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Quantifying the Enhanced Performance of Multifamily Residential Passive House over Conventional Buildings in Terms of Energy Use

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Abstract: In response to escalating energy demands and global warming concerns, the Passive House Standard has emerged as a solution in residential construction, aiming to drastically reduce energy consumption and operational costs primarily through high-performance building envelopes. While a considerable volume of the literature has focused on the Passivhaus Institute (PHI) standards, predominantly in European contexts, there is a gap in research on the Passive House Institute US (Phius) standards, particularly in North American climates. This study conducts a quantitative comparative analysis of two adjacent multifamily residential buildings in Central Pennsylvania, Climate Zone 5A—one built using conventional construction methods and the other following Passive House (PHIUS+ 2015) certification standards—to validate the energy efficiency improvements attributed to Passive House designs. A comparative analysis of the whole building energy use over two years reveals that the Passive House building consumes approximately 50% less energy than its conventional counterpart in terms of whole building energy use and the national median recommended benchmark metric defined by the Energy Star Portfolio Manager. These findings emphasize the potential for significant energy savings and greenhouse gas reductions in residential buildings, highlighting the necessity for policymakers and governments to incentivize the adoption of Passive House standards to achieve environmental sustainability and reduce energy costs for society.

Keywords: Passive House Standards (Phius); multifamily residential buildings; high-performance buildings; low-energy buildings; building energy performance; post occupancy data

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1. Introduction

Climate change and its effects have been widely recognized as significant challenges facing society and global ecology. The primary approach to climate mitigation involves stabilizing greenhouse gas concentrations in the atmosphere to allow ecosystems to adapt naturally to climate change over time [1]. Robust evidence indicates that current energy infrastructure systems are the most significant contributors to global greenhouse emissions [1]. The building sector plays a big part in energy consumption in both developed and developing societies. The United Nations Environment Program (UNEP) [2] reported that 38% (13.1 gigatons) of global carbon dioxide (CO_2) emissions in 2015 resulted from the construction and operation of buildings, prompting 90 countries to take action in 2015 to reduce the emissions. The International Energy Agency (IEA) [3] claimed that by 2050, buildings will account for approximately 28% of total CO_2 emissions and a 30% reduction in total energy use, figures that are insufficient to meet the necessary greenhouse gas emissions abatements required to curb global warming effectively.

The economic implications of energy consumption in the context of climate change are significant. A study by Acaroğlu and Güllü (2022) investigates the relationship between climate change and energy consumption, emphasizing the cost savings and economic benefits of adopting energy-efficient standards like Passive House. This study highlights how renewable energy consumption can reduce temperatures and mitigate the adverse effects of climate change, thereby providing a compelling economic argument for the adoption of such standards [4].

The transformative and long-term decarbonizing progress in the building sector remains limited. IEA [3] indicated that while energy efficiency actions have reduced energy intensity (final energy use per m^2) by 0.5% to 1% per year since 2010, this rate lags behind the annual building floor area growth rate of 2%. Furthermore, 82% of the world population still lives in countries without current applied energy codes, which need to be transformed into energy-efficient building environments by 2030 [2]. Therefore, increased effort to implement actual energy-efficient measures in the building design and construction is imperative to make progress toward decarbonization targets.

The Passive House standard is among the world's leading concepts for designing and constructing energy-efficient buildings [5]. It offers a cost-efficient way to minimize the energy demand of buildings while improving the building occupants' comfort. This voluntary standard establishes a foundation for meeting buildings' energy needs with renewable sources, remaining within the bounds set by the limited availability of renewables and the affordability of additional costs [6].

The primary purpose of this study is to quantify the reduction in energy consumption achievable through implementing Passive House (PHIUS+ 2015) standards compared to conventional building standards. To achieve this, we employed a methodology focusing on the yearly energy performance of two multifamily residential buildings. One building follows the Passive House standards, while the other is built according to conventional code-compliant standards. This approach highlights the tangible benefits of Passive House principles in reducing energy consumption in comparable settings. Initial findings indicate significant energy savings and reduced operational costs for the Passive House building.

Literature Review

Over the past few years, there has been a growing emphasis on low-energy and near-zero-energy buildings. Within this context, the Passive House concept has come to the forefront as a highly viable solution for decreasing building energy consumption. By advocating for low-energy building technology, the Passive House standard plays a role in advancing toward these challenging environmental targets [7].

Over the past two decades, several studies related to Passive House Standards have been conducted. Most of these studies have focused on the following topics: (1) energy performance; (2) Passive House life cycle costing (LCC); (3) Indoor Environmental Quality (IEQ), Indoor Air Quality (IAQ), and thermal comfort in diverse climatic conditions; (4) embodied and operational energy and CO_2; (5) Life Cycle Assessment (LCA); (6) transforming to Net Zero Building (NZB) by applying renewable energy, especially PV panels; (7) retrofitting buildings to Passive House standards; (8) investigating the building materials performance in Passive Houses [5].

The formal Passive House design principles were first standardized by the Passivhaus Institute (PHI) in Germany for the mild climate of central Europe. However, North America's more diverse and extreme climate zones present multiple challenges for passive buildings. These challenges include overheating and inaccuracies in predicting cooling demand, primarily the cooling demands that stem from the indoor activities of the occupant. Achieving a specific low annual heating demand in Europe often meets peak load requirements. Therefore, the incremental cost of tighter building envelopes to achieve this performance is cost-competitive. However, directly applying the same PHI principles to the US market poses challenges due to the more diverse climate zones of the US, as construction practices and material availability in the US can make achieving the same level of envelope performance more expensive compared to Europe.

In an effort to adapt German Passive House standards to the diverse climate zones of the United States, the US Department of Energy (DOE) worked with Phius and other collaborators to introduce the cost-effective and climate-specific “PHIUS+ 2015 Passive Building Standard—North America” in March 2015. Phius establishes climate-specific space-conditioning energy targets and sets various airtightness requirements for different building sizes. Phius claims that Phius-certified Passive House buildings offer energy savings ranging from 40% to 60% compared to regular buildings [8]. According to PHI and previous research, Passive House buildings achieve space heating savings of approximately 80% and a primary energy reduction of more than 50% compared to regular new buildings [9].

In terms of energy performance, several comparative studies, mostly conducted in Europe, have explored various categories as follows:

(1) Assessing the feasibility of applying PH concepts in different climate zones across the globe to meet PH standards;
(2) Comparing PH buildings with structures built based on conventional, national, local, or other standards using software simulation or measured data;
(3) Comparing two similar buildings, one built based on conventional codes and one built according to PH standards; and
(4) Comparing the same building before and after conversion to PH using software simulation or measured data.

Table 1 provides a summary of some of the research topics investigated according to PHI standards outside North America.

Table 1. Summary of research papers investigating the energy performance of PHI buildings outside North America.

Index	Pub. Year	Location	Building Type	Climate	PHI or Phius	Description	Method Monitored vs. Simulation	Energy Performance
[10]	2022	Spain	Single-family	Mediterranean	PHI	Comparative analysis of Passive House and Spanish building regulations for nZEB achievement in Seville	Mix of simulation and calculation in THERM, Climate Consultant, CypeTherm, The CE3x tool	Heating, cooling, and total primary energy consumption are lower than PH standard limit.
[11]	2010	Austria	Two units from two Multifamilies	Temperate—Cold winter, hot summer	PHI	Comparing apartments in passive and low-energy residential blocks in terms of energy use, CO_2 emissions, indoor environmental conditions, and construction costs.	Monitored indoor environmental conditions, user evaluation, metered energy use/small number of interviews	Passive houses achieve 65% and 35% savings in heating and electrical energy, respectively, over low-energy apartments.
[6]	2006	Central Europe	Single-family and Multifamily	Temperate—Cold winter, hot summer	PHI	Energy use benchmarking against new conventional buildings	Monitored data measurement/Several social research studies like survey	Significant energy savings: 80% less space heating, less than 50% total primary energy compared to conventional buildings.
[12]	2017	UK	Single-family	Temperate maritime	PHI	Annual performance comparison of Conventional vs. Passive House	Monitored data measurement/validation by simulation using DesignBuilder	For the Passive House, 47% lower than the requirement set in the Passive House standard. For the Conventional House, 17.8% lower than the national average level. PH consumes 55% less primary energy than conventional one.
[13]	2020	China	Retrofitted Multifamily	Temperate—Cold winter, hot summer	PHI	DesignBuilder-driven study on retrofitting for Passivhaus efficiency with annual data validation	Monitored data measurement/simulation using DesignBuilder/field studies like interviews and survey	It was found that the energy consumption of the building reduced by 96% for heating and 8.7% for cooling; totally reduced by 78.9% for a calendar year.
[14]	2021	Chile	Single-family	Varied (from hot and arid to glaciered)	PHI	Passivhaus standard adaptation across eight climates using Chilean single-family home model	Simulation using the energy performance by PHPP version 9.6a.	The country's average heating saving is 93% after incorporating PH into housing. The percentage of Primary energy use reduction ranges from 14% to 57% (32% country average and 57% in the south of the country).
[15]	2020	Germany	School and Office	Temperate—Cold winter, hot summer	PHI	School and office energy use evaluated against PHPP estimates with climate corrections (2002–2014)	Comparison of monitored data with PHPP calculations for each building (School: thermal indoor air quality and user survey)	Both school and office as expected, aligned with PHPP. Despite changes in usage patterns and intensity, both buildings maintained high performance in terms of energy efficiency and user comfort.
[16]	2005	Central Europe	Residential-variety	Temperate—Cold winter, hot summer	PHI	CEPHEUS project energy consumption compared to standard new buildings	Comparison of the measured, TFA-weighted energy consumption of all CEPHEUS projects with the ordinary, new buildings as a reference/Social science surveys.	Savings of more than 50% of the total primary energy consumption, i.e., for heating, DHW, ventilation and all electric appliances in 100+ dwelling units in five European countries. Space heat consumption was reduced by 80%.
[17]	2020	UK	Residential variety (Flat and house)	Temperate maritime	PHI	Comparative study of expected vs. actual heating energy in UK Passivhaus homes, using diverse data sources	Comparison of measured data with target number computed from the prediction on the PHPP certificates, as well as the Passivhaus maximum of 15 kWh/m^{2}a.	Of the 97 homes in our data set, 52 used less energy for annual space heating than predicted. Passivhaus design can limit the impacts of occupant behavior on performance gap.

Table 1. *Cont.*

Index	Pub. Year	Location	Building Type	Climate	PHI or Phius	Description	Method Monitored vs. Simulation	Energy Performance
[18]	2020	Indonesia	Single-family	Tropical	PHI	Simulation of a house for Passivhaus standard impact on energy and indoor comfort, validated by real-world data	Comparison of simulation result with field monitored data/the dynamic simulation software	Annual cooling energy of 11.41 MWh for the original building model, 10.89 MWh for the house with applied Passivhaus model, and 8.61 MWh for the Passivhaus building model without floor insulation.
[19]	2020	South Korea	Single-family	Hot, humid summer, cold, dry winter	PHI	Evaluating KPH efficiency and promotion through policy analysis, design case studies, and energy simulations	Using a simulation tool, Energy# v2.3 rather than PHPP software. Energy# is the official building simulation software of the PHIKO and the Korea Land and Housing Corporation (LH).	Total primary energy consumption of 182 kWh/m^{2}a for the KPH prototype compared to 336 kWh/m^{2}a for the conventional house. An 80% reduction in heating demand for the KPH.
[20]	2019	Brazil	Single-family social housing	Humid subtropical	PHI	Four-step study using EnergyPlus® for thermal performance and optimization to meet RTQ-R A level and Passive House standards	Using the EnergyPlus a multi-objective algorithm/optimization of the numerical model according to the RTQ-R.	Solution 1: 53% reduction in total energy demand for bioclimatic BZ1, 44% for bioclimatic zone BZ2, and for bioclimatic zone BZ3. A total of 20% higher energy demand in comparison with the base case. Solution 2: 88% reduction for bioclimatic zone BZ1, 56% for bioclimatic zone BZ2, and 64% for bioclimatic zone BZ3.
[21]	2021	Brazil	Three single-families	Humid subtropical	PHI	Methodology for evaluating energy performance of Brazilian single-family dwellings using RTQ-R standards and Passive House optimization with EnergyPlus	Using the EnergyPlus a multi-objective algorithm/optimization of the numerical model according to the RTQ-R.	For PH, a reduction in energy demand of 83.5%, 56.3%, and 55.1%, and a reduction in thermal discomfort, on an annual comfort basis established between 20 and 26 C, from 83.5%, 73.7%, and 86.2% for buildings located in Bioclimatic Zones BZ1, BZ2, and BZ3, respectively.
[22]	2017	Romania.	Single-family duplex	Temperate-Cold winter, hot summer	PHI	EnergyPlus simulation of a Bucharest passive house's energy demand, validated by actual 2014–2015 consumption data	Comparison of simulation results using EnergyPlus with actual data measurement.	The simulated energy demand for heating of 14.1 kWh/m^{2}a, and the actual energy consumption of 13.12 kWh/m^{2}a.
[23]	2016	Portugal	Single-family two-story	Mediterranean	PHI	Optimization of Passive House standards for Portugal, focusing on energy performance and overheating, using dynamic simulation.	Detached house simulation with EnergyPlus, incorporating patented designs, thermo-hygrometric data collection, multi-objective optimization, and THERM for thermal bridging in opaque elements	Significant reductions in heating (up to 42%) and cooling demands (64%) in optimized scenarios, particularly with triple glazing, enhanced insulation, and strategic building orientation.
[24]	2022	Denmark	Multifamily (renovation)	Temperate maritime	PHI	Energy savings evaluation in a PH-standard renovated block versus unrenovated, from 2014 to 2016	Comparison of monitored data in two different blocks of flats, one renovated vs. one non-renovated	Total primary energy demand of 102.2 kWh/m^2 and the Passivhaus requirement of 120 kWh/m^2 per year, therefore, reaching the renovation goal. Energy consumption for heating of 21.7 kWh/m^2 per year and the Passivhaus requirement of 15 kWh/m^2 per year, not fulfilling the requirement. heating energy consumption has been reduced by more than 50%.

Table 1. *Cont.*

Index	Pub. Year	Location	Building Type	Climate	PHI or Phius	Description	Method Monitored vs. Simulation	Energy Performance
[5]	2016	Cyprus	Single-family two-story	Subtropical	PHI	Passive House performance tracking: temperature, humidity, energy use	Monitored data, and comparing the results with PHPP requirement and limitation.	Annual heating requirements limited to 5 kWh/m^2 and compliance with the cooling requirements of the Passive House regulations.
[25]	2013	UK	Single-family	Temperate maritime	PHI	Monitoring system validates Passive House performance against PHPP targets	Monitored data, and comparing the results with PHPP requirement and limitation.	Annual space heating demand of 12.1 kWh/m^2, meeting the 15 kWh/m^2 Passive House target. The annual primary energy demand is 125 kWh/m^2, slightly above the 120 kWh/m^2 target. The total metered energy consumption65 kWh/m^2, one of the lowest energy small family dwellings monitored in the UK
[26]	2020	Poland	Single-family	Temperate—Cold winter, hot summer	PHI	Long-term energy assessment of a prefab passive house for 2011–2019, with a detailed 2012 device-use analysis.	Long-term experimental measurements to collect detailed results on energy use, especially for active systems like heating and mechanical ventilation	Energy consumption for heating is 50% lower than the requirement for passive buildings. Primary energy consumption exceeded the standard in the second year. Total annual electricity consumption of the heat1 pump is 2156.8 kWh, with a heating energy consumption of 7.5 kWh·m, in compliance with PH requirements.
[27]	2023	Tropical regions	Residential-affordable	Tropical	PHI	Adapting Passive House principles for thermal efficiency and CO_2 reduction in tropical regions	A theoretical approach, including qualitative comparative content analysis	No quantitative data
[28]	2014	UK	Two detached residential houses	Temperate maritime	PHI	Two-year energy and thermal performance comparison of two Welsh passive houses with different CSH certification levels	24 months of monitored data, comparing two adjacent Passivhaus, while one is also low carbon.	Dwelling 1 has an average space heating demand of 9.3 kWh/m^2 and a primary energy consumption of 158 kWh/m^2. Dwelling 2 space heating demand of 25.6 kWh/m^2 and primary energy consumption of 189 kWh/m^2. Dwelling 1 performed better in terms of energy efficiency.
[29]	2016	Portugal	Detached two-story light steel frame residential building	Mediterranean	PHI	Adapting a steel frame building to Passive House specs in Portugal, with emphasis on insulation, glazing, and shading impacts	Dynamic simulation using EnergyPlus software.	Significant reductions in heating and cooling demands in the adapted models; heating demand was reduced by 62%, Cooling demand was reduced by 72%, Primary energy demand was reduced by 30%.
[30]	2016	Romania	A semi-detached residential house	Temperate—Cold winter, hot summer	PHI	Energy efficiency comparison of Passive House vs. Romanian standard house	Both simulations and real-time monitoring data/PHPP and Romanian DOSET PEC software.	Significant reduction in heating energy demand and overall energy consumption; meeting PH design target of total primary energy requirement of less than 120 kWh/m^2 year.
[31]	2022	Algeria	Single-story family house.	Hot and arid	PHI	Parametric simulation of a regional single-story house using PH strategies with IES-VE, factoring in climate and design specifics.	Simulation using IES-VE software, based on a typical Algerian residential building's design and data from secondary sources.	Significant reductions in heating demand (up to 88% in one case) and moderate reductions in cooling demand (around 31%).

A review of scholarly papers in this area reveals that a majority of research follows PHI standards in Europe or locations other than the United States. The Phius website provides resources such as software simulations and energy predictions in a database of certified Passive House projects [32]. However, there is a gap in the academic literature published in North America that uses post-occupancy monitored data to validate the reduction in whole-building energy use in Passive House, especially in line with the climate-specific PHIUS+ standards. Studies conducted in the United States before 2015, predating the development of Phius, also adhere to PHI standards. Table 2 provides a summary of selected North American studies based on PHI standards before the introduction of PHIUS+ standards.

According to Phius, Passive House buildings must adhere to the following key principles:

- Continuous insulation is used throughout the building envelope to minimize heat loss and gain by reducing or eliminating thermal bridging.
- The design and construction of the building envelope are detail-oriented and extremely airtight to prevent outside air infiltration and conditioned air loss, thereby enhancing the durability and lifespan of the envelope.
- High-performance windows (double or triple-paned) and doors are used to take advantage of solar gain during the heating season and to prevent overheating during the cooling season.
- Balanced heat and moisture recovery ventilation systems are incorporated as they are necessary to significantly improve indoor air quality.
- The space conditioning system is downsized due to the reduced demand for space conditioning.

Table 2. Summary of research papers investigating the energy performance of PHI buildings in North America.

Index	Pub. Year	Location	Building Type	Climate	PHI or Phius	Description	Method Monitored vs. Simulation	Energy Performance
[33]	2012	Sonoma, CA	One-story single-family	Marine	PHI	Employing system commissioning, short-term tests, long-term monitoring, and detailed analysis to identify the performance attributes and cost-effectiveness of whole-house measures for retrofit standards. Monitoring a house for a full year compares whole-house energy usage from simulations to monitored performance to assess the applicability of individual measures to Building America retrofit standards.	Comparison of monitored data with simulation results using BEopt v1.1.	The measured energy use of the Sonoma House matches reasonably well with expectations from BEopt modeling and confirms that the project has attained its energy savings goals. Savings over the pre-retrofit case, estimated from BEopt, are 56% of total source energy.
[34]	2015	Las Vegas, NV	Two-story single-family	Cool dry	PHI	Demonstrating through hygro-thermal dynamic simulation, this paper explores the feasibility of realizing residential Passive Houses across various global climates, including Yekaterinburg, Tokyo, Shanghai, Las Vegas, Abu Dhabi, and Singapore.	Utilization of the DYNBIL hygrothermal simulation program developed at the Passive House Institute, validated under German climatic conditions, alongside PHPP for calculating heating demand post-Passive House standards adoption.	The resulting annual energy demand for space conditioning of the Passive Houses is 75 to 95% lower than that of a traditionally insulated building of the same geometry.
[35]	2013	Urbana, IL	Two-story single-family	Cool humid	PHI	Reassessing a certified passive house, this study employs both steady-state and dynamic building simulations to analyze thermal and hygric performance thoroughly. By utilizing both simulation methods, it provides a comprehensive understanding of the building's performance and its components.	Combination of steady-state and dynamic simulation methodologies using WUFI Passive tool, incorporating overall heat transfer coefficients, temperature differences, and dynamic hygrothermal simulation for each building component.	The steady-state method shows a heating demand of approximately 15 kWh/m^{2}yr, while the dynamic method predicts a slightly higher demand. The steady-state method estimates the cooling demand to be minimal, while the dynamic simulation predicts a slightly higher but still very low demand, indicative of the high efficiency of passive houses in maintaining comfortable indoor temperatures.
[36]	2013	US	Two-story single-family	All US climates	PHI	Conducting a comprehensive simulation analysis, this study examines the Passive House Standard's applicability across different U.S. climates. Using a full factorial experiment method, it explores how various building components and climatic conditions interact to meet Passive House criteria.	Application of PHPP across 1000+ climate data locations, comprising a full factorial experiment to analyze variables' impact on Passive House Standard compliance.	While it is technically possible to meet the PH Standard in more than 99% of the climates studied, economic viability is a limiting factor. Advancements, especially in window glazing and frames, could significantly improve the feasibility of meeting PH criteria even in extreme climates.

Although Phius claims that as of February 2024, a cumulative total of over 300 new construction projects have received Phius certification, and more than 800 have an in-progress certification, only a small number of publicly accessible journal articles compare the energy performance of PH with conventional buildings in the US. Iqbal and Manzoor (2020) used dynamic simulations with EnergyPlus and WUFI to examine Newfoundland's inaugural house under PHIUS+ 2015 standards. Their study unveiled substantial energy savings, notably a 15 kWh/m^{2}yr reduction in heating demand, despite a 12% higher construction cost compared to conventional structures [37]. The Glasswood Commercial Passive House Retrofit study exemplified the effectiveness of Passive House (PHIUS+) standards in bolstering energy efficiency and thermal comfort in commercial buildings, achieving an 80% reduction in energy consumption for heating and cooling through advanced insulation, airtight sealing, efficient windows, and an 88% efficient HRV [38]. Klingenberg et al. (2016) investigated the development of climate-specific passive building standards by Phius for North America, employing BEopt software to model a single-family home across diverse climates. Their findings underscore the importance of tailoring energy-efficient measures to achieve zero energy and carbon neutrality in varied climatic conditions, advocating for region-specific approaches to enhance sustainable building practices [39]. White (2019) focused on refining PHIUS+ standards to align with the diverse climate needs across North America, emphasizing the necessity of sustainable, energy-efficient building practices. By utilizing life-cycle cost optimization via BEopt software, this study facilitated the development of climate-specific, cost-effective heating and cooling criteria and set new benchmarks for energy efficiency and sustainability in construction [40]. Using the LeBois House as a case study, Saft [41] assessed the viability of Passive House standards in the hot and humid climate of Lafayette, Louisiana. Through detailed monitoring of temperature, humidity, and energy consumption over 18 months, this study showed that primary energy use exceeded PHPP predictions by 50%, primarily due to unanticipated dehumidification needs. This underscores the challenge of managing latent loads in such climates and advocates for adapting Passive House standards to ensure thermal comfort and energy efficiency [41]. The Casa Pasiva project, a retrofit of nine buildings in Bushwick, New York, employs PHIUS+ 2015 standards to achieve energy efficiency improvements. Targeting an air sealing metric of 0.08 CFM50/ft^2 of the envelope, the project integrates European-style windows with a liquid-applied air barrier on the existing brick façade for enhanced insulation. The retrofit resulted in a 50% reduction in energy use, as evidenced by Year-1 data showing minimal reliance on heating or cooling systems due to the improved building envelope's capability to maintain comfortable interior conditions regardless of external temperatures [42].

Based on this literature review, the majority of studies conducted in the US under Phius standards focus on assessing the viability of Passive House in diverse climate zones of North America without considering post-occupancy energy performance. Furthermore, while there is considerable research on low energy use in the US, it often lacks specificity to Passive House standards (PHIUS+).

To address the identified gaps in the literature and validate the claims of PHIUS+, this paper investigates two structures with the same orientation and conditions. Specifically, it aims to determine the percentage reduction in monthly and yearly energy use of Passive House compared to conventional building. To validate the claims of Phius, this paper uses post-occupancy energy use as a factor to compare the energy performance of Passive House with conventional buildings.

2. Methods

To bridge the gap identified in the literature, this study compares two structures with identical orientations and conditions. The primary objective is to quantify the reduction in energy consumption achieved through the implementation of Passive House (PHIUS+ 2015) standards compared to conventional building standards. Unlike most previous research that relies on simulations, this study adopts a more nuanced approach employing monitored data, which allows us to capture the intricacies of real-world scenarios. To achieve this, a comprehensive methodology focusing on the yearly energy performance of both buildings is employed. One structure follows the Passive House standard PHIUS+ 2015, while the other is built according to conventional code-compliant envelope standards. This approach discerns the tangible benefits of Passive House principles in reducing energy consumption within comparable settings. In the following sections, we delineate our methodology, including the details of the key parameters, data collection methods, and analytical techniques utilized in this comparative study.

2.1. Buildings Description

We studied two adjacent multifamily affordable senior housing rental buildings with similar layouts and solar orientations (Figure 1). The buildings, located in Central Pennsylvania in ASHRAE climate zone 5A (cool and humid), are spaced about 6 m apart and have an occupancy rate of one or two residents per unit. One building, completed in 2010, was built using conventional construction codes (Figure 2). It is a three-story building with a gross area of 27.90 m^2, hosting 36 residential units comprising one-bedroom and two-bedroom apartments. Natural gas and electricity are the energy sources for this building.

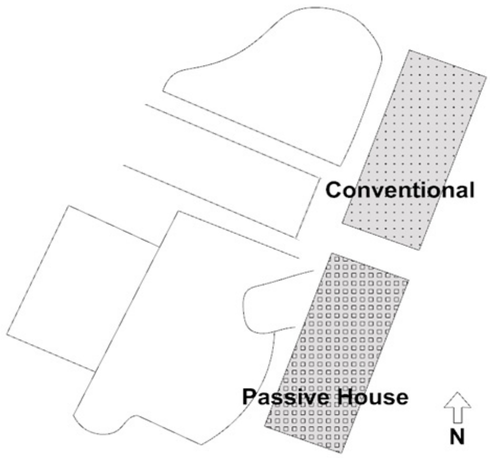

Figure 1. Diagrammatic site plan of conventional and Passive House buildings used in the case study.

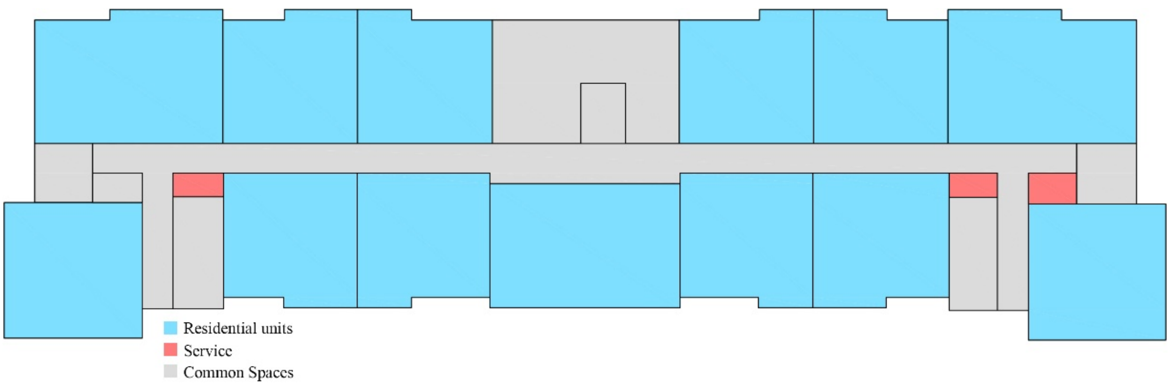

Figure 2. Schematic floor plan of the conventional building.

The second building, completed in 2018 (Figure 3), has four stories with a gross area of 4982 m^2, including 48 one-bedroom and two-bedroom residential units, and follows Passive House standards (PHIUS+ 2015). Electricity is the only energy source for this building.

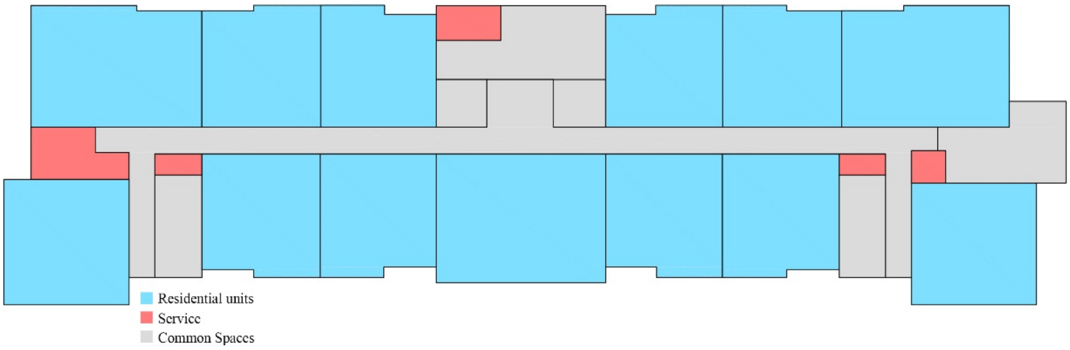

Figure 3. Schematic floor plan of the Passive House building.

2.2. HVAC (Heating, Ventilation, and Air Conditioning) System Description

In the conventional building, common spaces and residential units are equipped with split systems. Each residential unit has an outdoor air conditioning unit located on the roof and an indoor air handler unit. Each residential unit in the Passive House utilizes an electricity-based variable refrigerant flow (VRF) system for its heating and cooling. There are a total of five heat recovery ventilation (HRV) systems in a mechanical room located on the first floor. Three HRVs—one per floor—are connected to the VRFs in each unit, while two HRVs are connected to the VRFs servicing the entire first floor, such as a community room, building manager offices, corridors, and a kitchen on the first floor. One heat pump, sized at 5.3 kW, provides refrigerant to the VRFs for cooling, and electric heaters in the VRFs are used for heating. Additionally, four energy recovery ventilation (ERV) units and four ERV electric duct heaters are located in the mechanical room, with one on each floor. They are connected to the ventilation of units and common spaces, including corridors. In both buildings, each dwelling unit has a utility closet accessible from the circulation corridor. Figure 4 shows a schematic floor plan of a one-bedroom unit in each building.

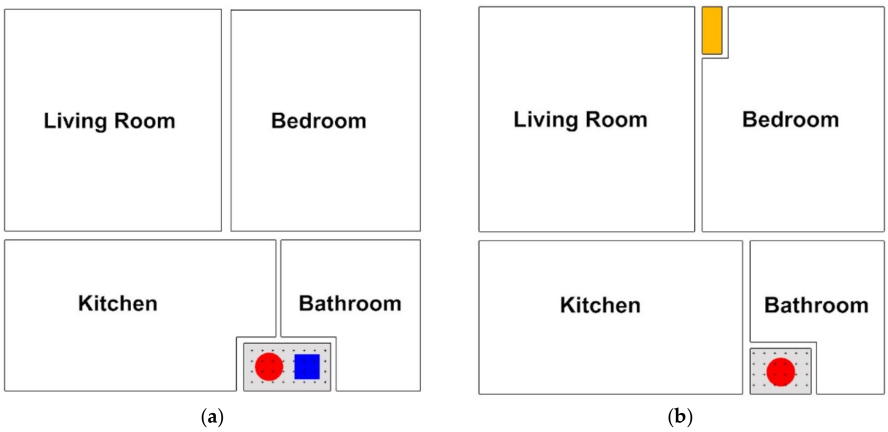

Figure 4. Schematic typical floor plan of a one-bedroom unit: (**a**) conventional building: Each unit has one closet accommodating a natural gas hot water heater with an integral storage tank (red circle) and an electric air handler (blue square); (**b**) Passive House: Each unit has one closet accommodating an electric heat-pump hot water heater with an integral storage tank (red circle). The air handling unit (AHU) for each unit is located behind a wall and accessed by a panel located in the bedroom (yellow rectangle).

2.3. Building Codes and Standards Criteria

The conventional building follows the IECC 2009 building code, which was the adopted code by the state of Pennsylvania at the time of project completion. The Passive House follows the PHIUS+ 2015 standards. Table 3 compares the requirements of each standard, highlighting the distinct criteria and performance metrics set by the IECC 2009 and PHIUS+ 2015.

Table 3. Comparison of IECC 2009 and PHIUS+ 2015 Standards for Residential Buildings in Climate Zone 5A.

Factor	IECC 2009	PHIUS+ 2015
Insulation	Walls: R-20 or R-13+5	Walls: >R-40
	Roof: R-30 to R-38	Roof: >R-60
	Floor: R-30	Floor: R-20 to R-40
Airtightness	Encouraged improvements, no specific target	Very stringent, 0.6 ACH50 or 0.06 CFM50/sqft of envelope area
Windows	<U-0.35	<U-0.14
	SHGC $\leq$ 0.40	Optimized SHGC values
Mechanical Systems	Minimum efficiency standards for HVAC	Ultra-efficient HVAC, including HRV or ERV systems
Overall Energy Use	Improvement over previous codes, no specific targets	Specific maximums for EUI, heating/cooling demand, and primary energy demand
Renewable Energy Integration	Encouraged but not required	Strongly encouraged, aiming for net-zero or net-positive energy buildings

2.4. Buildings' Monthly Operational Energy Performance

To monitor the energy use of the two case study buildings, monthly utility bills were collected for two years, 2019 and 2020. Since utility bills provide energy use data for the whole building, the comparison is based on whole-building energy use. Due to the differences in the layout and occupancy of the two buildings, energy use per square meter and energy use per square meter per person are calculated to compare the energy use of the two buildings relative to one another.

Equations (1) and (2) demonstrate how energy use per square meter and energy use per square meter per person are calculated for the conventional building.

$$\text{Energy Use}\left(\frac{\text{kWh}}{\text{m}^2}\right) = \frac{\text{monthly electricity usage(kWh)} + \text{monthly natural gas usage(kWh)}}{\text{occupied area}(\text{m}^2)} \quad (1)$$

$$\text{Energy Use}\left(\frac{\text{kWh}}{\text{m}^2}/\text{person}\right) = \frac{\text{monthly electricity usage(kWh)} + \text{monthly natural gas usage(kWh)}}{\text{occupied area}(\text{m}^2) \times \text{monthly number of occupants}} \quad (2)$$

Equations (3) and (4) demonstrate how energy use per square meter and energy use per square meter per person are calculated for the Passive House building.

$$\text{Energy Use}\left(\frac{\text{kWh}}{\text{m}^2}\right) = \frac{\text{monthly electricity usage(kWh)}}{\text{occupied area}(\text{m}^2)} \quad (3)$$

$$\text{Energy Use}\left(\frac{\text{kWh}}{\text{m}^2}/\text{person}\right) = \frac{\text{monthly electricity usage(kWh)}}{\text{occupied area}(\text{m}^2) \times \text{monthly number of occupants}} \quad (4)$$

Other considerations include:

- For each building, the area of unoccupied spaces is calculated and subtracted from the gross area.
- The conventional building uses both natural gas and electricity, while the Passive House building uses only electricity. The electricity usage in the bills is reported in kWh, and the natural gas usage reported in utility bills is shown in Ccf (100 cubic feet of natural gas). To make the values directly comparable, the natural gas data are converted from Ccf to kWh for calculations.
- For both buildings, the data for the monthly occupancy rate are applied. Each unit houses one or two residents. Table 4 shows the monthly occupancy rate for each building.

- The records of the number of occupants in each building for each month over the two-year period were provided by the community manager and the operational manager.

Table 4. The occupancy percentage for both buildings in each month for the years 2019 and 2020.

Year	Occupancy (%)	Month (Year 2019)											
		J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.
2019	Conventional building	97	91	88	91	97	97	97	97	97	97	97	100
	Passive House	75	73	77	83	90	92	90	100	96	96	96	96
2020	Conventional building	97	97	97	97	97	97	97	100	100	97	97	94
	Passive House	95	91	91	91	91	95	93	93	93	95	100	93

2.5. Benchmarking for Building Energy Use

Benchmarking comprises a set of activities aimed at helping building stakeholders understand the energy consumption characteristics of a building. It also helps them compare the energy use of similarly sized buildings that serve similar functions (e.g., residential, commercial office, etc.). Additionally, benchmarking methods help municipalities establish targets for improving building performance [43]. Energy Use Intensity (EUI) serves as one metric used in the US Environmental Protection Agency's (EPA) energy benchmarking tool, "ENERGY STAR Portfolio Manager". EUI, defined as "energy per square meter per year", is calculated by "dividing the total energy consumed by a building in one year by the total gross floor area of the building" [44,45].

The Portfolio Manager provides both site and source EUI benchmark references for different property types. Site energy can be delivered in the form of primary energy, encompassing losses in fuel distribution, storage, and dispensing, or secondary energy, involving conversion losses in the utility plant and primary energy losses. Site energy represents the energy consumed by the building as recorded on utility bills. Table 5 compares the site energy of both buildings in 2019 and 2020 based on utility bill data.

Table 5. The Site Energy Use Intensity (EUI) comparison of conventional and Passive House buildings for 2019 and 2020.

Year	Building	EUI (kWh/m^{2}yr)		
		Natural Gas	Electricity	Site Energy
2019	Conventional building	96.54	96.54	193.08
	Passive House	-	100.00	100.00
2020	Conventional building	97.80	102.41	200.21
	Passive House	-	96.11	96.11

Source energy considers all energy requirements back to the primary fuel for the energy source and includes losses for enabling thermodynamic assessment. According to EPA standards, source energy is recommended for evaluation as it accounts for all energy generation, transmission, and distribution losses. Also, source energy is considered a complete primary energy assessment of the energy efficiency of the building and a path to determining total primary energy utilization as well as global warming emissions associated with building operations. The EPA recommends considering national average ratios for conversion to source energy since they reflect the median energy use for most properties. These ratios are typically revised on a five-year average basis. The last revision, released in 2020, calculated the average ratios for the years 2012 to 2016. According to this report, the average source-site ratio for grid electricity is 2.80, and for natural gas, it is 1.05 [46].

Based on the 2020 revision, Equations (5)–(7) demonstrate how Site EUI is calculated for the conventional building.

$$\text{Source EUI} = (\text{Site EUI for electricity} \times 2.80) + (\text{Site EUI for natural gas} \times 1.05) \quad (5)$$

$$\text{for 2019 : Source EUI} = (96.54 \times 2.80) + (96.54 \times 1.05) = 371.68 \frac{\text{kWh}}{\text{m}^2\text{yr}} \quad (6)$$

$$\text{for 2020 : Source EUI} = (102.41 \times 2.80) + 97.80 \times 1.05) = 389.43\ \text{kWh}/\text{m}^2\text{yr} \quad (7)$$

Equations (8)–(10) demonstrate how Site EUI is calculated for the Passive House building.

$$\text{Source EUI} = (\text{Site EUI for electricity} \times 2.80) \quad (8)$$

$$\text{for 2019 : Source EUI} = 100.00 \times 2.80 = 280.00 \frac{\text{kWh}}{\text{m}^2\text{yr}} \quad (9)$$

$$\text{for 2020 : Source EUI} = 96.11 \times 2.80 = 269.10 \frac{\text{kWh}}{\text{m}^2\text{yr}} \quad (10)$$

The national median EUI is recommended as a benchmark for measuring building energy performance across all buildings. The median values represent the line that separates the top and bottom half of the buildings nationally in terms of energy use. For energy performance comparison, the EPA [46] recommends using the median instead of the average since it represents an accurate midpoint for energy use in most property types. The national median is typically based on Commercial Building Energy Consumption Survey (CBECS) data, with only five exclusions: data centers, hospitals, multifamily, senior living communities, and wastewater treatment plants—where the national median is calculated based on survey data [47].

The buildings in this case study fall under the broad category of "residential" as their and "Senior Living Community" based on their primary function. Although the rental units are independent living units, the buildings are part of a complex defined in the Energy Star Portfolio Managers as "Buildings that house and provide care and assistance for elderly residents, specifically homes (skilled nursing facilities) and assisted living facilities" [45]. Table 6 compares the source and site EUI of the two buildings with the senior living community category in the ENERGY STAR Portfolio Manager. Table 3 compares the EUI of the Passive House and the conventional building with the Senior Living Community benchmark in terms of both source and site energy. While both buildings consume less energy than the national median, the Passive House shows significantly better energy performance in both the site and source EUI.

Table 6. Comparison of EUI of a senior living community in ENERGY STAR Portfolio Manager with the buildings in the case study in 2019 and 2020.

Year		Source Energy EUI (kWh/m^{2}yr)	Site Energy EUI (kWh/m^{2}yr)
	Senior Living Community (Portfolio Manager)	672.40	312.20
2019	Conventional building	371.68	193.08
	Passive House	280.00	100.00
2020	Conventional building	389.43	200.21
	Passive House	269.10	96.11

3. Results

The energy use of both buildings is calculated using the utility bill data. Figures 5 and 6 compare the energy use of the Passive House building and the conventional building in 2019 and 2020. Figures 7 and 8 provide a comparison of energy use per person of the two buildings in 2019 and 2020.

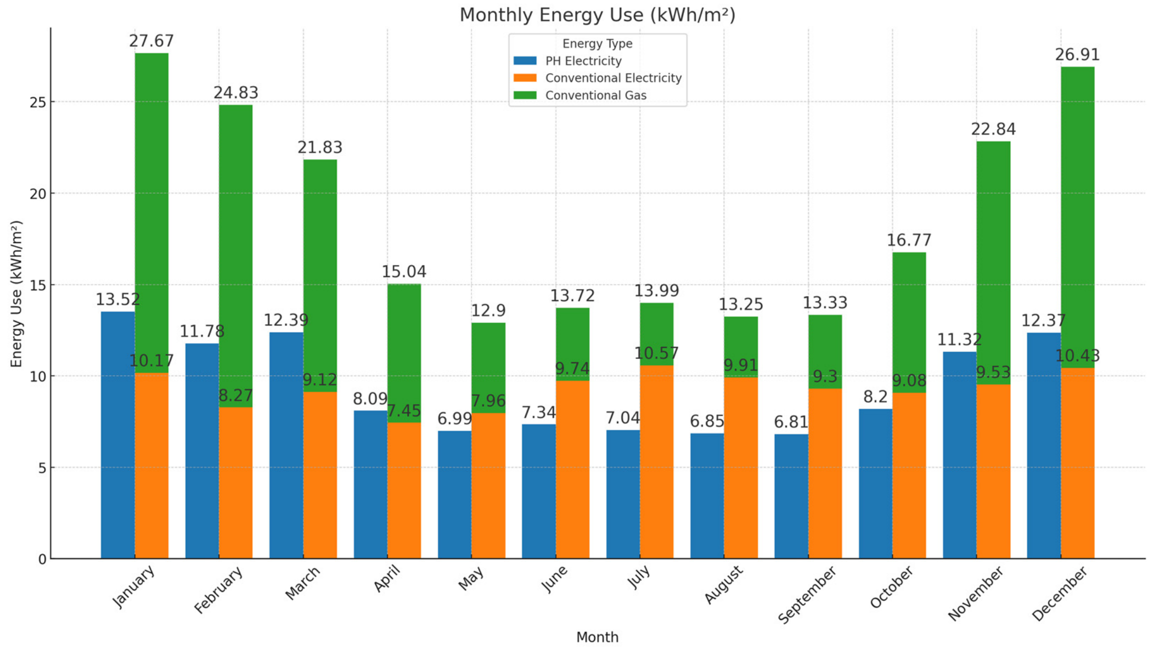

Figure 5. Comparison of whole-building monthly electricity and natural gas usage (kWh) of the Passive House and the conventional building per m^2 in 2019.

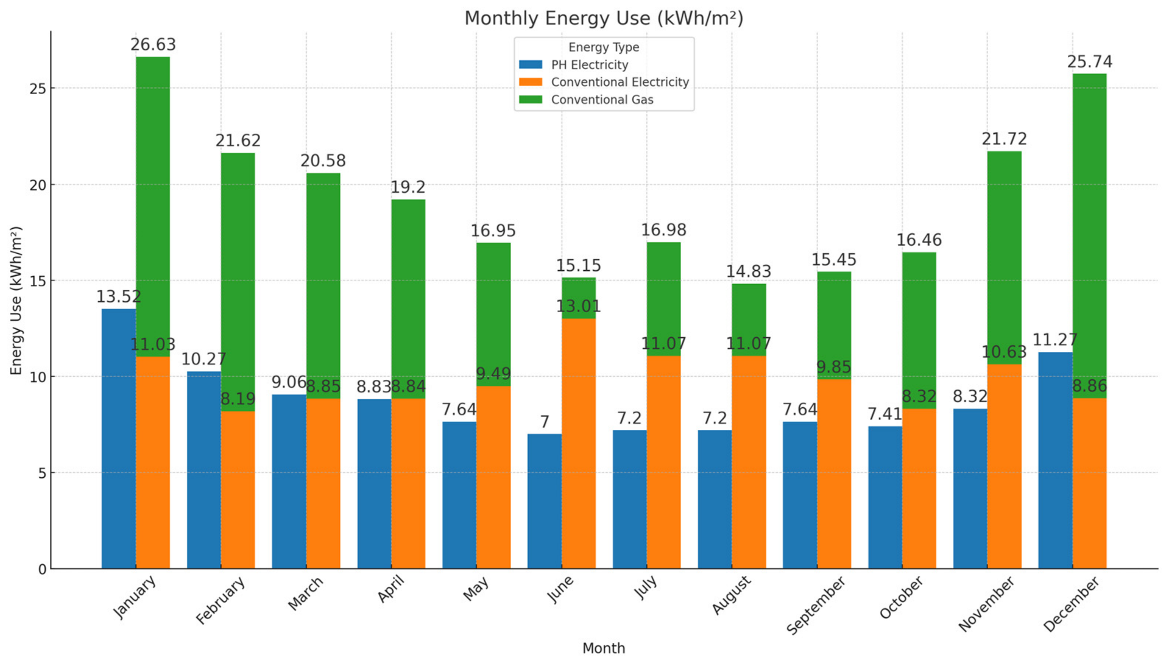

Figure 6. Comparison of whole-building monthly electricity and natural gas usage (kWh) of the Passive House and the conventional building per m^2 in 2020.

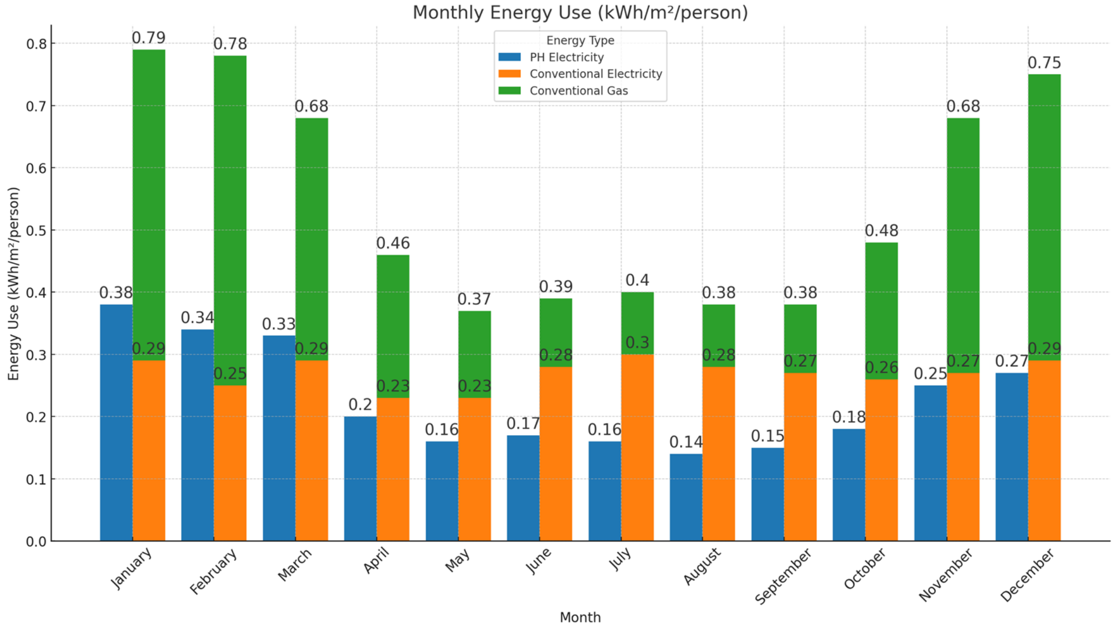

Figure 7. Comparison of whole-building monthly electricity and natural gas usage (kWh) of the Passive House and the conventional building per m^2 per person in 2019.

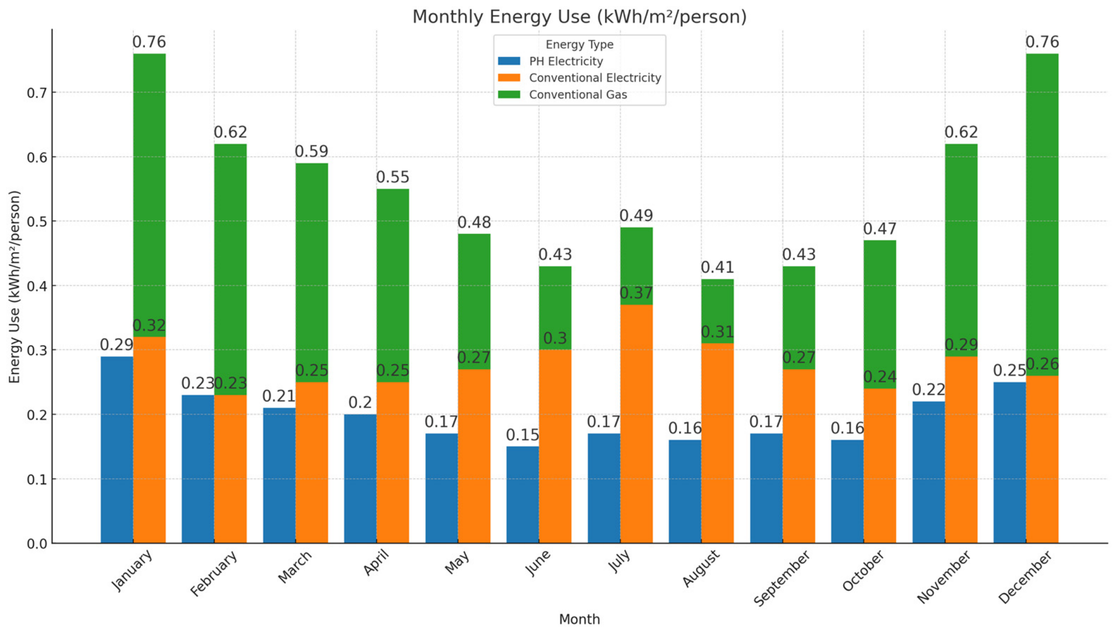

Figure 8. Comparison of whole-building monthly electricity and natural gas usage (kWh) of the Passive House and the conventional building per m^2 per person in 2020.

In both 2019 and 2020, the Passive House consistently showed a lower energy consumption profile throughout the year compared to the conventional building. Data observations show that the Passive House maintains a relatively flat energy use pattern across all seasons. On the other hand, the conventional building demonstrated variability, with peaks during the winter months. Overall, in both years, the Passive House used approximately 50% less energy compared to the conventional building. Further analysis using occupancy data reveals an even larger performance gap between the Passive House and the conventional building.

To investigate the climate dependency of the buildings, energy performance is compared in Figures 9 and 10, illustrating the energy performance trends of each building in relation to temperature fluctuations for 2019 and 2020 in Philipsburg, PA. The energy use curves of both buildings exhibit a similar general trend, with energy consumption increasing during the colder months. However, the Passive House demonstrates lower fluctuations in energy use compared to the conventional building, even with changing temperatures throughout the year. This suggests that the overall lower energy use in the Passive House is not entirely due to reduced heating demand. Even during the summer months, when heating demand is minimal, the Passive House maintains a lower level of energy consumption.

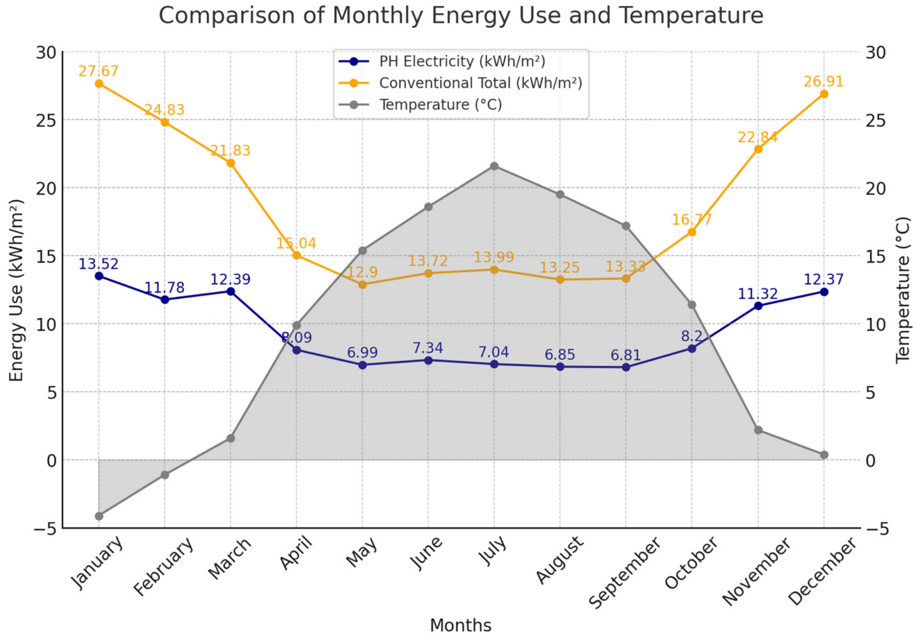

Figure 9. Comparison of average monthly outdoor temperature (°C) and whole-building monthly energy use (kWh) of the Passive House and the conventional building per m^2 in 2019.

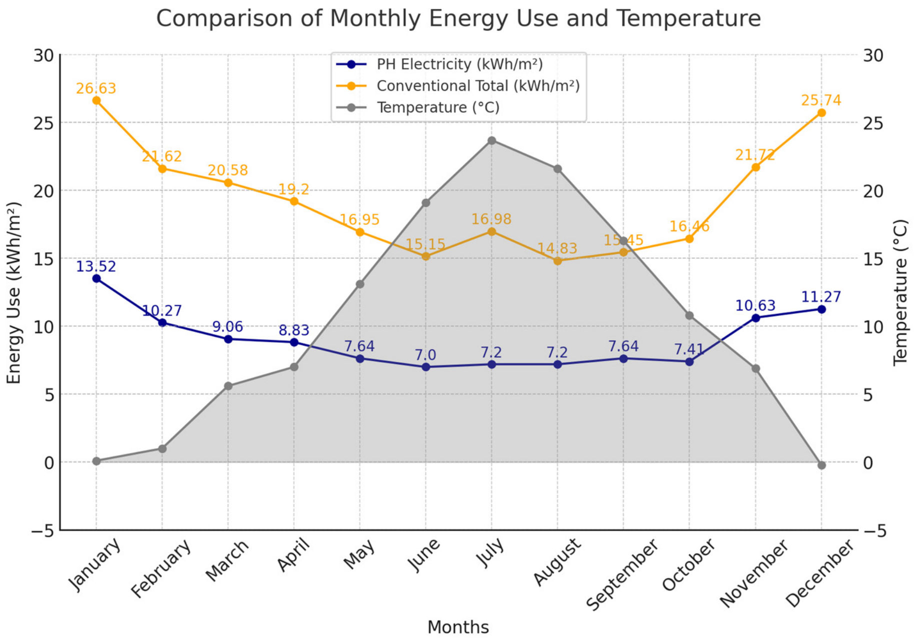

Figure 10. Comparison of average monthly outdoor temperature (°C) and whole-building monthly energy use (kWh) of the Passive House and the conventional building per m^2 in 2020.

4. Discussion

The comparative analysis between the Passive House building and the conventional building reveals substantial energy savings achieved by the Passive House design. In 2019, the conventional building consumed a total of 222.27 kWh of energy, whereas the Passive House utilized only 112.70 kWh, indicating a 49% reduction in site energy consumption in the Passive House compared to the conventional building (Figure 5). Moreover, after adjusting for occupancy data, the conventional building's energy consumption per occupant amounted to 6.48 kWh, while in comparison, the Passive House's per-occupant energy use stood at 2.78 kWh, representing a 57% reduction in energy use per occupant (Figure 7).

Similarly, in 2020, the conventional building exhibited a total energy consumption of 231.31 kWh, whereas the Passive House consumed 107.67 kWh during the same period, marking a 53% decrease in energy use in the Passive House compared to the conventional building (Figure 6). Upon factoring in occupancy data, the conventional building's energy consumption per occupant reached 6.61 kWh, while in comparison, the Passive House's per-occupant energy use was significantly lower at 2.38 kWh, translating to a substantial 63% reduction in energy consumption per occupant (Figure 8).

These findings highlight significant energy efficiency gains achieved by Passive House design principles in Central Pennsylvania. Furthermore, the energy consumption trends observed in Philipsburg, PA, demonstrate the better performance of Passive House. The lower fluctuations in energy use observed in the Passive House compared to the conventional building also suggest a more stable indoor temperature. Passive House design principles, including continuous insulation and airtight construction, create a thermal buffer that reduces the impact of outdoor temperature variations. Consequently, the HVAC system in the Passive House likely requires fewer frequent adjustments to maintain comfortable indoor temperatures, resulting in steadier energy consumption compared to the conventional building (Figures 9 and 10).

Additionally, benchmarking analysis using the Energy Use Intensity (EUI) metric further reinforces the superior energy performance of the Passive House. In comparison to the national median EUI values for residential buildings, both the Passive House and the conventional building in this study exhibit energy consumption levels below the median. Nevertheless, the Passive House notably outperforms the conventional building in both site and source EUI metrics.

Overall, the results underline the substantial energy savings potential of Passive House design compared to conventional building standards, positioning Passive House as a highly effective strategy for reducing energy consumption in climate zone 5A in Central Pennsylvania.

This study provides a direct comparison of energy consumption between a Passive House building and a conventional building over a two-year period. Utilizing real-world data from two adjacent multifamily residential buildings in Central Pennsylvania, the results are grounded in practical post-occupancy evaluation rather than simulation results. It provides empirical evidence from real-world monitored data demonstrating the energy efficiency benefits of Passive House standards (PHIUS+ 2015) in a North American climate. Focused on the Phius standards, this study addresses a gap in the existing literature, which predominantly covers the PHI standards in Europe. This research addresses a gap in the existing literature by offering a direct comparative analysis of two similar buildings, one constructed to conventional standards and the other to Passive House standards.

However, the two-year observation period, while valuable, may not capture long-term performance trends and potential maintenance issues associated with Passive House buildings. Variations in building usage patterns, including occupancy rates and resident behavior, could influence energy consumption patterns and, thus, the results. The assumption that resident behavior did not significantly differ between the two buildings is a limitation because variations in behavior can have a substantial impact on energy use.

5. Conclusions

The primary objective of this research was to quantify the reduction in energy consumption achieved by the Passive House design (PHIUS+ 2015) compared to the conventional building in similar orientations and conditions.

To fulfill this objective, utility billing data spanning the years 2019 and 2020 were collected and analyzed. The investigation is based on the monitored data in monthly utility bills, focusing on whole-building energy use and energy use per occupant. Additionally, benchmarking analysis utilizing EUI metrics was undertaken to gauge the energy efficiency of the buildings relative to national median values for similar property types.

The findings of the analysis unveiled significant energy efficiency gains realized by the Passive House design in climate zone 5A. Across both 2019 and 2020, the Passive House exhibited approximately 50% less energy consumption compared to the conventional building in terms of monthly whole-building energy performance. The 50% reduction in whole building energy use in this study validates Phius's claims of a 40% to 60% reduction and aligns with the targets presented in previous studies. Furthermore, upon factoring in occupancy data, the Passive House achieved substantial reductions of 57% and 63% in energy use per occupant in 2019 and 2020, respectively, in the studied buildings in Central Pennsylvania.

Moreover, benchmarking analysis utilizing site and source EUI metrics further validated the more efficient energy performance of the Passive House in North America. Despite an initial construction cost premium, the study findings suggest that the long-term energy savings accrued by the Passive House can offset the initial investment. The economic benefits of Passive House standards, such as reduced energy costs, underscore the importance of adopting such energy-efficient measures. These findings align with the economic principles outlined in recent research, emphasizing the broader economic impact of energy-efficient building standards at both the micro and macroeconomic levels [4].

6. Future Work

This study highlights the imperative for further research evaluating the energy performance of buildings under climate-specific Phius standards in the United States. Future work should seek to break down whole-building energy consumption in the two comparative buildings into different sub-metered areas. Disaggregating the loads, including lighting, HVAC systems, refrigeration, and plug loads, will allow for a more detailed observation of performance in the two buildings. Additionally, monitoring energy use in the buildings on an hourly or daily basis over a longer period of time would provide a better understanding of operational energy performance. Regarding the limitations, both buildings in this study are categorized as affordable senior housing. Thus, further investigation is necessary to verify these results across other building categories. Additionally, future research should consider occupant behavior to better understand its impact on energy consumption and further refine the findings. While this study highlights the potential for significant energy savings and reduced operational costs, future work should also include a detailed economic analysis to explore the cost-benefit aspects and financial implications of implementing Passive House standards.

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References

1. IPCC. *Climate Change 2014: Mitigation of Climate Change*; Cambridge University Press: Cambridge, UK, 2014. Available online: https://www.ipcc.ch/report/ar5/wg3/ (accessed on 10 October 2022).
2. United Nations Environment Programme (UNEP). *2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme (UNEP): Nairobi, Kenya, 2021. Available online: https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf (accessed on 10 October 2022).
3. International Energy Agency (IEA). *The Critical Role of Buildings: Perspectives for the Clean Energy Transition*; IEA: Paris, France, 2019. Available online: https://www.iea.org/reports/the-critical-role-of-buildings (accessed on 10 October 2022).
4. Acaroğlu, A.; Güllü, G. Climate Change Caused by Renewable and Non-Renewable Energy Consumption and Economic Growth: A Time Series ARDL Analysis for Turkey. *Renew. Energy* **2022**, *192*, 194–206. [CrossRef]
5. Fokaides, P.A.; Christoforou, E.; Ilic, M.; Papadopoulos, A. Performance of a Passive House under Subtropical Climatic Conditions. *Energy Build.* **2016**, *133*, 14–31. [CrossRef]
6. Schnieders, J.; Hermelink, A. Cepheus Results: Measurements and Occupants' Satisfaction Provide Evidence for Passive Houses Being an Option for Sustainable Building. *Energy Policy* **2006**, *34*, 151–171. [CrossRef]
7. Alajmi, A.; Rodríguez, S.; Sailor, D. Transforming a Passive House into a Net-Zero Energy House: A Case Study in the Pacific Northwest of the U.S. *Energy Convers. Manag.* **2018**, *172*, 39–49. [CrossRef]
8. PHIUS. *Passive Building Principles*; PHIUS: Chicago, IL, USA, 2022. Available online: https://www.phius.org/passive-building/what-passive-building (accessed on 10 October 2022).
9. Wang, Y.; Kuckelkorn, J.; Zhao, F.-Y.; Spliethoff, H.; Lang, W. A State of Art Review on Interactions between Energy Performance and Indoor Environment Quality in Passive House Buildings. *Renew. Sustain. Energy Rev.* **2017**, *72*, 1303–1319. [CrossRef]
10. Borrallo-Jiménez, M.; LopezDeAsiain, M.; Esquivias, P.M.; Delgado-Trujillo, D. Comparative Study between the Passive House Standard in Warm Climates and Nearly Zero Energy Buildings under Spanish Technical Building Code in a Dwelling Design in Seville, Spain. *Energy Build.* **2022**, *254*, 111570. [CrossRef]
11. Mahdavi, A.; Doppelbauer, E.-M. A Performance Comparison of Passive and Low-Energy Buildings. *Energy Build.* **2010**, *42*, 1314–1319. [CrossRef]
12. Liang, X.; Wang, Y.; Royapoor, M.; Wu, Q.; Roskilly, T. Comparison of Building Performance between Conventional House and Passive House in the UK. *Energy Procedia* **2017**, *142*, 1823–1828. [CrossRef]
13. Huang, H.; Wan Mohd Nazi, W.I.B.; Yu, Y.; Wang, Y. Energy Performance of a High-Rise Residential Building Retrofitted to Passive Building Standard–A Case Study. *Appl. Therm. Eng.* **2020**, *181*, 115902. [CrossRef]
14. Bravo-Orlandini, C.; Gómez-Soberón, J.M.; Valderrama-Ulloa, C.; Sanhueza-Durán, F. Energy, Economic, and Environmental Performance of a Single-Family House in Chile Built to Passivhaus Standard. *Sustainability* **2021**, *13*, 1199. [CrossRef]
15. Hasper, W.; Kirtschig, T.; Siddall, M.; Johnston, D.; Vallentin, G.; Harvie-Clark, J. Long-Term Performance of Passive House Buildings. *Energy Effic.* **2021**, *14*, 5. [CrossRef]
16. Feist, W.; Schnieders, J.; Dorer, V.; Haas, A. Re-Inventing Air Heating: Convenient and Comfortable within the Frame of the Passive House Concept. *Energy Build.* **2005**, *37*, 1186–1203. [CrossRef]
17. Mitchell, R.; Natarajan, S. UK Passivhaus and the Energy Performance Gap. *Energy Build.* **2020**, *224*, 110240. [CrossRef]
18. Sigalingging, R.C.; Chow, D.; Sharples, S. Applying the Passivhaus Standard to a Terraced House in a Hot and Humid Tropical Climate–Evaluation of Comfort and Energy Performance. *Build. Serv. Eng. Res. Technol.* **2020**, *41*, 247–260. [CrossRef]
19. Lee, J.; Shepley, M.M.; Choi, J. Exploring the Localization Process of Low Energy Residential Buildings: A Case Study of Korean Passive Houses. *J. Build. Eng.* **2020**, *30*, 101290. [CrossRef]
20. Dalbem, R.; da Cunha, E.G.; Vicente, R.; Figueiredo, A.; Oliveira, R.; da Silva, A.C.S.B. Optimisation of a Social Housing for South of Brazil: From Basic Performance Standard to Passive House Concept. *Energy* **2019**, *167*, 1278–1296. [CrossRef]
21. Vettorazzi, E.; Figueiredo, A.; Rebelo, F.; Vicente, R.; da Cunha, E.G. Optimization of the Passive House Concept for Residential Buildings in the South-Brazilian Region. *Energy Build.* **2021**, *240*, 110871. [CrossRef]
22. Mihai, M.; Tanasiev, V.; Dinca, C.; Badea, A.; Vidu, R. Passive House Analysis in Terms of Energy Performance. *Energy Build.* **2017**, *144*, 74–86. [CrossRef]

23. Figueiredo, A.; Kämpf, J.; Vicente, R. Passive House Optimization for Portugal: Overheating Evaluation and Energy Performance. *Energy Build.* **2016**, *118*, 181–196. [CrossRef]
24. Rose, J.; Kragh, J.; Nielsen, K.F. Passive House Renovation of a Block of Flats–Measured Performance and Energy Signature Analysis. *Energy Build.* **2022**, *256*, 111679. [CrossRef]
25. Ridley, I.; Clarke, A.; Bere, J.; Altamirano, H.; Lewis, S.; Durdev, M.; Farr, A. The Monitored Performance of the First New London Dwelling Certified to the Passive House Standard. *Energy Build.* **2013**, *63*, 67–78. [CrossRef]
26. Wąs, K.; Radoń, J.; Sadłowska-Sałęga, A. Maintenance of Passive House Standard in the Light of Long-Term Study on Energy Use in a Prefabricated Lightweight Passive House in Central Europe. *Energies* **2020**, *13*, 2801. [CrossRef]
27. Wagner, K. Reducing CO_2 in Passivhaus-Adapted Affordable Tropical Homes. *Encyclopedia* **2023**, *3*, 168–181. [CrossRef]
28. Ridley, I.; Bere, J.; Clarke, A.; Schwartz, Y.; Farr, A. The Side by Side In Use Monitored Performance of Two Passive and Low Carbon Welsh Houses. *Energy Build.* **2014**, *82*, 13–26. [CrossRef]
29. Figueiredo, A.; Figueira, J.; Vicente, R.; Maio, R. Thermal Comfort and Energy Performance: Sensitivity Analysis to Apply the Passive House Concept to the Portuguese Climate. *Build. Environ.* **2016**, *103*, 276–288. [CrossRef]
30. Dan, D.; Tanasa, C.; Stoian, V.; Brata, S.; Stoian, D.; Nagy Gyorgy, T.; Florut, S.C. Passive House Design—An Efficient Solution for Residential Buildings in Romania. *Energy Sustain. Dev.* **2016**, *32*, 99–109. [CrossRef]
31. Adeyina, D.L.; Anderson, T.; Ghaffarian Hoseini, A. A Parametric Study of Passive House Strategies in a Cooling Dominated Climate–A Case Study of Algeria. In *7th New Zealand Built Environment Research Symposium*; School of Built Environment, Massey University: Auckland, New Zealand, 2022; p. 321.
32. Certified Project Database. Phius. Available online: https://www.phius.org/certified-project-database (accessed on 9 March 2024).
33. German, A.; Weitzel, B.; Backman, C.; Hoeschele, M.; Dakin, B. *Sonoma House: Monitoring of the First US Passive House Retrofit*; No. NREL/SR-5500-55218; DOE/GO-102012-3632; National Renewable Energy Lab (NREL): Golden, CO, USA, 2012.
34. Schnieders, J.; Feist, W.; Rongen, L. Passive Houses for Different Climate Zones. *Energy Build.* **2015**, *105*, 71–87. [CrossRef]
35. Antretter, F.; Klingenberg, K.; Pazold, M. All-in-One Design Tool Solution for Passive Houses and Buildings—Monthly Energy Balance and Hygrothermal Simulation. In Proceedings of the Thermal Performance of the Exterior Envelopes of the Whole Buildings XII International Conference, Clearwater, FL, USA, 1–5 December 2013; pp. 1–5.
36. Abendroth, R.M. BEST4 Conference. In *Proceedings of the BEST4 Conference*; National Institute of Building Sciences Building Enclosure Technology and Environment Council (BETEC): Kansas City, MO, USA, 2015.
37. Iqbal, T.; Manzoor, S. Building Performance Modelling for the First House in Newfoundland Built on PHIUS+ 2015 Standards and Design of Renewable Energy System. *Int. J. Renew. Energy Res.* **2020**, *10*, 3.
38. Hagerman, S. Hammer & Hand's Construction Methods and Approach to the Glasswood Commercial Passive House Retrofit. *J. Green Build.* **2014**, *9*, 23–36.
39. Klingenberg, K.; Kernagis, M.; Knezovich, M. Zero Energy and Carbon Buildings Based on Climate-Specific Passive Building Standards for North America. *J. Build. Phys.* **2016**, *39*, 503–521. [CrossRef]
40. White, L. Setting the Heating/Cooling Performance Criteria for the PHIUS 2018 Passive Building Standard. In *ASHRAE Topical Conference Proceedings*; American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.: Peachtree Corners, GA, USA, 2019; pp. 399–409.
41. Saft, C. Does Passive House Have a Home in the Deep South? In *Subtropical Cities 2013, Braving a New World: Design Interventions for Changing Climates: Paper Proceedings*; Abbate, A., Lyn, F., Kennedy, R., Eds.; Association of Collegiate Schools of Architecture: Washington, DC, USA, 2013; pp. 71–82.
42. Earle, L.; Torcellini, P.; Chappoz, L. *Deep Retrofits for Multifamily: Experiences in Scaling to Zero Energy*; No. NREL/CP-5500-77410; National Renewable Energy Lab (NREL): Golden, CO, USA, 2020.
43. Wang, L.; Greenberg, S.; Fiegel, J.; Rubalcava, A.; Earni, S.; Pang, X.; Yin, R.; Woodworth, S.; Hernandez-Maldonado, J. Monitoring-Based HVAC Commissioning of an Existing Office Building for Energy Efficiency. *Appl. Energy* **2013**, *102*, 1382–1390. [CrossRef]
44. Estrella Guillén, E.; Samuelson, H.W.; Cedeño Laurent, J.G. Comparing Energy and Comfort Metrics for Building Benchmarking. *Energy Build.* **2019**, *205*, 109539. [CrossRef]
45. Energy Star. US Energy Use Intensity by Property Type. Energy Star Portfolio Manager. 2023. Available online: https://portfoliomanager.energystar.gov/pdf/reference/US%20National%20Median%20Table.pdf (accessed on 10 February 2024).
46. Energy Star. Glossary. Energy Star Portfolio Manager. 2023. Available online: https://www.energystar.gov/buildings/tools-and-resources/portfolio-manager-technical-reference-source-energy (accessed on 10 February 2024).
47. Energy Star. What Is Energy Use Intensity (EUI)? Energy Star. 2023. Available online: https://www.energystar.gov/buildings/benchmark/understand-metrics/what-eui (accessed on 9 March 2024).