (Peterson, Torcellini, and Grant 2015). In achieving ZEC, the most commonly used form of on-site renewables is the rooftop solar photovoltaic (P.V.) panels (Seto et al. 2016). Especially in India, where the solar capturing potential is enormous, proven by the fact that the country has already targeted about 40 G.W. of rooftop solar energy by 2022, moving towards community-solar appears to be the most lucrative energy alternative program for ensuring ZECs.

There are a couple of advantages to moving towards community-based solar adoption for mass building retrofit. Compared with individual building rooftop solar P.V. installations, the oversizing of the energy systems can be significantly reduced owing to the varied load diversity. Furthermore, grid efficiencies are improved along with the incurred savings because of the reduction of additional infrastructure required to meet individual rooftops. Since larger solar P.V. arrays can capture more sunlight by adjusting their orientation across the day, such community solar programs attract more electricity generated, which is not possible in the case of individual small rooftop solar P.V. panels (Hledik, Tsuchida, and Palfreyman 2018). However, community-based solar investigation using urban building energy modeling techniques for achieving the ZEC status is not popularly encountered in the research space. In addition, no such programs have evolved so far in the country to the best of our knowledge. The proposed study envisages the feasibility and outcomes of implementing such a program. The objectives of the proposed research to bridge some of the gaps mentioned above are as given below:

1. To develop a customizable net-zero assessment method for a focussed residential building community using the UBEM approach
2. To validate the developed community building energy model against actual energy consumption data, to ensure the consistency of the framework
3. To validate the renewable assessment of the developed UBEM, using geospatial techniques

By achieving the set of objectives listed, the study aims to contribute to the field of building community energy modelling, especially in the Indian context, towards reaching net-zero emission targets. The developed framework can be easily adapted to study and validate any further community-based energy analysis, which will help achieve the net-zero emission shift practically feasible and implementable.

METHODOLOGY

The various stages of the workflow towards developing the framework to assess the net-zero potential of the residential building community are delineated as part of the study. A quick summary of the same is given in Figure 1 below. Each stage of the workflow is explained in detail in the coming sections, and a case study on a residential building community is developed based on the outlined methodology.

Stage 1: Establishing model classification framework and characteristics
Stage 2: Data Acquisition
Stage 3: UBEM Charecterization
Stage 4: UBEM Cooling Load Assessment
Stage 5: Baseline UBEM Energy Simulation & Validation
Stage 6: UBEM Renewable Assessment & Validation

Figure 1 Proposed UBEM workflow

STAGE-1: MODEL CLASSIFICATION FRAMEWORK AND CHARACTERISTICS

The fundamental unit of the analysis, the model classification framework, is mainly classified into different layers, as shown in Figure 2. The model characteristics definition at each layer selected for the framework is given in Table 1.

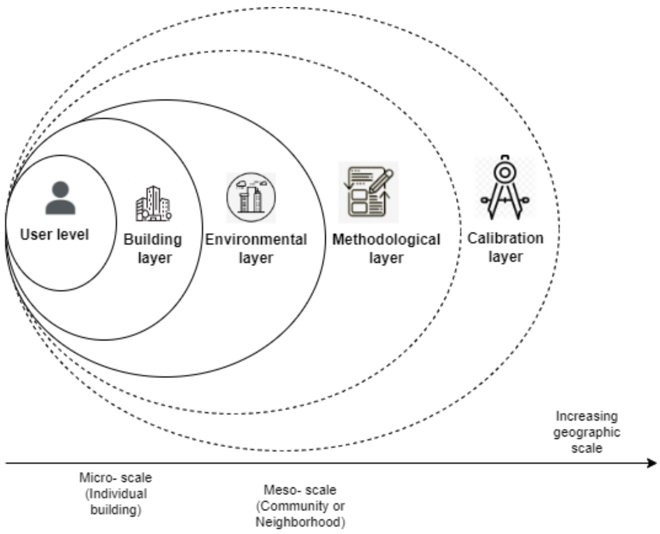

Figure 2 Model classification framework

User	Building	Environment	Methodology	Model calibration
• Occupancy : Deterministic–single profile	• Zoning: Zone per floor • Archetypes: SiGeometry : 2.5 D • Zoning: Zone per floor • Archetypes: Based on use-type	• Climate : Typical Meteorological year (TMY) • Context: Contextual shading	• Stock dynamics: Point in time/snapshot • Temporal Resolution: Annual • Treatment of uncertainty: Deterministic • Form of calculation: Shoe box model	• Spatial resolution: Archetype level, Building level • Temporal resolution: Annual

Table 1 Model characteristics definition

STAGE-2: DATA ACQUISITION

Once the model characteristics are well defined, the next phase is to acquire the data required for the UBEM analysis. This data is collected by contacting the appropriate government bodies through focused discussions and detailed site surveys. Pre-processed Geographical Information system (GIS) footprint details of the buildings are extracted from the free and open-source OpenStreetMap (OSM) geographic database. The same is cross-validated with the one collected from data collection or site surveys to ensure the reliability of the building geometry. The data collected from OSM, without cross-validating with survey results, will reduce the overall modeling time, sacrificing accuracy.

STAGE-3: UBEM CHARACTERIZATION

Since the framework is for the residential building community with buildings similar in their use type, date of construction, air conditioning, and ventilation networks utilized, a separate classification is not intended for the UBEM analysis. In UBEM characterization, non-geometric parameters are assigned to the building community energy models. Since a building community typically does not differ much in its construction materials and operational schedules, deterministic characterization is adopted. Similarly, appropriate database manuals for building communities with average monthly energy consumption values of 50 – 100 kWh per household (Chunekar and Khosla 2017) are adopted to define building envelope thermal characteristics (Bureau of Energy Efficiency 2017) and various non-geometric parameters as given in Table 2, for the analysis. The occupancy load factor comes from the survey results of 800 households in four climate zones of India (Shukla et al. 2011). The equipment loads follow the Performance Rating Method of ANSI/ASHRAE 90.1, used for rating the energy efficiency of high-rise residential buildings (Appendix C - Schedules | COMNET 2021).

Occupancy/Electrical system	**Non-geometric parameter**	**Granularity**	**Source**
Occupancy-related	Occupant load factor	m^2/person	(Shukla et al. 2011)
	Occupant internal heat gain	Hourly	(ASHRAE 2017)
Electrical systems related (heat gains, consumption, and schedule)	Computer	Hourly	(Appendix C - Schedules | COMNET 2021)
	Fluorescent lighting	Hourly	
	Other equipment's	Hourly	

Table 2 Other non-geometric parameter details with references that can be adopted for UBEM development

STAGE-4: UBEM COOLING LOAD ASSESSMENT

One of the general limitations observed in the UBEM studies developed in tropical climate regions is the inaccurate estimation of heating or cooling space in the selected building stock, as the buildings are primarily naturally ventilated and use individual room-wise A.C. units (Nikhil Singh, Rawal, and Mathur 2020). The proposed framework presents an approach to represent the cooling load for the building stock by finding out the quantity of Air-Conditioner (A.C.) outdoor units fixed at every building in the community by site investigation, thereby by passing the detailed questionnaire surveys. The statistical results obtained through investigating the patterns of electricity consumption among residential buildings across four different climatic zones by Rawan and Shukla (2014) are also adopted to determine the set points and mode of operation of A.C.s in the proposed study.

STAGE-5: BASELINE UBEM SIMULATION AND VALIDATION

Following the cooling space assessment, the building height information is annexed to the attribute table through OSM. This is performed by geospatial joins operation onto the individual shapefiles through a free and open-source geospatial platform called Quantum GIS (QGIS) (Agus et al. 2018). Following this, the energy simulation is performed. For this study, a new tool, IES-Intelligent Communities Lifecycle (ICL), is adopted for conducting energy simulations (Integrated Environmental Solutions | IES 2021). IES-ICL incorporates the capability of doing urban building simulations accompanied by water simulation and tree-inclusion features in a single interface and hence, explored. Post simulation, the average Energy Use Intensity (EUI) of the building stock is compared and cross-validated with the actual energy consumption readings collected utilizing the most common Percent Error (P.E.) between simulated and actual energy consumption values (Huerto-Cardenas et al. 2020)

STAGE-6: RENEWABLE ASSESSMENT AND VALIDATION

After the baseline UBEM simulation and validation, a rooftop solar assessment is performed using the ICL framework. Further, the validation of solar assessment results is done with the help of geospatial analysis. The notion of the framework is to present a scalable validation methodology for any solar assessment results from any UBEM tools available in the market. The validation uses the

Solar Energy on Building Envelopes model (SEBE) available in the geospatial interface of QGIS, mainly to estimate the solar irradiance on the ground, roofs, and building walls (Lindberg et al. 2015). The geospatial analysis was further extrapolated to find out the photovoltaic potential of building rooftops. The detailed methodology of validation is given in Figure 3 below. However, unlike energy validation with real-time energy bills, solar assessment validation compares the results of two different simulations, UBEM and geospatial.

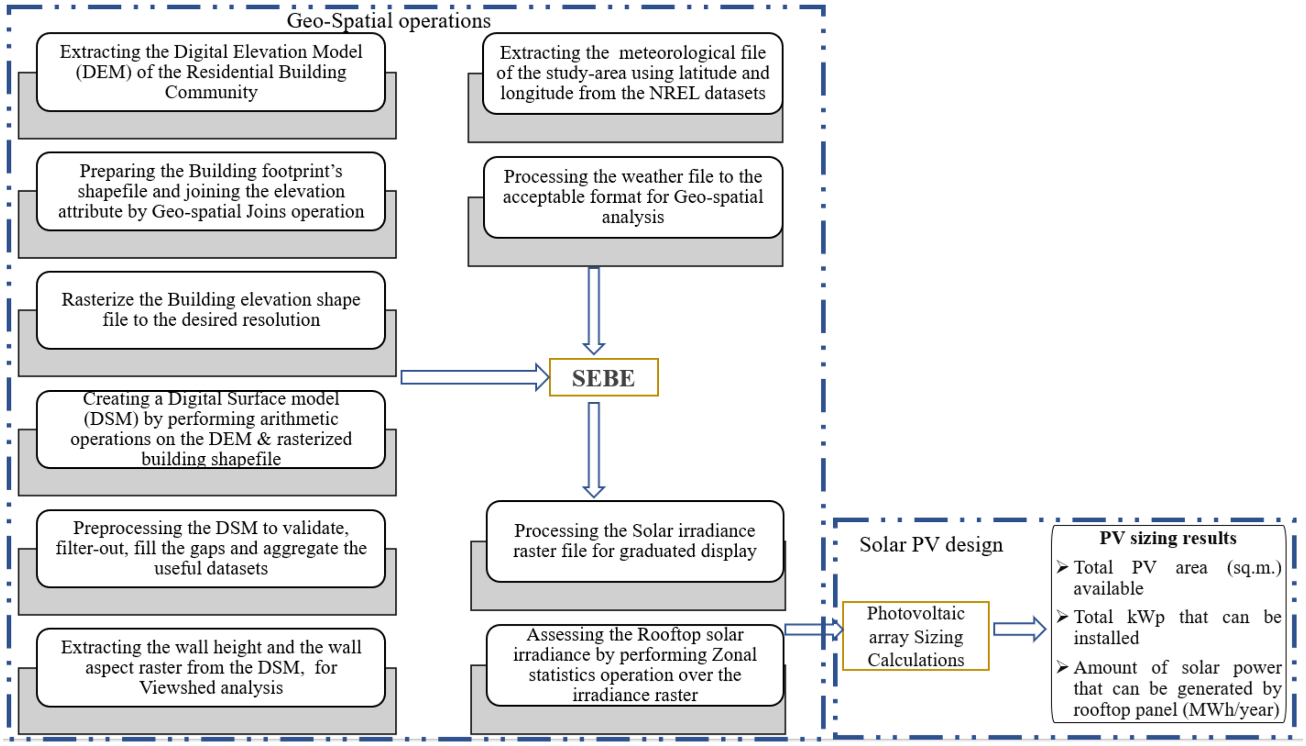

Figure 3 Solar assessment validation workflow

CASE STUDY

A residential building community of an educational institution in the city of Mumbai, India, with a set of 14 individual apartment-type buildings, is chosen for the case study. The framework discussed in the methodology section is implemented step by step. The fundamental details to be collected from the residential building community are the construction year of different buildings within the community, the building envelope construction materials, the footprint area of the buildings, and their corresponding heights. The building envelope material description taken from the site survey, with their corresponding thermal transmittances listed out from suitable reference codes, are given in Table 3 below.

Building fabric	Roof	External wall	External window
Description	100 mm RCC + 50 mm foam concrete + waterproofing	1.25 cm cement plaster + 22.5 cm brick + 1.25 cm cement plaster	Single clear glass with SHGC 0.8
U value (W/m^2-K)	1.08	2.13	5.8
Reference	(Bureau of Energy Efficiency 2017) (BIS 2016)		

Table 3 Building envelope material properties

The visual interface of the developed UBEM model set in the IES-ICL urban simulation tool, along with the rooftop solar panels generated, is as given in Figure 4, and the UBEM is simulated using the IES-VE engine, which is one of the most commonly used thermal-engine worldwide (Oleiwi et al. 2019).

Figure 4 Visual interface of the developed UBEM

RESULTS:

The results after the UBEM simulation show that the average Energy Use Intensity (EUI) of the building community is 26.18 kWh/m^2, with the total building community energy consumption of 369.69 MWh. The cooling energy consumption is 4% of the total energy consumption, corresponding to 17.4 MWh. When the simulated model is validated as proposed by the framework, the percent error is estimated to be 7.46%, which is within the generally acceptable range between 1% and 15%, as suggested by the literature (Cerezo Davila, Reinhart, and Bemis 2016). The comparison between the mean EUI between the annual simulated and actual energy consumption is shown in Figure 5 below. The actual energy consumption of the 14 residential buildings is collected by contacting the respective building energy manager and through the field visit.

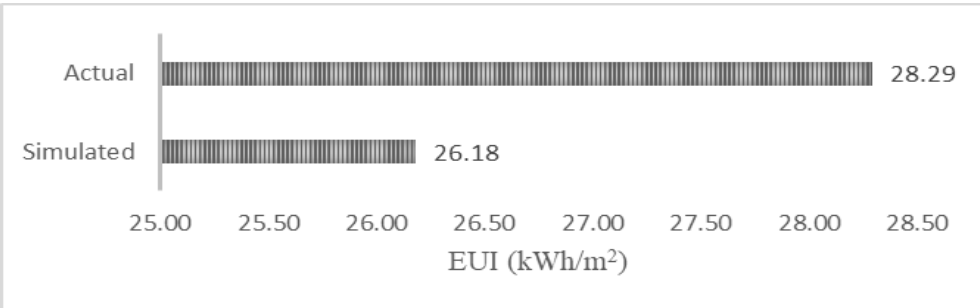

Figure 5 Annual average EUI (kWh/m^2) comparison between the simulated model and actual building community

The results of the UBEM solar assessment show that the solar power generated on the rooftop of the buildings within the community varies widely between 15 MWh/year and 41 MWh/year. The variation in the rooftop potential is mainly attributed to the available rooftop area and the shading of the neighbouring buildings. The rooftop area of the buildings varies from 131 sq.m to 361 sq.m, and the heights of the buildings range from 10 m to 14 m. The solar assessment results from the simulation platform are cross-validated with the geospatial results by following the workflow proposed in the adopted framework. The QGIS visualization of the average annual horizontal radiation (kWh/m^2/year) upon the building rooftops after the geospatial analysis is shown in Figure 6. The yearly solar power assessment results are then generated from rooftops from both the simulation tool and geospatial workflow, as given in Figure 7, and the distribution is very similar.

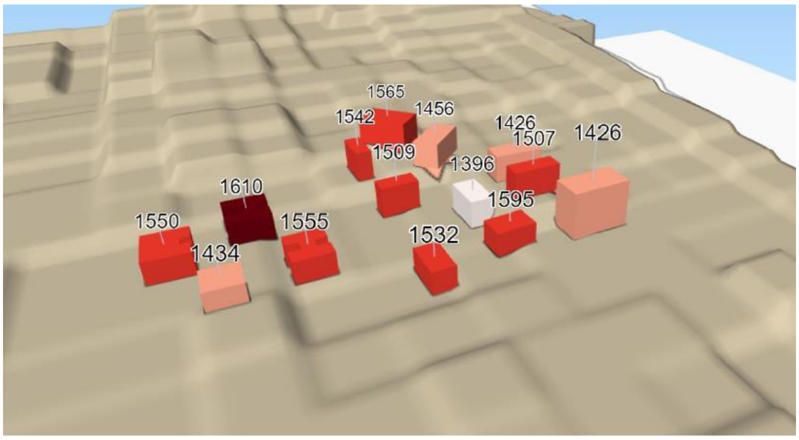

Figure 6 Visualization of the average annual horizontal radiation (kWh/m^2/year) upon the rooftops in QGIS

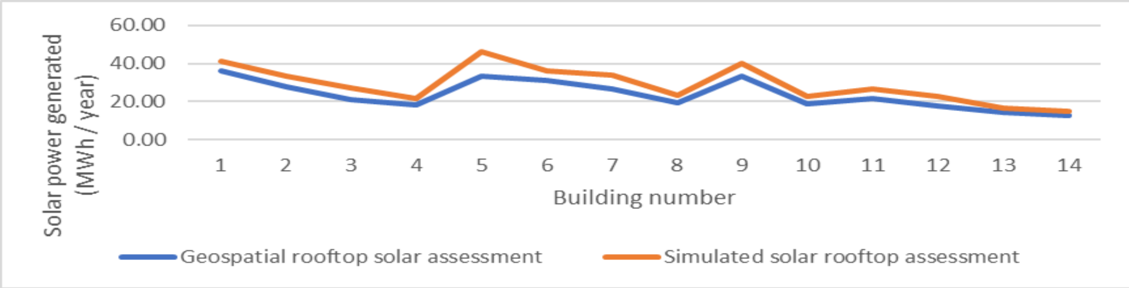

Figure 7 Solar assessment results comparison between simulated UBEM and geospatial workflow

The cumulative annual percent error between the simulated UBEM and geospatial assessments is 22%, and the comparison between the two is shown in Figure 8. The observed percent error of 22% in the solar assessment can be contributed mainly by the assumptions to estimate the module coverage factor for installing the panels. On investigation, it is found that the percent error drops to a negligible value when the module coverage factor is increased from 47.5% to 58%.

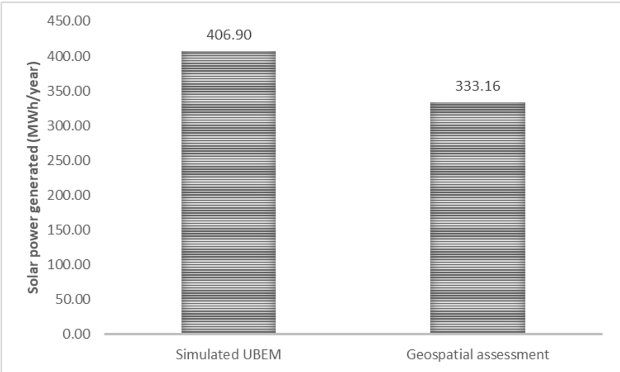

Figure 8 Annual solar power generated (MWh/year) comparison between the simulated model and geospatial assessment

The potential of the building community to be net-zero is discussed as follows. The validated UBEM energy simulation and solar assessment show that out of all the buildings within the building community, some buildings' individual rooftop solar power generation potential alone cannot meet their total energy demand. This is because of the existing building structure and its orientation and shading effects, which influence the solar irradiation incident on the roofs. The net-zero energy potential, considered the ratio of energy generated by the rooftop solar panels to the energy required by the building, is estimated and given as in Figure 9.

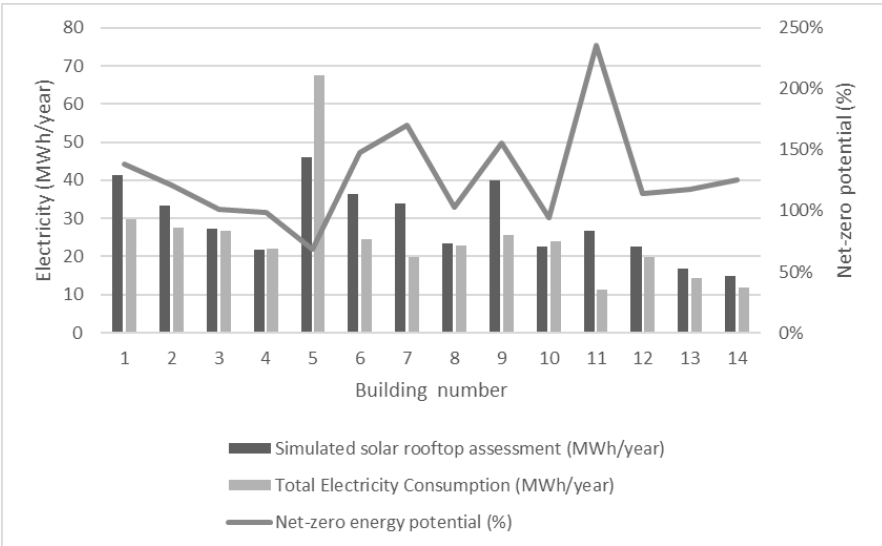

Figure 9 Net-zero energy potential of various buildings within the community

The net-zero potential of an individual building varies from as low as 68% to as high as 236%. 3 out of 14 buildings are falling short of net-zero energy potential. In contrast, four buildings are just meeting the net-zero energy needs, and the remaining seven buildings generate more than 20% of what is required for their consumption. If the building community taken for the case study adopts a community-solar approach, the community, on the whole, proves capable of producing 17% of energy more than the actual requirement by utilizing the available rooftop space. However, the different strategies to adopt a community-solar approach are not elucidated as part of this study.

DISCUSSIONS

Overall, both the energy simulation and the renewable assessment, along with the validation of the present case study, show the reliability of the framework developed and the tool used. In evaluating the net-zero potential of the building community, it is observed that not every building can meet its energy demand by the rooftop solar power generated in the same building. However, if the solar power generated is shared between the buildings, the community as a whole can achieve ZEC status. It can even produce 17% more energy than the community consumes. With the arrival of new policies which encourage community-solar programs, the community, as a whole, has the potential to become a net positive energy community, producing more energy from rooftop solar photovoltaic panels than it imports electricity from external power utilities.

CONCLUSIONS

This study presents a holistic framework for developing and validating a detailed Urban Building Energy Model for focused residential building communities to transition towards net-zero energy targets, especially for developing countries. The framework is adopted for a case-study residential building community in Mumbai, India and the results show that the energy use intensity of the community is about 26.18 kWh/m^2. The individual rooftop solar potential of the building community is assessed, and it is found that the net-zero energy potential of buildings dramatically varies, and not every building, as a stand-alone, can achieve nZECB status. It is observed that the solar power generated from individual building rooftops is between the range of 15 MWh/year and 40 MWh/year. In terms of net-zero energy potential, the ratio varies from 68% and 236%. The results reinforce the theme of this study for policies to be driven to achieve collective community-based net-zero energy targets rather than just focusing few individual buildings. Even when net-energy metering cannot be adopted immediately for a building, such community-based approaches can profit hugely mainly because of the possibility of sharing the energy generated within the community. The proposed framework also describes in detail different validation techniques that can be employed to ensure the reliability of any existing or emerging urban building energy simulation technologies. However, the framework does not address the possibility of checking how much energy generation instantaneously overlaps with the energy demand, and further exploration is required in this direction. The future scope of work can also address the likelihood of using geospatial photogrammetry techniques for data collection instead of time-intensive manual site investigation, which can significantly reduce the computational cost.

REFERENCES

Agus, F. et al. 2018. “Mapping Urban Green Open Space in Bontang City Using QGIS and Cloud Computing.” *IOP Conference Series: Earth and Environmental Science* 144(1).

“Appendix C - Schedules | COMNET.” https://www.comnet.org/appendix-c-schedules (October 31, 2021).

ASHRAE. 2017. “Standard 90.1-Performance Rating Method Reference Manual.” *ASHRAE Standards* (September). http://www.osti.gov/servlets/purl/1398228/.

BIS. 2016. “National Building Code of India, 2016 Volume 1.” *National Building Code of India* 80: 1 v. (various pagings).

Bureau of Energy Efficiency. 2017. “Energy Conservation Building Code for Residential Buildings (Part I: Building Envelope Design).” *ECBC*: 35. http://www.beepindia.org/sites/default/files/resources/Draft Code.pdf.

Cerezo Davila, Carlos, Christoph F. Reinhart, and Jamie L. Bemis. 2016. “Modeling Boston: A Workflow for the Efficient Generation and Maintenance of Urban Building Energy Models from Existing Geospatial Datasets.” *Energy* 117: 237–50.

Chunekar, A, and R Khosla. 2017. “A Collection of Insights on Electricity Use in Indian Homes.” *Plugging in: Prays (Energy group)* (December). https://www.prayaspune.org/peg/publications/item/download/859_85c7654a1c0b86ae5443c7428ea69084.html.

Crawley, Drury B, and Paul A Torcellini. 2006. “Understanding Zero-Energy Buildings.” *AHRAE J.* (September 2006).

Hamilton, Ian, and Oliver Rapf. 2020. “Executive Summary of the 2020 Global Status Report for Buildings and Construction.” *Global Alliance for Buildings and Construction*: 1–7.

Hledik, Ryan, Bruce Tsuchida, and John Palfreyman. 2018. “Beyond Zero Net Energy? Alternative Approaches to Enhance Consumer and Environmental Outcomes PREPARED FOR PREPARED BY.”

Huerto-Cardenas, H. E. et al. 2020. “Validation of Dynamic Hygrothermal Simulation Models for Historical Buildings: State of the Art, Research Challenges and Recommendations.” *Building and Environment* 180(June): 107081. https://doi.org/10.1016/j.buildenv.2020.107081.

“Integrated Environmental Solutions | IES.” https://www.iesve.com/ (October 28, 2021).

Javadekar, Prakash, Rabul Superiyo, R.P. Gupta:, and Ravi S. Prasad. 2021. “India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change.” *Ministry of Environment, Forest and Climate Change, Government of India.* Report: 3: 163–67.

Lindberg, Fredrik, Per Jonsson, Tsuyoshi Honjo, and Dag Wästberg. 2015. “Solar Energy on Building Envelopes - 3D Modelling in a 2D Environment.” *Solar Energy* 115: 369–78.

Nikhil Singh, Yaduvanshi, Rajan Rawal, and Anmol Mathur. 2020. “Limiting Energy Consumption in Ahmedabad’s Central Business District Using Urban Energy Modelling.” *uSIM2020 - Building to Buildings: Urban and Community Energy Modelling, November 12th, 2020*.

Oleiwi, Maryam Qays et al. 2019. “Thermal Environment Accuracy Investigation of Integrated Environmental Solutions-Virtual Environment (IES-VE) Software for Double-Story House Simulation in Malaysia.” *ARPN Journal of Engineering and Applied Sciences* 14(11): 3659–65.

Peterson, Kent, Paul Torcellini, and Roger Grant. 2015. “US Department of Energy: A Common Definition for Zero Energy Buildings.” *DOE* (September): 22. https://www.energy.gov/sites/prod/files/2015/09/f26/bto_common_definition_zero_energy_buildings_093015.pdf.

Rai, Varun, and Scott A. Robinson. 2015. “Agent-Based Modeling of Energy Technology Adoption: Empirical Integration of Social, Behavioral, Economic, and Environmental Factors.” *Environmental Modelling and Software* 70: 163–77. http://dx.doi.org/10.1016/j.envsoft.2015.04.014.

Ritchie, Hannah, and Max Roser. 2018. “Urbanization - Our World in Data.” https://ourworldindata.org/urbanization (May 9, 2021).

Ruparathna, Rajeev, Kasun Hewage, and Rehan Sadiq. 2016. “Improving the Energy Efficiency of the Existing Building Stock: A Critical Review of Commercial and Institutional Buildings.” *Renewable and Sustainable Energy Reviews* 53: 1032–45. http://dx.doi.org/10.1016/j.rser.2015.09.084.

Seto, Betty et al. 2016. “Zero Net Energy Communities: Three Cities Leading the Way.” *ACEEE Summer Study on Energy Efficiency in Buildings* (Usdn): 1–13. https://aceee.org/files/proceedings/2016/data/papers/10_1034.pdf.

Shukla, Yashkumar et al. 2011. “Residential Buildings in India : Energy Use Projections and Savings Potentials.” In *Eceee Summer Study Proceedings*, , 1193–1206.