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Systems-level Methodology for Optimizing Urban Infrastructure Energy Resilience#

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ABSTRACT

Urban population growth and extreme weather events challenge the balance of energy supply and demand, stressing power grids and leading to higher prices and potential blackouts. Addressing these challenges requires sustainable and resilient energy systems. This research aims to develop a methodology to optimize urban infrastructure energy resilience by integrating urban-scale building energy modeling (UBEM) with smart grid technologies. The methodology encompasses building energy analysis, renewable energy optimization, and systems-level integration. Using the Toyosu area of Tokyo as a case study, the research examines a normal baseline with 2023 historical weather data and an extreme weather scenario with future climate datasets. Each case contains 11 input variables and 4 output variables, with 6 input variables used in UBEM to generate the load profile. The study employs the REopt tool to identify optimal combinations of renewable energy and storage technologies. Simulation results demonstrate the feasibility of the proposed methodology, providing insights into enhancing urban energy system resilience and achieving sustainability goals. The proposed methodology allows for a more robust and dynamic response to fluctuations in energy demand and supply that is particularly critical during extreme weather events which are becoming more frequent due to climate change.

Keywords: urban building energy modeling, smart grid, design of experiment, digital twins, energy resilience

NONMENCLATURE

Abbreviations	
UBEM	Urban Building Energy Modeling
BEM	Building Energy Modeling
BAPV	Building-Applied Photovoltaics
BIPV	Building-Integrated Photovoltaics
FAR	Floor Area Ratio
DOE	Design of Experiment
W2W	Window-to-Wall Ratio
Symbols	
n	Year

1. INTRODUCTION

With the growing population and increasing economic activities, cities face a significant challenge in balancing energy supply and demand. Extreme weather conditions, particularly the increase in extreme heat events during the past four decades [1], exacerbate the strain on existing power grids, leading to spikes in energy pricing, or even blackouts that disrupt daily life and compromise safety. These events also lead to a growing gap between energy supply and demand, highlighting the urgent need for systems that are not only sustainable but also accessible and resilient [2]. City planners must explore alternative energy tactics to address these challenges effectively. Implementing renewable energy sources, such as solar and wind power, can help diversify the energy mix and reduce reliance on the grid. This diversification is crucial for improving the resiliency of the energy grid, enabling it to withstand high demand and disruptive events more effectively.

Moreover, the development of a smart grid is essential for meeting the dynamic energy needs of

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modern urban centers. A smart grid leverages advanced technologies to monitor, predict, and respond to energy consumption patterns in real time. This responsiveness ensures a more efficient distribution of energy, reducing waste and optimizing the use of available resources. It also allows for better integration of renewable energy sources, which can be unpredictable in their output.

In formulating regulatory and technology roadmaps, policymakers must prioritize long-term infrastructure sustainability, carbon emissions reduction, accessibility, and resiliency. These roadmaps should include strategies for upgrading existing infrastructure, investing in new technologies, and creating policies that encourage the adoption of sustainable practices. The decision-making process regarding the scale of new energy infrastructure should consider various factors, including projected population growth, anticipated economic activities, and potential environmental impacts. By planning for future energy needs and potential challenges, city planners can ensure that the energy grid remains robust and capable of supporting urban development sustainably.

To overcome and respond to urban climate challenges, this research aims to optimize urban infrastructure energy resilience by effectively integrating urban-scale building energy modeling with smart grid technologies. It seeks to address the crucial question of how to design and develop an urban-scale energy system that significantly enhances energy resiliency within metropolitan grids. By answering the main research questions, the research endeavors to deliver a systems-level methodology to optimize urban infrastructure energy resilience, ensuring future resilient urban development based on the use case of Toyosu area of Tokyo.

2. LITERATURE REVIEW

2.1 Digital Infrastructure

Digital representation in infrastructure design is a pivotal innovation that leverages advanced technologies to optimize planning, construction, and management processes. [3] To be effective, these digital representations need to be multi-attribute, allowing the assessment of multiple factors concurrently. This holistic approach ensures that various elements such as structural integrity, energy efficiency, and environmental impact are evaluated simultaneously, providing a comprehensive understanding of the infrastructure's performance.

Moreover, utilizing digital models enables the execution of numerous experiments without the need for extensive physical materials. This digital approach significantly reduces costs and resource consumption, important to grid planning as it is done with very limited physical testing. By simulating different scenarios and conditions, planners and engineers can identify the most effective and sustainable design solutions.

Additionally, parametric modeling plays a crucial role in managing uncertainty within the design process. Parametric models allow for the adjustment of various parameters and variables, enabling the exploration of a wide range of design possibilities. This flexibility helps in anticipating potential issues and adapting the design to meet specific requirements or constraints effectively.

2.2 From Building Energy Modeling (BEM) to Urban Building Energy Modeling (UBEM)

Technology breakthroughs and community makeovers are essential for increasing building energy efficiency, particularly in metropolitan areas. Understanding how building energy efficiency is affected by urban-level design elements like density, building use, and urban shape is crucial, but research on this topic is still lacking when it comes to urban-level aspects because of gaps in information, inconsistent data, and poor modeling. Therefore, for maximum energy performance and sustainable urban development, combining multidisciplinary research is crucial [4].

The ability of buildings to create and consume energy should be examined. They may generate electricity through solar power plants, which gives urban planners further challenges and opportunities [5]. Due to its efficiency and viability for decentralized energy generation in urban settings, the installation of solar panels on building surfaces, known in practice as Building-Applied Photovoltaics (BAPV) or Building-Integrated Photovoltaics (BIPV), is growing in popularity [6]. With installed capabilities that are expanding quickly, several nations are aggressively pushing solar-powered buildings as a way to lessen reliance on fossil fuels [7]. A vision for future sustainable urban development is emerging: the “solar city" [8–10]. In the field of simulation, digital tools like UBEM are becoming more and more essential, especially when it comes to urban-scale design. At the neighborhood and city levels, UBEM plays a key role in evaluating, optimizing, and directing decisions related to sustainable planning and policy [11,12].

There have been many studies of single building models for simulating the energy requirements of buildings and developing related concepts for energysaving design. However, many unknown factors exist in cities, which contain many large-scale dynamic systems. At this level, building energy models (BEMs), which mainly consider single or small clusters of buildings, are not sufficient for assessing the actual performance of the building stock [13]. Moreover, most studies regarding the energy performance of archetype buildings under climate change find it difficult to obtain refined results for individual buildings when scaling up to an urban area. Therefore, it is necessary to identify similar energy consumption patterns and propose urban-scale building energy management strategies.

3. METHODOLOGY

To study the emerging properties of energy by connecting the buildings and the energy grid systems, a comprehensive systems-level methodology shown in Fig. 1. was developed to capture the complexity of energy interactions. This methodology consists of three interconnected sections, each addressing a different scale: the building energy level, the renewable energy analysis, and the systems level optimization.

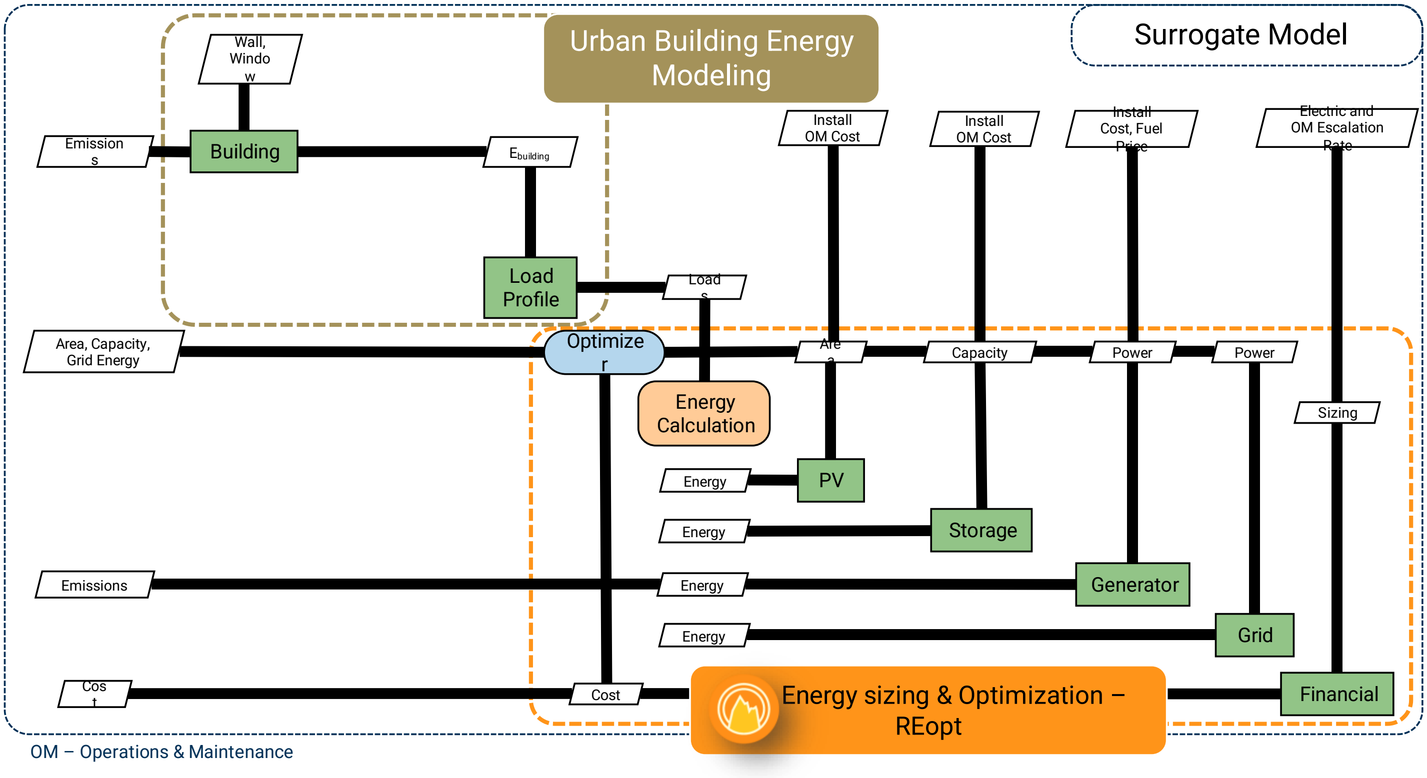


Fig. 1 Proposed methodology

To test the feasibility of the proposed methodology, this study utilized Toyosu area as a case study. Two scenarios and 11 input variables are identified: The scenarios include a normal baseline scenario with nominal weather profile using historical data in 2023, and an extreme weather scenario with a heat-wave attack weather profile using hourly future climate scenario datasets [14]. 11 input variables included Floor Area Ratio (FAR), Window-to-Wall Ratio, Floor-to Floor Height, Occupancy Schedule, Building Type Distribution Percentage, Building Energy Performance Efficiency, PV Cell Installation Cost, Solar Panel Operation & Maintenance Cost, Battery Energy Storage System Installation Cost, Generator Installation Cost, and Generator Operation & Maintenance Cost.

4. RESULTS

4.1 Methodology Overview

In this study, the methodology includes building energy level, the renewable energy analysis, and the systems level. At the building energy level, the energy model accounts for various factors such as occupancy, building design, and systems efficiency such as HVAC to generate accurate load profiles. These load profiles are crucial as they serve as the foundation for subsequent analysis and optimization processes. To link the building energy modeling to systems level optimization, the BEM needs to be transformed to UBEM. Shifting to renewable energy analysis, these detailed load profiles are input into REopt, an energy sizing and optimization tool developed by the National Renewable Energy Laboratory. REopt is designed to optimize the sizing and operation of renewable energy, storage, and conventional generation systems. It identifies the most cost-effective combination of renewable energy and storage technologies to meet specific energy needs. By optimizing the mix of on-site generation and storage, REopt enhances energy system resilience and improves reliability during grid outages. Finally, at the systems design level, the methodology includes a surrogate model to enable design space analysis and to identify trends and interactions between variables at different levels. Here, the focus is on understanding how the optimized urban scale building energy systems interact with the overall energy grid. This involves assessing the impact of integrating renewable energy sources on grid sustainability, sizing potential renewable energy infrastructure, and determining the overall efficiency of the energy system.

4.2 Urban Building Energy Modeling (UBEM)

The methodology used in UBEM follows a systematic approach that leverages digital analysis and modeling tools. It begins by creating a digital representation of the site conditions using UBEM simulation inputs, such as weather files and building geometry. The weather file was customized using actual collected data of year 2023 and predictive datasets for the year of 2030, including key climatic inputs like temperature, relative humidity, and wind speeds. The geometry was modeled in Rhino by accurately depicting building outlines and heights.

4.3 Energy Sizing and Optimization using REopt

REopt is a techno-economic decision support tool designed to optimize energy systems by identifying the infrastructure with the best economic performance while meeting energy demands. In the Toyosu case study, five key variables within REopt were varied to investigate the impact of renewable energy costs on overall grid performance. These variables included:

- Solar Panel Installation Cost per kW, ranging from $250 to $350
- Solar Panel Operation & Maintenance Cost per kW, ranging from $25 to $35
- Battery Energy Storage System Installation Cost per kWh, ranging from $50 to $90
- Generator Installation Cost per kW, ranging from $300 to $500
- Generator Operation & Maintenance Cost per kW, ranging from $5 to $12

By integrating these variables with the load profiles and other constants, REopt was able to determine the most optimal combination of energy infrastructure. The optimization process yielded four key outputs for further analysis:

- Annual CO2 Emission in Tons
- Solar Panel Sizing in kW
- Battery Energy Storage System Sizing in kW
- Total Renewable Energy Percentage

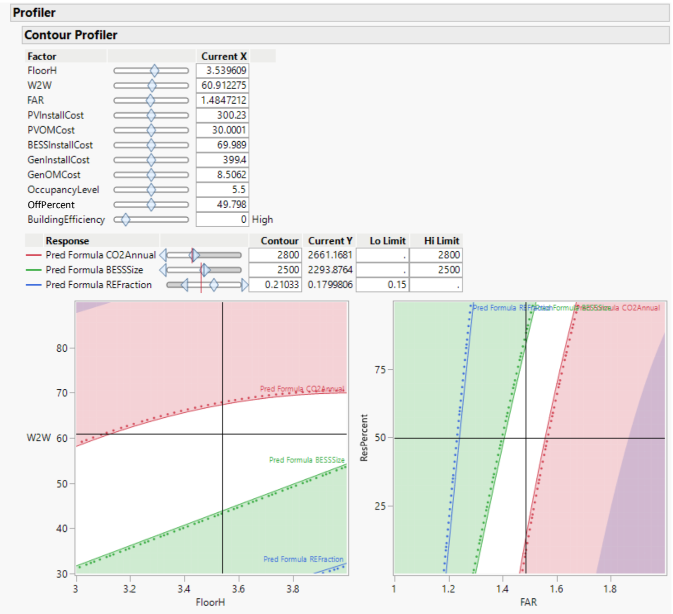
4.4 Simulations for Normal and Extreme Weather Scenarios

To build the surrogate model, 220 simulations were run in a space filling Design of Experiment (DOE) for two scenarios: the normal scenario and the extreme weather scenario. The paper includes a demonstration of a design space analysis for the Normal Weather Scenario and includes results for the Extreme Weather Scenario.

Normal scenario represents the historical data of year 2023 including weather file and occupancy schedule. Occupancy schedule is collected from GIS data for the residential, office and retail building types.

Figure 2 (Fig. 2) illustrates a design point within the feasible design space. In this context, CO2 emissions have a high limit of 2800 tons, set as a sustainability goal, and the Battery Energy Storage System (BESS) size has a high limit of 2500 kWh, potentially due to fire hazard concerns.

Initially, the user adjusted the ResPercent variable, which increases the percentage of office space area (OffPercent). However, this adjustment caused the design point to move into an infeasible space, as depicted in Fig. 3. This shift indicates that the current configuration exceeded the established limits for BESS size, showing the design violating the given constraints.



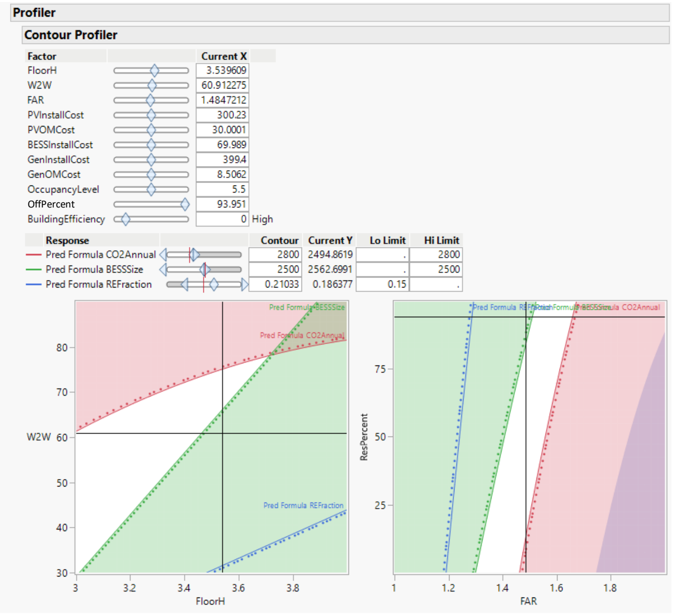
Profiler

Contour Profiler

Factor	Current X	
FloorH	3.539609	
W2W	60.912275	
FAR	1.4847212	
PVInstallCost	300.23	
PVOMCost	30.0001	
BESSInstallCost	69.989	
GenInstallCost	399.4	
GenOMCost	8.5062	
OccupancyLevel	5.5	
OffPercent	49.798	
BuildingEfficiency	0	High

Response	Contour	Current Y	Lo Limit	Hi Limit
Pred Formula CO2Annual	2800	2661.1681	.	2800
Pred Formula BESSSize	2500	2293.8764	.	2500
Pred Formula REFraction	0.21033	0.1799806	0.15	.

Fig. 2 Sarting in a feasible space



Profiler

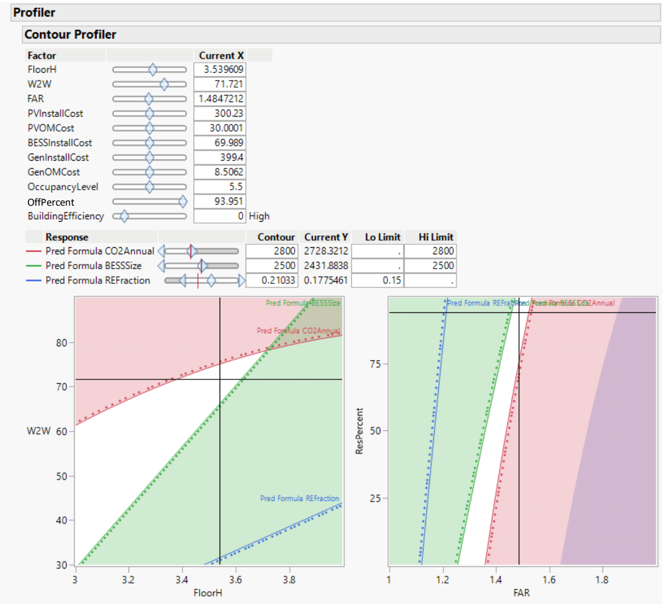
Contour Profiler

Factor	Current X	
FloorH	3.539609	
W2W	60.912275	
FAR	1.4847212	
PVInstallCost	300.23	
PVOMCost	30.0001	
BESSInstallCost	69.989	
GenInstallCost	399.4	
GenOMCost	8.5062	
OccupancyLevel	5.5	
OffPercent	93.951	
BuildingEfficiency	0	High

Response	Contour	Current Y	Lo Limit	Hi Limit
Pred Formula CO2Annual	2800	2494.8619	.	2800
Pred Formula BESSSize	2500	2562.6991	.	2500
Pred Formula REFraction	0.21033	0.186377	0.15	.

Fig. 3 Moving to an infeasible space by increasing office percentage

To expand the feasible design space and bring the design point back within acceptable limits, the user can make strategic adjustments. Increasing the Window-to-Wall (W2W) ratio or decreasing the floor height are two effective strategies. These adjustments can mitigate the excesses BESS sizing, as they influence the building's overall energy efficiency and capacity requirements. As shown in Fig. 4, these modifications successfully return the design point to the feasible space, demonstrating the flexibility and adaptability of the design space analysis.



Profiler

Contour Profiler

Factor	Current X	
FloorH	3.539609	
W2W	71.721	
FAR	1.4847212	
PVInstallCost	300.23	
PVOMCost	30.0001	
BESSInstallCost	69.989	
GenInstallCost	399.4	
GenOMCost	8.5062	
OccupancyLevel	5.5	
OffPercent	93.951	
BuildingEfficiency	0	High

Response	Contour	Current Y	Lo Limit	Hi Limit
Pred Formula CO2Annual	2800	2728.3212	.	2800
Pred Formula BESSSize	2500	2431.8838	.	2500
Pred Formula REFraction	0.21033	0.1775461	0.15	.

Fig. 4 Moving back to feasible space by increasing W2W ratio

By carefully balancing key variables to achieve optimal design solutions, it is possible to meet sustainability goals and constraints while maximizing the functional and economic performance of the energy system.

The extreme weather scenario shows similar trends in the design space while being more sensitive to office space percentage. Comparing the two most desirable design points, the extreme weather scenario resulted in more CO2 emissions, requires more battery energy storage, and has a lower renewable energy percentage.

5. CONCLUDING REMARKS & FUTURE WORK

This study successfully developed and validated a comprehensive methodology for optimizing urban infrastructure energy resilience by integrating urban-scale building energy modeling with smart grid technologies. The methodology demonstrated its effectiveness in the Toyosu case study, where it managed to assess and optimize energy distribution under both normal and extreme weather scenarios. By identifying the optimal combinations of renewable energy and storage technologies, the research highlighted the potential for significant improvements in grid resiliency and sustainability. The findings emphasize the critical role of smart grid technologies and advanced modeling techniques in urban energy management, confirming that such integrated approaches can effectively respond to the dynamic demands of modern urban environments.

The proposed methodology presented in this research is essential to address both current challenges and future needs in urban energy management. Unlike traditional energy models that focus on individual buildings or small clusters, this methodology considers the entire urban fabric, facilitating a holistic view of energy flows and interactions across a cityscape. This systems-level perspective is crucial for identifying synergies and conflicts between various energy sources and demands, enabling more strategic and informed decision-making. The integration of smart grid technologies allows the energy system to predict, monitor, and respond to changes in energy usage and production in real-time. The proposed methodology not only addresses immediate and practical energy management challenges but also aligns with broader sustainability and resilience goals. Its implementation could lead to significant improvements in how cities plan, build, and manage.

Future research should focus on expanding the application of the developed methodology to other urban areas with different climatic, economic, and social conditions to validate its adaptability and scalability. Additionally, further studies could explore the integration of more diverse renewable energy sources, such as geothermal and biomass, to broaden the energy mix. Advancements in artificial intelligence and machine learning could be leveraged to enhance the predictive accuracy of energy consumption patterns and optimize the deployment of energy resources dynamically. Lastly, ongoing development of policy frameworks that encourage the adoption of sustainable practices and technologies will be essential for fostering broader implementation of resilient urban energy systems.

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