# A Regional Investigation of Near-Zero Energy Buildings: Assessing the Impact of PV Integration and Building Design

**Elsayed Salem[1], Emad Elwakil[2] and Ashraf Salem[3]**

[1,2]School of Construction Management Technology, Purdue University, United States
[1]Civil Engineering Department, Faculty of Engineering, Kafrelsheikh University, Egypt
[3]Senior Risk Manager, WSP Canada Inc., Canada
esalem@purdue.edu, eelwakil@purdue.edu, ashraf.salem@wsp.com

**Abstract –**

**Building energy research faces challenges in predicting complex interactions, integrating renewable energy, bridging real-world applications, addressing economic feasibility, and designing buildings to adapt to climate conditions. Zero energy building (ZEB) is an innovative approach aiming to generate renewable energy equivalent to building demand, but its development is hindered by industry flexibility and complexity. The research explores the feasibility of achieving near ZEB by utilizing roof photovoltaics technology for energy production and optimizing consumption in four US climate regions. Building Information Modeling (BIM) was used in this study to simulate the building operation energy. Actual Location and real weather data were used to adopt results accurate enough for the study objective. Additionally, the local energy prices were used to costly-wise introduce an effective feasibility. Colorado's model has the highest energy and cost percentages, at (75.34%) and (88.61%), respectively. Georgia ranked second in terms of energy savings (71.21%). Due to the high local energy prices, San Francisco, Ca achieved the largest cost-saving percentage (88.61%), which is like Colorado, despite having a lower percentage of energy savings (59.83%). The study found that wall and roof construction, along with HVAC system types, are effective in optimizing building energy consumption, but its results are limited by climate regions and office building types.**

**Keywords –**

**Sustainability; Building Performance; Renewable Energy; Reconstruction; Building Operation; Retrofit; Building Design; Zero Energy Building; ZEB; Energy Analysis; Building Information Modeling; Restoration.**

## 1 Introduction

Urban regions are moving toward sustainable energy by converting the infrastructure into energy-efficient systems. Advanced energy analysis techniques and Building Information Modeling (BIM) are being employed to forecast energy generation and demand to support self-sufficient, and energy-independent communities [1], [2]. Computational techniques provide an accurate and reliable way to address uncertainty and sensitivity analysis in energy efficiency buildings, addressing intricate linkages [3], [4], [5]. The building industry is still in the developing stage for sustainability due to the high complexity of building systems and the involvement of many stakeholders [6]. Therefore, computational techniques are used to overcome this difficulty [7], [8]. Energy and environmental concerns are addressed by integrating renewable and energy-efficient technologies [9], [10], [11]. There are many barriers to the adoption of renewable energy [12]. Reaching the point of optimal building energy performance could be impacted by several factors [13], [14], [15].

The World Green Building Council (WGBC) and the United Nations Framework Convention on Climate Change (UNFCCC) are collaborating to create a common approach for assessing and grading building sustainability. Most scholars use generative computation for aesthetic form-finding without using zero-energy-driven global performance standards, and there is no standard seal or measure for Net-Zero Energy buildings [16]. Using a Digital Twin model, ZEB buildings in the UK have successfully integrated renewable technology into their current buildings. The model has shown a 23-year return period for solar panels and wind turbines but does not provide design recommendations for new buildings [17]. The study [18] revealed that countries plan to convert traditional buildings to Zero Energy, despite challenges like high initial costs for renewable energy systems compared to overall building costs, gaining more interest and support. The study [19] analyzed cost barriers to Zero Energy Building (ZEB) implementation, revealing gaps in energy-saving calculations, comparative studies, life cycle cost analysis, and high initial costs.

BIM and cloud optimization platforms are popular building energy simulation software for simulating building materials and geometry. Cloud-based optimization tools were used to analyze an academic building in Pakistan, focusing only on roof isolation and building orientation, demonstrating the effectiveness of BIM in optimizing energy efficiency [20]. The cloud tools were utilized in an evaluation strategy for the Middle East and North Africa, analyzing building energy use and identifying solutions to reduce it. The study focused on photovoltaic panels and HVAC system enhancement, not considering alternative construction materials [10]. Furthermore, computational design methods were used to improve the energy performance of concrete residential towers in cold climates [21], and pre-trained language model-based methods were used to transform the building information model into an energy model [22].

According to the literature review, the impact of climate on designing a new ZEB or retrofitting existing buildings was not well understood. Additionally, little is known about how climate influences design factors. By examining design features and using special design scenarios to rebuild a sustainable and highly energy-efficient building using BIM software, this paper will bridge this gap by examining four different climates for an office building to achieve near Zero-Energy objective.

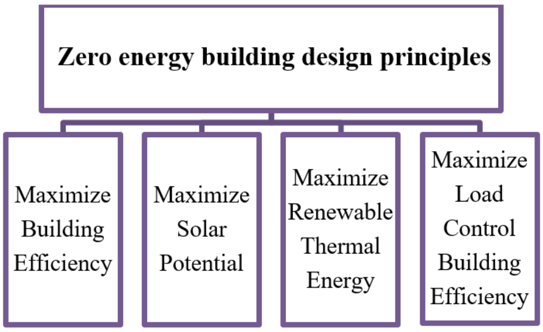


Figure 1. Zero energy building design principles adapted from [25].

Zero energy building (ZEB) is an innovative approach aiming to balance building energy demand and renewable energy production. This study aims to identify the impact of climate on achieving near ZEB by analyzing the unique design scenarios of factors such as location, design, renewable energy use, energy consumption trends, and budget when planning, erecting, restoring, and reconstructing such a high-efficiency building. The literature examining the building designs that can achieve the high-energy performance building concept is severely lacking [18], [19], [23], [24]. This study will cover this gap by modeling the operation performance of an office building using BIM, Energy analysis, and optimization tools. It also applies distinctive design scenarios for each design parameter to achieve near ZEB requirements. Finally, the optimization values for each design parameter were determined based on the impact of reducing the overall building energy consumption and cost. Figure 1 summarizes the main key steps optimize a ZEB.

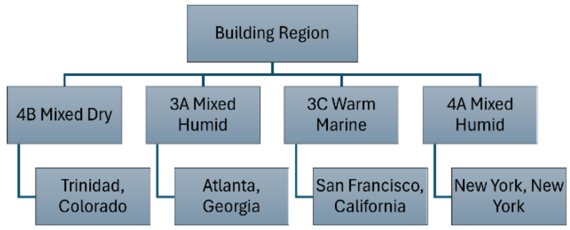


Figure 2. Different building regions

This study aims to fill the literature gap and provide a roadmap for designers and practitioners to adopt passive solar design for high-performance buildings and sustainable targets. It aims to accelerate zero-energy buildings by reducing energy consumption and introducing energy production techniques. The paper investigates the influence of climate region on building energy consumption and solar energy production in four different regions as shown in Figure 2. The climate regions classification is according to Building America and the International Energy Conservation Code (IECC) 2021 Updates as shown in Figure 3. The four locations were selected from different climate regions after excluding extreme climates that are expected to consume very high energy due to the weather.

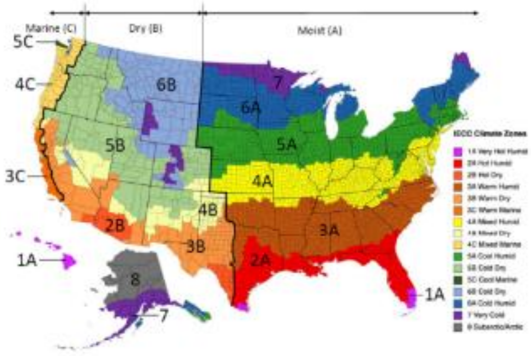


Figure 3. Climate Zone by County according to Building America and International Energy Conservation Code (IECC) 2021 Updates adapted from [26].

The study aims to identify the feasibility of adopting ZEB. It utilizes BIM simulation tools to connect the effects of different variables and deal with the complexity of the building systems. The fundamental presumptions of this research are as follows.

- The selected building represents its local location for weather and environmental parameters.

- The results generated from the simulation tools are accurate enough for the study objective to compare energy savings for different cases.
- The secondary simulation parameters have a negligible impact when comparing different scenarios.

The study focuses on office buildings and considers the standard energy usage rates for simulating different energy modules. However, additional studies should be conducted to expand the scope due to limited case studies and climate regions.

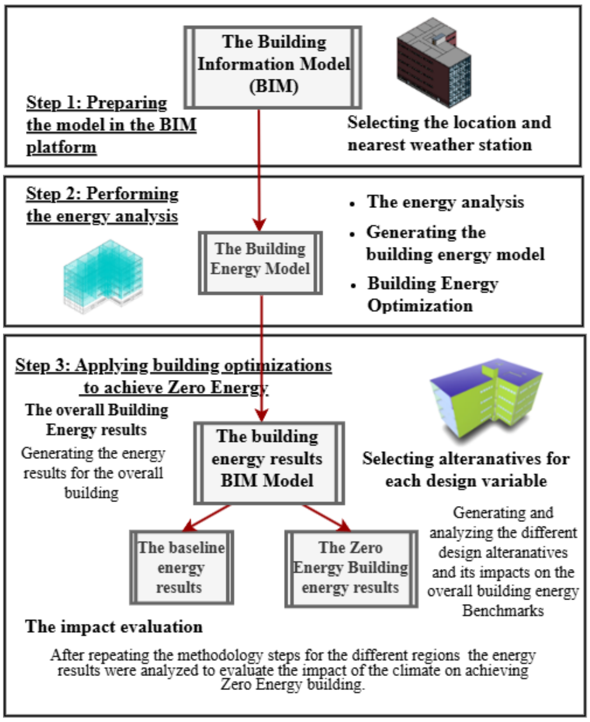


Figure 4. The Study Methodology Flow Chart.

## 2 Methods

This study is examining the building operation performance in 4 different locations through applying three main steps for each location, as illustrated in Figure 4, starting with step 1: Preparing the model in the BIM platform. Following that, the energy analysis is performed in step 2 to generate the building energy model. In step 3, the building energy model will be used to apply the energy optimizations to reduce the energy consumption and optimize the photovoltaic energy production trying to achieve near ZEB. Finally, the baseline energy and cost will be compared to the near ZEB energy and cost for each location.

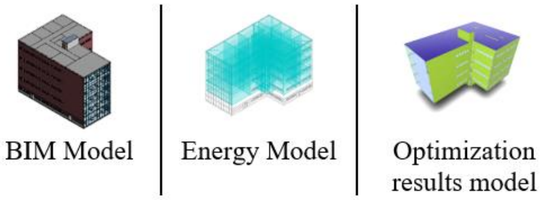


Figure 5: BIM Model, Energy Model, and Optimization results model. (BIM model source [27])

### 2.1 Preparing the model in the BIM platform

Autodesk Revit was used as the BIM tool to model the building geometry and materials. Additionally, its integrated GIS (Geographic Information System) functionality enabled the incorporation of location-specific weather data, enhancing the analysis with real-world environmental conditions.


Figure 6: The selection of the building location and the nearest Weather Station.

Figure 5 illustrates BIM Model, Energy Model, and Optimization results model. For instance, Figure 6 shows the selected location and the nearest available weather station, and Figure 7 reports the monthly temperature rates for first location.

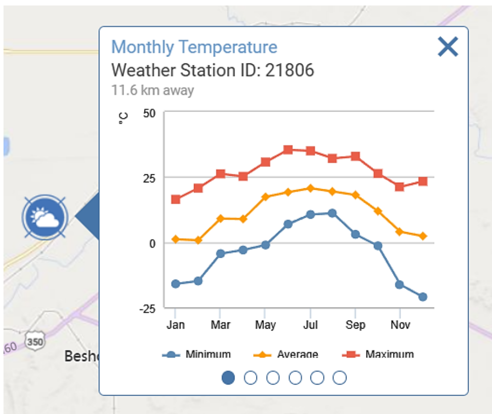


Figure 7. The monthly temperature rates in the selected location.

## 2.2 Performing the energy analysis

The energy analysis tools were used to perform a complete energy analysis. Figure 5 shows the generated building energy model.

Finally, the energy model for each location were exported to the optimization platform. At this step, different variables for each design parameter were applied, which gave different results for each variable. For example, different wall construction types including (R13 Wood- Uninsulated- R2CMU- R3 Metal- R13+R10 Metal- 14-inch ICF- 12.25-inch SIP- R38Wood) gave the Energy Use Intensity (EUI) results shown in Figure 8. Figure 5 illustrates the results of the BIM model generated in the optimization platform.

| **Wall construction Types** | R13 Wood | Uninsulated | R2CMU | **Baseline (BIM)** | R3 Metal | R13+R10 Metal | 14-inch ICF | 12.25-inch SIP | R38Wood |
|---|---|---|---|---|---|---|---|---|---|
| **Energy Impact (kwh/m²/yr.)** | +50 | +30 | +10 | 0 | -5 | -45 | -48 | -49 | -50 |

Figure 8. The energy impact of using different Wall Construction Types in Trinidad, CO - 4B Mixed Dry region.

## 2.3 Applying building optimizations to achieve zero energy

Different energy scenarios are achieved by setting distinctive design parameters to a specific value. For example, wall construction materials can be set to different types. A total of 24 design parameters were used in the optimization process as given in Figure 9. A new scenario is added to the results after setting all the design parameters to a specific value. This study applied the scenario that achieves the ZEB target to compare it with the baseline scenario. The design parameters were determined based on the impact of energy consumption and cost reduction. The findings of this study were analyzed and compared at the end of this paper.

| **Design Parameters** | |
|---|---|
| • Building Orientation (Degrees)<br>• Daylighting & Occupancy Controls<br>• HVAC Types<br>• Infiltration (ACH)<br>• Lighting Efficiency<br>• Operating Schedule<br>• Panel Efficiency<br>• Payback limit<br>• Plug Load Efficiency<br>• Roof Construction<br>• Surface Coverage<br>• Wall Construction | • Window Glass Types - North<br>• Window Glass Types - East<br>• Window Glass Types - West<br>• Window Glass Types- South<br>• Window Shades - East<br>• Window Shades - North<br>• Window Shades - South<br>• Window Shades - West<br>• WWR - Eastern Walls<br>• WWR - Northern Walls<br>• WWR - Southern Walls<br>• WWR - Western Walls |

Figure 9. Design Parameters

# 3 Results

The study results were analyzed to visualize and evaluate each building location for constructing or retrofitting existing buildings to become a near ZEB. Figure 10, and Figure 12 explain the comparison analysis for the building energy consumption and cost, respectively for the four building locations for the baseline scenario. Figure 12, and Figure 13 compare the results of building energy consumption values for the four building regions for the near ZEB scenario with the baseline results.

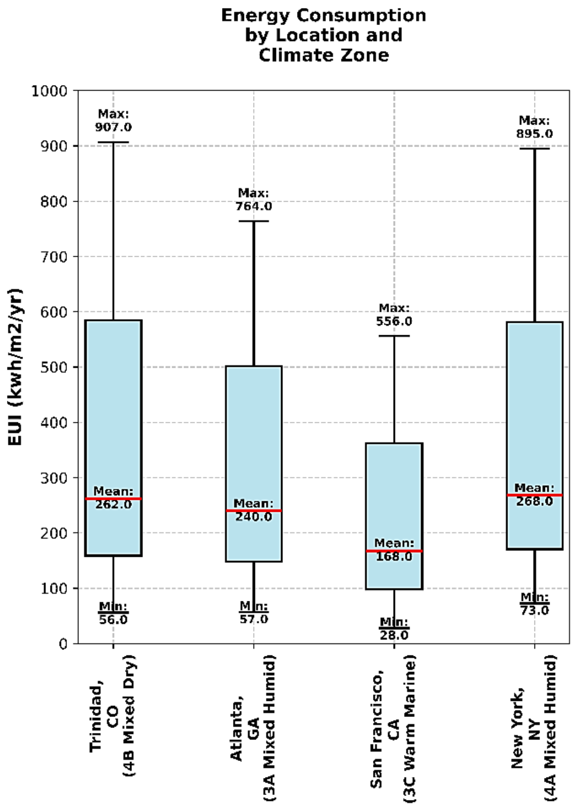


Figure 10. Comparing the Minimum, Mean, and

Maximum building energy consumption results by location and climate zone for the baseline scenario.

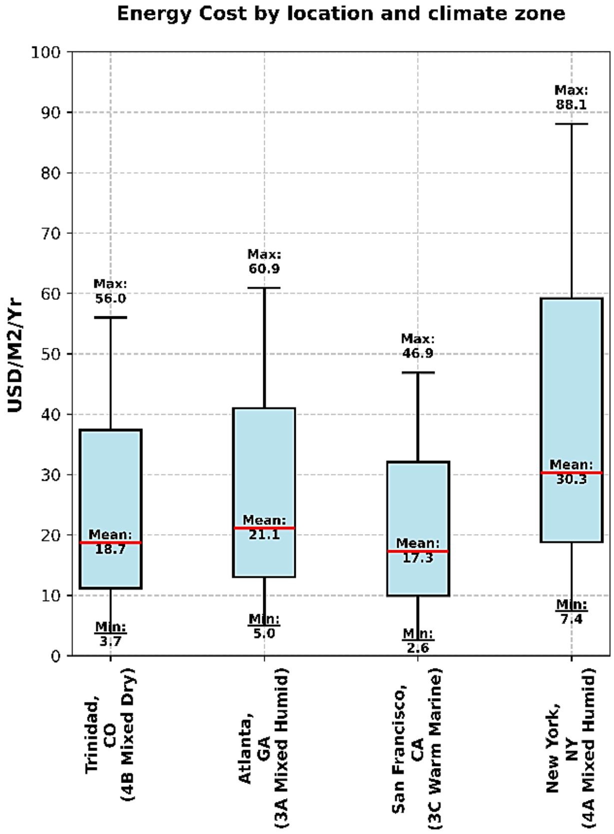


Figure 11. Energy Cost by location and climate zone for the baseline scenario.

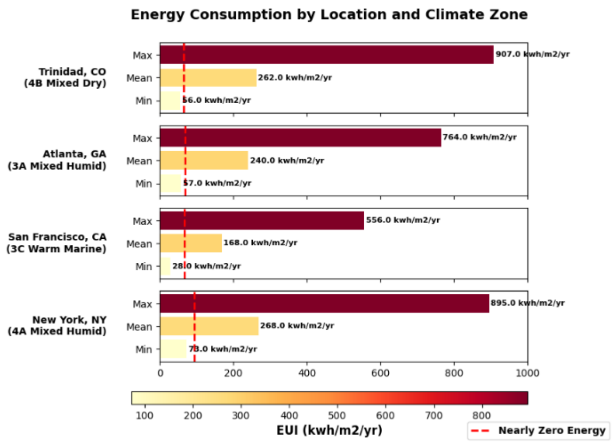


Figure 12. Comparing the building energy consumption results by location for the near ZEB scenario with the baseline results.

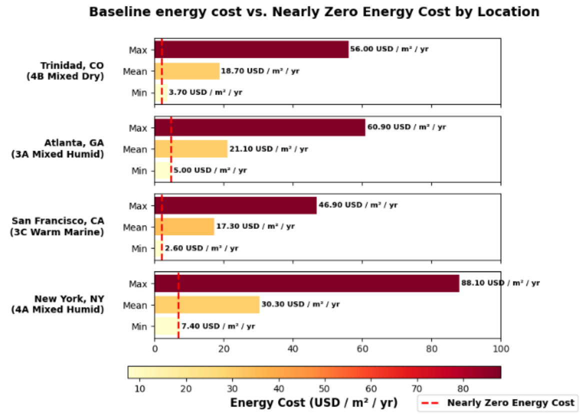


Figure 13. Comparing the building energy cost results by location for the near ZEB scenario with the baseline results.

The near ZEB results were compared with the baseline mean values to visualize the feasibility in energy and cost savings between the four locations as illustrated in Figure 14, and Figure 15.

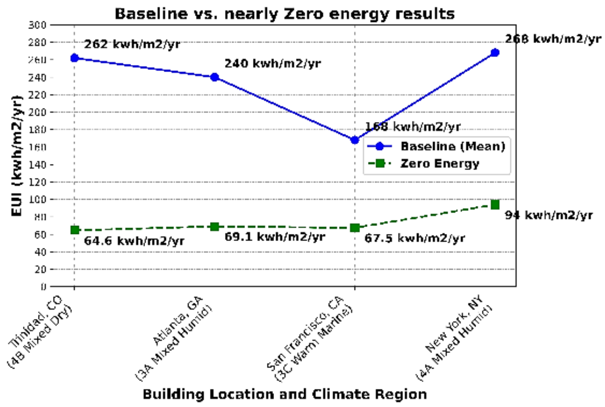


Figure 14. Comparing the near ZEB energy with the baseline Mean results.

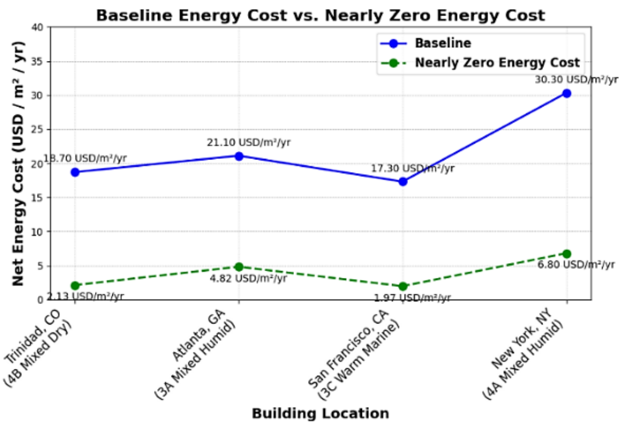


Figure 15. Comparing the near ZEB cost with the baseline Mean results.

Finally, the percentages of energy and cost savings were calculated and plotted in Figure 16 to find the best near ZEB locations. The model in Colorado recorded the best energy and best cost with (75.34%) and (88.61%). Georgia was the second-best location in energy savings (71.21%). However, the lower percentage of energy savings (59.83%) in San Francisco, CA, it recorded the highest cost saving percentage (88.61%) same as Colorado, due to the high local energy prices. New York was the 3rd in energy and cost saving percentages recording (64.93%) and (77.56%), respectively.

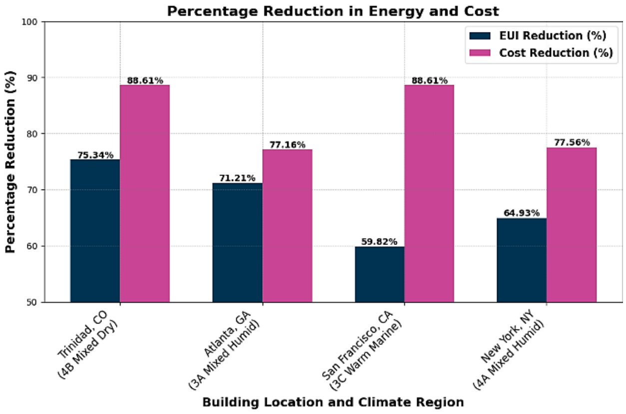


Figure 16. Comparing the percentages of reduction in energy and cost by location.

## 4 Discussion and Conclusion

This study assessed the influence of building location on operational performance by examining four distinct office building locations in different climate regions in United States including Colorado, Georgia, San Francisco (California), and New York. Retrofitting strategies were implemented to enhance operational efficiency and achieve the objectives of a near Zero Energy Building (ZEB). The baseline energy consumption of each location was first simulated, and subsequent performance outcomes were evaluated after applying various design alternatives. Building Information Modeling (BIM) was employed to simulate building geometry, while energy optimization tools generated energy analysis models. These models were further analyzed using an optimization platform. The evaluation adhered to the World Green Building Council's zero-energy building standards, assessing the feasibility of retrofitting, restoration, or reconstruction and the potential energy and cost savings across the four climate regions.

The study results revealed that the operation performance is highly sensitive to the building location. The model in Colorado recorded the best energy and cost savings (75.34%) and (88.61%), Respectively. Georgia was the second-best location in energy savings (71.21%). However, the lower percentage of energy savings (59.83%) in San Francisco, CA, it recorded the highest cost savings (88.61%) same as Colorado, due to the high local energy prices. New York was the 3rd in energy and cost savings (64.93%) and (77.56%), respectively.

The results are limited to the four climates included in this study and office buildings. Future work is highly recommended in other climates and for other building types. Future work will focus on validating the proposed method using real-world data to further assess its accuracy and performance. Also, simultaneously simulating a group of buildings may have additional impacts on overall building consumption. This paper contributes to the acceleration of ZEB targets and sustainable buildings by introducing an evaluation of the energy and cost savings for designers, stakeholders, and governments. This study contributes to the field by applying existing methods, such as BIM simulations and energy modeling, to specific climate regions, highlighting the importance of location-specific factors in optimizing energy efficiency. This approach offers valuable insights for real-world applications, demonstrating the potential for significant energy and cost savings based on regional conditions.

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