DESIGNING A SUSTAINABLE TINY HOUSE: THE IMPACT OF USING MYCELIUM-BASED MATERIALS, PHOTOVOLTAIC CELLS, AND WINDOW TO WALL RATIOS.

by

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ABSTRACT

PARHAM KHEIRKHAH SANGDEH. Designing a Sustainable Tiny House: The Impact of Using Mycelium-Based Materials, Photovoltaic Cells, and Window to Wall Ratios (Under the direction of DR. KYOUNG-HEE KIM)

It was not until the late 1980s that the United Nations proposed the notion of 'sustainability' to address three key issues: economic development, social equity, and environmental protection [1].

From an environmental standpoint, buildings can play a crucial role in developing the concept of sustainability. The building sector is responsible for 40% of CO2 emissions and 70% of electricity consumption in the United States, surpassing all other sectors [2] [3] [4]. Among these, residential buildings account for two-thirds of the total energy consumption in the building sector [5] [4]. Over the past few decades, the size of houses has been gradually increasing [6] [7]. The growth in home size can have detrimental environmental effects, including land loss, increased pollution, changes in energy consumption, and various other harmful impacts [8] [9] [10]. Conventional buildings require substantial amounts of water and energy during construction, operation, and demolition stages [11] [12]. Therefore, the concept of tiny houses can be a potential solution to the existing crises in these sectors.

On the other hand, there is currently a growing demand for zero-energy buildings. Net-zero energy buildings generate at least as much energy as they consume [13]. In the United States, the Department of Energy (DOE) has set goals for marketable zero-energy homes by 2020 and commercial zero-energy buildings by 2025 [14]. Additionally, California has mandated that all newly constructed homes and commercial buildings be net-zero by 2020 and 2030, respectively [15]. By 2030, Net Zero Energy Buildings (NZEBs) should be commercially viable according to

the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Other countries have also established long-term goals for implementing NZEBs [13]. Therefore, the inclination towards zero-energy buildings is inevitable.

Since 2007, mycelium-based composites have been recognized as inventions and have been studied scientifically. Due to the numerous advantages of this material, it is essential to gather information from scientific literature, patent documents, and personal experience to evaluate the potential and limitations of using mycelium-based composites in industrial manufacturing, particularly for decorative objects in interior architectural design [16].

This project aims to utilize mycelium-based materials for efficient insulation and photovoltaic cells for electricity generation. Moreover, the impact of the window-to-wall ratio is investigated in this study. The outcomes of this study demonstrate that the window-to-wall ratio has a significant impact on energy consumption. Remarkably, among the 15 investigated cities, all cases in seven cities achieved zero-energy status. This high prevalence indicates a significant opportunity for designing and implementing net-zero energy tiny houses, showcasing the viability of sustainable practices across diverse urban landscapes.

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DEDICATION

This thesis is dedicated to my beloved parents and my wife, whose love, sacrifices, and unwavering support have been the foundation of my academic journey. Throughout my life, you have been my pillars of strength, providing endless encouragement and believing in my potential even when I doubted myself.

Your constant belief in my abilities and your selfless dedication to my education have been the driving force behind my pursuit of knowledge and academic excellence. Your sacrifices and hard work have inspired me to persevere through challenges and strive for success.

I am forever grateful for the values you instilled in me, the life lessons you taught me, and the endless encouragement you provided. This thesis is a testament to your love and devotion, and I dedicate this accomplishment to you both with all my heart.

Thank you for being my biggest cheerleaders, for standing by my side through thick and thin, and for being the most extraordinary parents I could ever ask for.

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1. INTRODUCTION

It wasn't until the late 1980s that the United Nations introduced the concept of 'sustainability' to address economic development, social equity, and environmental protection [1]. Buildings, particularly in the U.S., contribute significantly to environmental issues, responsible for 40% of CO2 emissions and 70% of electricity consumption [2] [3] [4]. Residential buildings, constituting two-thirds of the building sector's energy consumption [4] [5], have seen a gradual increase in size over the past few decades, causing adverse environmental impacts [6] [7] [8] [9] [10]. Conventional construction methods also entail substantial water and energy use [11] [12]. The emergence of tiny houses presents a potential solution to these challenges.

Concurrently, there is a rising demand for zero-energy buildings, aiming to generate as much energy as they consume [13]. The U.S. Department of Energy (DOE) has set targets for marketable zero-energy homes and commercial buildings [14]. California mandates net-zero construction for new homes and commercial buildings by 2020 and 2030, respectively [15]. This shift towards net-zero energy buildings is evident globally, with other countries establishing similar long-term goals [13]

Since 2007, mycelium-based composites have been recognized for their potential in industrial manufacturing and interior design [16]. Their numerous advantages necessitate thorough evaluation through scientific literature, patent documents, and practical experience.

Various factors, including location, orientation, materials, and window-to-wall ratio (WWR), significantly impact a building's energy consumption and thermal comfort. WWR, in particular, influences aesthetics and thermal comfort, as evidenced by numerous studies [17] [18] [19] [20]. Windows, considered crucial components of building envelopes, affect energy use and occupant comfort [22] [23]. The ASHRAE Handbook of Fundamentals offers an equation to calculate energy flow through window assemblies based on glazing properties and climatic conditions, emphasizing the impact of WWR [24] [25].

Building orientation is another critical factor, affecting heating and lighting through solar radiation. Proper orientation enhances solar gain, impacting energy demand [30] [31] [32]. Optimizing orientation and shape can result in substantial energy savings [33]. This project aims to evaluate the impact of insulation, orientation, and WWR on the energy consumption of a tiny house. Additionally, it assesses the potential for designing net-zero energy buildings using photovoltaic cells in different cities and climate zones.

2. BACKGROUND

The construction, maintenance, and demolition of houses have several detrimental effects on the environment, resulting from factors such as the production of toxic gases for raw materials and the generation of building debris during demolition. Reducing the overall area of houses is an effective strategy to mitigate these consequences. By embracing tiny houses, which are inherently smaller, the need for material and workforce is reduced. Multi-purpose spaces and the absence of unnecessary areas lead to decreased cooling and heating needs, consequently lowering energy consumption and minimizing the environmental impact. However, it's essential to note that not all tiny houses are automatically environmentally friendly; their ecological footprint depends on factors such as construction materials, energy-efficient design, waste management, and renewable energy sources [38] [39].

A well-designed tiny house that incorporates sustainable materials and energy-saving features can significantly reduce its environmental impact. Conversely, if constructed using conventional materials without energy-efficient elements, a tiny house may not offer substantial environmental benefits [40]. Therefore, careful consideration of design, materials, and practices is crucial for maximizing the positive environmental impact of tiny houses [40].

Living in tiny houses can contribute to a reduction in the consumption of fossil fuels and the production of harmful substances like CFCs. Additionally, the limited space in tiny houses encourages individuals to distance themselves from consumerist lifestyles, leading to reduced overall consumption [41] [42] [43] [44]. The complex issue of consumption is influenced by various factors, including culture and income levels [91]. Nevertheless, the housing area has a direct impact on energy consumption, with smaller houses generally requiring less energy.

Studies on the energy consumption of tiny houses and their environmental savings are limited compared to conventional homes. However, the environmental motivations behind adopting a tiny house lifestyle indicate a potential positive impact. The elements shaping energy consumption in tiny houses include resident behaviour and technical issues. Resident behaviours, such as buying second-hand goods, recycling, and environmental awareness, play a vital role in determining the environmental impact [47] [48]. Tiny houses, as a lifestyle, can lead to cultural modifications by promoting a smaller and simpler way of life [49] [50]. They offer solutions for economical and sustainable living, countering consumerism and increasing well-being [51] [52] [53] [54] [55] [56].

From a technical standpoint, tiny houses can reduce energy consumption through multi-purpose spaces, limited appliance usage, efficient heating and cooling due to smaller areas, and reliance on solar panels for energy supply. The global crisis of air pollution, primarily caused by the consumption of fossil fuels, underscores the importance of sustainable practices in the housing sector. The construction industry, especially housing, is a significant contributor to carbon dioxide emissions. The Paris Convention emphasizes the need for housing sustainability to address the environmental impact of the construction sector [58]. Of the greenhouse gas emissions from the housing sector, 4% is attributed to cooking, 60% to heating, and 20% to heating water [59]. Table 1 depicts the current situation of greenhouse gas emissions in the context of the use of tiny houses.

Table 1- The current situation regarding greenhouse gas emissions as well as the effects that the use of tiny houses has on reducing it.

Traditional Houses	Tiny Houses
9884 trillion cubic meters of natural gas is consumed annually [59].	Greenhouse gas emissions are reduced compared to conventional homes [60].
For every 100 cubic feet natural gas, 12 pounds of carbon dioxide are produced [61].	A 50 percent reduction in home area could reduce emissions by 63 percent [62].
Each house produces 2.2 tons of carbon dioxide due to the consumption of natural gas [58].	The amount of greenhouse gases produced at Tyne House is pounds 900, which is 77% less than standard homes in Australia [63].
	The energy consumption of tiny houses is 419 kW per year, which is 33721 kW for conventional houses [64].
	Save water by using rainwater and compost toilets [65] [4] [66].

Tiny houses have the potential to significantly reduce the consumption of natural gas for heating, water heating, and cooking [62]. Table 2 provides a comparison of the carbon dioxide emissions from an average-sized house and a tiny house, measured in pounds per year. The data in the table clearly shows that the average carbon dioxide emissions from a conventional home are 13 times higher than those from a tiny house [4]. This emphasizes the environmental benefits of adopting tiny houses, particularly in terms of reducing greenhouse gas emissions associated with natural gas usage.

Table 2- the amount of carbon dioxide produced by an average house and one tiny house (in pounds per year) [4].

The amount of carbon dioxide emitted for:	Conventional homes (kg)	Tiny-houses (kg)
Electricity	16000	1114
Heating	8000	558
Cooling	4000	286
Total	28000	2000

Crafting an energy-efficient tiny house involves careful consideration of key parameters, including achieving a balance in the window-to-wall ratio, ensuring ample natural light while minimizing heat loss or gain. The thickness of insulation is another critical element influencing the regulation of internal temperatures and overall energy consumption. The selection of appropriate insulation materials and meticulous installation practices significantly contributes to the overall thermal performance of the tiny house. Additionally, the orientation of the tiny house plays a pivotal role in optimizing energy efficiency by strategically placing windows and facilitating effective passive solar heating. By incorporating these parameters—window-to-wall ratio, insulation thickness, and orientation—into the design process, a well-designed tiny house can seamlessly integrate energy efficiency, comfort, and practicality.

The efficiency of a building's energy use, particularly in terms of heating and lighting through solar radiation, is significantly influenced by its orientation. Wong and Fan [30] emphasize the importance of correctly orienting a building to maximize its solar contribution, crucial for optimizing energy efficiency. Building orientation plays a key role in the utilization of heating and lighting systems, major factors affecting overall energy consumption [67]. Proper orientation is essential to enhance solar gain, especially during colder seasons [68] [30]. Morrissey et al. [31] highlight orientation as a paramount factor influencing passive solar gain. Pacheco et al. [32] assert that building orientation profoundly impacts a building's energy demand. Additionally, Aksoy and Inalli [33] propose that optimizing both building orientation and shape can result in substantial energy savings, up to 36%. Spanos et al. [34] argue that strategic orientation, site location, and landscaping changes can potentially reduce a building's energy requirements by 20%, emphasizing the importance of maximizing daylight entry. Fallahtafti and Mahdavinejad [35] conducted a study on the impacts of various building formations in relation to a fixed orientation. Xu et al. [36] utilized Energy Plus to analyze energy-saving performance by optimizing building orientation in representative Chinese cities. Al-

Fahmawee [37] employed mathematical techniques, such as linear regression models, to assess the effects of different floor heights and building orientations on atrium daylighting levels.

Regarding the impact of Window-to-Wall Ratio (WWR) on building energy consumption, there has been extensive investigation and discourse in current research. Although there isn't much debate on what constitutes a reasonable WWR, most findings support a positive linear relationship between building energy consumption and WWR [19] [69] [20] [70] [71]. The methodologies employed in these studies often include dynamic simulation and steady-state computation, but the conclusions about the proper value of WWR differ. One study indicates that energy consumption and WWR in residential buildings in the Hot-Summer and Cold-Winter (HSCW) zone of China have a power-of-quadratic correlation in the southern direction but a positive linear relationship in other orientations [72]. Another study demonstrates a positive linear relationship in all directions between heating consumption and WWR [16] using a steady-state calculation method. Interestingly, both studies point to a greater influence of smaller WWR values on building energy efficiency. Dynamic simulation analysis is employed in China's current "Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone" (JGJ134-2010) to investigate the connection between WWR and the thermal insulation capabilities of external windows. According to the standard, south-facing windows can have a maximum WWR of 0.6 only if the external windows' heat transfer coefficient is lowered to 2.5 W/(m^2°C). Furthermore, the WWR can be raised to 0.6 for windows facing east and west if an external shading structure is used, which has a solar radiation transmittance of less than 0.25. The relationship between WWR and human thermal comfort has also been studied by several researchers [27] [73] [74] [75] [76] [77] [78] [21], with studies determining the ideal WWR value to create comfortable conditions for the longest periods of the year [77]. It is important to recognize, though, that the influence of window characteristics on comfort in real-world settings depends on human performance [72]. Sub-studies for various building types are scarce, despite the abundance of optimization analyses of WWR for residential buildings. By providing pertinent foundational information in this field, this paper seeks to close this gap. Crucially, research on WWR, energy use in homes, and human thermal comfort is still conducted independently of the other two [72].

3. LITERATURE REVIEW

3.1. Net zero energy building

In recent years, there has been a significant global interest in Zero Energy Building (ZEB) as an emerging concept, now recognized as the ultimate goal in building design.

International efforts to promote the implementation of Zero Energy Buildings (ZEBs) have been discussed and proposed at various levels. For example, in the United States, the Energy Independence and Security Act of 2007 (EISA 2007) introduced the Net-Zero Energy Commercial Building Initiative, aiming for all new commercial buildings to achieve net-zero energy consumption by 2030. Additionally, the EISA 2007 sets a target for 50% of U.S. commercial buildings to reach zero-energy status by 2040, with the goal of all commercial buildings achieving net-zero energy by 2050 [79].

Similarly, at the European level, the recast of the Directive on Energy Performance of Buildings (EPBD) in May 2010 established the objective of "nearly zero energy buildings" as the standard for all public buildings owned or occupied by public authorities by 2018 and for all new buildings by 2020. This ambitious target aims to make nearly ZEBs a reality in just eight years in Europe [80].

By outlining these goals, both in the USA and Europe, there is a clear emphasis on promoting the adoption of ZEBs as the future standard for energy-efficient buildings, with specific timelines and targets set to drive progress towards sustainable and energy-efficient construction practices [81].

Architects and multidisciplinary researchers in architectural engineering and building physics have given great importance to the design of zero energy buildings. A zero-energy building is defined as a building that, on average, consumes no net energy throughout a typical year. This means that the building reduces its demand for heat and electrical power and fulfills this reduced demand through renewable energy sources over the course of a year. The renewable energy supply can be integrated into the building's design or can be specifically provided for the building, such as through a community renewable energy system [82].

Additionally, zero-energy building design typically involves utilizing the electrical grid to supply power when renewable sources are unavailable, while also allowing the building to export excess power back to the grid when it generates more than it needs. This two-way flow of energy should ideally result in either a net positive or zero export of power from the building to the grid [82].

The concept of zero-energy building design represents a progression from passive sustainable design. Its objective is not only to minimize energy consumption through passive design methods but also to create a building that achieves a balance between energy requirements and active techniques and renewable technologies. Examples of these techniques and technologies include solar photovoltaics, solar thermal systems, and wind turbines. Moreover, some solutions can play a key role in reducing energy consumption such as window to wall ratio and insulation thickness [82].

In their study, Clarke et al. [83] utilized a well-known integrated software environment that combined various tools such as ESP-r for building simulation, Merit for renewable energy modeling and matching, and EnTrak for fuel use information management. They conducted a case study focusing on hybrid renewable energy systems in residential buildings in Korea. The aim was to assess the viability of new technologies using a simulation-based decision support system. By using this integrated software environment, they were able to determine appropriate types and capacities of technologies during the initial design phase.

Biaou et al. [84] conducted a simulation using TRNSYS to analyze a zero net energy residence located in Montreal. The house was equipped with photovoltaic (PV) panels for generating electricity and a geothermal heat pump for heating and cooling purposes. The findings demonstrated that it is indeed feasible to achieve a zero net energy status for a home of R-2000 classification by employing PV panels and a ground source heat pump.

Bolling and Mathias [85] conducted a comparative analysis of four heating and cooling systems for a residential house situated in four different cities across America. The comparison was made considering various factors such as the overall life cost, energy usage, exergetic efficiency, and exergy destruction. The four systems investigated were a high-efficiency furnace with an electric air conditioner, a ground source heat pump, an absorption air conditioner with direct heating, and a thermally driven heat pump. The latter two systems utilized solar thermal energy along with non-renewable energy as a backup. The findings of the study revealed that the vertical ground source heat pump demonstrated the quickest payback period among the four systems assessed.

In their study, Norton and Christensen [86] provided a comprehensive analysis of energy performance data for a three-bedroom zero energy home located in Denver. The home achieved its energy efficiency through various means, including an optimized building envelope, energy-efficient appliances and lighting, a photovoltaic system, and both passive and active solar thermal features. The findings of this case study highlight the feasibility of constructing cost-effective zero energy homes in cold weather conditions.

Wang et al. [82] explored potential approaches for designing zero energy buildings in the UK. The authors utilize simulation software, specifically Energy Plus and TRNSYS 16, to investigate and analyze different aspects of zero energy building design. Energy Plus simulations are employed to study facade design, taking into account factors such as building materials, window sizes, and orientations. TRNSYS is utilized to assess the viability of zero energy houses, considering renewable electricity, solar hot water systems, and energy-efficient heating systems specifically in the context of Cardiff's weather conditions.

3.2. Bioclimatic design

3.2.1 Insulation

Generally, the proposed measures primarily involve increasing the thickness of insulation, using energy-efficient windows, employing high-efficiency HVAC systems, and promoting the installation and utilization of photovoltaic panels for energy generation [87] [88] [89] [90] [91]. However, it is important to note that the extensive use of materials to achieve zero energy goals leads to a notable rise in the embodied life cycle energy of buildings [92] [93] [94] [95] [96] [97]. In certain cases, the embodied energy associated with technical installations and energy production systems can be nearly as significant as the environmental impact resulting from the structural components of the building [98].

As the utilization of materials increases, studies indicate that the choice of materials plays a role in the initial embodied energy and the final thermal energy demand, especially when considering embodied energy in the calculation process [99]. Often overlooked factors, such as embodied energy and occupants' transportation, contribute to over 50% of the total energy consumption, as highlighted by Stefan and Crawford [100]. Furthermore, since the recurring embodied energy from material replacements can represent a substantial portion of the initial embodied energy of building assemblies [101], there is a significant increase observed in the recurring embodied energy during the stages of replacement and maintenance in net zero-energy buildings [102].

The rise in embodied energy in buildings suggests the necessity for a whole-life energy cycle analysis. The literature also suggests adopting a life cycle perspective in energy regulations to account for the complete energy usage throughout a building's lifespan [103]. This perspective aligns with other studies that emphasize the consideration of embodied energy and life cycle energy analysis in energy regulations as a means to achieve sustainability goals [104]. Models that provide a holistic approach and measure embodied energy and life cycle energy demand of buildings beyond energy efficiency regulations support this viewpoint [100] [105]. Even a simplified life cycle approach can be beneficial in decision-making processes by considering embodied energy [106].

The construction sector, encompassing residential, industrial, and commercial buildings, plays a significant role in consuming a substantial amount of energy to ensure thermal comfort. However, this sector has the potential to reduce its energy consumption by implementing suitable and efficient insulation strategies. By employing effective insulation methods, energy can be conserved, resulting in reduced energy requirements for cooling during summer and minimizing heat loss to keep buildings warm during winter [107].

There is a clear need for a transformative shift towards environmentally friendly materials to tackle the extensive environmental and efficiency concerns associated with existing methods. One promising area for improvement is polymeric foams, including EPS, which are widely used in housing construction for thermal insulation and lightweight fill. These petroleum-derived materials possess several beneficial qualities, such as hydrophobicity, lightweight nature, and excellent sound and thermal insulation properties. However, their substantial environmental impact from production to disposal underscores the urgency for a green material revolution [108] [109].

Nevertheless, similar to many artificial materials, polymeric foams entail significant ecological and societal drawbacks across their entire lifecycle. Starting from the extraction of oil to their ultimate disposal, these hydrocarbon-based materials pose challenges due to their non-renewable nature. Additionally, their production involves intricate manufacturing procedures, substantial energy consumption, and the generation of waste streams, further exacerbating their negative impacts on the environment and society [110]. Moreover, polymeric foams present a significant challenge in terms of decomposition, as they can take thousands of years to break down. This extended decomposition period creates significant issues related to their reuse, recycling, and proper operation of landfills. Finding sustainable and efficient solutions for managing and disposing of these foams becomes imperative in order to mitigate their long-lasting environmental impact [109].

Substantial amounts of polymeric foams have inevitably entered the broader terrestrial and marine ecosystems. Notably, these plastics have a strong attraction to chemical pollutants, including heavy metals and carcinogenic compounds, leading to their accumulation within food chains. As a result, these pollutants have the potential to accumulate in various organisms within the food webs of both land and aquatic environments [111].

In the past ten years, significant progress in MB (mycelium-based) technology has brought attention to its potential as an environmentally friendly substitute for various manufacturing materials. This includes applications in areas like building insulation, packaging, and more, where MB technology has already started to find its way into commercial use. The rapid advancements in this field have underscored the viability of MB as a green alternative in various industries [109] [112].

Many studies have been conducted about the mechanical properties of mycelium-based materials. The results of these studies are summarized in table 2.

Foams are commonly recognized for their effective insulation properties, and the utilization of microcellular bio-based foams (MBFs) has also been proposed as a means of thermal insulation. These MBFs can be employed to manufacture panels designed for placement within the core of walls, thereby enhancing their insulation capabilities [113].

In addition to their thermal conductivity, microcellular bio-based foams (MBFs) have also been found to possess a high specific heat capacity (7.4–10.2 kJ/kg−1 K−1) compared to commercially available materials [114] [115] [116] [117] [118]. A novel fungus-based material for thermal insulation was developed and characterized by Amstivslavski et al. (2017), resulting in a patent in the USA based on the previously published results by Yang et al. (2017) [109]. The authors created a scaffolded structure through repeated layer deposition, with each layer consisting of a colonized substrate. The mycelium growth acted as a cementing agent, providing cohesion between the layers. Thermal conductivity values were found to be the lowest reported in the literature, particularly for the dried samples. While a certain moisture fraction is typically acceptable for other MBF applications, this study highlighted the importance of complete drying to optimize insulation properties. Interestingly, Holt et al. (2012) [119] reported higher conductivity values despite the lower density of the tested material. Velasco et al. (2014) [120] similarly observed a decrease in the thermal conductivity of clay bricks when incorporating spent mushroom compost (SMC) in proportions exceeding 10%. However, the data provided by the same authors regarding the SMC itself were inconsistent and lacked a unified measurement approach, specific moisture percentage, and verifiable sources.

MBFs, overall, demonstrate promising potential as thermal insulators when compared to a wide range of commonly used commercial materials in engineering. However, their thermal conductivity generally remains higher. To become fully competitive with commercial materials, a reduction of approximately 33% in thermal conductivity is necessary [115] [121]. In addition to thermal insulation, MBFs have also been investigated for their acoustic insulation properties.

Pelletier et al. [122] tested panels using different substrates and reported acoustic absorption rates exceeding 70–75% at 1000 Hz, even with the least performing samples. Comparisons of audio spectra revealed that the highest absorption occurred when the substrate consisted of a 50–50% mixture of switchgrass and sorghum. The study primarily focused on attenuating dominant road frequencies, suggesting that intra-wall panels could be employed for combined thermal and acoustic insulation [123]. Furthermore, external wall insulation has been proposed, as increased surface roughness in panels enhances acoustic absorption.

Table 2- Physical, mechanical, and thermal values available in literature for mycelium-based composites. MBF=mycelium-based foam; MBSC=mycelium-based sandwich composite (Values are not comparable with literature as normalized by the standard polystyrene density).

Density (g cm^{-3})	Thermal Conductivity (Wm−1K−1)	Young's Modulus (MPa)	Compressive Strength (kPa)	Flexure Strength (kPa)	Tensile Strength (kPa)	Material	Ref.
0.183±15.1			41.72±13.49	10.91±4.41	49.90±20.00	MBF	[124]
0.05–0.06	0.078–0.081					MBF	[114]
0.10–0.14		66.14–71.77	670–1180		100–200	MBSC	[125]
0.16–0.28						MBF	[126]
0.07–0.22	0.10–0.18	123–675	1–72	7–26		MBF	[119]
0.10–0.24		2–97		50–860	10–240	MBF	[127]
0.16–0.28	0.05–0.07	5.39–58.63	29–567			MBF	[113]
	4.27–8.35					Other	[120]
0.3–0.55						MBF	[122]
0.19–0.59						MBF	[123]
0.29–0.35			156–340			MBF	[128]
0.29–0.34			125–311			MBSC	[128]

2.2.2. WWR (window to wall ratio)

Given that the proportion of glazing to opaque areas on a building facade greatly influences indoor visual and thermal comfort, as well as energy consumption, it is essential to investigate the optimal Window-to-Wall Ratio [129].

A research study was carried out to examine how building orientation affects the ideal size of glazing for passive houses in various European climates. The findings of the study indicate that the optimal areas of glazing can be approximated using a quadratic equation [130].

A study was conducted using a school building in Eskisehir, Turkey, as a case study to investigate the optimal glazing ratio and window combination. The findings revealed that incorporating a glazing ratio of 50% can result in a reduction of over 15% in artificial lighting demand, leading to improved indoor conditions and greater comfort [131].

Goia et al. [132] studied the ideal Window-to-Wall Ratios (WWRs) for office buildings located in the mild maritime climate zone of Italy, with a focus on energy consumption criteria. The research findings indicate that minimizing building energy consumption is achieved when all four facades have WWRs ranging from 35% to 45%, which falls within the optimal range.

In another study, Goia [133] utilized Energy Plus, a simulation tool, to assess the thermal and daylighting performances of office buildings situated in various climatic zones across Europe. The objective was to determine the optimal Window-to-Wall Ratio (WWR). The research findings highlight that while the ideal WWR varies based on building orientation and local climate, it typically falls within the range of 30% to 45% for office buildings. Additionally, when compared to an inappropriate WWR, incorporating an appropriate WWR leads to a reduction in building energy consumption ranging from 5% to 25%.

Wen [134] considered indoor daylighting, air temperature, and window orientation as evaluation parameters to determine the optimal Window-to-Wall Ratios (WWRs) for various facing facades of a standard office building in ten prefectures of Japan. The study also examined the relationship between WWR and the emission of CO2 from the building.

A study was conducted to examine the impact of thermal insulation thickness on energy consumption in office buildings with a Window-to-Wall Ratio (WWR) of 40% in three cities in China. The objective was to determine the optimal thickness of external wall insulation that would result in the lowest cooling and heating energy consumption [135].

Bojic et al. [136] investigated the impact of insulation position on the cooling energy loads of residential buildings in Hong Kong. This was achieved by simulating a wall model with a 15 cm insulation thickness and exploring different placements of the insulation, including the internal side, middle part, and external side of the wall. The aim was to assess how the positioning of insulation affects the cooling energy requirements of the buildings.

2.2.3. Solar integration

Another solution for reducing energy consumption involves integrating technologies and systems, with energy systems broadly categorized into electricity and heat. In the realm of electricity systems, studies have compared the performance of systems relying solely on batteries with those incorporating a hybrid combination of batteries and hydrogen storage.

Das et al. [137] conducted a comparative analysis to assess the feasibility of three different energy systems for meeting the electricity demand of 50 households in a Malaysian village (51 MWh/year). The systems investigated were PV-battery, PV-battery-hydrogen storage (utilizing a fuel cell), and a diesel generator. The PV-battery system, meeting electricity needs directly from solar PV panels during the day and utilizing stored energy from batteries at night, emerged as the most favorable option with a Cost of Energy (COE) of 0.36 €/kWh. In contrast, the diesel generator system had a higher COE due to fuel costs.

Studies by Nelson et al. [138] and Bezmalinović et al. [139] supported these findings, indicating that the PV-battery system exhibited a lower COE compared to the PV-battery-fuel cell system. While fuel cells offer longer-duration energy storage, the study highlighted their higher costs. The excess energy generation observed in both scenarios emphasized the challenge of optimizing system sizes, considering daytime energy load and solar irradiation variations.

In contrast, Kharel and Shabani [140] found in South Australia that a hybrid battery-hydrogen storage system had a significantly lower COE (0.74 €/kWh) compared to a battery-only system (3.16 €/kWh). This larger-scale system, supplying the entire state's demand (15,859 MWh/year) and incorporating wind energy, showcased how scale impacts cost competitiveness.

Excess hydrogen production, if effectively utilized for purposes like fuel cell electric vehicles (FCEV), further decreased the COE.

Considering France, Mohammed et al. [141] deemed a PV-hydrogen storage system without a battery feasible, resulting in a low COE of 0.16 €/kWh.

Comparisons between renewable energy sources have been explored by different research groups. Luta and Raji [142] found a wind-hydrogen storage system with a fuel cell less economically competitive than a hybrid PV-wind-fuel cell system in South Africa (394 MWh/year). Grid extension was considered a more viable option if kept under a certain distance, although it poses challenges related to reliance on non-renewable energy.

Mudgal et al. [143] assessed a combination of PV, wind, and biogas systems to meet the electricity demand in India (64.4 MWh/year). The optimal configuration included a 12-kW PV system, a 3-kW wind turbine, and a 15-kW biogas generator, yielding a low COE of 0.10 €/kWh. However, the economic evaluation did not specify the inclusion of feedstock costs for the biogas generator.

While these studies showcase the diverse approaches to integrating technologies for energy systems, there is a notable gap in research on the energy consumption of tiny houses, an area that warrants further investigation.

2.2.4. Constructing smaller

It is crucial to identify the elements shaping energy consumption, with two main parameters significantly influencing it. The first factor is the behavior of residents, equally important as the second factor encompassing technical issues and equipment [144] [145] [146]. Consequently, residents' lifestyle and behaviors directly impact their environmental footprint [147]. Behaviors like purchasing second-hand goods, recycling materials, choosing the size and location of the house, and the level of environmental concern among residents play a pivotal role [148].

Often attributed to culture, this mindset implies that lifestyle has the capacity to directly influence and shape culture. Tiny houses embody a lifestyle that transforms conventional living on individual and social levels, leading to cultural modifications [149] [150]. They introduce a smaller and simpler way of living [151], addressing fundamental home needs intentionally and sustainably [152]. Generally, tiny houses provide an affordable housing solution by challenging consumerism and enhancing overall well-being [153] [154] [155] [156].

Regarding the second factor, technical issues contribute to reducing energy consumption in various ways. The smaller size of tiny houses requires less energy for heating and cooling, and strategically positioned openings fulfill lighting needs [157]. In some cases, a few solar panels can meet energy requirements, excluding winter. Additionally, limited space discourages the installation of energy-consuming appliances, promoting the use of public facilities when feasible [149].

The issue of consumption is complex, influenced by aspects such as culture and income levels [91]. However, focusing on the housing area's impact on energy consumption, it's essential to recognize that consumption of fossil fuels is a major contributor to greenhouse gas emissions.

Therefore, efforts to reduce energy consumption can mitigate harmful environmental effects. Despite fewer studies on the energy consumption of tiny houses compared to traditional homes, their potential environmental benefits, driven by a focus on sustainability, can contribute positively to popularizing this lifestyle.

In summary, understanding the factors influencing energy consumption, including resident behavior and technical considerations in tiny houses, sheds light on the potential for sustainable living practices.

4. GAPS AND CHALLENGES

The existing landscape of research on tiny houses underscores significant gaps and challenges, particularly in the limited number of academic studies dedicated to energy consumption and sustainable design for these compact dwellings. Many of the current studies heavily rely on field measurements and personal experiences, lacking a robust academic foundation. This deficiency in scholarly investigations hampers our understanding of the nuanced aspects of energy efficiency in tiny houses.

Moreover, there is a notable research gap in addressing design considerations for tiny houses across all climate zones in the United States. While several studies focus on specific regions or climates, a comprehensive exploration of designing for diverse climatic conditions is conspicuously absent. The present study, cantered around a couple with significant outdoor activities during the day, introduces a unique perspective. However, it is essential to acknowledge that the analysis of a high number of cases may lead to the oversight of critical factors, especially regarding daylight considerations. The prevalence of outdoor activities for the couple may diminish the importance of daylight-related analyses, emphasizing the need for a more nuanced understanding of design implications and energy dynamics in the context of different tiny house occupants and usage patterns.

As researchers continue to explore the intricacies of tiny house living, addressing these gaps will be crucial in developing comprehensive guidelines for energy-efficient and sustainable tiny house design that cater to diverse climates and lifestyles. A more rigorous academic foundation and a holistic approach to climatic considerations will contribute significantly to advancing our knowledge in this area.

5. PROJECT AIMS AND IMPACTS

Presently, the world is grappling with an air pollution crisis primarily fuelled by the consumption of fossil fuels. Among its primary contributors, the construction sector, particularly housing, stands out as one of the most energy-consuming sectors, exacerbating this crisis. Consequently, the Paris Convention places significant emphasis on the sustainability of housing [17]. Within the housing sector, the distribution of carbon dioxide emissions is as follows: 4% for cooking, 60% for heating, and 20% for heating water [18].

The consumption of fossil fuels stands as a primary contributor to greenhouse gas emissions, and as a result, significant emphasis has been placed on reducing energy consumption to mitigate a multitude of adverse environmental impacts. Nevertheless, the existing body of research on the energy consumption of tiny houses falls far short of what is necessary to address this crucial issue.

Identifying the factors that influence energy consumption is crucial. Typically, two primary parameters exert a significant impact on energy usage. The first factor relates to the behavior of residents, which is equally vital and influential as the second factor encompassing technical aspects and equipment [19] [20] [21]. Consequently, the lifestyle and habits of residents have a direct bearing on their environmental footprint [22]. These behaviors, which encompass activities such as buying second-hand items, recycling materials, considering the size and location of the house, and gauging the level of environmental consciousness among residents, play a pivotal role in this context [23].

In many cases, this mindset is closely associated with culture, suggesting that lifestyle has the power to directly impact and create culture. Tiny houses exemplify a lifestyle that reshapes the traditional way of life at both the individual and societal levels, ultimately resulting in cultural changes [24] [25]. Tiny houses introduce individuals to a more compact or straightforward way of existence [26], all the while meeting the basic requirements of a home in a more deliberate and sustainable fashion [27]. Broadly speaking, tiny houses offer a solution for affordable housing [28], challenging consumerism [29], and enhancing overall well-being [30] [31].

As for the second factor, which encompasses technical considerations, it can play a pivotal role in reducing energy consumption through various means. The compact size of tiny houses requires less energy for heating and cooling, while strategically placed openings can effectively provide natural lighting [32]. In certain instances, the installation of just four solar panels may be adequate to meet energy needs (excluding winter). Additionally, the constrained space may make it impractical to install appliances like washing machines, thereby promoting the use of public facilities whenever possible [24].

Tiny houses hold the potential to decrease the use of natural gas for purposes such as heating, water heating, and cooking [33]. In recent years, the tiny house movement has gained momentum in numerous countries and cities, owing to its attributes, including low energy consumption, affordability, minimal adverse environmental effects, and the sense of independence it offers [34] [35] [36].

The current crises emphasize the significance of directing attention towards both the phenomenon of tiny houses and sustainable buildings. This research endeavors to amalgamate these two aspects into a unified project through the introduction of a sustainable tiny house. The incorporation of multiple climates into this study is imperative to ensure the applicability of its findings across various environmental conditions. Additionally, it is crucial for designers and manufacturers to gain insights into the most effective systems under diverse environmental circumstances.

The outcomes of this investigation can serve as a valuable resource for a wide-ranging audience, encompassing researchers, by shedding light on the advantages and necessity of tiny houses. It can furnish builders and designers with a comprehensive guide on achieving sustainability in their constructions tailored to specific climates. The findings will also enable comparisons of cases with different orientations, window-to-wall ratios (WWR), and insulation thicknesses within the same climate, showcasing their energy-generating capabilities.

This research aims to investigate the following key research questions:

Is it possible to design and construct net-zero energy tiny houses in all climates, or are such designs only viable in specific climatic conditions?

What is the correlation between the thickness of insulation and energy consumption in tiny houses?

To what extent can PV (photovoltaic) cells contribute to supplying energy consumption in net-zero energy tiny houses?

What window-to-wall ratio offers the optimal balance between utilizing natural daylight and minimizing energy consumption in tiny house designs?

6. SIGNIFICANCE

The current global landscape, marked by crises such as unaffordable housing, rapid population growth, ozone layer depletion from excessive fossil fuel consumption, and the rise in homelessness due to natural disasters, underscores the need for alternative housing solutions. Tiny houses and sustainable buildings emerge as inevitable alternatives to traditional large, high-consumption structures. Despite their potential, many remain unaware of the significant benefits offered by tiny houses. This lack of awareness can be attributed, in part, to the absence of comprehensive studies on the energy optimization of tiny houses that can be widely applied.

This research addresses the crucial gap in knowledge by simulating the performance of a sample tiny house, aiming to provide generalizable results. The absence of design guidelines further complicates the construction of tiny houses, leaving builders uncertain about material selection, design priorities, and suitable parameters for different climates. The research not only fills this void but also contributes to raising awareness about the potential of tiny houses to establish sustainable buildings.

By conducting this research, readers will gain a deeper understanding of how tiny houses can contribute to sustainable living. The research aims to offer practical guidance for the design and construction of tiny houses, serving as a handbook for builders and designers. This step is crucial for advancing the Tiny House Movement, as increased awareness of the benefits of tiny houses is likely to drive a greater adoption of this housing type.

Moreover, the research explores the potential of photovoltaic (PV) cells for electricity generation in different climates. By demonstrating the effectiveness of PV cells in diverse environmental conditions, the research provides valuable insights for designers and builders. This information can inform decisions on incorporating solar technology into tiny house designs, further enhancing their sustainability.

In summary, conducting this research represents a significant stride for the Tiny House Movement. It not only addresses the lack of comprehensive studies on energy optimization but also provides practical design guidelines and highlights the potential of PV cells. Ultimately, the research contributes to creating a more sustainable and widely embraced housing solution for the challenges of the modern world.

7. HYPOTHESIS

• Climatic Influence: The first hypothesis suggests that designing net-zero tiny houses may not be feasible in all climates. Specifically, in regions characterized by intense climates such as 1A (very hot and humid), 2A (hot and humid), and 1B (very hot and dry), the energy consumption required for maintaining thermal comfort, including heating, cooling, and lighting, may exceed the electricity generation capacity of the tiny house integrated PV cells.

• Insulation Impact: The hypothesis posits that the relationship between insulation thickness and energy consumption will vary significantly across different climates. In colder climates, increasing insulation thickness is expected to have a more pronounced effect on reducing energy consumption, as it aids in heat retention. Conversely, in warmer climates, the impact of insulation thickness on energy consumption may be less pronounced due to the emphasis on cooling rather than heating. The hypothesis suggests that the optimal insulation thickness may differ according to specific climatic conditions, playing a critical role in achieving energy efficiency in tiny house designs.

• Orientation Optimization: The third hypothesis suggests that the effectiveness of solar power production in tiny houses is significantly influenced by the orientation of photovoltaic (PV) panels and will vary depending on the geographical location and climate. In regions with higher solar insolation, such as those closer to the equator, a south-facing orientation for PV panels is expected to yield optimal solar energy generation. Conversely, in regions with lower solar insolation or extreme seasonal variations, the effectiveness of different orientations may vary, necessitating the need for climate-specific recommendations to maximize solar power production in tiny houses.

• Window-to-Wall Ratio: The fourth hypothesis explores the relationship between the window-to-wall ratio and energy consumption. It posits that the optimal window-to-wall ratio in tiny house design varies across different climates. Climate conditions significantly influence the ideal ratio for balancing natural daylight utilization while effectively managing heat gain and heat loss.

8. OBJECTIVES

The research aims to address the following key objectives:

Measuring the Net Zero Energy Potential: Evaluate and measure the net zero energy potential of tiny houses by implementing strategies focused on reducing energy consumption.

Identification of Optimal Design Parameters: Identify and establish optimal design parameters, including orientation, window-to-wall ratio, and R-value, to enhance the energy efficiency of tiny houses.

Efficiency of PV Cells: Compare the efficiency of photovoltaic (PV) cells in different arrangements to determine the most effective configuration for electricity generation in tiny houses.

Impact of Shading: Investigate the impact of shading on the generated electricity in various cities, considering different geographical locations and climates.

Cities with Highest Potential: Determine and rank cities based on their potential for generating electricity through PV cells, considering factors such as solar insolation and climate variations.

Formula for Net Zero Tiny House Design: Develop a comprehensive formula or set of guidelines for designing net zero energy tiny houses tailored to different climates, incorporating the identified optimal design parameters.

By achieving these objectives, the research aims to contribute valuable insights and practical guidance for designing and constructing energy-efficient and sustainable tiny houses across diverse environmental conditions.

9. VARIABLES

9.1. Independent variables

- Building orientation (for building and PV cells)
- Window to wall ratio
- Thickness of insulation
- Climate zones (cities) including:

    1A Miami, FL

    2A Houston, TX

    2B Pheonix, AZ

    3A Charlotte, NC

    3B Los Angeles, CA

    3C San Francisco, CA

    4A Washington, DC

    4B Albuquerque, NM

    4C Seattle, WA

    5A Boston, MA

    5B Denver, CO

    6A Minneapolis, MN

    7A Fargo, ND

    7B Jackson, WY

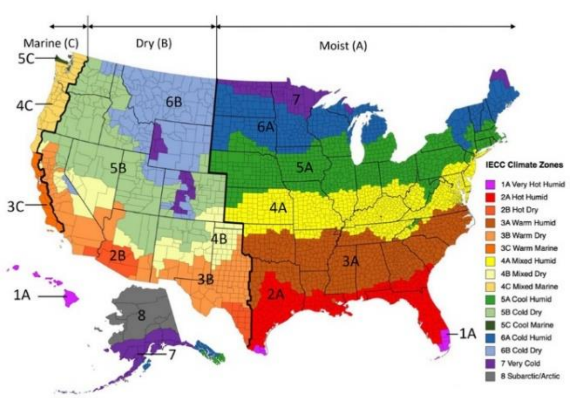
9.2. Dependant Variables

- Energy consumption
- Generated electricity.

10. METHODOLOGY

The objective of this research is to conduct a comprehensive simulation study employing Design Builder software [158] to evaluate and analyze distinct scenarios involving varying window-to-wall ratios, climate zones, orientations, and insulation thicknesses, as well as the configuration of PV cells. Design Builder was selected as the simulation tool due to its robust capabilities in building performance analysis and its adaptability to different parameters influencing the energy consumption and CO_2 emissions of tiny houses [158].

This study adopts a quantitative, simulation-based methodology, focusing on the performance analysis of tiny houses under diverse conditions using Design Builder. The simulation encompasses a 24m² single-zone tiny house situated in 15 different cities, each representing distinct climates (Figure 1). Occupied by a young couple, the tiny house utilizes electricity for heating and cooling. Lighting specifications and glazing types are determined in accordance with ASHRAE 90.1 2016 standards [158].



Num	City	State	Climate	Population	Average rent
1	Miami	FL	1A	439,890	$2,438
2	Houston	TX	2A	2.288 million	$1342
3	Phoenix	AZ	2B	1.625 million	$1,319
4	Charlotte	NC	3A	879,709	$1,670
5	Los Angeles	CA	3B	3.849 million	$2,418
6	San Francisco	CA	3C	815,201	$3336
7	Washington DC		4A	712,816	$2,401
8	Albuquerque	NM	4B	562,599	$1320
9	Seattle	WA	4C	733,919	$2260
10	Boston	MA	5A	654,776	$3,500
11	Denver	CO	5B	711,463	$2000
12	Minneapolis	MN	6A	425,336	$1680
13	Billings	MT	6B	117,445	$1,404
14	Fargo	ND	7	126,748	$ 1,006
15	Fairbanks	AK	8	32,702	$1,063

Figure 1- investigated cities and their properties.

The decision to utilize Design Builder as the primary simulation tool is based on its userfriendly interface, advanced simulation capabilities, and versatility across various building types. Notably, its capacity to model energy consumption, CO2 emissions, and energy generation aligns seamlessly with the objectives of this research (Figure 2).95

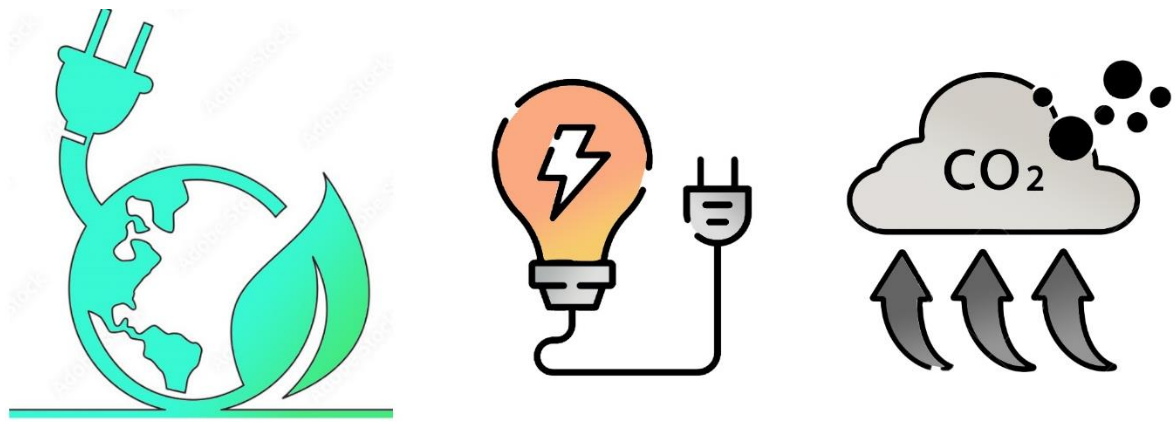


Figure 2- different metrics of this study.

Assumptions are integrated into the modelling process to facilitate simulation coherence. These include the consistent use of materials across all climates for the tiny house and the young couple's absence from the dwelling between 7 AM and 5 PM on weekdays, with weekends marked as home-stay periods.

Input data for the simulation are derived from EPW climatic files provided by the software, with the accuracy of the simulation model contingent upon the reliability of this input data.

The simulation model is meticulously developed in Design Builder by incorporating the collected data. This involves creating a precise representation of the building geometry, defining thermal zones, and assigning materials. The model undergoes iterative refinement to ensure a high level of accuracy.

Simulations are executed using Design Builder, with parameters tailored to each defined scenario. The simulations span one year to comprehensively capture both short-term and long-term effects on performance. This temporal scope enables a holistic understanding of the tiny house's behaviour under diverse conditions.

One of the investigated parameters is the window-to-wall ratio (WWR). Figure 3 shows the investigated cases in the range of 10% to 90%. Based on the literature review, WWR has a significant impact on the energy consumption and CO2 emissions of a building.

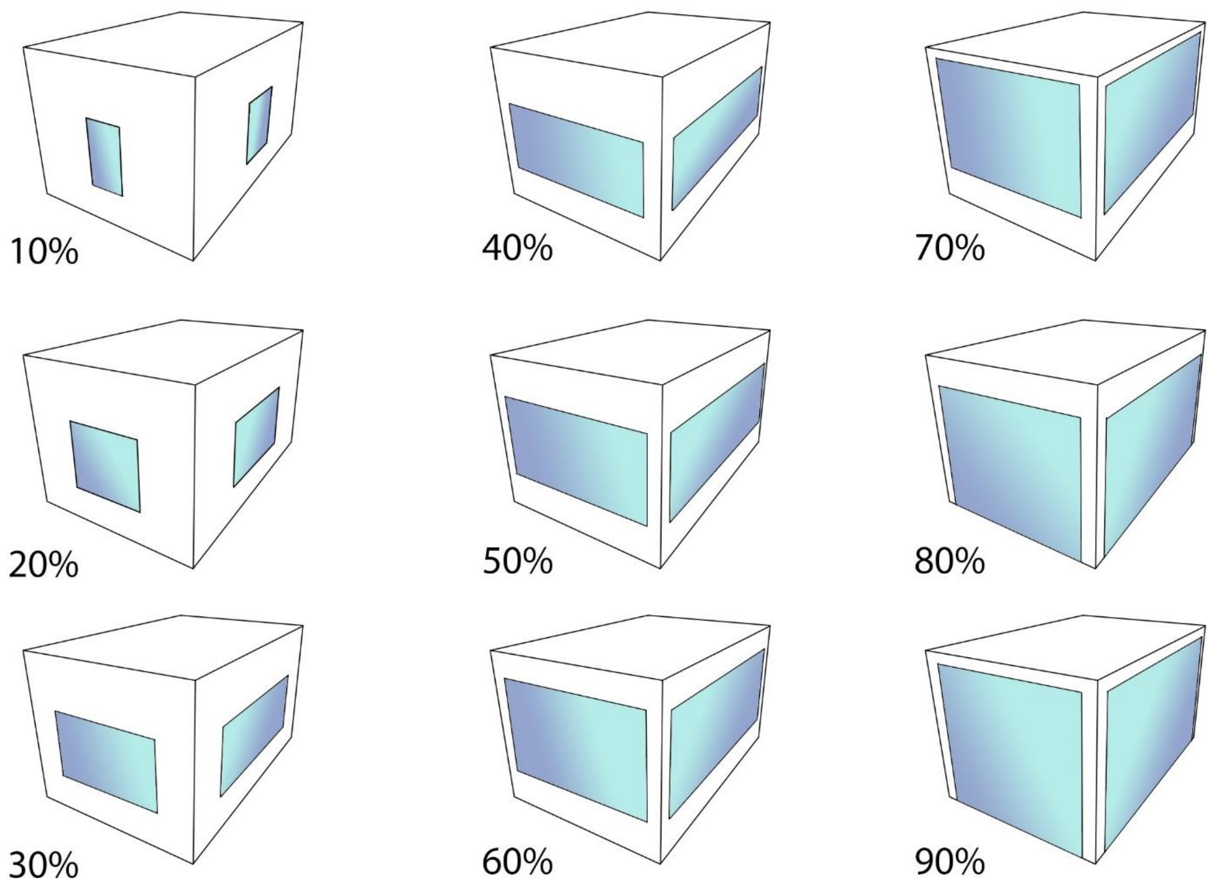


Figure 3- The investigated WWRs in this study.

Moreover, different orientations are studied here (Figure 4). Due to the direction of sun rays and differences in receiving daylight and solar heat gain, orientation plays a key role in heating load, cooling load, and lighting load. Therefore, two orientations (north-south and east-west) are investigated.

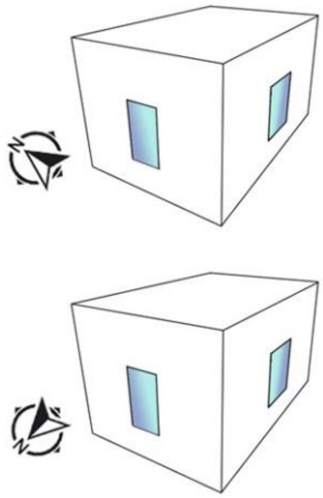


Figure 4- different investigated orientations.

Also, insulation thickness is an effective parameter on the energy performance of the building. Mycelium-based material is considered as the material for insulating the building with three different thicknesses. Its properties are used to calculate the required thickness as follows:

R-10 = 0.07 * 10 = 0.7 in = 1.78 cm

R-20 = 0.07 * 20 = 1.4 in = 3.56 cm

R-30 = 0.07 * 30 = 2.1 in = 5.33 cm

In this regard, according to the mentioned points, the parameters include WWR, orientation, different cities, and insulation thicknesses. As a result, 810 cases were investigated in this study (Figure 5).

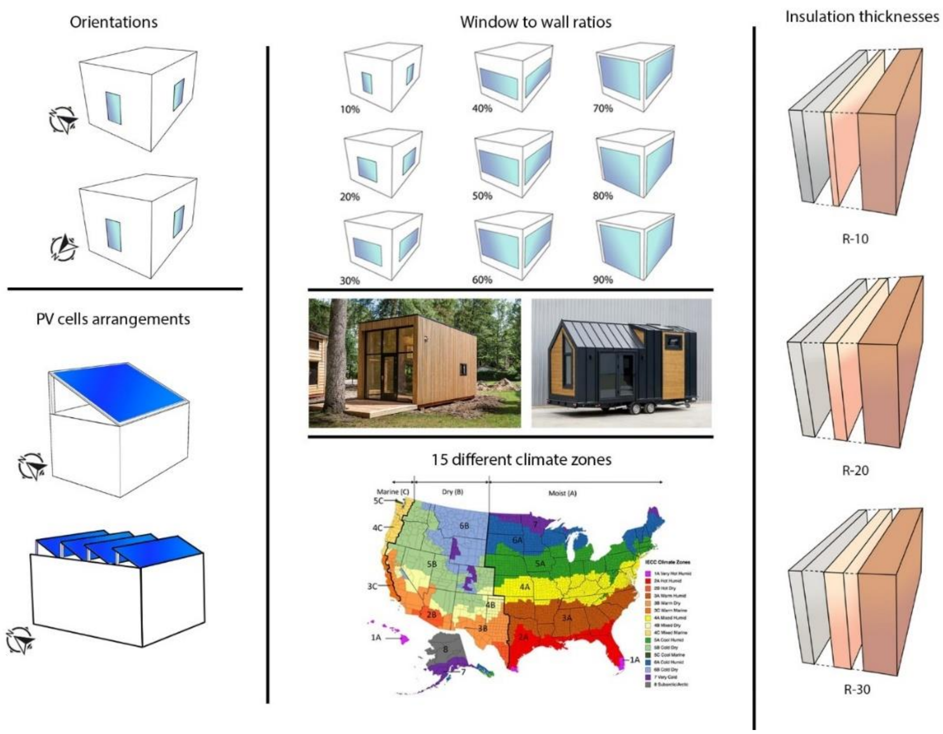


Figure 5- Summary of investigated parameters.

In summary, the simulation setting is depicted in Figure 6. This methodology outlines a systematic approach to conducting a simulation study utilizing Design Builder software. The carefully chosen parameters, assumptions, and simulation settings contribute to a thorough exploration of the performance dynamics of tiny houses across varied climates and conditions. This study involves the utilization of 15 cities, representing 15 different climates across the United States. The United States has different climates, and this study attempts to select the most populous city of each climate.

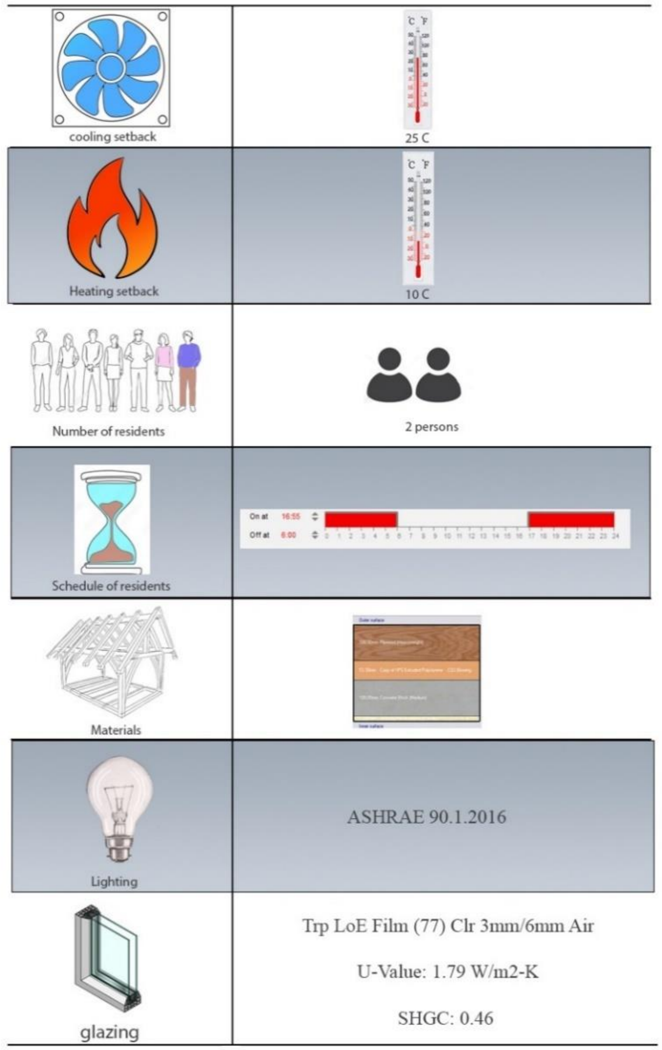


Figure 6- Used simulation setting.

10.1. Geometry

The definition of a tiny house can vary, and according to the 2018 North Carolina Residential Code, the maximum area for a tiny house is 400 square feet. For the purpose of sampling simulation and to streamline the simulation process, a 6m*4m room is utilized as a representation of a tiny house [159].

In the endeavour to design a sustainable tiny house incorporating innovative elements such as mycelium, photovoltaic cells, and a thoughtful consideration of the window-to-wall ratio, the geometry of the building plays a crucial role. The compact dimensions of 6 by 4 units not only embody the concept of a "tiny house" but also pose a unique challenge and opportunity for optimizing spatial efficiency and resource utilization. The modest footprint underscores a commitment to minimalism, aligning with the principles of sustainable design.

This specific geometry requires a careful balance in placing mycelium-based materials for insulation and structural support, strategic integration of photovoltaic cells to efficiently harness renewable energy, and a meticulous approach to the window-to-wall ratio to maximize natural light and ventilation while minimizing energy consumption. The geometric parameters, combined with the chosen sustainable features, showcase a holistic approach to designing a compact, environmentally conscious dwelling that embodies both functionality and ecological responsibility.

11. RESULTS

11.1. 1A Miami, FL

Table 3 displays the energy consumption for all 54 cases in Miami. The cells marked in green signify that the energy consumption is lower than the generated electricity, indicating that the tiny house achieves zero energy. The unit for these values is kWh.

Table 3- Energy consumption (kWh) of all cases in Miami.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	1877.917	1786.952	1713.378	1934.305	1825.45	1743.344
20	2240.991	2181.769	2132.897	2348.59	2280.771	2228.102
30	2551.728	2517.725	2487.501	2703.495	2667.003	2636.171
40	2807.479	2791.759	2774.958	2991.625	2977.823	2962.504
50	2989.614	2996.933	2989.149	3213.965	3215.305	3210.249
60	3112.668	3117.312	3115.847	3356.875	3367.836	3369.174
70	3171.618	3179.357	3180.869	3435.049	3450.316	3455.548
80	3174.849	3184.006	3186.732	3454.773	3470.606	3477.488
90	3114.717	3122.273	3124.859	3407.27	3420.471	3426.809
Generation	5797.787	5797.787	5797.787	5268.548	5268.548	5268.548

Table 4 illustrates the CO2 emissions for all cases. Since the consumed energy in all instances is less than the generated electricity, all numbers are negative. The green color indicates that these cases are zero-emission.

Table 4- Carbon emissions (Kg) of all cases in Miami.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-2478.564	-2536.082	-2582.604	-2108.268	-2177.098	-2229.014
20	-2248.989	-2286.437	-2317.339	-1846.312	-1889.194	-1922.498
30	-2052.509	-2074.009	-2093.119	-1621.903	-1644.977	-1664.473
40	-1890.795	-1900.735	-1911.358	-1439.716	-1448.443	-1458.13
50	-1775.63	-1771.001	-1775.924	-1299.129	-1298.282	-1301.478
60	-1697.821	-1694.885	-1695.812	-1208.766	-1201.835	-1200.989
70	-1660.547	-1655.654	-1654.698	-1159.336	-1149.682	-1146.374
80	-1658.504	-1652.714	-1650.99	-1146.864	-1136.853	-1132.501
90	-1696.526	-1691.748	-1690.113	-1176.901	-1168.553	-1164.546

Figure 7 compares the energy consumption across different window-to-wall ratios, east-west orientation, and R-10 insulation. As depicted in the figure, PV cells can adequately supply the required energy for all ratios. Notably, the highest energy consumption occurs with an 80% window-to-wall ratio, while the lowest energy consumption is observed at a 10% ratio, representing the best-case scenario. Specifically, the annual energy consumption for a 10% window-to-wall ratio is 1877.917 kWh, whereas for an 80% ratio, it rises to 3174.849 kWh. The substantial difference between these two cases highlights a 78% increase in energy consumption when the ratio is increased from 10% to 80%.

It's important to note that the PV cells generate 5797.787 kWh of electricity, exceeding the highest energy consumption of 3174.849 kWh. This surplus implies that residents can potentially sell 2,622.938 kWh of electricity throughout the year.

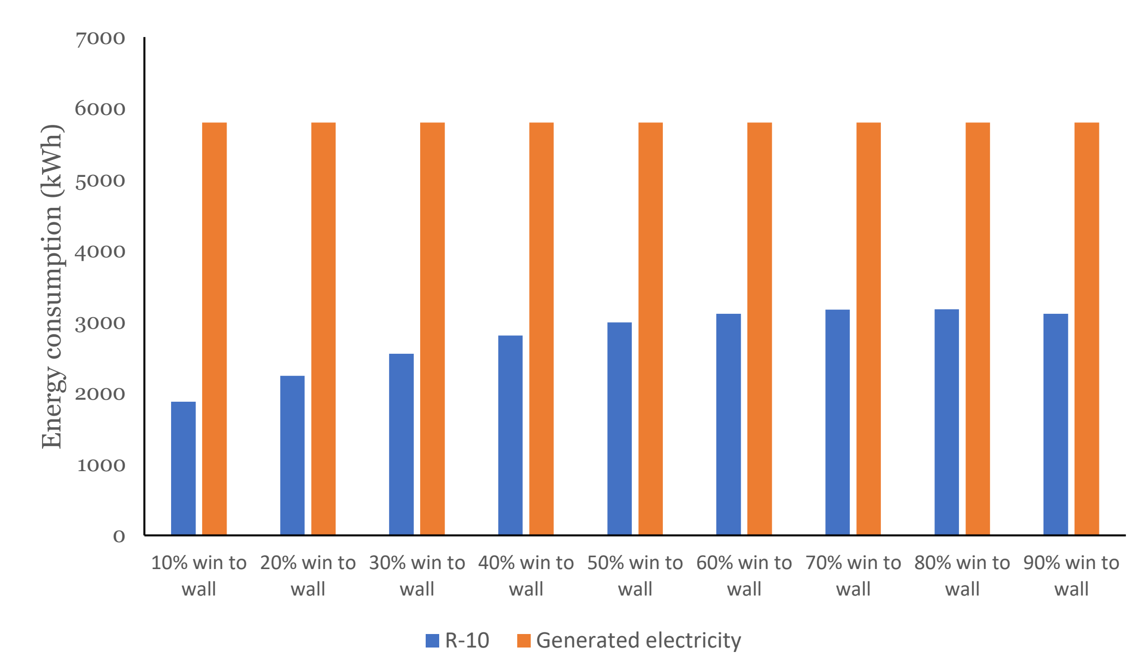


Figure 7- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Miami.

Figure 8 presents an analysis of energy consumption variations across different window-to-wall ratios, east-west orientations, and R-20 insulation levels. The results indicate that PV cells effectively meet energy demands in all scenarios. Significantly, the scenario with an 80% window-to-wall ratio exhibits the highest energy consumption, while the 10% ratio records the lowest annual consumption at 1786.952 kWh. The contrast is notable, with the 80% ratio showing a substantial annual consumption of 3184.006 kWh—a 78% increase compared to the 10% ratio.

It's crucial to highlight that the PV cells generate a total of 5797.787 kWh of electricity, surpassing the highest recorded energy consumption of 3184.006 kWh. Consequently, residents have the potential to sell 2613.781 kWh of surplus electricity throughout the year.

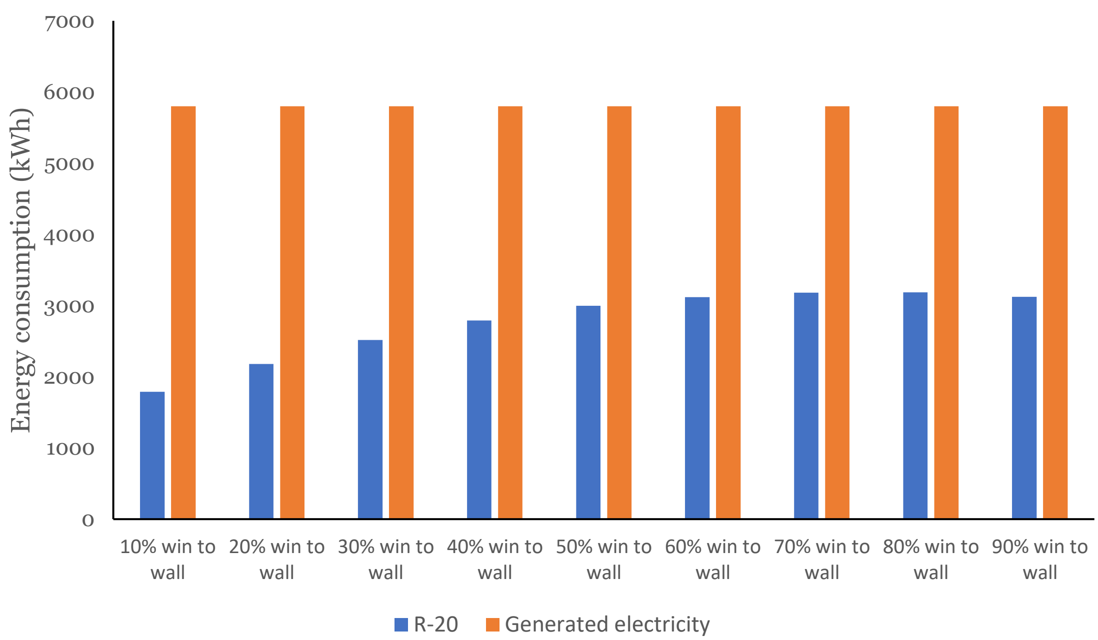


Figure 8- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Miami.

In the context of Figure 9's analysis, the study explores various scenarios to outline energy consumption variations across different window-to-wall ratios, east-west orientations, and R-30 insulation levels. Results from the study underscore the effectiveness of photovoltaic (PV) cells in meeting energy demands in these diverse scenarios. Notably, the 80% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio exhibits the lowest annual consumption at 1713.378 kWh. This discrepancy is substantial, as the 80% ratio demonstrates a significantly higher annual consumption of 3186.732 kWh, marking an 85% increase in energy consumption during the transition from a 10% to an 80% window-to-wall ratio.

Moreover, the PV cells generate a total of 5797.787 kWh of electricity, surpassing the peak energy consumption recorded at 3186.732 kWh. As a result, residents have the potential to sell 2,611.055 kWh of surplus electricity throughout the year. This detailed examination of the graph provides insights into the intricate interplay between window-to-wall ratios and energy consumption, highlighting the pivotal role of PV cells in meeting diverse energy requirements within architectural contexts.

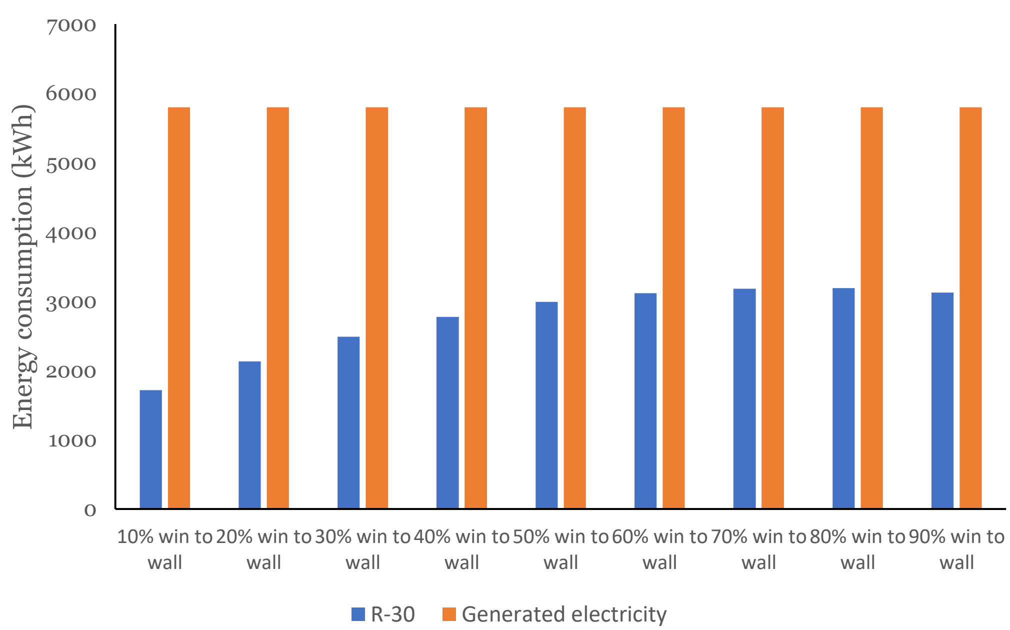


Figure 9- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Miami.

Figure 10 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. The results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges, with the 80% window-to-wall ratio linked to the highest annual energy consumption at 3454.773 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 1934.305 kWh. The significant disparity between these extremes, revealing a 79% increase in energy consumption during the transition from a 10% to an 80% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, generating a total of 5268.548 kWh of electricity, surpassing the peak energy consumption recorded at 3454.773 kWh. This surplus electricity generation implies a notable potential for residents to contribute to the energy grid, with the possibility of selling 1,813.775 kWh of excess electricity throughout the year. This dual revelation not only highlights the capability of PV cells to offset energy demand but also presents a tangible economic opportunity for residents. In essence, this detailed examination of the graph provides a holistic understanding of the intricate interplay between window-to-wall ratios and energy consumption, emphasizing the instrumental role of PV cells in meeting the diverse energy requirements inherent in various architectural contexts.

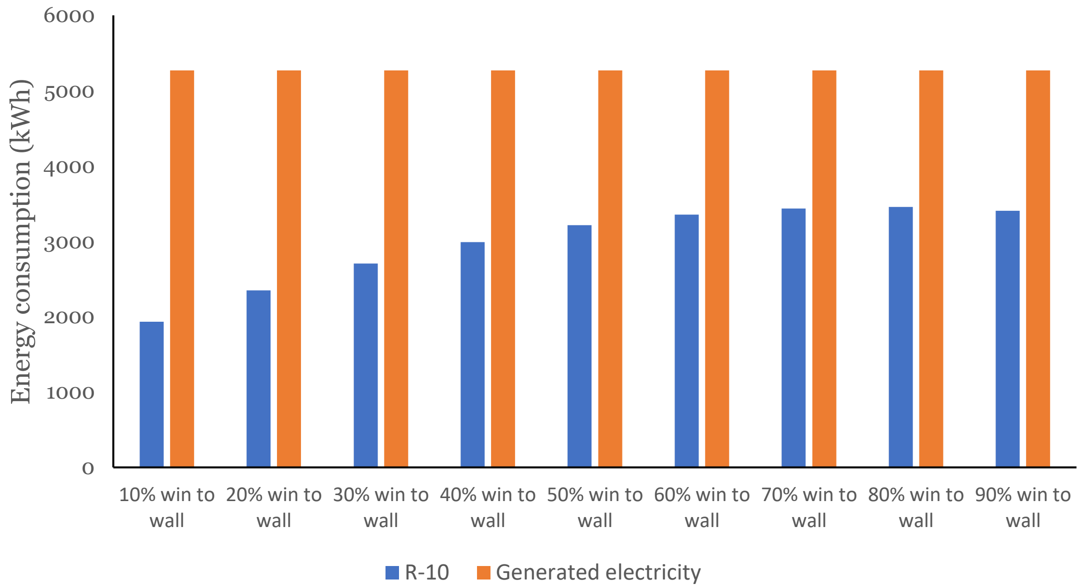


Figure 10- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Miami.

The annual energy consumption of the proposed tiny house, with a north-south orientation and R-20 insulation, is illustrated in Figure 11. In this orientation, photovoltaic panels are still facing south. According to this figure, the highest annual energy consumption occurs with an 80% window-to-wall ratio. In other words, the trend of changes in energy consumption is consistent with the previous orientation. The annual energy consumption in the worst case is 3470.606 kWh, and the annual energy consumption for the best case is 1825.45 kWh. This indicates that increasing the window-to-wall ratio from 10% to 80% can lead to a 90% increase in energy consumption.

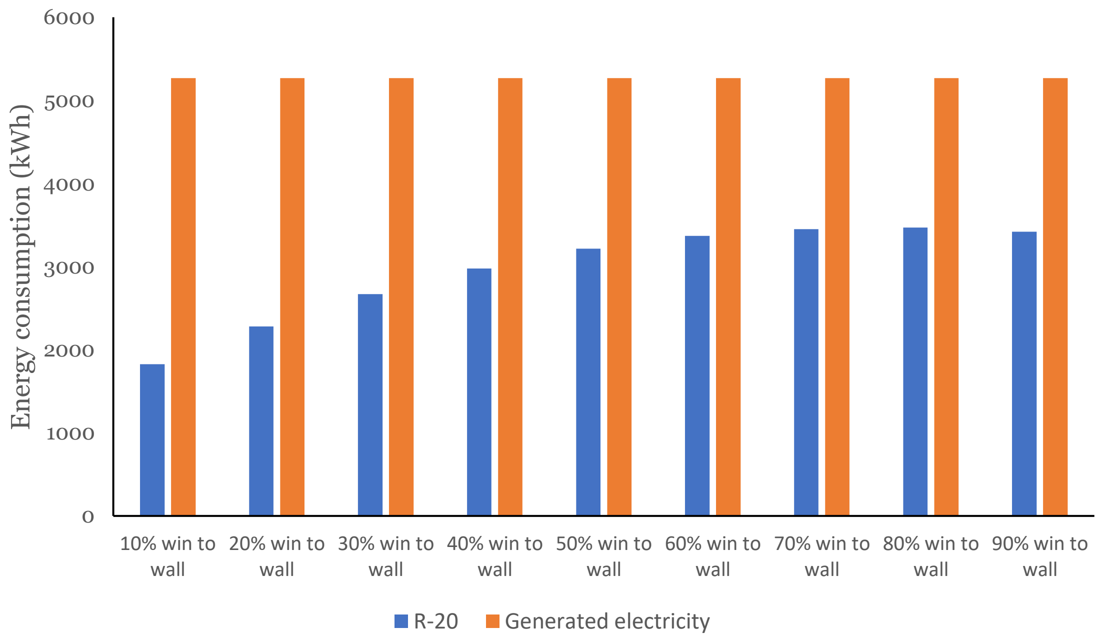


Figure 11- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Miami.

Figure 12 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with an 80% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 1743.344 kWh, whereas for an 80% window-to-wall ratio (worst case), it is 3477.488 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 80% results in a 99% increase in energy consumption. The amount of electricity supplied by PV cells is 5268.548 kWh. As mentioned before, the highest energy consumption is 3477.488 kWh. This means that the residents can sell 1,791.06 kWh of electricity during the year.

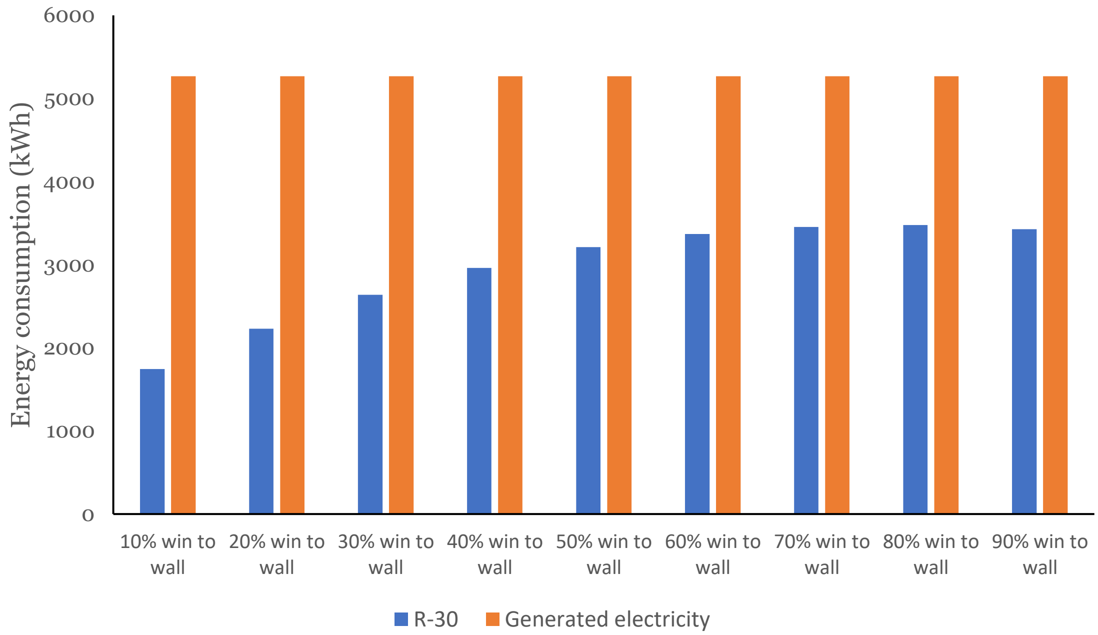


Figure 12- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Miami.

Figure 13 shows the energy consumption of the building with R-10 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 56.388 kWh in 10% window to wall, 224.351 kWh in 50% window to wall and 279.924 kWh in 80% WWR.

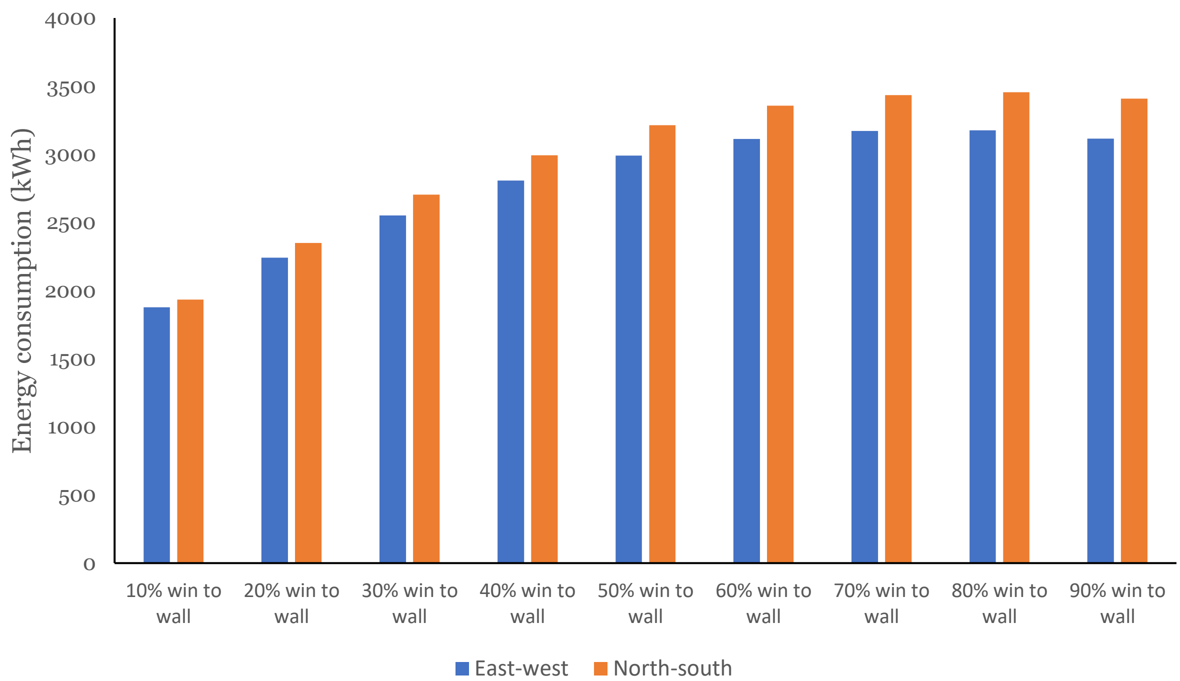


Figure 13- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Miami.

Figure 14 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 38.498 kWh in 10% window to wall, 218.372 kWh in 50% window to wall and 301.95 in 90% WWR.

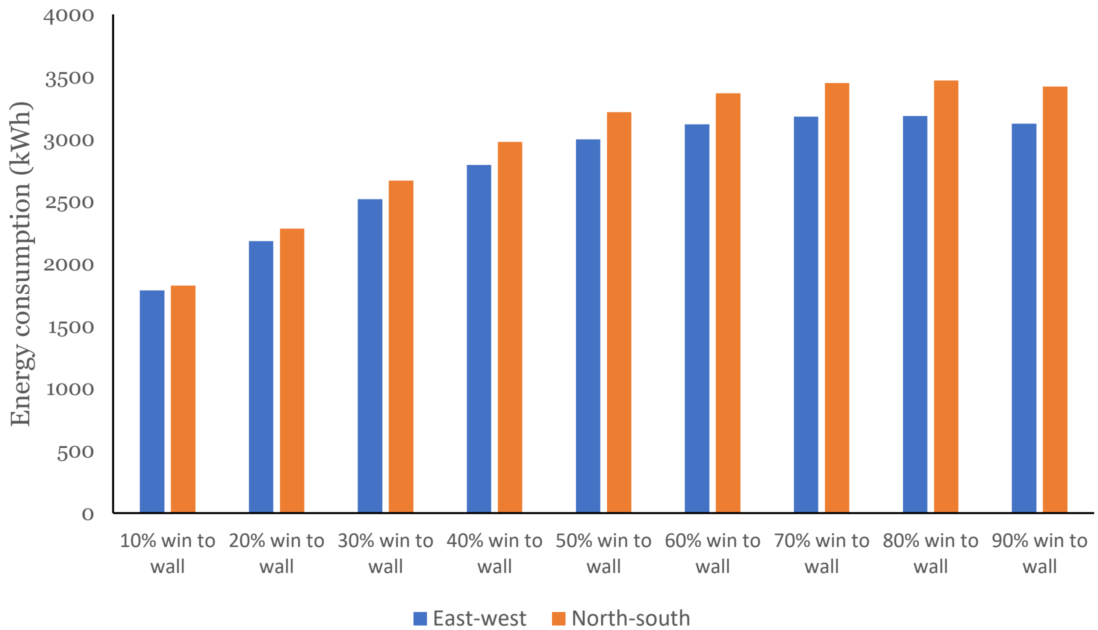


Figure 14- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Miami.

Figure 15 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 29.966 kWh in 10% window to wall, 221.1 kWh in 50% window to wall and 301.95 kWh in 90%.

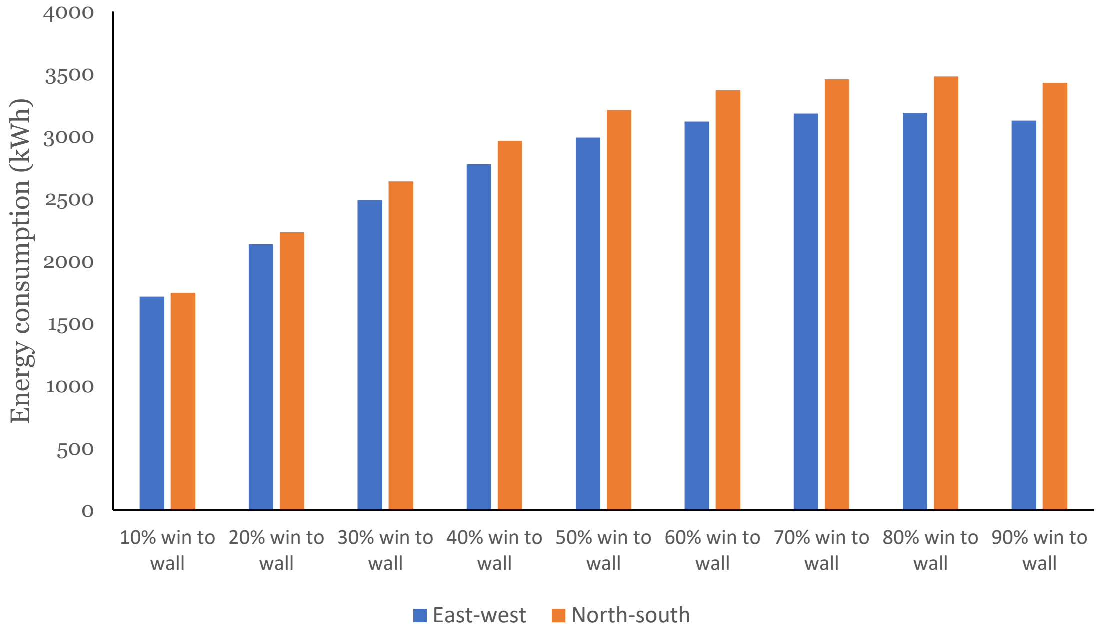


Figure 15- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Miami.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 16 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5797.787 kWh and for north-south orientation is 5268.548 kWh. In other words, the generated electricity in east-west orientation is 10% more than the generated electricity in north-south condition.

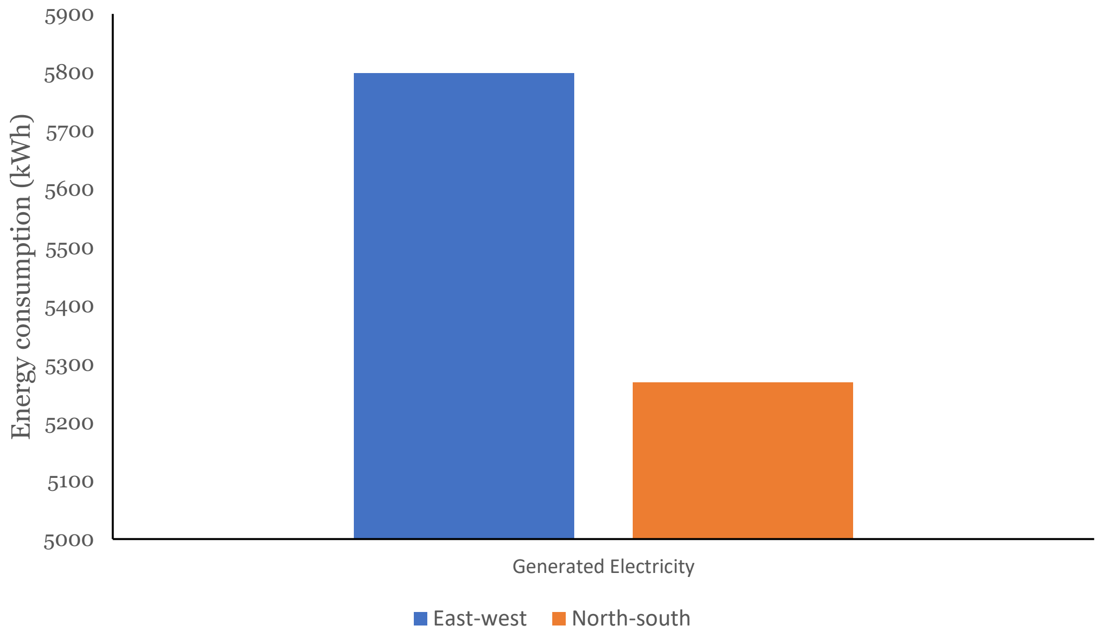


Figure 16- Generated electricity in different configurations of PV cells in Miami.

Figure 17 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10%-40% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 60%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

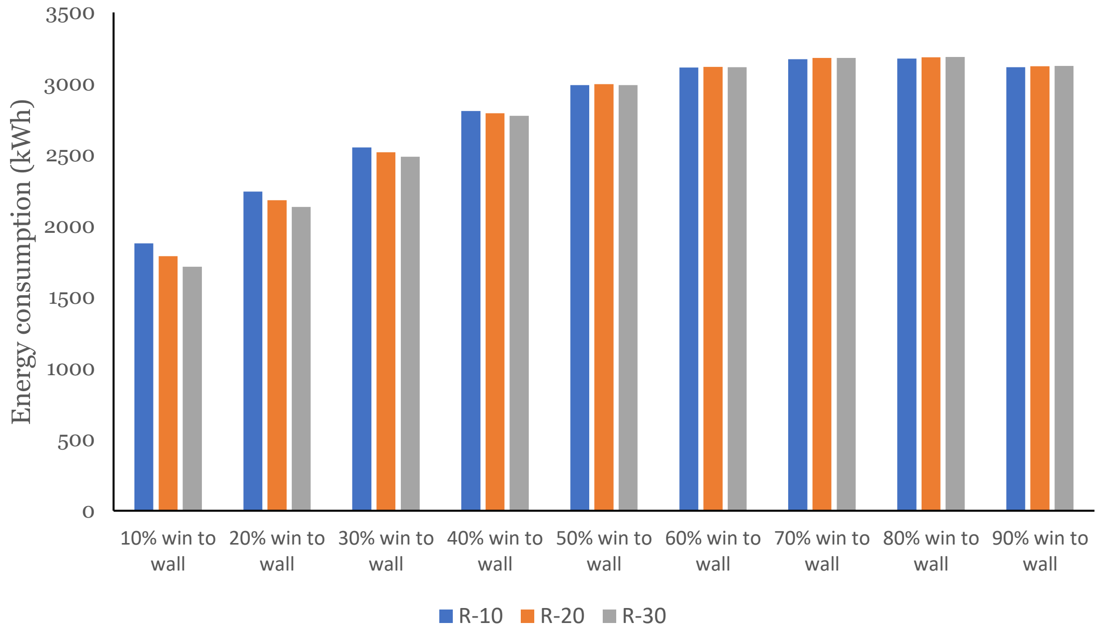


Figure 17- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Miami.

Figure 18 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10% -40% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 60% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.

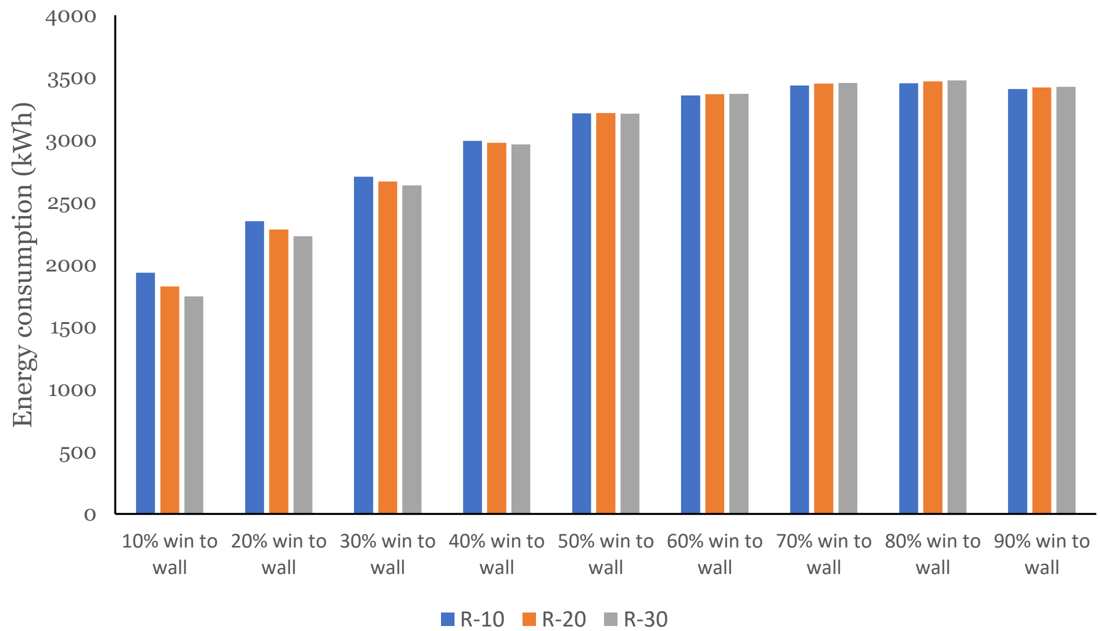


Figure 18- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Miami.

The CO2 Emissions for cases with east-west orientation is shown in figure 19 Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

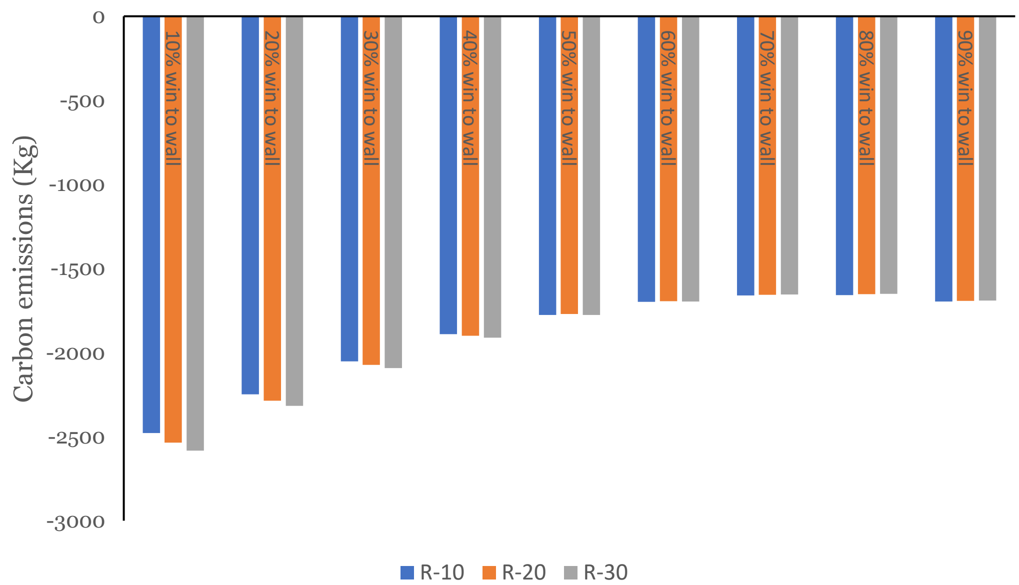


Figure 19- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Miami.

Figure 20 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

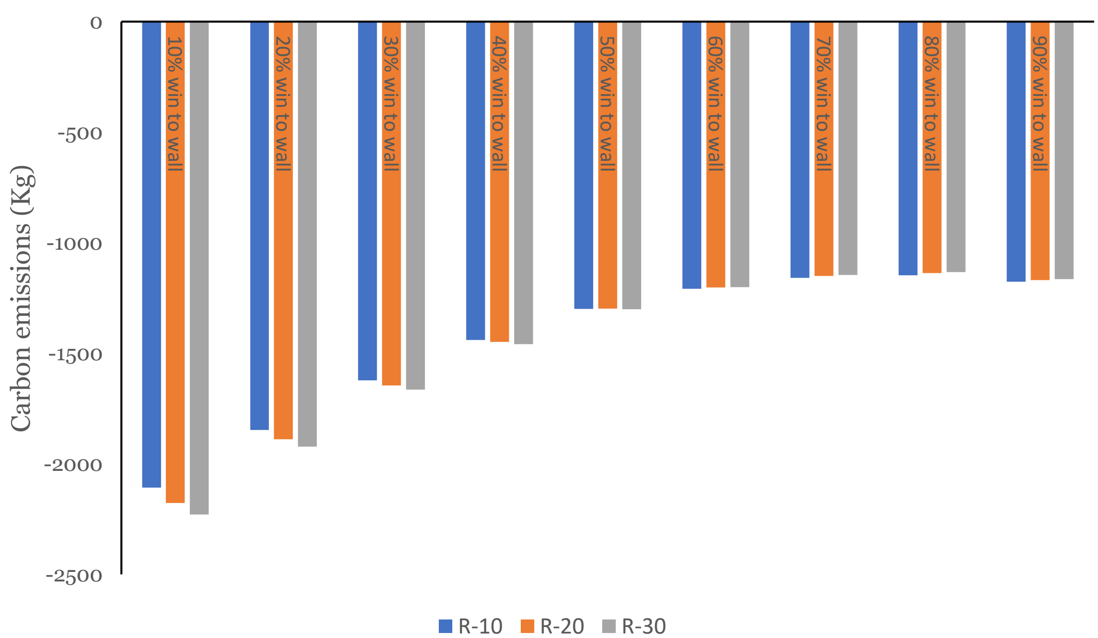


Figure 20- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Miami.

11.2. 2A Houston, TX

Displayed in Table 5 are the energy consumption details for all 54 cases in Houston. The cells highlighted in green within the table signify instances where energy consumption falls below the generated electricity, indicating that the respective tiny houses have achieved a net-zero energy status. The unit of measurement for these values is kilowatt-hours (kWh), providing a standardized basis for assessing the energy dynamics of each case. The green-highlighted cells visually underscore the successful balance between energy generation and consumption, showcasing the potential for net-zero energy outcomes within the unique context of tiny houses living in the Houston region.

Table 5- Energy consumption (kWh) of all cases in Houston.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	2450.814	2311.219	2200.565	2432.915	2266.691	2142.866
20	2594.025	2474.966	2379.403	2619.036	2481.245	2378.066
30	2741.599	2641.515	2559.769	2809.249	2698.728	2615.77
40	2884.081	2800.129	2731.357	2988.391	2902.412	2836.106
50	3004.021	2936.547	2879.552	3146.902	3080.766	3027.861
60	3102.746	3046.181	2997.998	3268.768	3217.825	3175.665
70	3183.469	3137.318	3096.48	3372.302	3331.718	3296.944
80	3245.802	3206.719	3170.629	3453.618	3420.592	3391.299
90	3293.883	3260.822	3229.499	3510.368	3482.159	3456.135
Generation	5224.847	5224.847	5224.847	4863.32	4863.32	4863.32

Table 6 details the CO2 emissions across all cases. As the energy consumed in each case is consistently less than the generated electricity, all numerical values in the table are negative. The incorporation of a green color scheme within the cells serves as a visual cue, highlighting instances where the cases exhibit zero-emission characteristics. This color-coded representation underscores the positive environmental impact of the tiny houses, emphasizing their contribution to a reduction in carbon footprint. The negative values, coupled with the green coloration, signify that the cases have effectively achieved a net-zero or even a carbon-negative status, reflecting a commendable commitment to sustainable and eco-friendly practices across the entirety of the cases examined.

Table 6- Carbon emissions (Kg) of all cases in Houston.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-1842.122	-1934.822	-2008.302	-1613.933	-1724.316	-1806.542
20	-1747.021	-1826.084	-1889.543	-1490.337	-1581.839	-1650.356
30	-1649.024	-1715.485	-1769.77	-1364.025	-1437.418	-1492.506
40	-1554.407	-1610.156	-1655.825	-1245.064	-1302.159	-1346.19
50	-1474.76	-1519.567	-1557.415	-1139.803	-1183.722	-1218.853
60	-1409.2	-1446.764	-1478.76	-1058.877	-1092.706	-1120.703
70	-1355.596	-1386.243	-1413.361	-990.1242	-1017.075	-1040.167
80	-1314.203	-1340.157	-1364.123	-936.1259	-958.05711	-977.5089
90	-1282.274	-1304.229	-1325.03	-898.4401	-917.1727	-934.4543

Figure 21 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 2450.814 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 3293.883 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 34% increase in energy consumption.

The amount of electricity supplied by PV cells is 5224.847 kWh. As mentioned before, the highest energy consumption is 3293.883 kWh. This means that the residents can sell 1,930.964 kWh of electricity during the year.

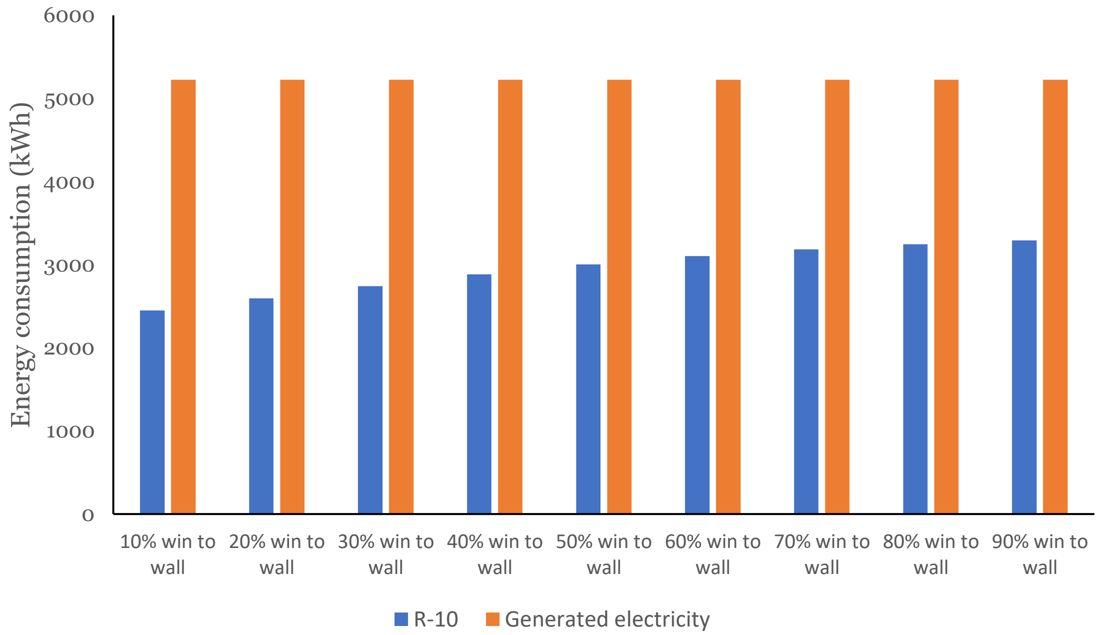


Figure 21- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Houston.

In all scenarios examined in Figure 22, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 2311.219 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 3260.822 kWh, translating to a noteworthy 41% increase in energy consumption when transitioning from a 10% to an 90% window-to-wall ratio.

The PV cells generate a total of 5224.847 kWh of electricity, surpassing the highest recorded energy consumption of 3260.822 kWh. Consequently, residents have the potential to sell 1,964.025 kWh of surplus electricity throughout the year.

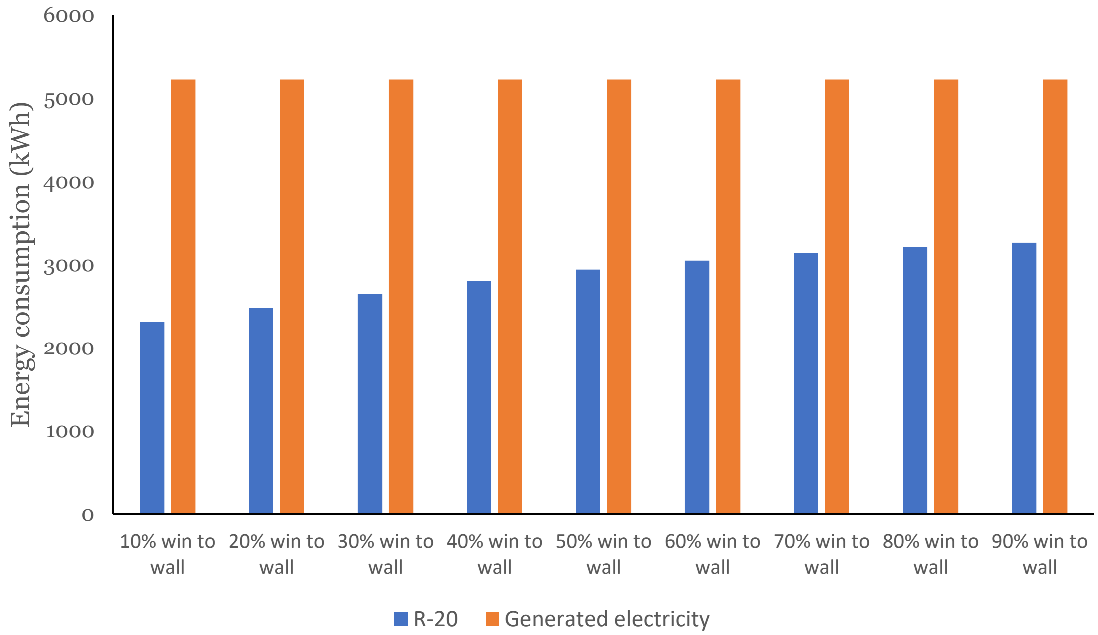


Figure 22- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 insulation (East-west) Houston.

Within the scope of Figure 23's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to effectively meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 2200.565 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 3229.499 kWh, reflecting a notable 46% increase in energy consumption during the transition from a 10% to a 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 5224.847 kWh of electricity, surpassing the peak energy consumption recorded at 3229.499 kWh. Consequently, residents possess the potential to sell 1,995.348 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

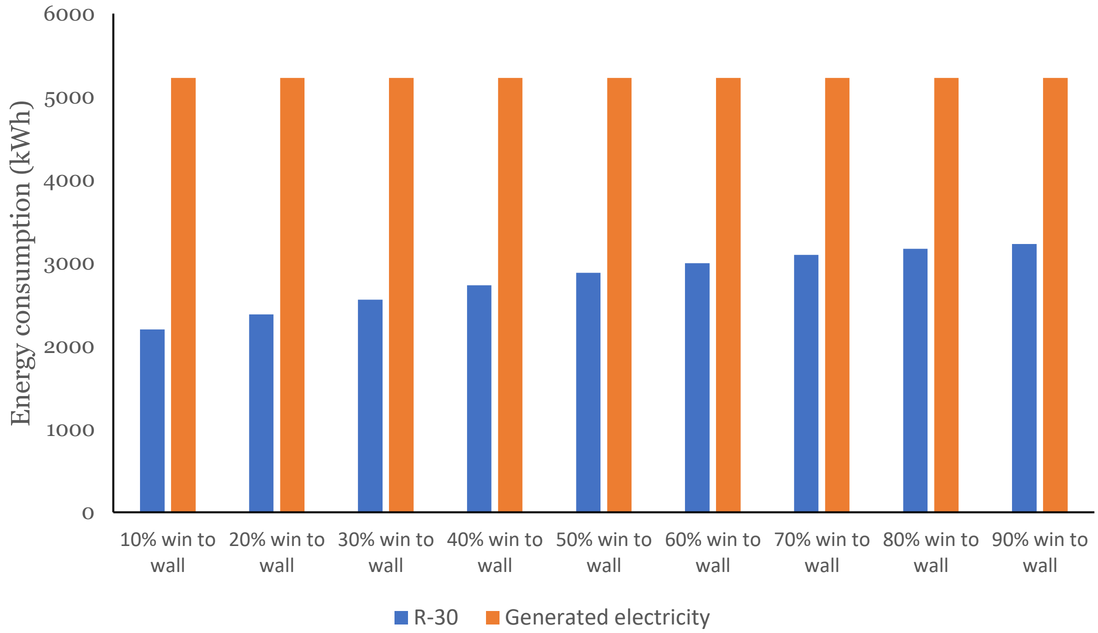


Figure 23- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 insulation (East-west) in Houston.

Figure 24 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 3510.368 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 2432.915 kWh. The significant disparity between these extremes, revealing a 44% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 4863.32 kWh of electricity, surpassing the peak energy consumption recorded at

3510.368 kWh. This surplus electricity generation implies a notable potential for residents to contribute to the energy grid, with the possibility of selling 1,352.952 kWh of excess electricity throughout the year. This dual revelation not only highlights the capability of PV cells to offset energy demand but also presents a tangible economic opportunity for residents. In essence, this detailed examination of the graph provides a holistic understanding of the intricate interplay between window-to-wall ratios and energy consumption, emphasizing the instrumental role of PV cells in meeting the diverse energy requirements inherent in various architectural contexts.

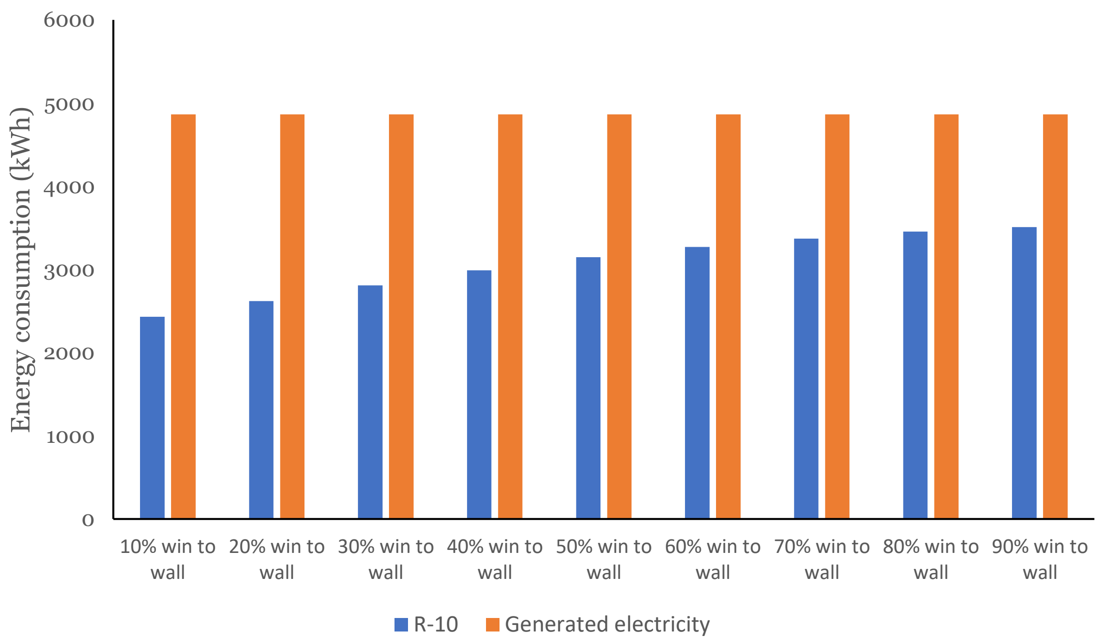


Figure 24- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (north-south) in Houston.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 25. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 3482.159 kWh and the annual energy consumption for the best case 2266.691 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 53%.

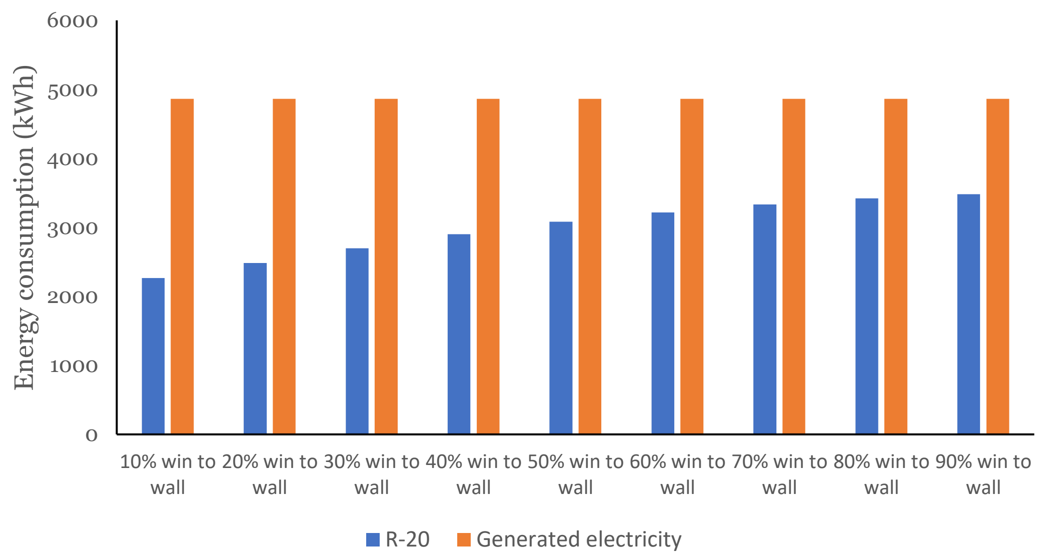


Figure 25- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 insulation (north-south) in Houston.

Figure 26 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 2142.866 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 3456.135 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 61% increase in energy consumption.

The amount of electricity supplied by PV cells is 4863.32 kWh. As mentioned before, the highest energy consumption is 3456.135 kWh. This means that the residents can sell 1,407.185 kWh of electricity during the year.

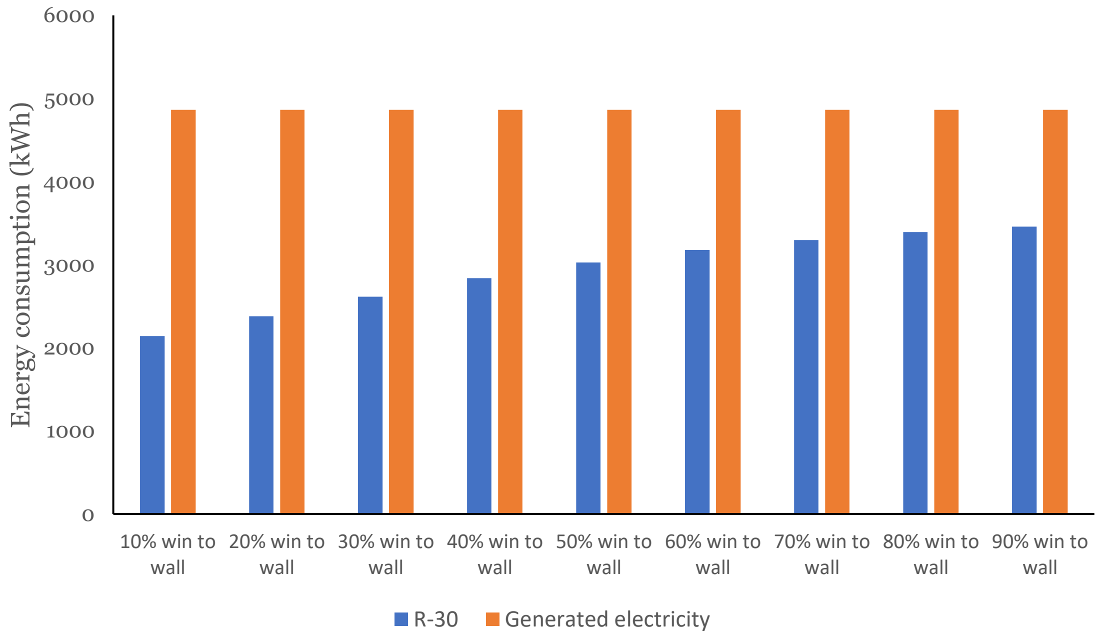


Figure 26- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 insulation (north-south) in Houston.

Figure 27 shows the energy consumption of the building with R-10 insulation in different orientations. Almost in all cases the energy consumption in the east-west orientation is less than in the north-south orientation (except of 10% of WWR). As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 17.899 kWh in 10% window to wall, 142.881 kWh in 50% window to wall and 216.485 kWh in 90% WWR.

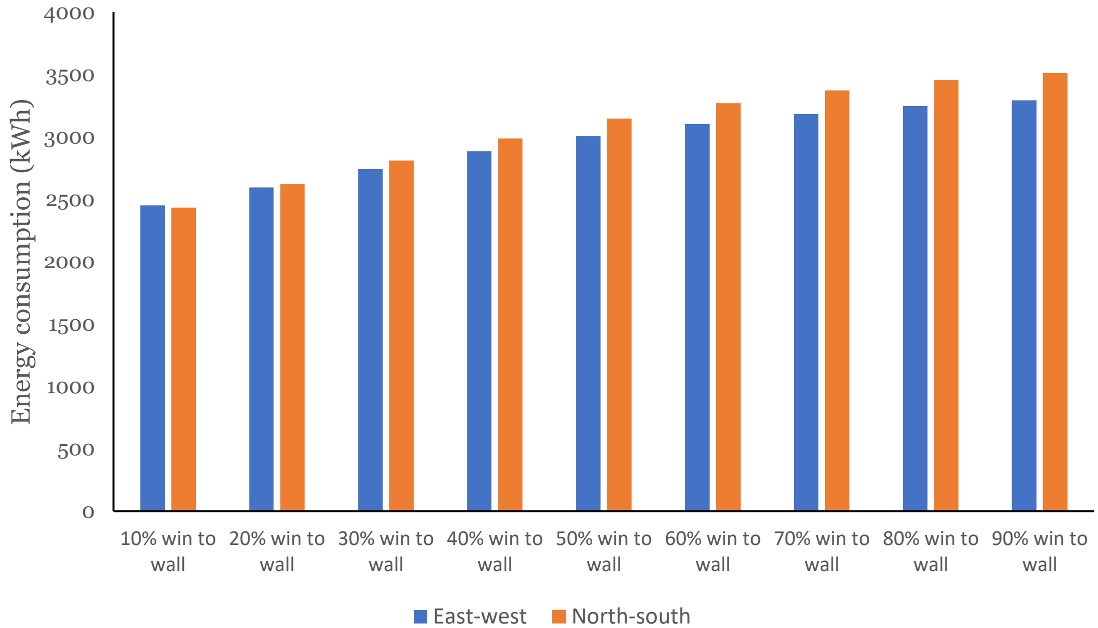


Figure 27- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Houston.

Figure 28 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios (except for 10% WWR) the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 44.528 kWh in 10% window to wall, 144.219 kWh in 50% window to wall and 221.337 kWh in 90% WWR.

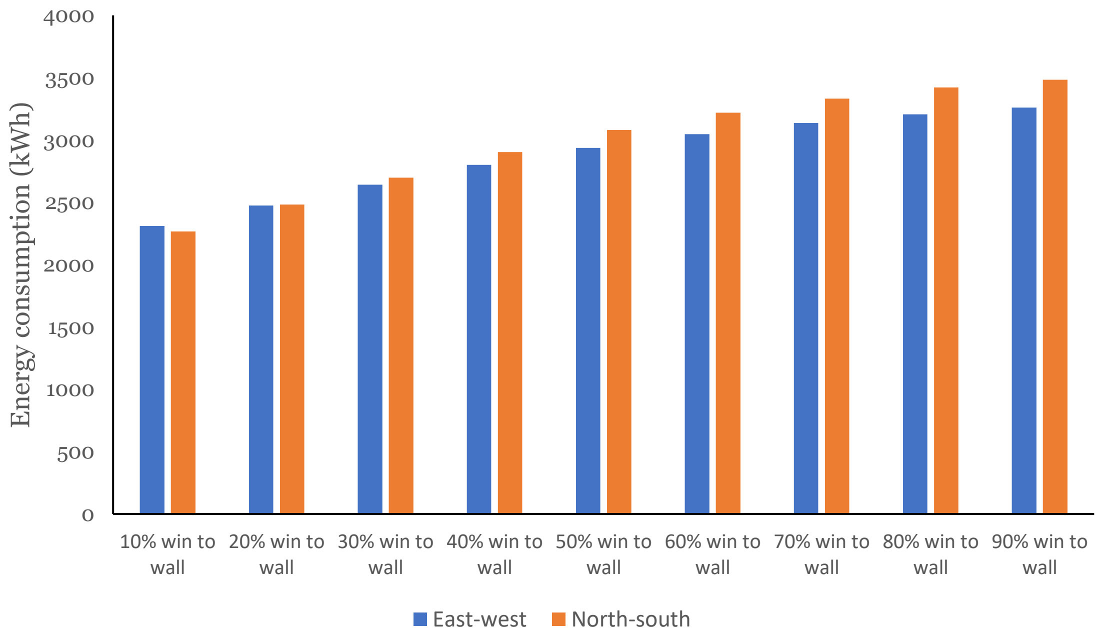


Figure 28- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Houston.

Figure 29 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it’s clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 29.966 kWh in 10% window to wall, 221.1 kWh in 50% window to wall and 301.95 kWh in 90%.

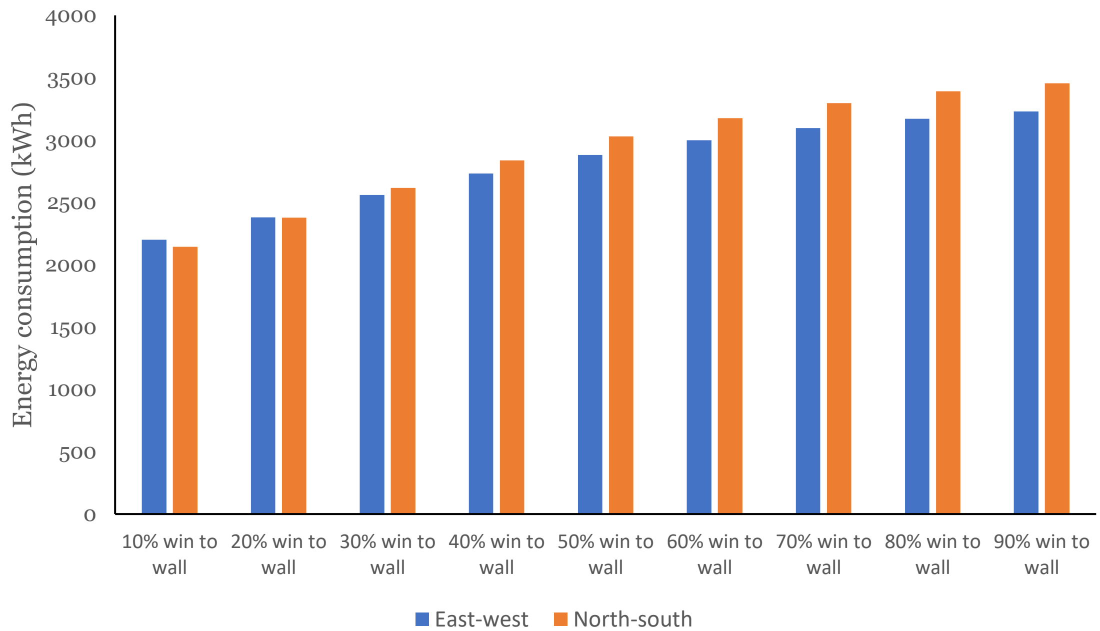


Figure 29- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Houston.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 30 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5224.847 kWh and for north-south orientation is 4863.32 kWh. In other words, the generated electricity in east-west orientation is 7.5% more than the generated electricity in north-south condition.

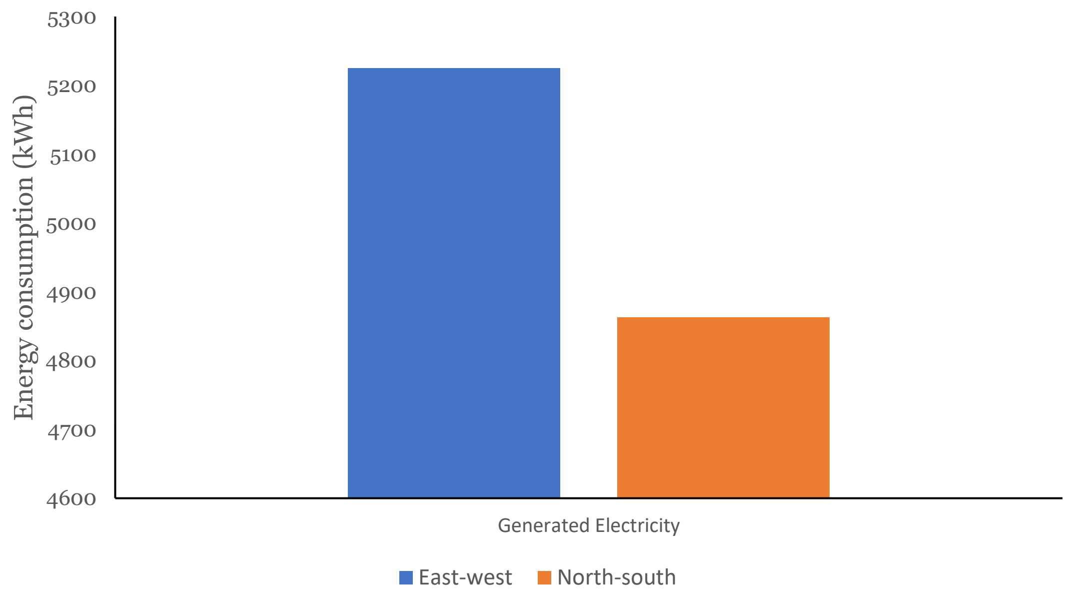


Figure 30- Generated electricity in different configurations of PV cells in Houston.

Figure 31 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. An increase in R-values correlates with a reduction in energy consumption.

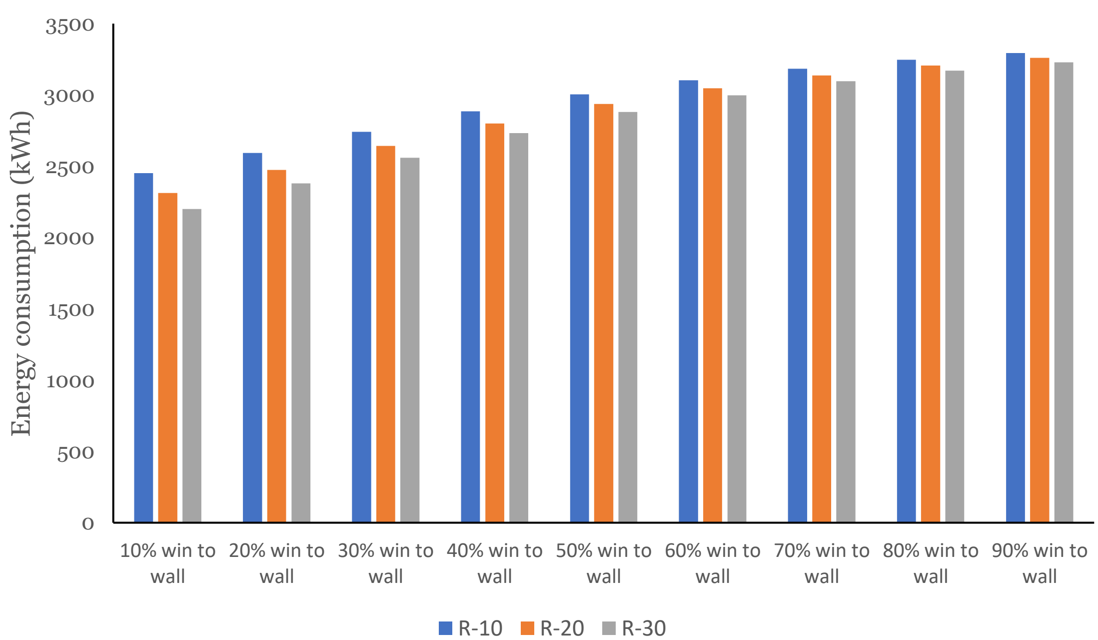


Figure 31- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Houston.

Figure 32 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. An increase in R-values correlates with a reduction in energy consumption.

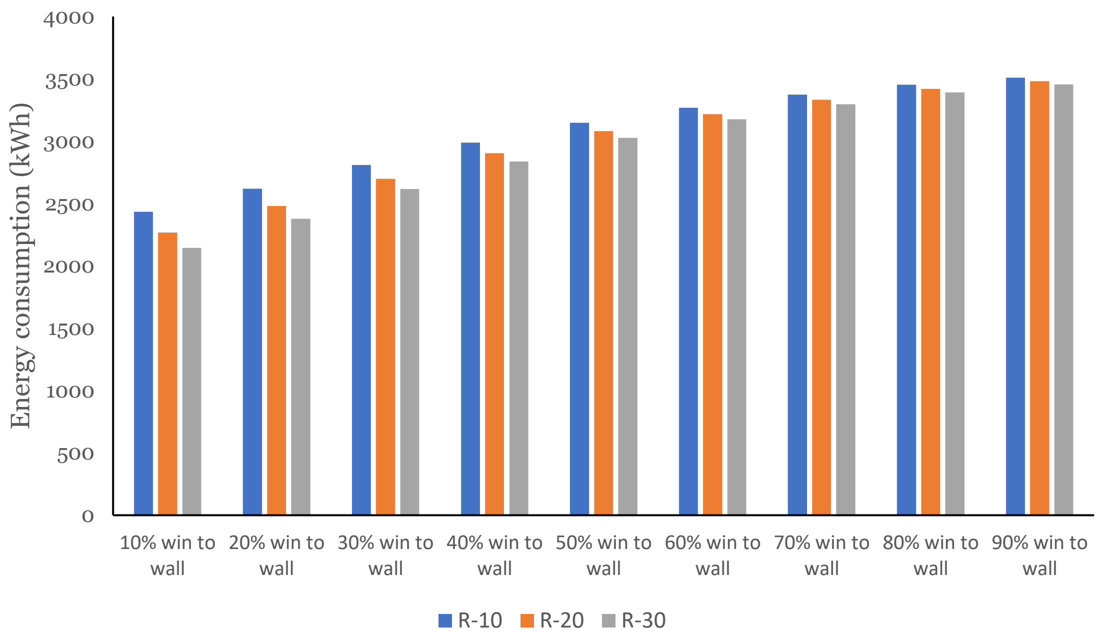


Figure 32- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Houston.

CO_2 emissions for cases with east-west orientation is shown in figure 33. Because the generated electricity is more than energy consumption, CO_2 emissions are negative in all cases. Generally, an increase in WWR causes an increase in CO_2 emissions, therefore the lowest CO_2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO_2 emissions.

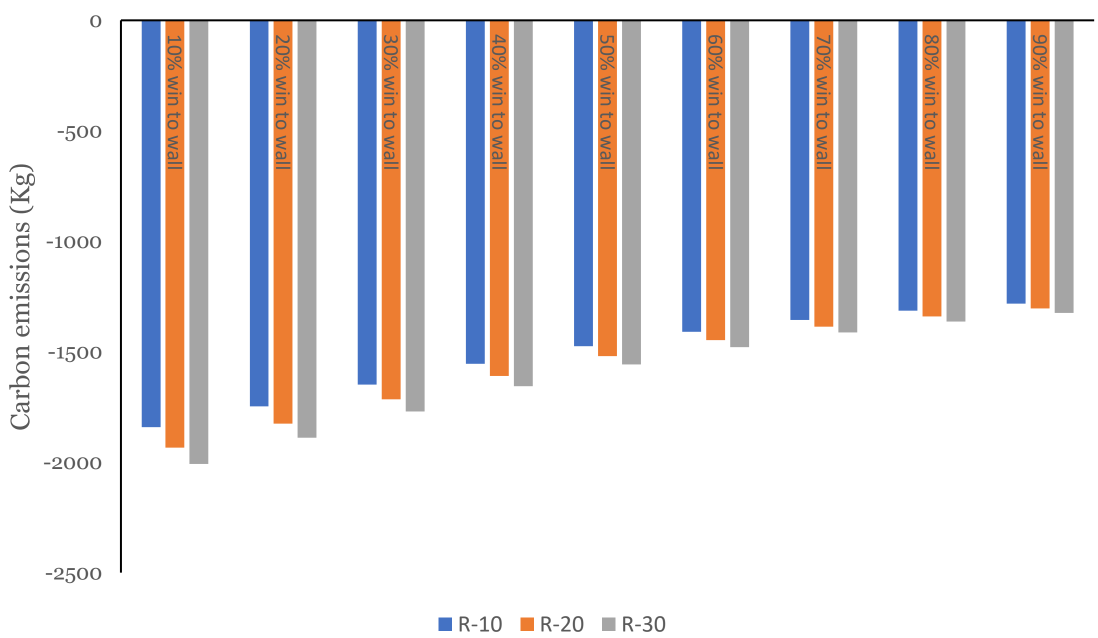


Figure 33- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Houston.

Figure 34 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

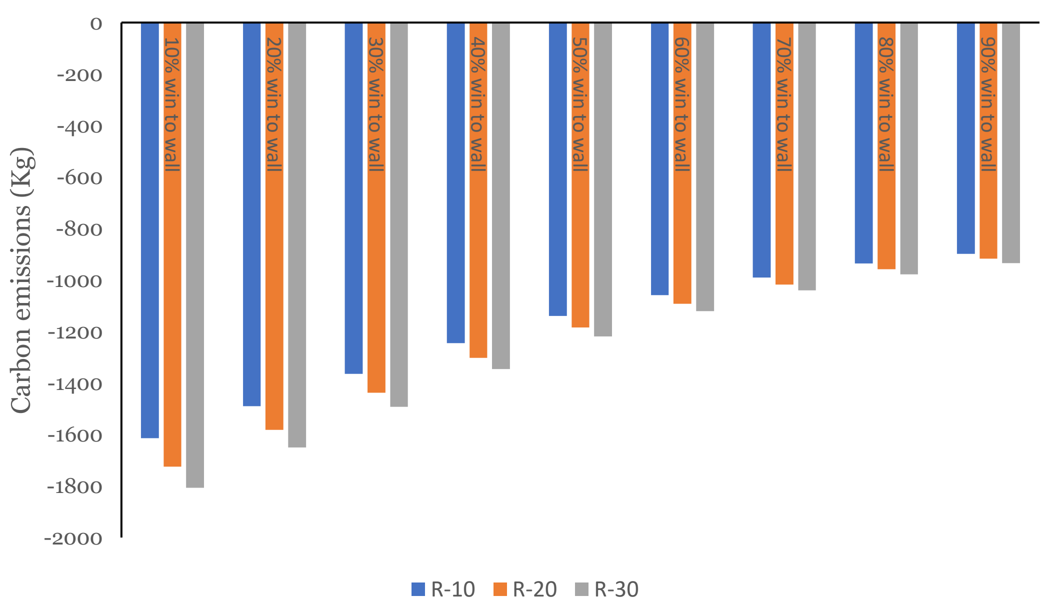


Figure 34- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Houston.

11.3. 2B Pheonix, AZ

Table 7 shows the energy consumption of all 54 cases in Phoenix. The Green color of cells indicates that energy consumption is less than generated electricity, so the tiny house is zero energy. The unit of these numbers is kWh.

Table 7- Energy consumption (kWh) of all cases in Pheonix.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	2455.048	2306.283	2189.042	2550.165	2369.551	2236.317
20	2682.115	2556.887	2458.509	2853.722	2705.24	2596.022
30	2926.343	2828.097	2749.584	3166.078	3052.54	2967.412
40	3163.619	3089.168	3028.715	3465.454	3382.027	3318.348
50	3370.838	3316.963	3272.47	3729.954	3671.574	3625.438
60	3536.841	3498.768	3465.641	3945.558	3906.271	3873.868
70	3651.239	3623.385	3605.531	4107.785	4081.582	4058.247
80	3730.771	3709.112	3688.611	4224.179	4205.69	4188.037
90	3785.917	3766.26	3747.333	4298.601	4283.254	4268.197
Generation	7295.075	7295.075	7295.075	6544.478	6544.478	6544.478

Table 8 outlines CO2 emissions for all cases, with negative values indicating that energy consumption is consistently lower than generated electricity. A green color scheme visually highlights instances of zero-emission characteristics, emphasizing the positive environmental impact of the tiny houses and their significant contribution to reducing the carbon footprint. The negative values, paired with the green coloration, signify the effective achievement of net-zero or even carbon-negative status across all cases, showcasing a commendable commitment to sustainable and eco-friendly practices.

Table 8- Carbon emissions (Kg) of all cases in Phoenix.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-2305.169	-2376.021	-2431.86	-1902.379	-1988.4	-2051.856
20	-2197.023	-2256.666	-2303.521	-1757.804	-1828.521	-1880.538
30	-2080.705	-2127.497	-2164.89	-1609.037	-1663.112	-1703.656
40	-1967.697	-2003.156	-2031.948	-1466.453	-1506.187	-1536.515
50	-1869.004	-1894.663	-1915.854	-1340.479	-1368.283	-1390.257
60	-1789.941	-1808.075	-1823.852	-1237.792	-1256.504	-1271.937
70	-1735.457	-1748.723	-1757.226	-1160.528	-1173.008	-1184.122
80	-1697.578	-1707.894	-1717.658	-1105.093	-1113.899	-1122.307
90	-1671.313	-1680.676	-1689.69	-1069.648	-1076.957	-1084.129

Figure 35 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 2455.048 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 3785.917 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 54% increase in energy consumption.

The amount of electricity supplied by PV cells is 7295.075 kWh. As mentioned before, the highest energy consumption is 3174.849 kWh. This means that the residents can sell 3,509.158 kWh of electricity during the year.

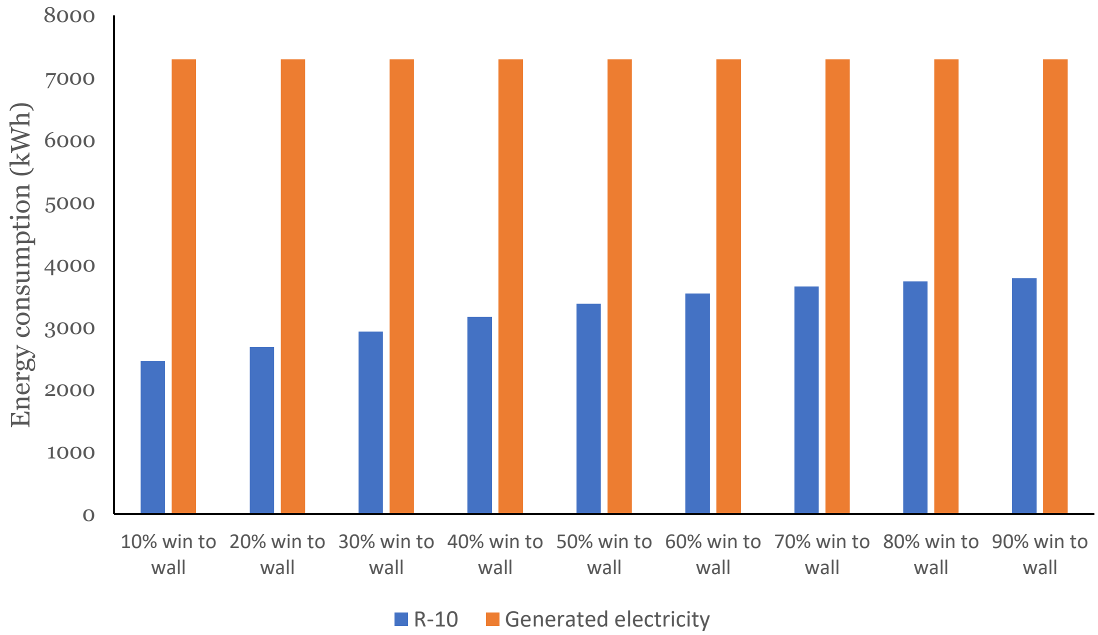


Figure 35- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Pheonix.

In all scenarios examined in Figure 36, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 2306.283 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 3766.26 kWh, translating to a noteworthy 63% increase in energy consumption when transitioning from a 10% to an 90% window-to-wall ratio.

The PV cells generate a total of 7295.075 kWh of electricity, surpassing the highest recorded energy consumption of 3766.26 kWh. Consequently, residents have the potential to sell 3528.815 kWh of surplus electricity throughout the year.

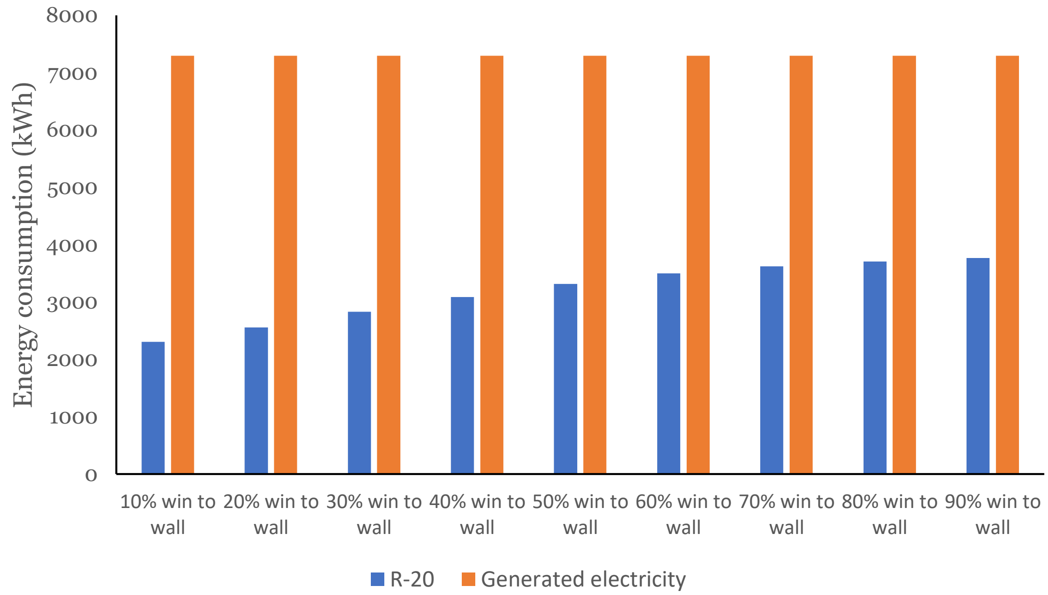


Figure 36- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 insulation (East-west) in Pheonix.

Within the scope of Figure 37's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to effectively meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 2189.042 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 3747.333 kWh, reflecting a notable 71% increase in energy consumption during the transition from a 10% to a 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 7295.075 kWh of electricity, surpassing the peak energy consumption recorded at 3747.333 kWh. Consequently, residents possess the potential to sell 3547.742 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios

and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

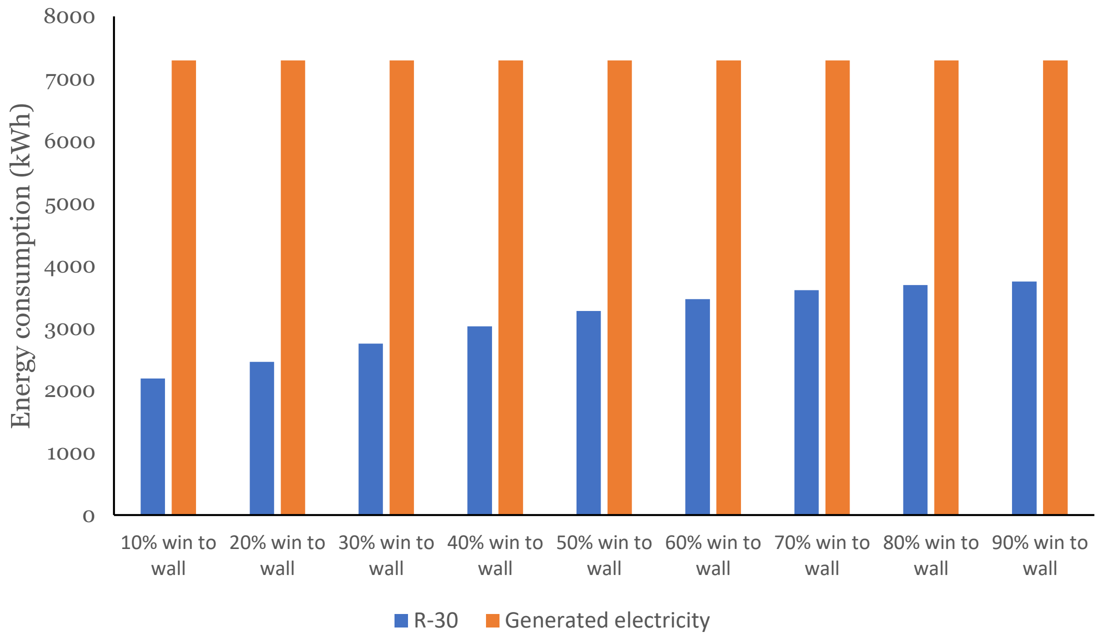


Figure 37- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 insulation (East-west) in Pheonix.

Figure 38 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 4298.601 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 2550.165 kWh. The significant disparity between these extremes, revealing a 68.5 % increase in energy consumption during the transition from a 10% to a 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 6544.478 kWh of electricity, surpassing the peak energy consumption recorded at 4298.601 kWh. This surplus electricity generation implies a notable potential for residents to contribute to the energy grid, with the possibility of selling 2,245.877 kWh of excess electricity throughout the year. This dual revelation not only highlights the capability of PV cells to offset energy demand but also presents a tangible economic opportunity for residents. In essence, this detailed examination of the graph provides a holistic understanding of the intricate interplay between window-to-wall ratios and energy consumption, emphasizing the instrumental role of PV cells in meeting the diverse energy requirements inherent in various architectural contexts.

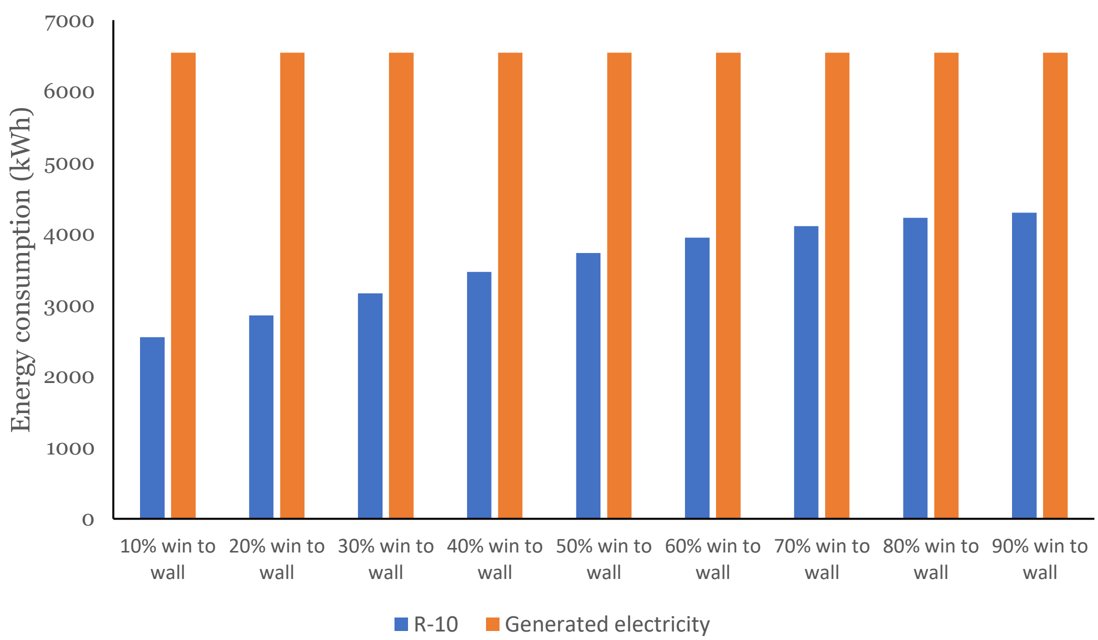


Figure 38- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (north-south) in Pheonix.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 39. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 4283.254 kWh and the annual energy consumption for the best case 2369.551 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 81%.

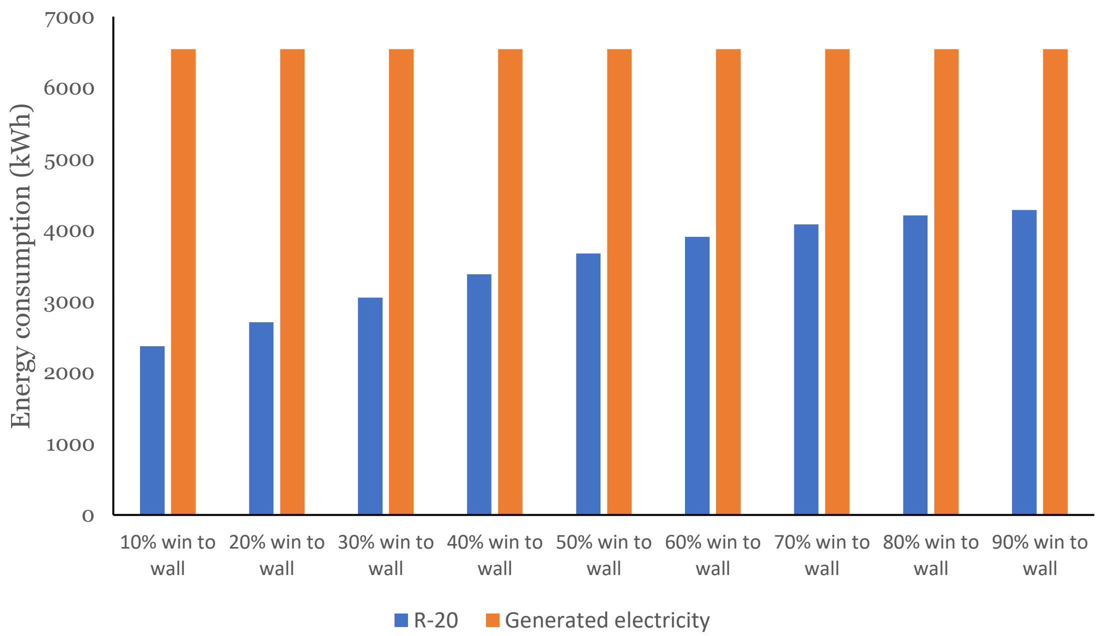


Figure 39- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 insulation (north-south) in Pheonix.

Figure 40 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 2236.317 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 4268.197 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 91% increase in energy consumption.

The amount of electricity supplied by PV cells is 6544.478 kWh. As mentioned before, the highest energy consumption is 4268.197 kWh. This means that the residents can sell 2,276.281 kWh of electricity during the year.

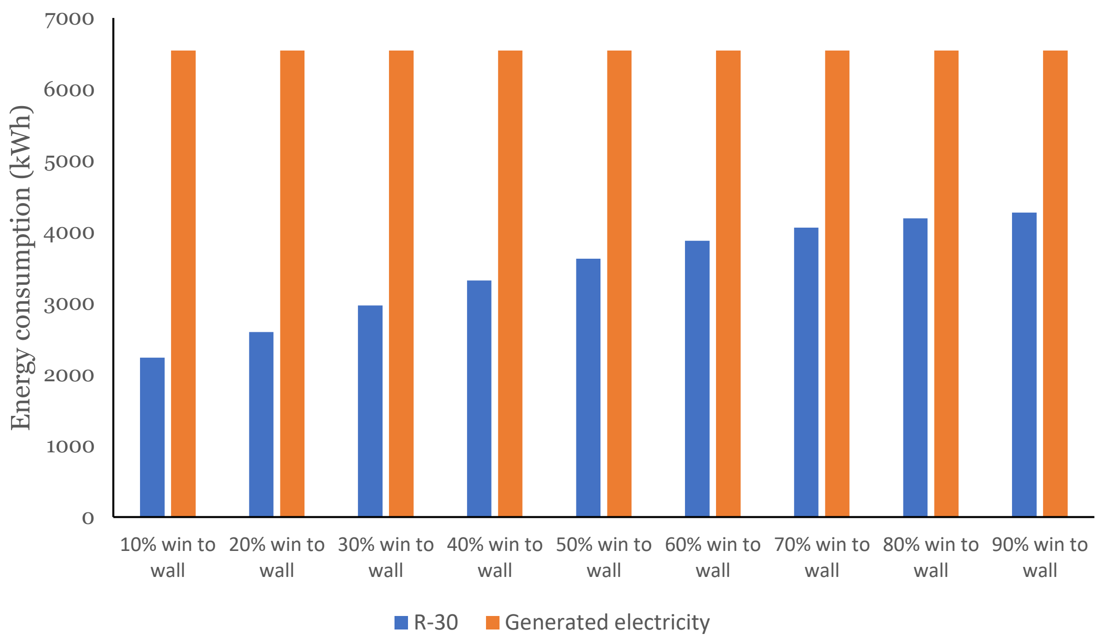


Figure 40- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 insulation (north-south) in Pheonix.

Figure 41 shows the energy consumption of the building with R-10 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 95.117 kWh in 10% window to wall, 359.116 kWh in 50% window to wall and 512.684 kWh in 90% WWR.

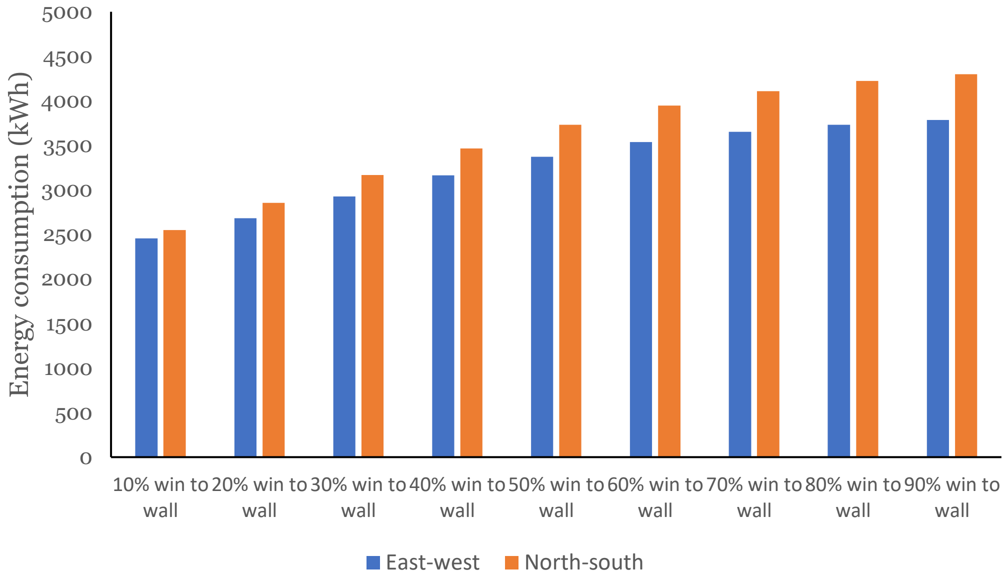


Figure 41- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Pheonix.

Figure 42 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 63.268 kWh in 10% window to wall, 354.611 kWh in 50% window to wall and 516.994 in 90% WWR.

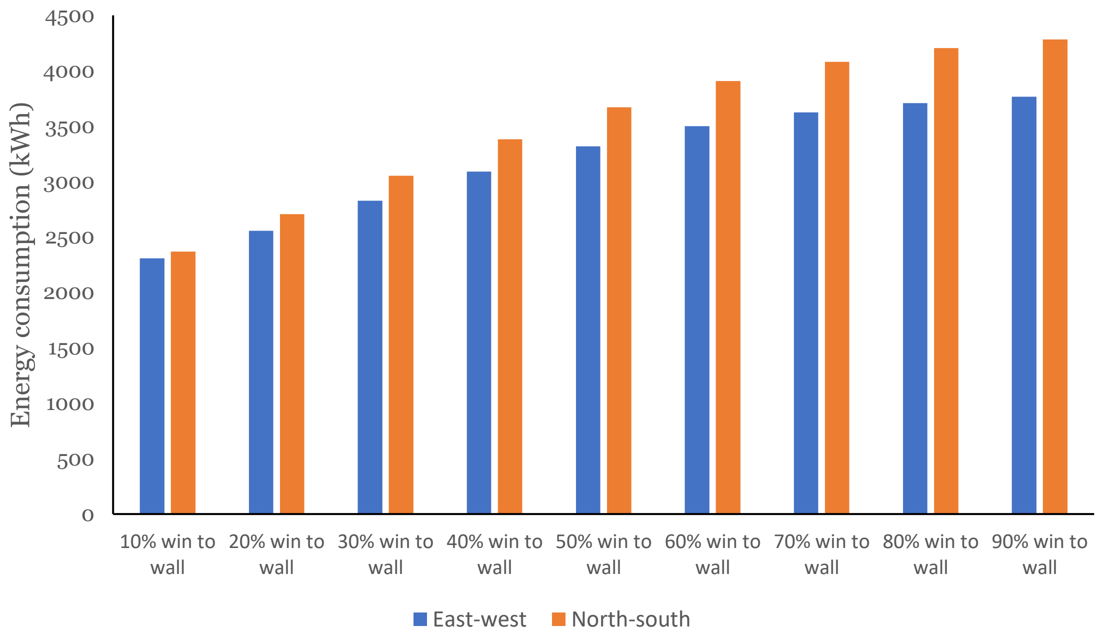


Figure 42- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Pheonix.

Figure 43 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 47.275 kWh in 10% window to wall, 352.968 kWh in 50% window to wall and 520.864 kWh in 90%.

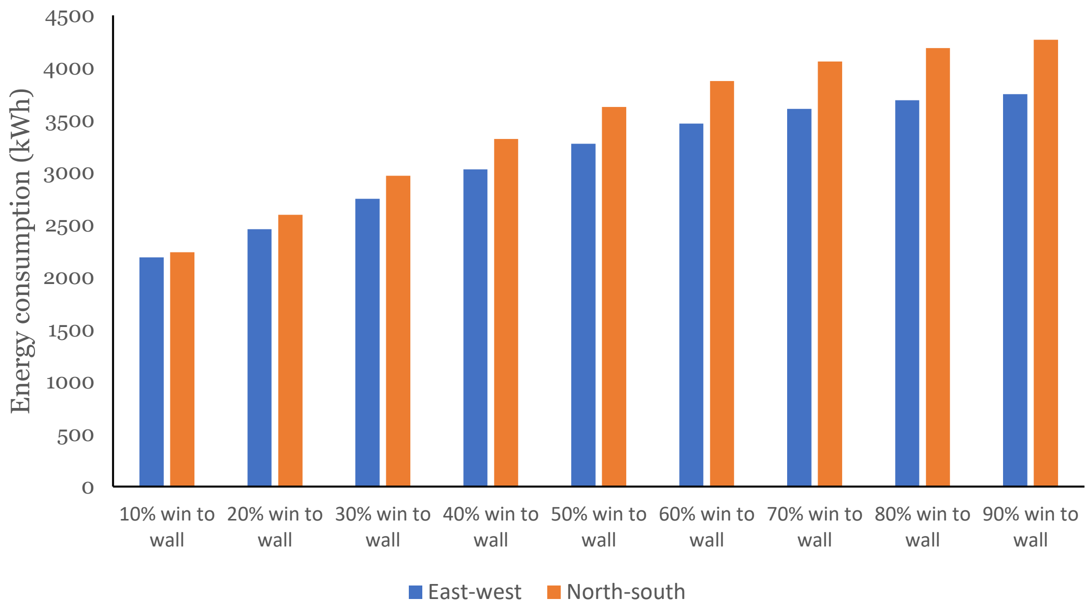


Figure 43- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Pheonix.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 44 is about generated electricity in two orientations. The generated electricity for east-west orientation is 7295.075 kWh and for north-south orientation is 6544.478 kWh. In other words, the generated electricity in east-west orientation is 11% more than the generated electricity in north-south condition.

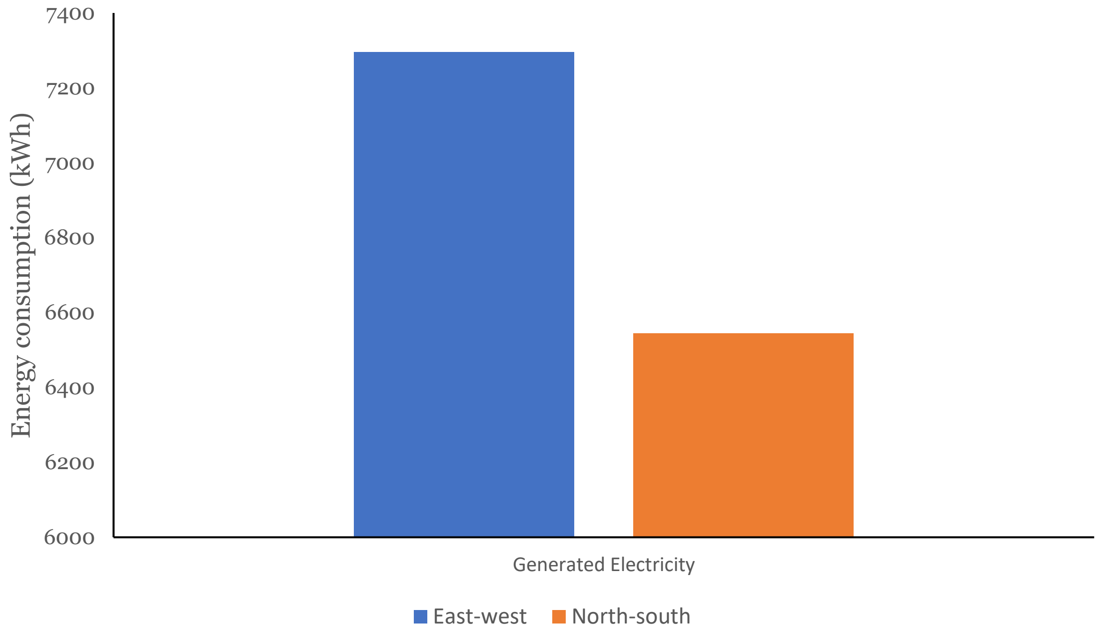


Figure 44- Generated electricity in different configurations of PV cells in Pheonix.

Figure 45 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10%-90% WWR range, an increase in R-values correlates with a reduction in energy consumption.

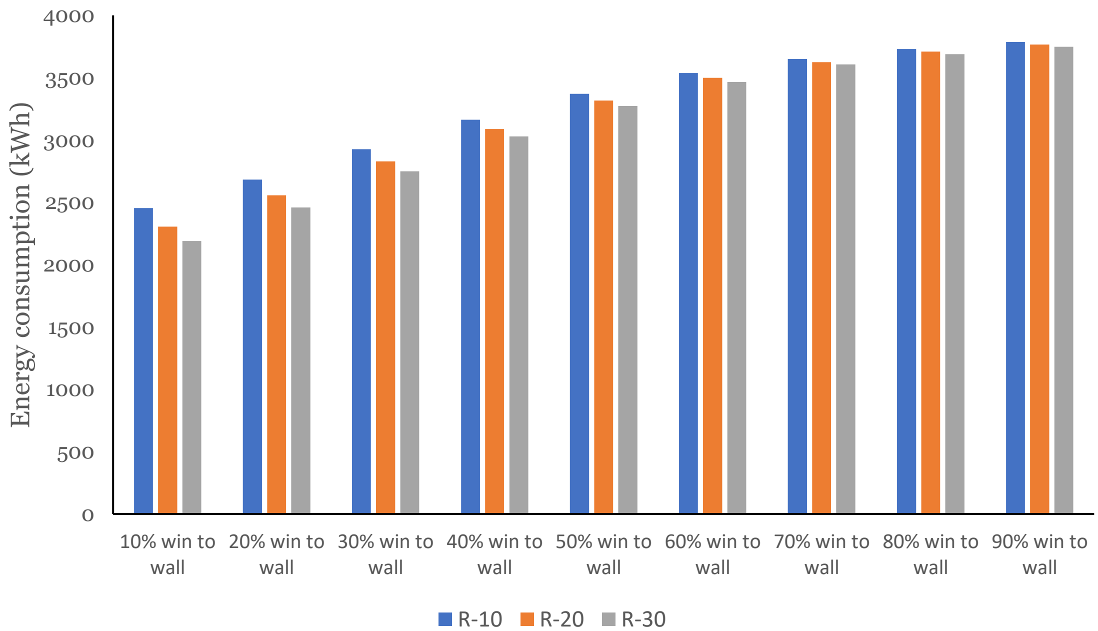


Figure 45- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Pheonix.

Figure 46 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10% -90% WWR range, an increase in R-values correlates with a reduction in energy consumption.

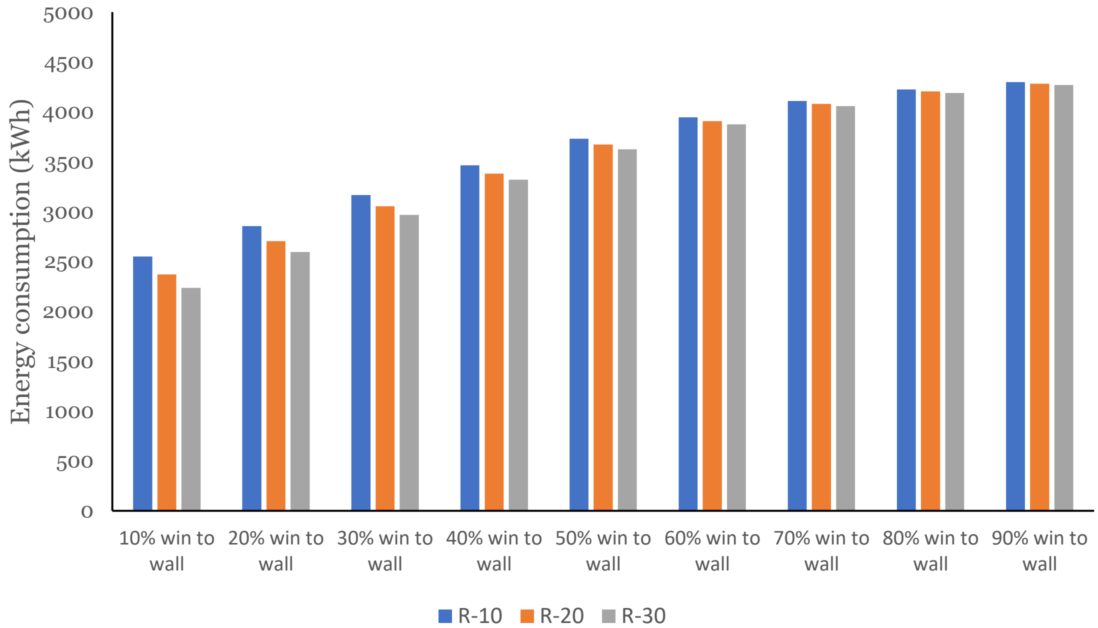


Figure 46- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Pheonix.

The CO2 Emissions for cases with east-west orientation is shown in figure 47. Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

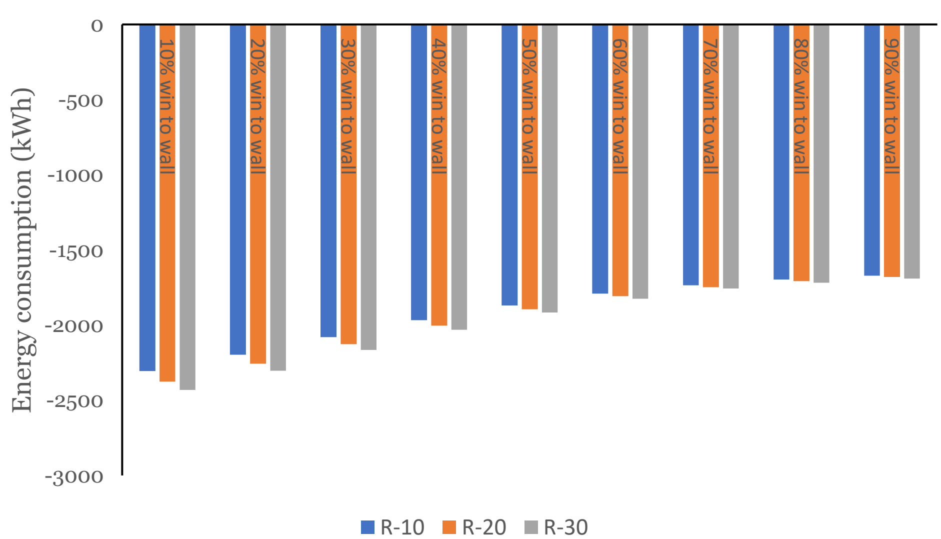


Figure 47- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Pheonix.

Figure 48 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

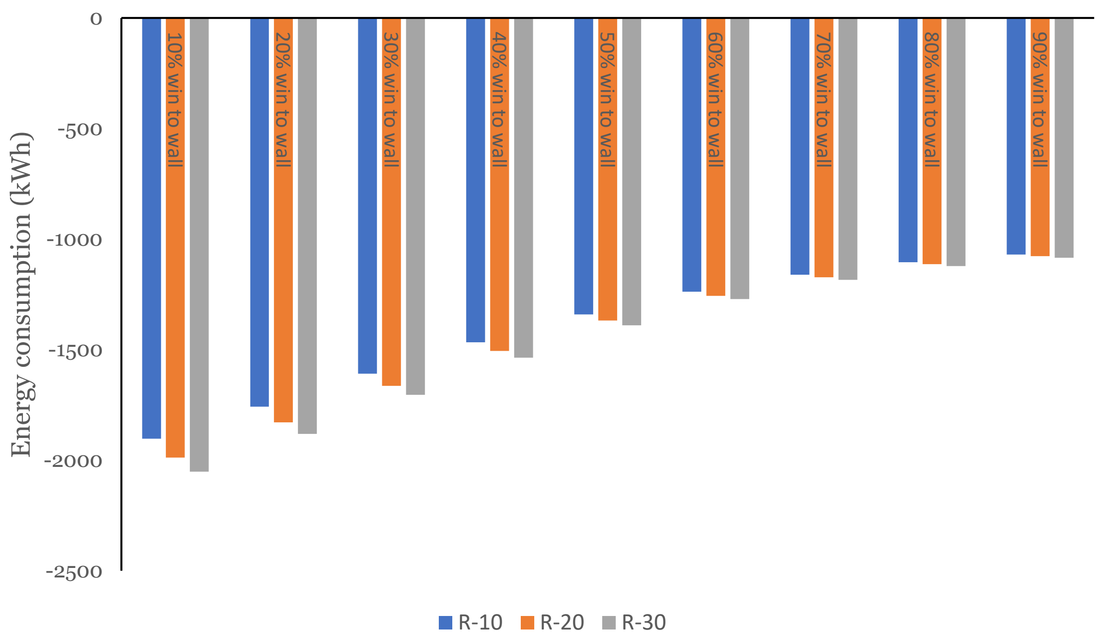


Figure 48- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north south) in Pheonix.

11.4. 3A Charlotte, NC

Table 9 displays energy consumption for all 54 cases in Charlotte. Green cells indicate instances where energy consumption is less than generated electricity, signifying a net-zero energy status for the tiny houses. The unit of measurement is kilowatt-hours (kWh). The green-highlighted cells underscore the successful balance between energy generation and consumption in the specific context of tiny house living in Charlotte.

Table 9- Energy consumption (kWh) of all cases in Charlotte.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	3165.414	2974.152	2821.865	3193.564	2964.303	2793.403
20	3172.12	2997.167	2857.884	3250.6	3045.34	2892.946
30	3218.312	3061.314	2936.586	3341.472	3161.747	3028.395
40	3292.227	3153.663	3043.322	3456.443	3301.576	3186.267
50	3366.668	3246.419	3151.176	3566.304	3436.376	3339.272
60	3452.834	3350.179	3266.652	3684.469	3575.606	3491.715
70	3552.035	3464.138	3391.218	3807.631	3716.54	3645.288
80	3653.08	3578.175	3513.937	3926.091	3851.327	3789.608
90	3779.74	3716.83	3660.534	4059.446	3997.502	3944.187
Generation	5665.917	5665.917	5665.917	5045.056	5045.056	5045.056

Table 10 details CO2 emissions for all cases. Negative values indicate energy consumption consistently below generated electricity, highlighting zero-emission characteristics. The green coloration signifies the effective achievement of net-zero or even carbon-negative status across all cases, showcasing a commendable commitment to sustainable practices.

Table 10- Carbon emissions (Kg) of all cases in Charlotte.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-1408.688	-1516.438	-1602.23	-1043.06	-1172.217	-1268.495
20	-1404.91	-1503.472	-1581.938	-1010.928	-1126.564	-1212.417
30	-1378.887	-1467.333	-1537.601	-959.7345	-1060.984	-1136.11
40	-1337.246	-1415.308	-1477.469	-894.9642	-982.2098	-1047.171
50	-1295.309	-1363.052	-1416.709	-833.0723	-906.2689	-960.9738
60	-1246.766	-1304.598	-1351.654	-766.5026	-827.832	-875.0931
70	-1190.88	-1240.398	-1281.479	-697.118	-748.4351	-788.576
80	-1133.955	-1176.154	-1212.343	-630.3824	-672.5016	-707.2714
90	-1062.6	-1098.041	-1129.756	-555.2552	-590.1523	-620.1877

Figure 49 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 3165.414 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 3779.74 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 19 increase in energy consumption.

The amount of electricity supplied by PV cells is 5665.917 kWh. As mentioned before, the highest energy consumption is 3779.74 kWh. This means that the residents can sell 1,886.177 kWh of electricity during the year.

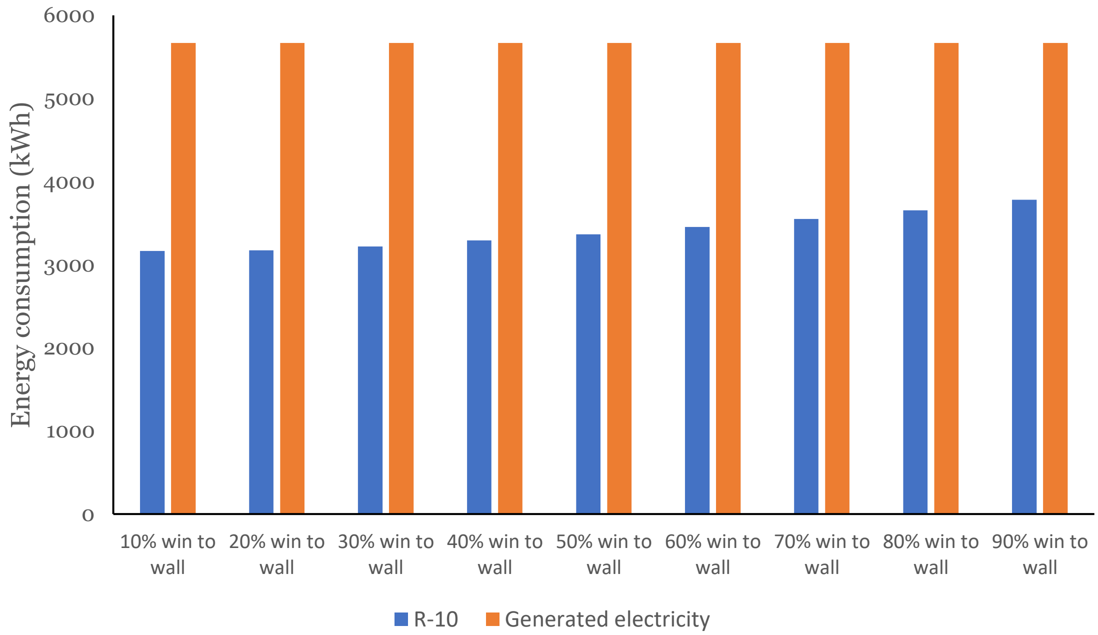


Figure 49- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Charlotte.

In all scenarios examined in Figure 50, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 2974.152 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 3716.83 kWh, translating to a noteworthy 25% increase in energy consumption when transitioning from a 10% to an 90% window-to-wall ratio.

The PV cells generate a total of 5665.917 kWh of electricity, surpassing the highest recorded energy consumption of 3716.83 kWh. Consequently, residents have the potential to sell 1,949.087 kWh of surplus electricity throughout the year.

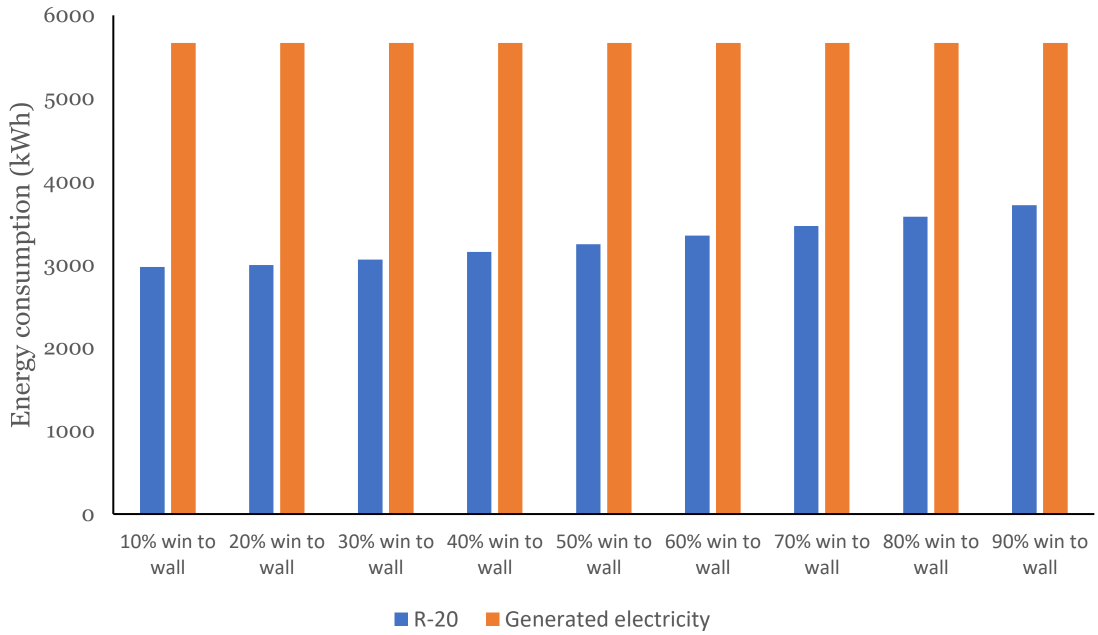


Figure 50- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 insulations (East-west) in Charlotte.

Within the scope of Figure 51's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to effectively meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 2821.865 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 3660.534 kWh, reflecting a notable 30% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 5665.917 kWh of electricity, surpassing the peak energy consumption recorded at 3660.534 kWh. Consequently, residents possess the potential to sell 2,005.383 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

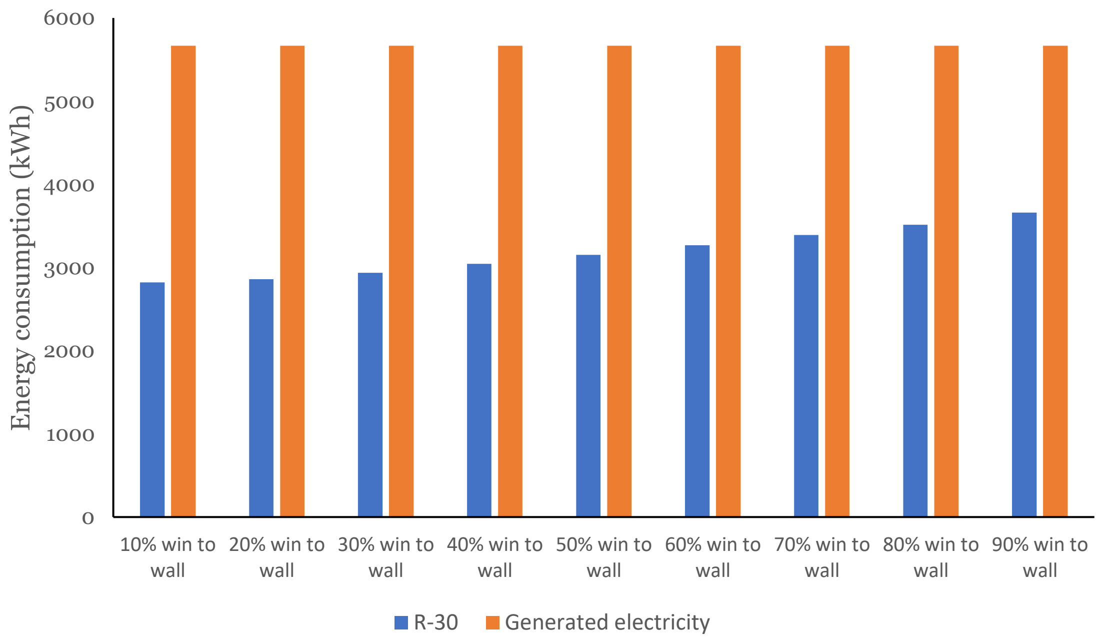


Figure 51- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 insulation (East-west) in Charlotte.

Figure 52 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 4059.446 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 3193.564 kWh. The significant disparity between these extremes, revealing a 27% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 5045.056 kWh of electricity, surpassing the peak energy consumption recorded at 4059.446 kWh. This surplus electricity generation implies a notable potential for residents to contribute to the energy grid, with the possibility of selling 985.61 kWh of excess electricity throughout the year. This dual revelation not only highlights the capability of PV cells to offset energy demand but also presents a tangible economic opportunity for residents. In essence, this detailed examination of the graph provides a holistic understanding of the intricate interplay between window-to-wall ratios and energy consumption, emphasizing the instrumental role of PV cells in meeting the diverse energy requirements inherent in various architectural contexts.

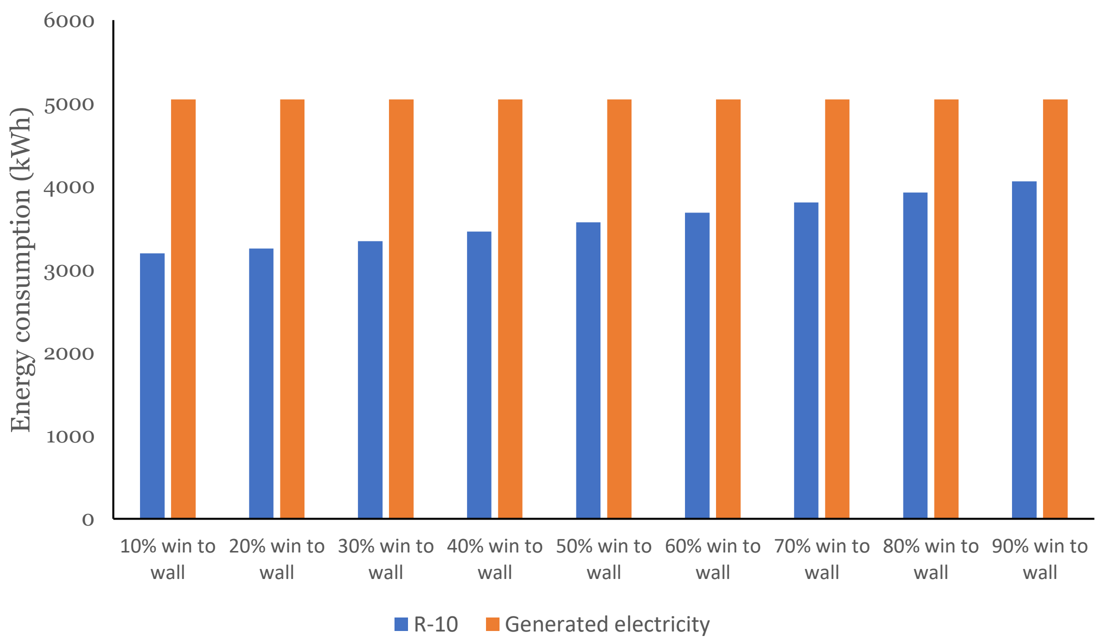


Figure 52- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (north-south) in Charlotte.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 53. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window

to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 3997.502 kWh and the annual energy consumption for the best case 2964.303 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 35%.

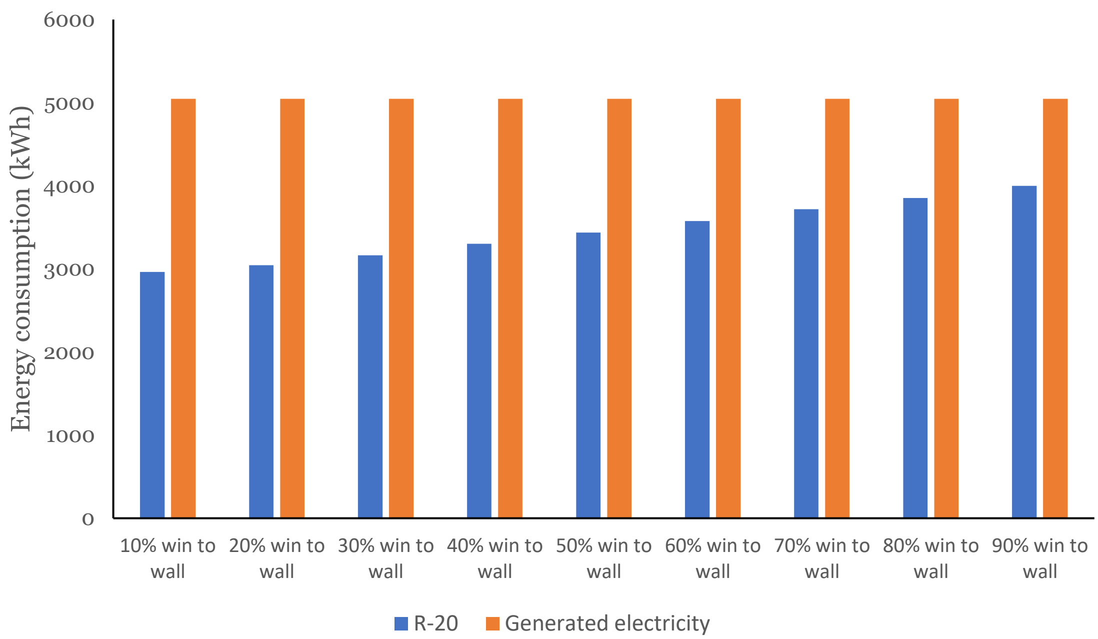


Figure 53- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 insulation (north-south) in Charlotte.

Figure 54 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 2793.403 kWh, whereas for an 80% window-to-wall ratio (worst case), it is 3944.187 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 41% increase in energy consumption.

The amount of electricity supplied by PV cells is 5045.056 kWh. As mentioned before, the highest energy consumption is 3944.187 kWh. This means that the residents can sell 1100.869 kWh of electricity during the year.

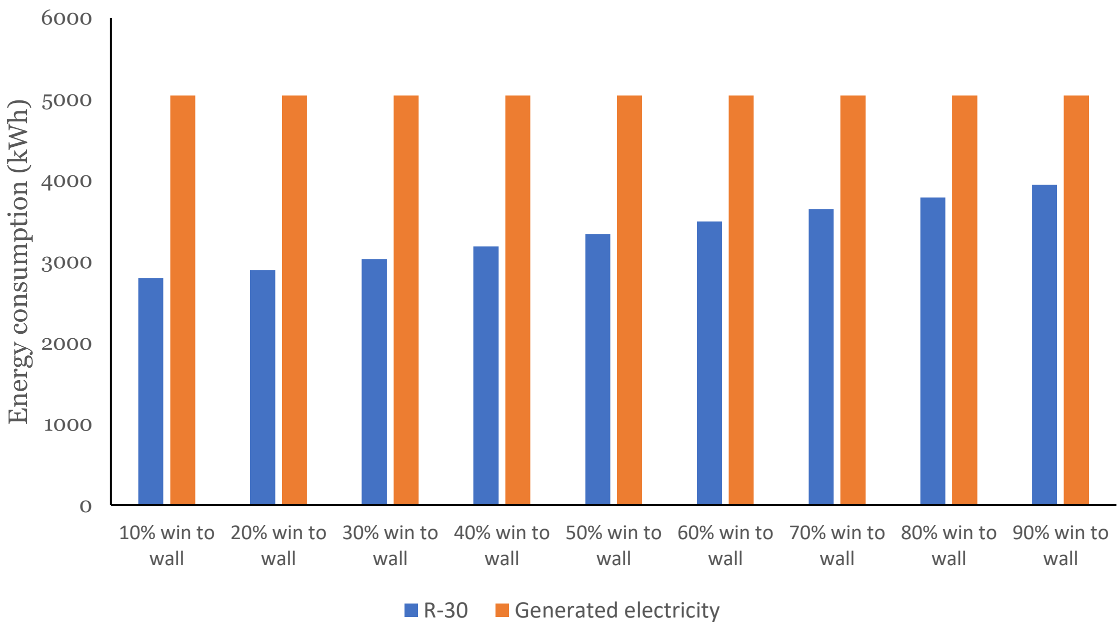


Figure 54- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 insulation (north-south) in Charlotte.

Figure 55 shows the energy consumption of the building with R-10 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 28.15 kWh in 10% window to wall, 199.636 kWh in 50% window to wall and 279.706 kWh in 90% WWR.

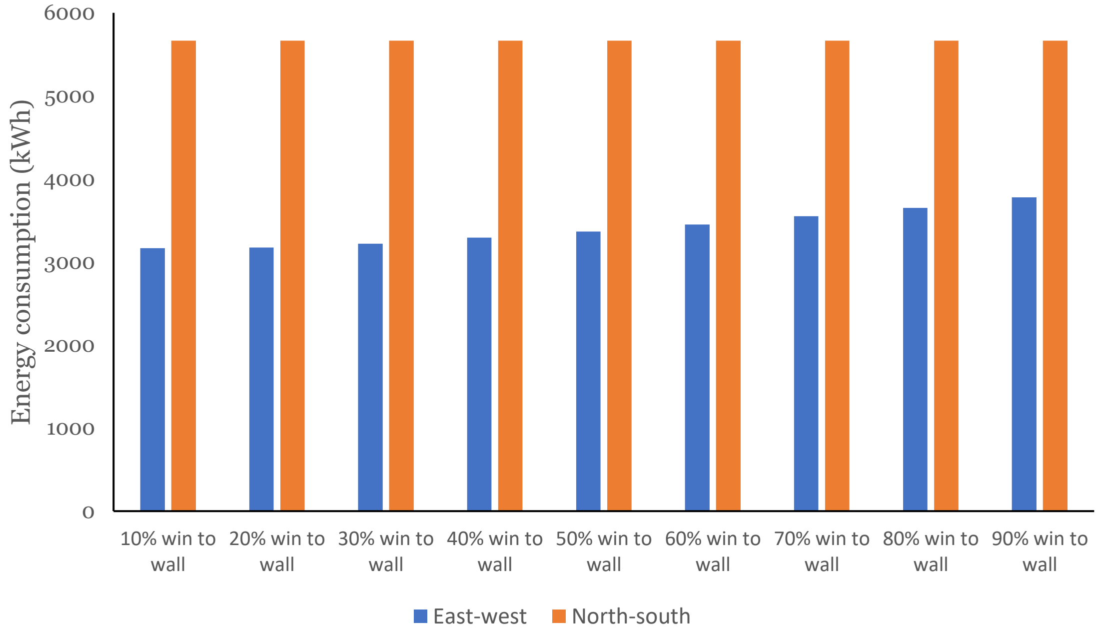


Figure 55- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Charlotte.

Figure 56 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios the energy consumption of tiny houses with north-south orientation is higher (except for 10% of WWR). As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 9.849 kWh in 10% window to wall, 189.957 kWh in 50% window to wall and 280.672 kWh in 90% WWR.

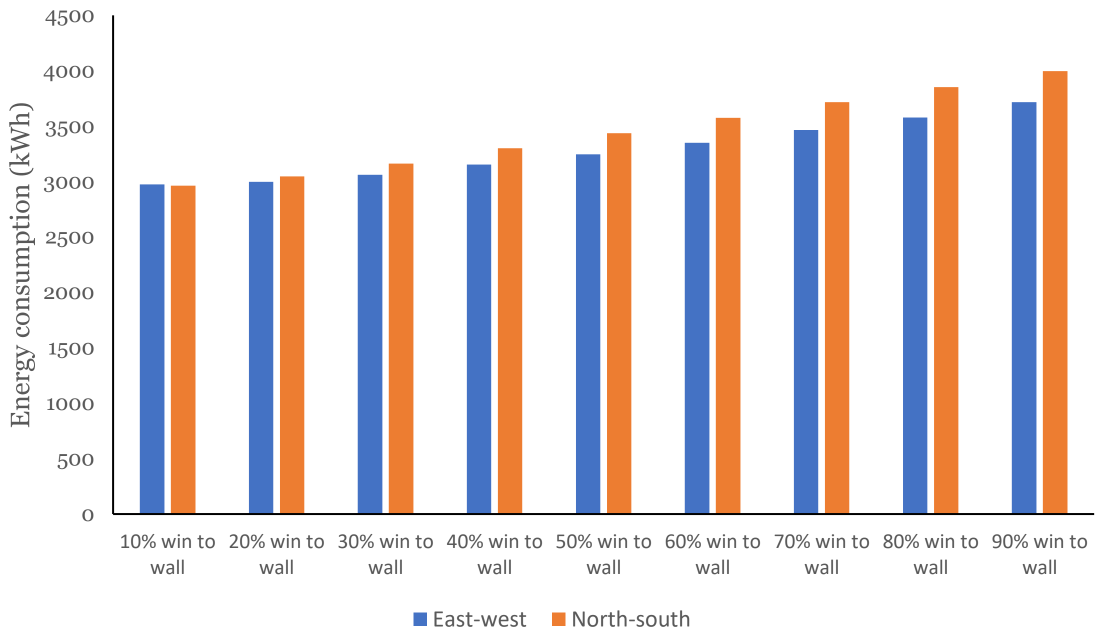


Figure 56- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Charlotte.

Figure 57 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation (except for 10% of WWR). As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 28.462 kWh in 10% window to wall, 188.096 kWh in 50% window to wall and 283.653 kWh in 90%.

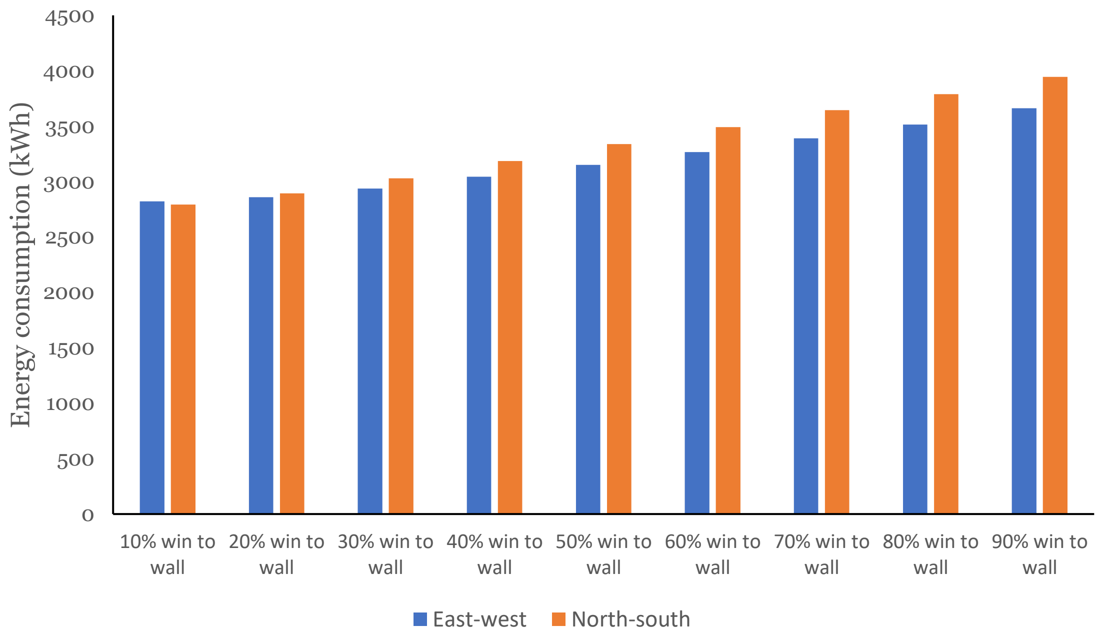


Figure 57- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Charlotte.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 58 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5665.917 kWh and for north-south orientation is 5045.056 kWh. In other words, the generated electricity in east-west orientation is 12% more than the generated electricity in north-south condition.

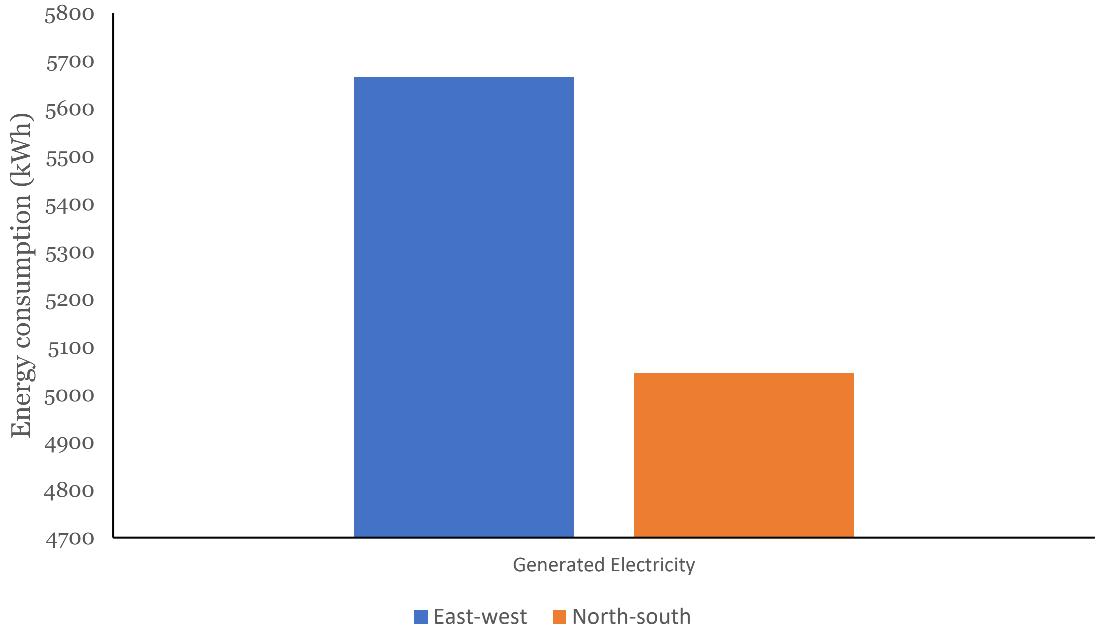


Figure 58- Generated electricity in different configurations of PV cells in Charlotte.

Figure 59 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10%-90% WWR range, an increase in R-values correlates with a reduction in energy consumption.

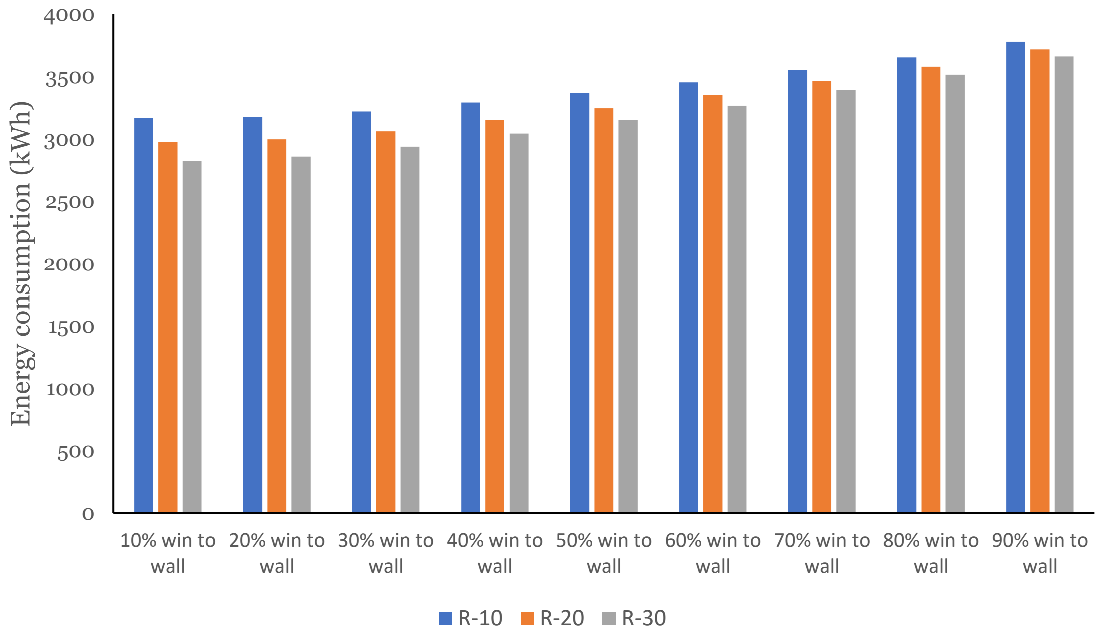


Figure 59- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Charlotte.

Figure 60 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10% -90% WWR range, an increase in R-values correlates with a reduction in energy consumption.

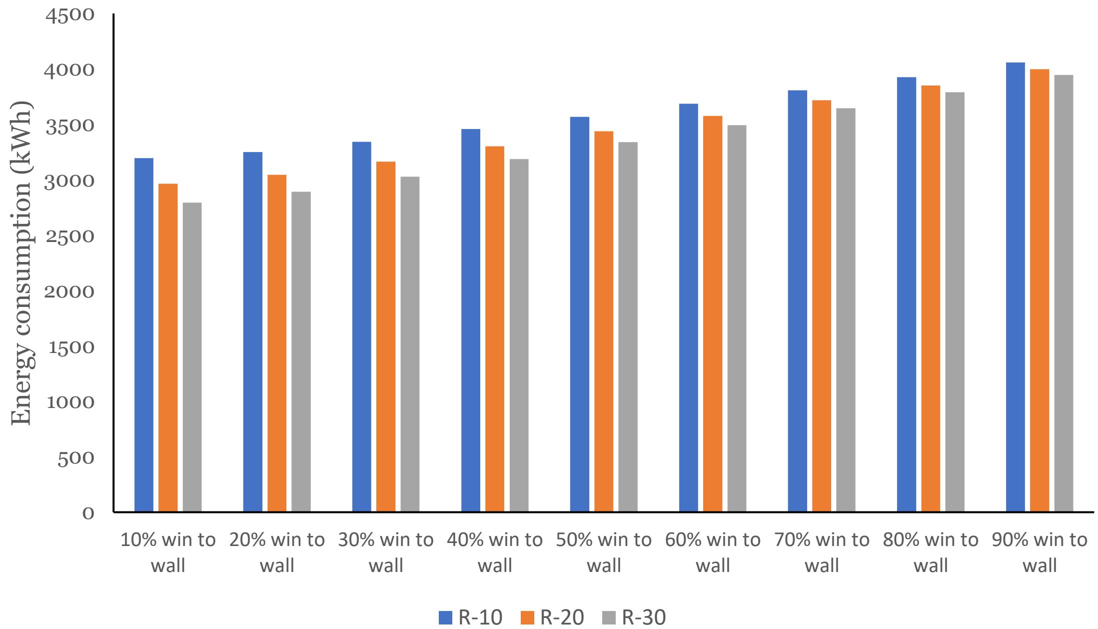


Figure 60- Comparing the annual energy consumption in different window to wall ratios and different R-values (North-South) in Charlotte.

CO2 emissions for cases with east-west orientation is shown in figure 61 Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

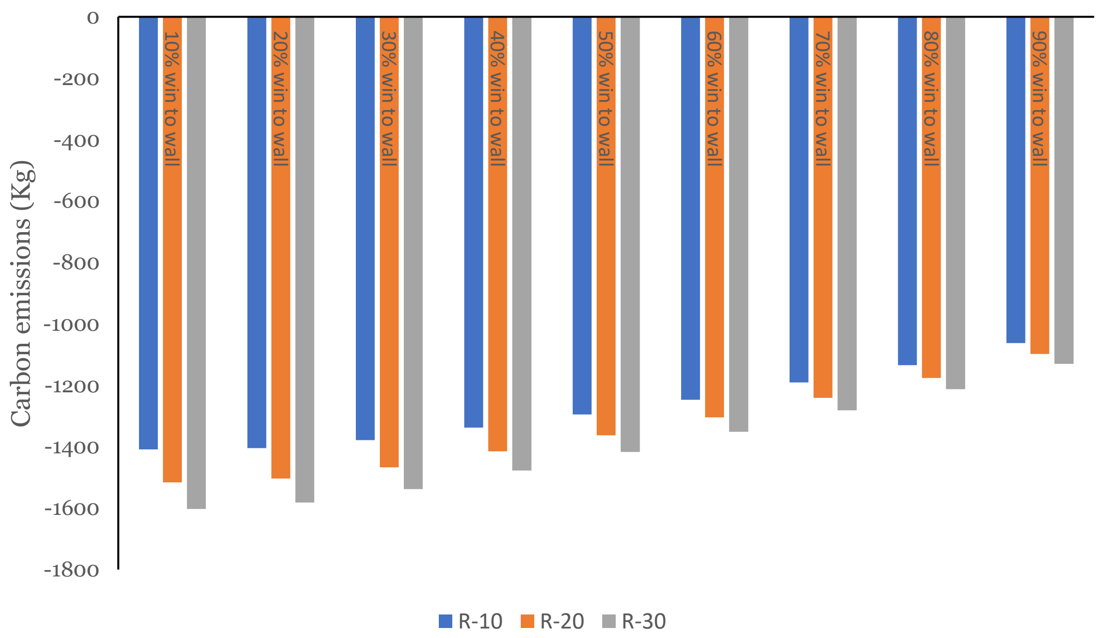


Figure 61- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Charlotte.

Figure 62 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

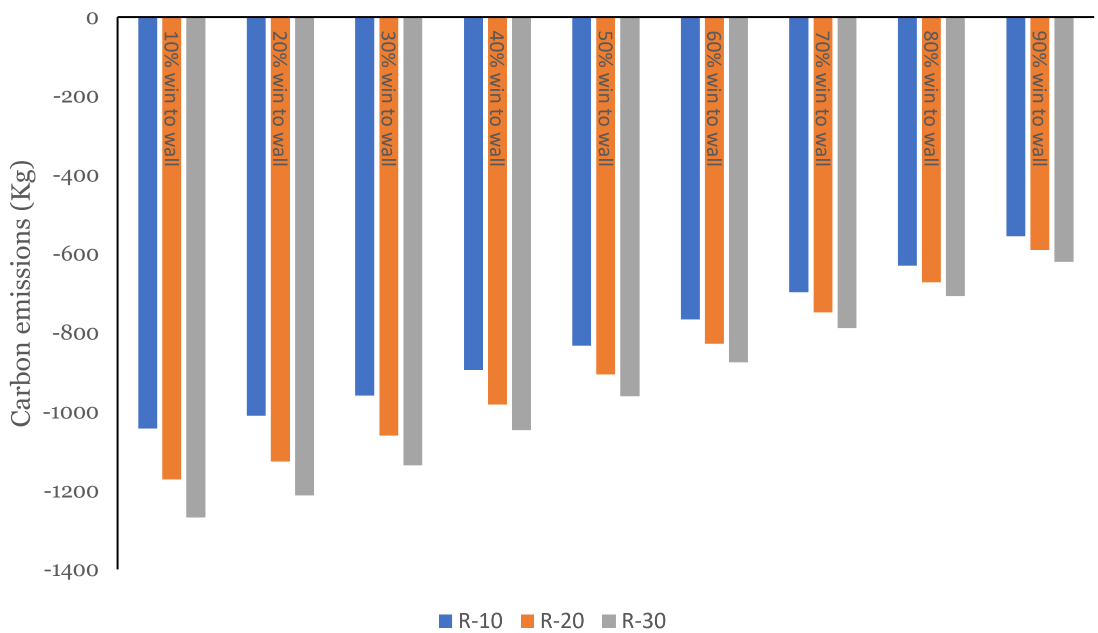


Figure 62- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Charlotte.

11.5. 3B Los Angeles, CA

Displayed in Table 11 are the energy consumption details for all 54 cases in Loas Angeles. The cells highlighted in green within the table signify instances where energy consumption falls below the generated electricity, indicating that the respective tiny houses have achieved a net-zero energy status. The unit of measurement for these values is kilowatt-hours (kWh), providing a standardized basis for assessing the energy dynamics of each case. The green-highlighted cells visually underscore the successful balance between energy generation and consumption, showcasing the potential for net-zero energy outcomes within the unique context of tiny houses living in the Los Angeles region.

Table 11- Energy consumption (kWh) of all cases in Los Angeles.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	989.8085	940.9837	901.3936	1022.35	964.3148	919.6477
20	895.7167	846.786	808.9801	977.869	926.9277	889.8987
30	909.6418	873.3025	845.9931	1042.586	1009.913	987.107
40	978.2046	953.5694	936.1616	1151.603	1133.229	1120.853
50	1065.338	1048.641	1037.01	1269.917	1261.621	1255.786
60	1154.358	1141.348	1131.697	1383.763	1378.815	1375.065
70	1241.842	1228.074	1216.42	1486.315	1479.665	1474.176
80	1331.37	1313.674	1298.498	1584.707	1573.805	1564.458
90	1428.023	1405.416	1384.957	1684.554	1667.451	1652.402
Generation	6290.622	6290.622	6290.622	5641.418	5641.418	5641.418

Table 12 outlines CO2 emissions for all cases. Negative values indicate energy consumption consistently below generated electricity, emphasizing zero-emission characteristics. Green coloration signifies the successful achievement of net-zero or even carbon-negative status across all cases, reflecting a notable commitment to sustainable practices.

Table 12- Carbon emissions (Kg) of all cases in Los Angeles.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-1457.072	-1470.492	-1481.375	-1269.676	-1285.628	-1297.906
20	-1482.935	-1496.385	-1506.777	-1281.902	-1295.905	-1306.083
30	-1479.108	-1489.096	-1496.603	-1264.113	-1273.094	-1279.363
40	-1460.261	-1467.033	-1471.818	-1234.147	-1239.197	-1242.599
50	-1436.31	-1440.9	-1444.097	-1201.625	-1203.906	-1205.509
60	-1411.841	-1415.417	-1418.07	-1170.331	-1171.691	-1172.722
70	-1387.793	-1391.578	-1394.781	-1142.142	-1143.97	-1145.479
80	-1363.184	-1368.048	-1372.22	-1115.097	-1118.093	-1120.663
90	-1336.616	-1342.831	-1348.454	-1087.651	-1092.352	-1096.489

Figure 63 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 20% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 895.7167 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 1428.023 kWh. The difference between these two cases is significant: increasing the ratio from 20% to 80% results in a 59% increase in energy consumption.

The amount of electricity supplied by PV cells is 6290.622 kWh. As mentioned before, the highest energy consumption is 1428.023 kWh. This means that the residents can sell 4,862.599 kWh of electricity during the year.

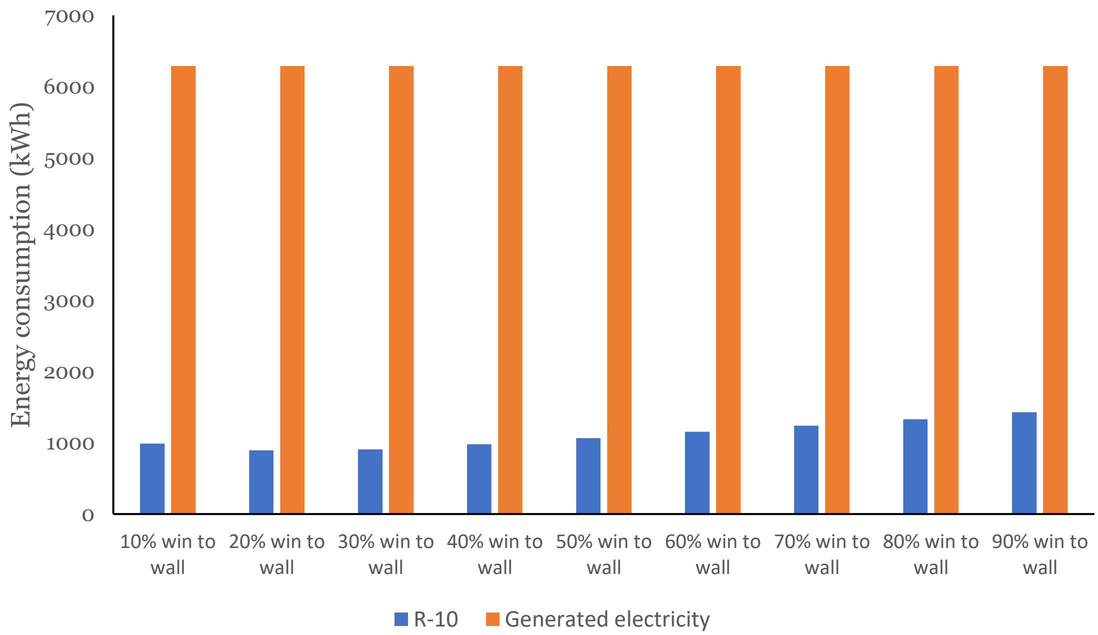


Figure 63- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Los Angeles.

In all scenarios examined in Figure 64, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 846.786 kWh, is associated with a 20% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 1405.416 kWh, translating to a noteworthy 66% increase in energy consumption when transitioning from a 20% to a 90% window-to-wall ratio.

The PV cells generate a total of 6290.622 kWh of electricity, surpassing the highest recorded energy consumption of 1405.416 kWh. Consequently, residents have the potential to sell 4,885.206 kWh of surplus electricity throughout the year.

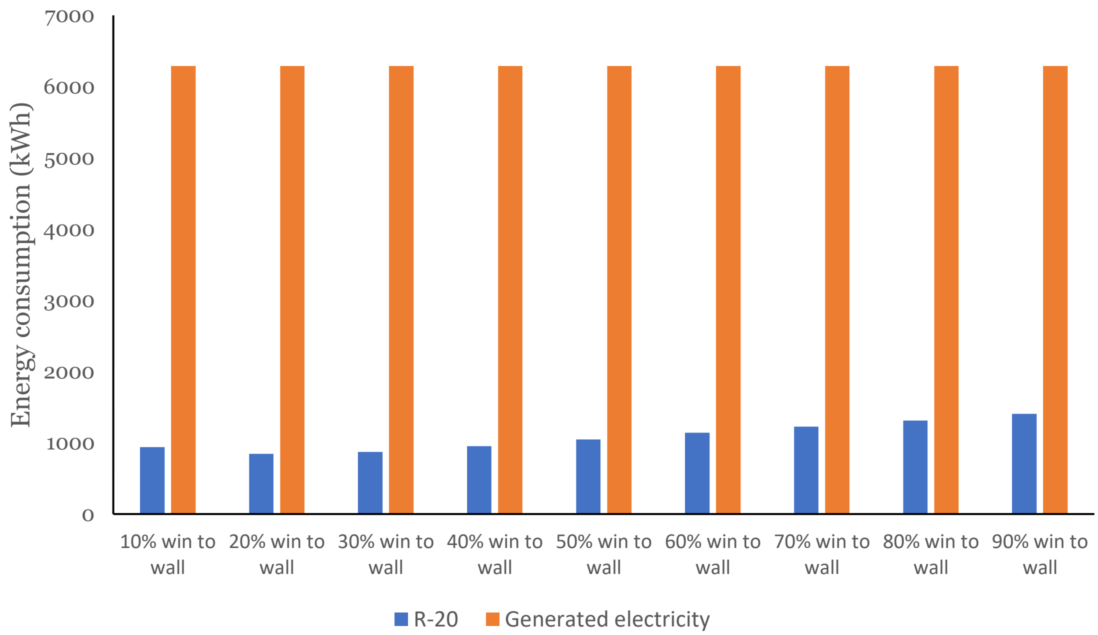


Figure 64- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 insulation (East-west) in Los Angeles.

Within the scope of Figure 65's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to effectively meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 20% ratio demonstrates the lowest annual consumption at 808.9801 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 1384.957 kWh, reflecting a notable 71% increase in energy consumption during the transition from a 20% to an 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 6290.622 kWh of electricity, surpassing the peak energy consumption recorded at 1384.957 kWh. Consequently, residents possess the potential to sell 4,905.665 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios

and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

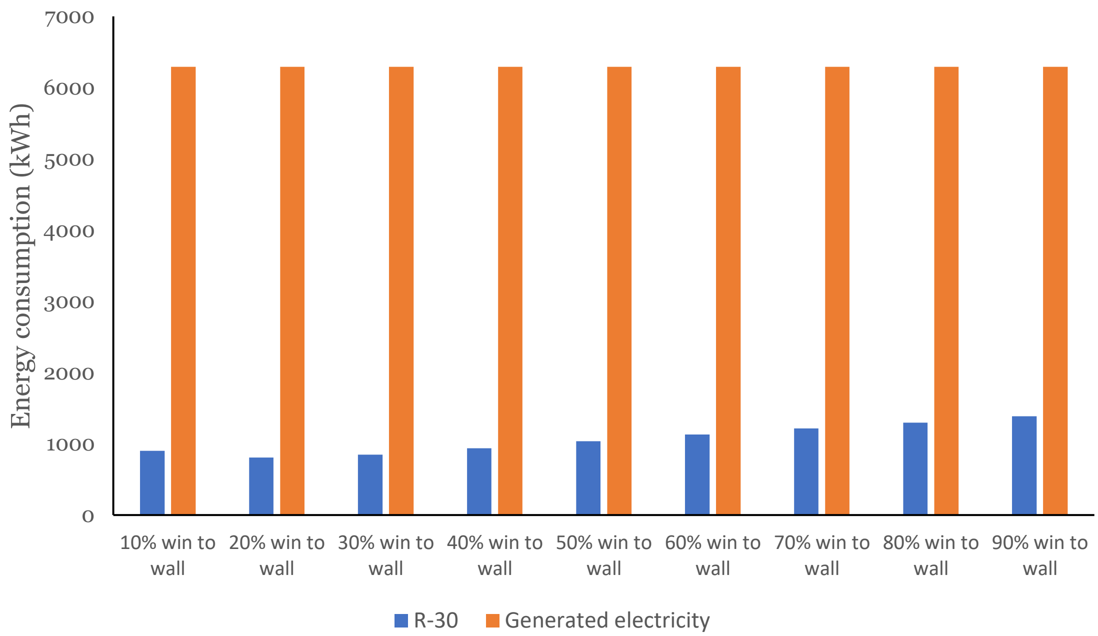


Figure 65- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 insulation (East-west) in Los Angeles.

Figure 66 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 1684.554 kWh, while the 20% ratio exhibits the lowest consumption, recording an annual total of 977.869 kWh. The significant disparity between these extremes, revealing a 72% increase in energy consumption during the transition from a 20% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 5641.418 kWh of electricity, surpassing the peak energy consumption recorded at 1684.554 kWh. This surplus electricity generation implies a notable potential for residents to contribute to the energy grid, with the possibility of selling 3,956.864 kWh of excess electricity throughout the year. This dual revelation not only highlights the capability of PV cells to offset energy demand but also presents a tangible economic opportunity for residents. In essence, this detailed examination of the graph provides a holistic understanding of the intricate interplay between window-to-wall ratios and energy consumption, emphasizing the instrumental role of PV cells in meeting the diverse energy requirements inherent in various architectural contexts.

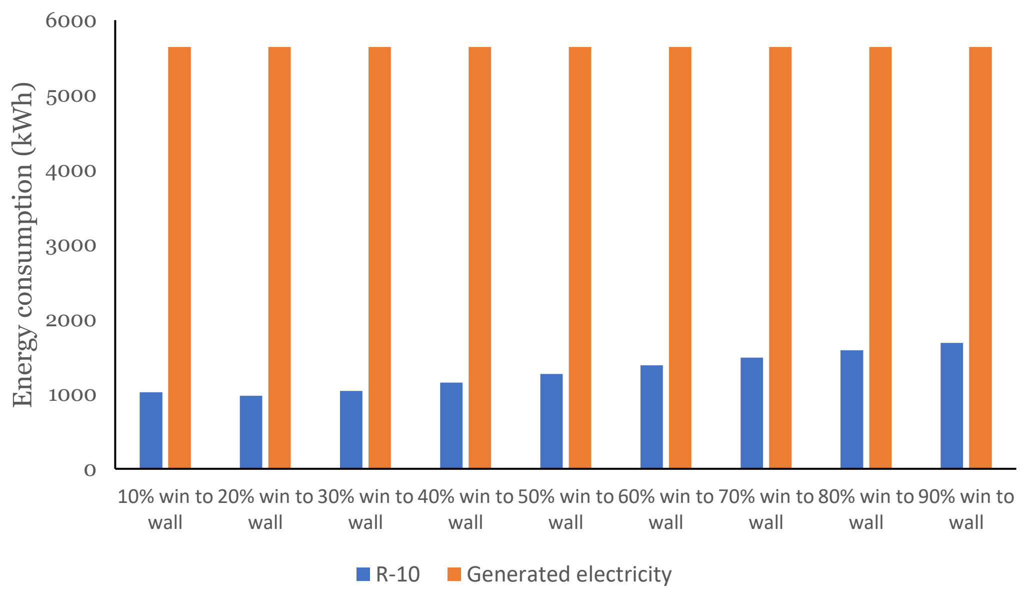


Figure 66- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (north-south) in Los Angeles.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 67. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window

to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 1667.451 kWh and the annual energy consumption for the best case 926.9277 kWh. It means increasing the window-to-wall ratio from 20% to 90% can increase energy consumption by 90%.

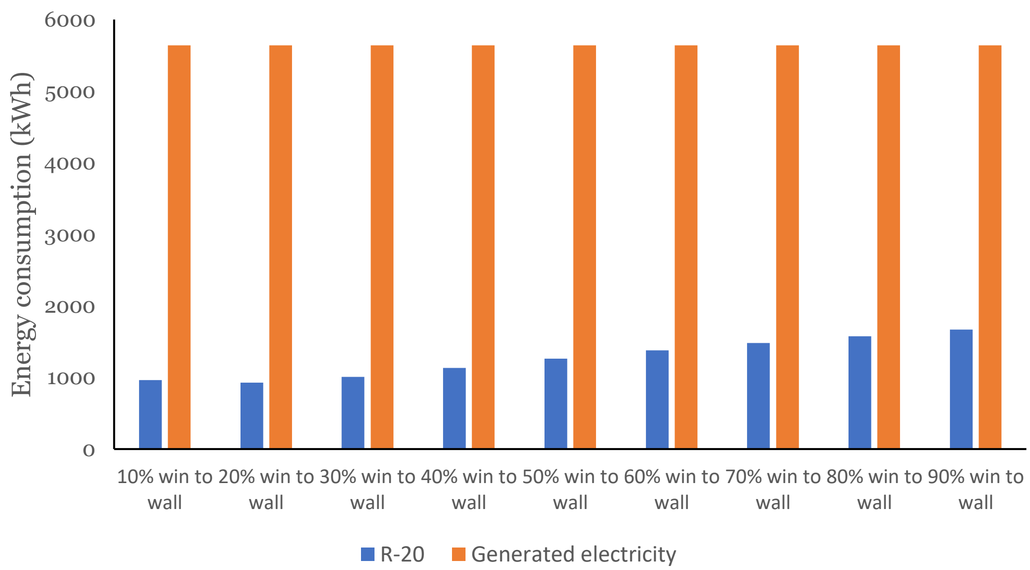


Figure 67- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 insulation (north-south) in Los Angeles.

Figure 68 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 20% ratio has the lowest energy consumption during the year. The annual energy consumption for a 20% window-to-wall ratio (best case) is 889.8987 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 1652.402 kWh. The difference between these two cases is significant: increasing the ratio from 20% to 90% results in a 86% increase in energy consumption.

The amount of electricity supplied by PV cells is 5641.418 kWh. As mentioned before, the highest energy consumption is 1652.402 kWh. This means that the residents can sell 3989.016 kWh of electricity during the year.

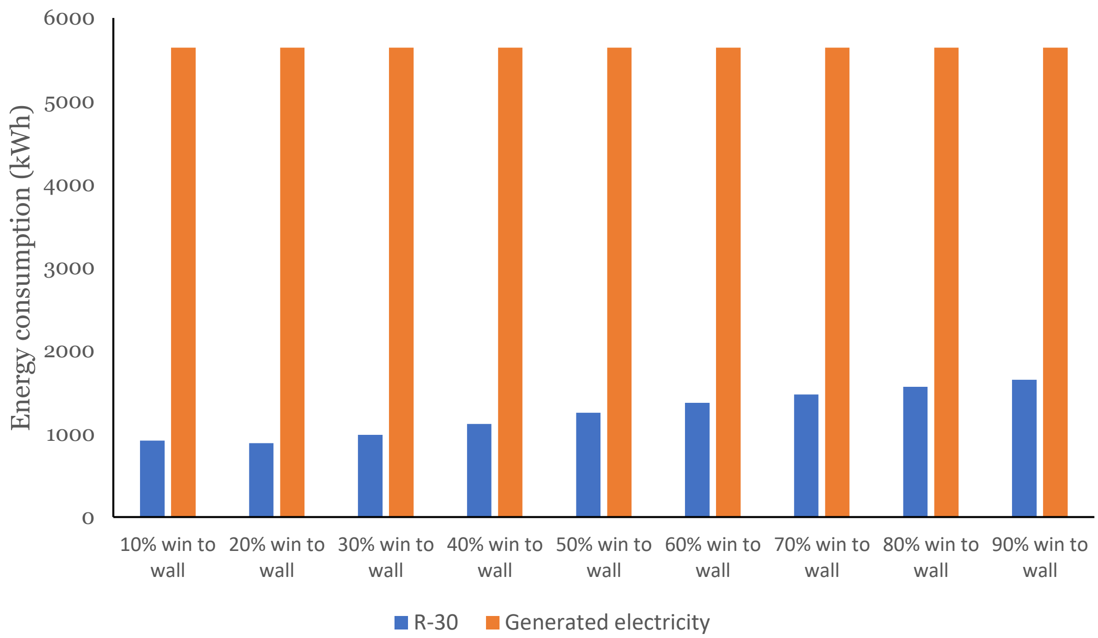


Figure 68- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 insulation (north-south) in Los Angeles.

Figure 69 shows the energy consumption of the building with R-10 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 32.5415 kWh in 10% window to wall, 204.579 kWh in 50% window to wall and 256.531 kWh in 90% WWR.

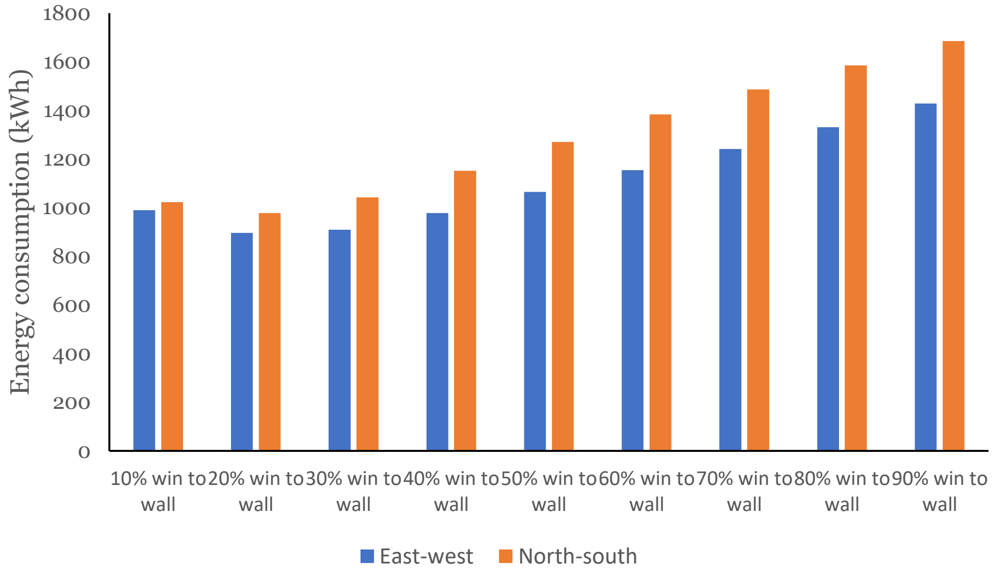


Figure 69- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Los Angeles.

Figure 70 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 23.3311 kWh in 10% window to wall, 212.98 kWh in 50% window to wall and 262.035 in 90% WWR.

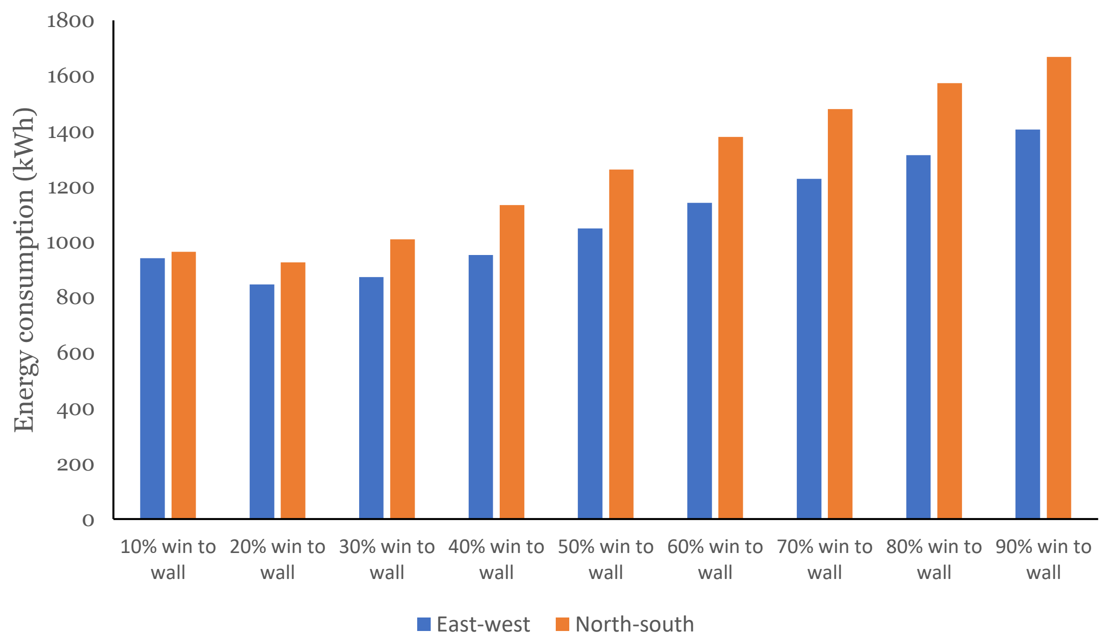


Figure 70- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Los Angeles.

Figure 71 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 18.2541 kWh in 10% window to wall, 218.776 kWh in 50% window to wall and 267.445 kWh in 90%.

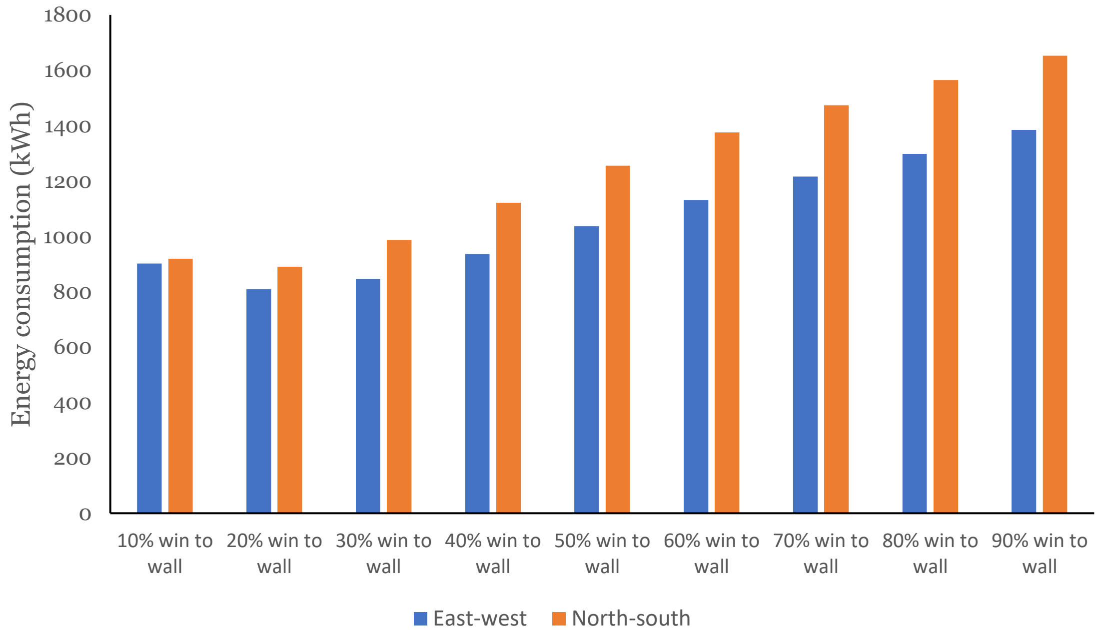


Figure 71- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Los Angeles.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 72 is about generated electricity in two orientations. The generated electricity for east-west orientation is 6290.622 kWh and for north-south orientation is 5641.418 kWh. In other words, the generated electricity in east-west orientation is 11.5 % more than the generated electricity in north-south condition.

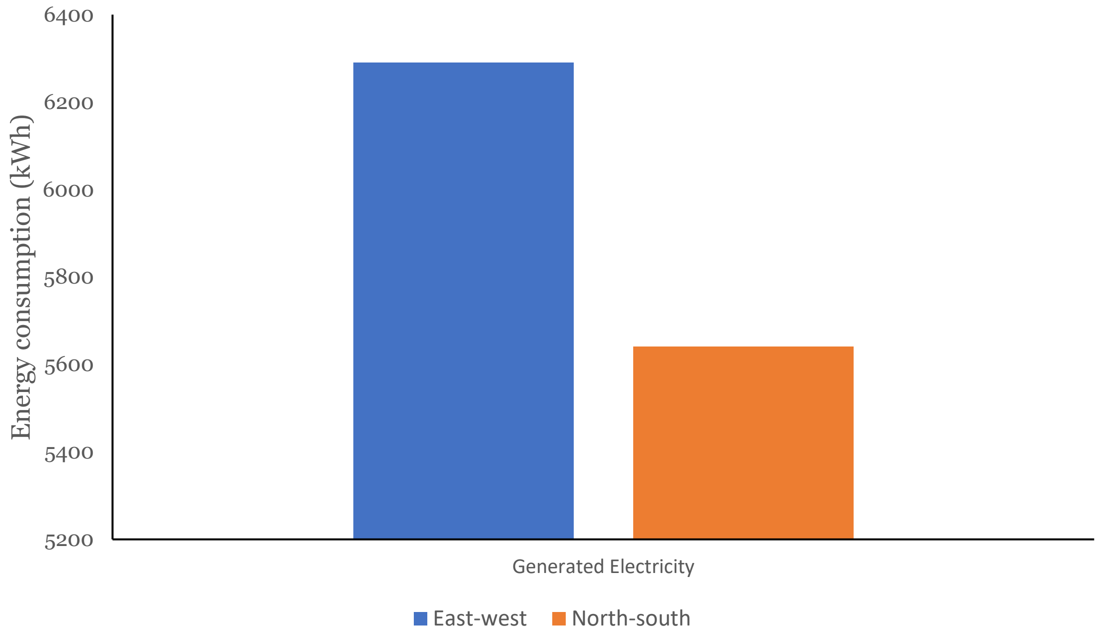


Figure 72- Generated electricity in different configurations of PV cells in Los Angeles.

Figure 73 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10%-20% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 20%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

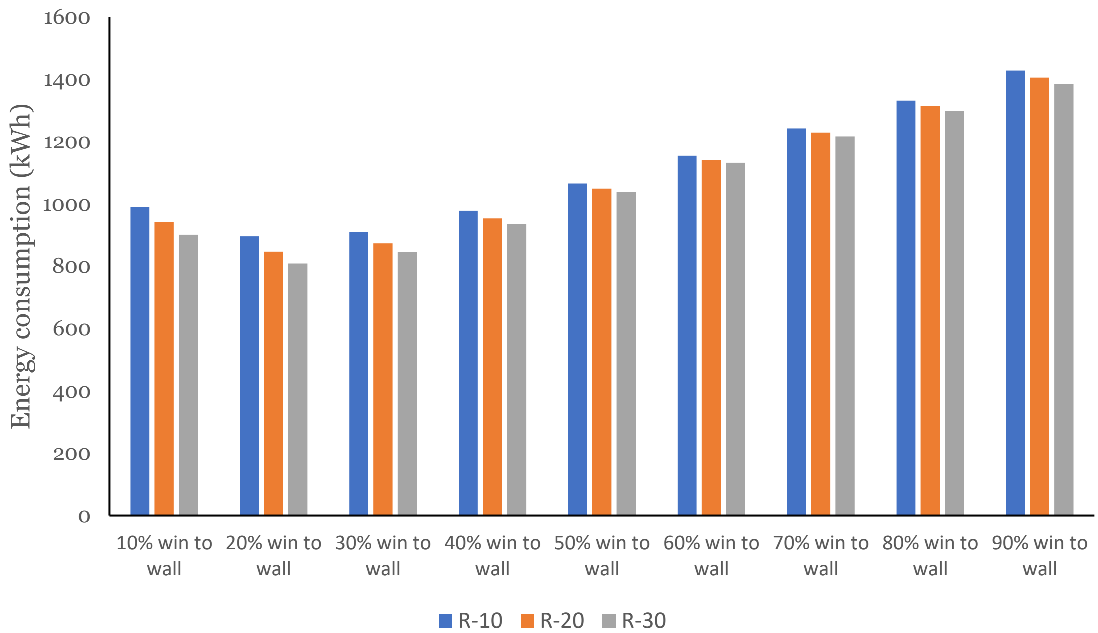


Figure 73- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west in Los Angeles.

Figure 74 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10% -20% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 20% -90% WWR range, an increase in R-value is associated with an increase in energy consumption.

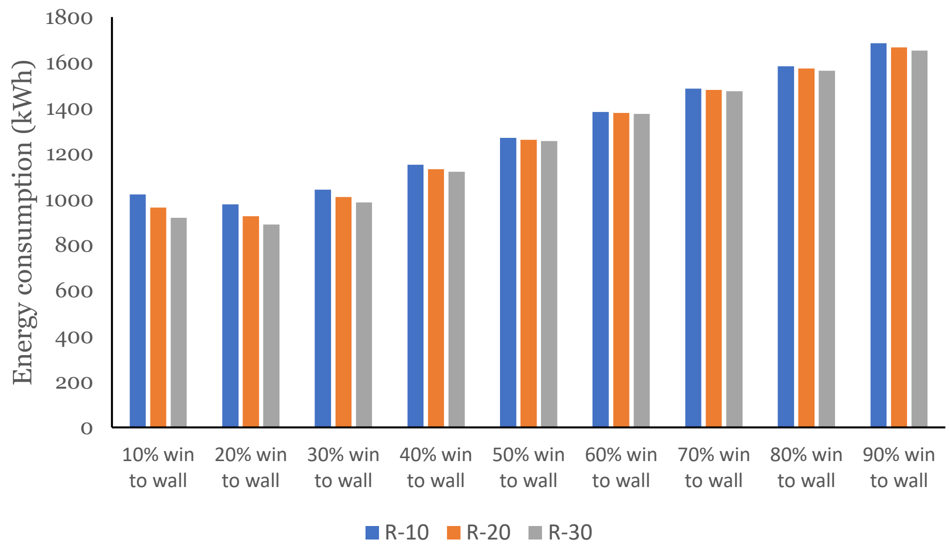


Figure 74- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Los Angeles.

The CO2 Emissions for cases with east-west orientation is shown in figure 75 Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. Generally, an increase in WWR causes an increase in CO2 emissions (except for 10%-20%), therefore the lowest CO2 emissions is 20% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

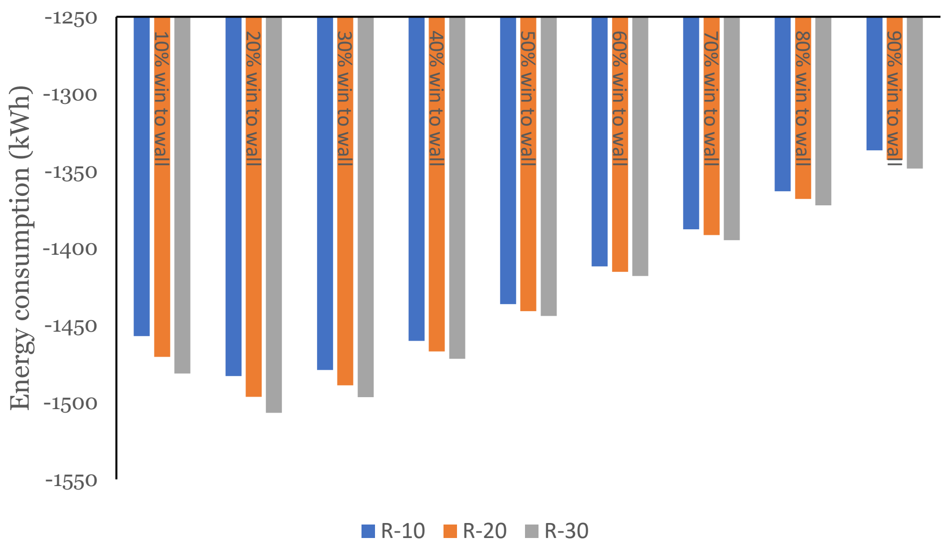


Figure 75- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east west) in Los Angeles.

Figure 76 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 20% WWR.

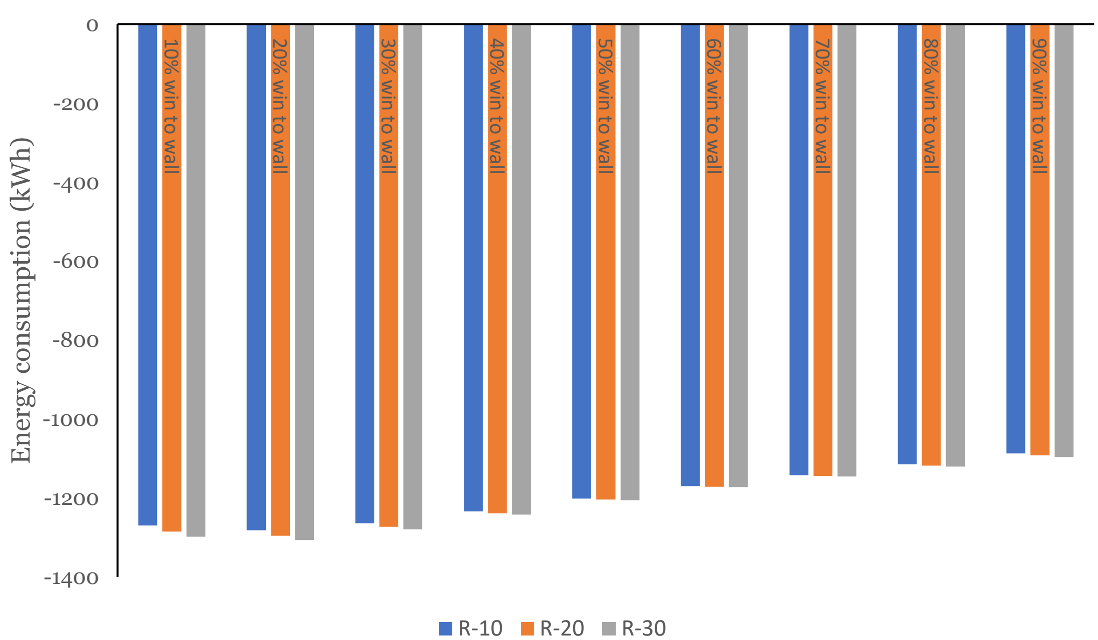


Figure 76- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north south) in Los Angeles.

11.6. 3C San Francisco, CA

Table 13 shows the energy consumption of all 54 cases in San Francisco. The Green color of cells indicates that energy consumption is less than generated electricity, so the tiny house is zero energy. The unit of these numbers is kWh.

Table 13- Energy consumption (kWh) of all cases in San Francisco.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	1813.961	1714.074	1633.141	1828.534	1708.653	1617.543
20	1619.626	1515.492	1432.508	1647.902	1526.094	1435.058
30	1502.963	1402.57	1324.136	1562.757	1453.456	1374.818
40	1462.397	1372.057	1302.296	1567.145	1475.949	1411.047
50	1470.629	1391.072	1329.608	1620.127	1544.127	1489.631
60	1523.276	1453.053	1398.016	1709.372	1643.627	1595.621
70	1613.5	1550.344	1499.079	1825.683	1767.219	1722.831
80	1729.704	1671.837	1623.577	1960.84	1907.779	1865.478
90	1887.502	1834.139	1787.179	2129.665	2080.367	2038.409
Generation	5988.185	5988.185	5988.185	5340.05	5340.05	5340.05

Table 14 presents CO2 emissions for all cases, with negative values indicating that consumed energy is consistently less than generated electricity, resulting in a net-negative outcome. This signifies a commendable commitment to sustainable practices, showcasing a positive environmental impact across the cases examined.

Table 14- Carbon emissions (Kg) of all cases in San Francisco.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-1147.398	-1174.855	-1197.101	-965.2351	-998.1876	-1023.232
20	-1200.816	-1229.44	-1252.251	-1014.887	-1048.369	-1073.392
30	-1232.884	-1260.48	-1282.04	-1038.291	-1068.335	-1089.951
40	-1244.035	-1268.867	-1288.043	-1037.085	-1062.152	-1079.993
50	-1241.772	-1263.641	-1280.536	-1022.521	-1043.412	-1058.392
60	-1227.301	-1246.603	-1261.732	-997.9901	-1016.062	-1029.257
70	-1202.5	-1219.86	-1233.952	-966.0187	-982.0891	-994.2905
80	-1170.558	-1186.465	-1199.73	-928.8673	-943.4525	-955.0801
90	-1127.183	-1141.852	-1154.76	-882.461	-896.012	-907.5452

Figure 77 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 40% ratio has the lowest energy consumption during the year. The annual energy consumption for a 40% window-to-wall ratio (best case) is 1462.397 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 1887.502 kWh. The trend of energy consumption in different WWRs indicates that finding a pattern here is complicated.

The amount of electricity supplied by PV cells is 5988.185 kWh. As mentioned before, the highest energy consumption is 1887.502 kWh. This means that the residents can sell 2,622.938 kWh of electricity during the year.

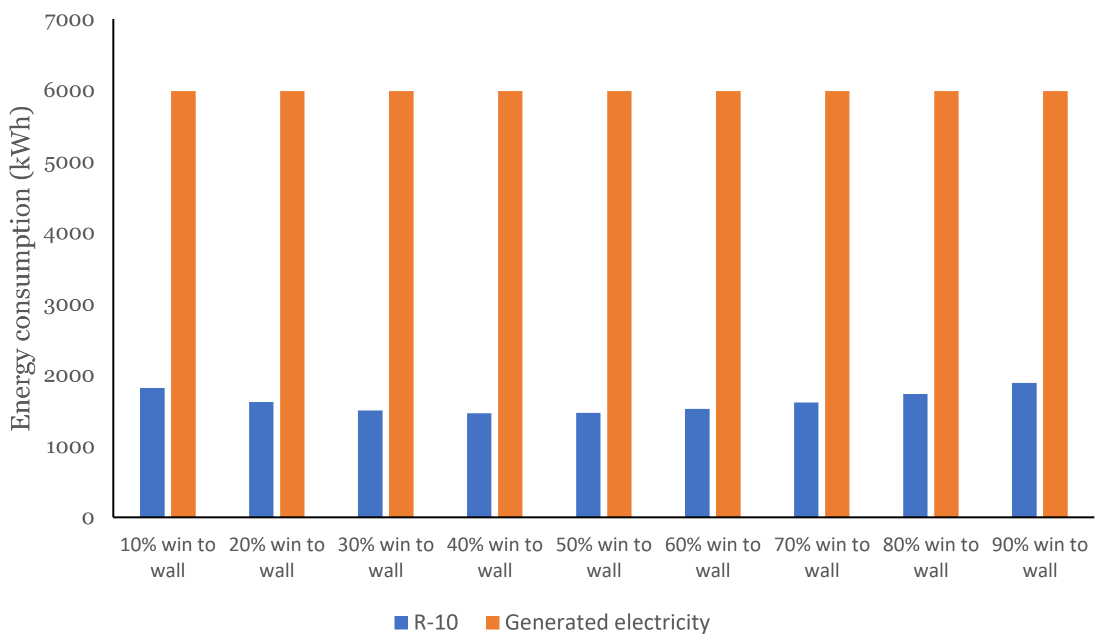


Figure 77- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in San Francisco.

In all scenarios examined in Figure 78, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 1372.057 kWh, is associated with a 40% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 1834.139 kWh, translating to a noteworthy 34% increase in energy consumption when transitioning from a 40% to an 90% window-to-wall ratio. Within 10%-40% increasing WWR leads to an increase in energy consumption, whereas, within the 50%-90% range the trend is opposite.

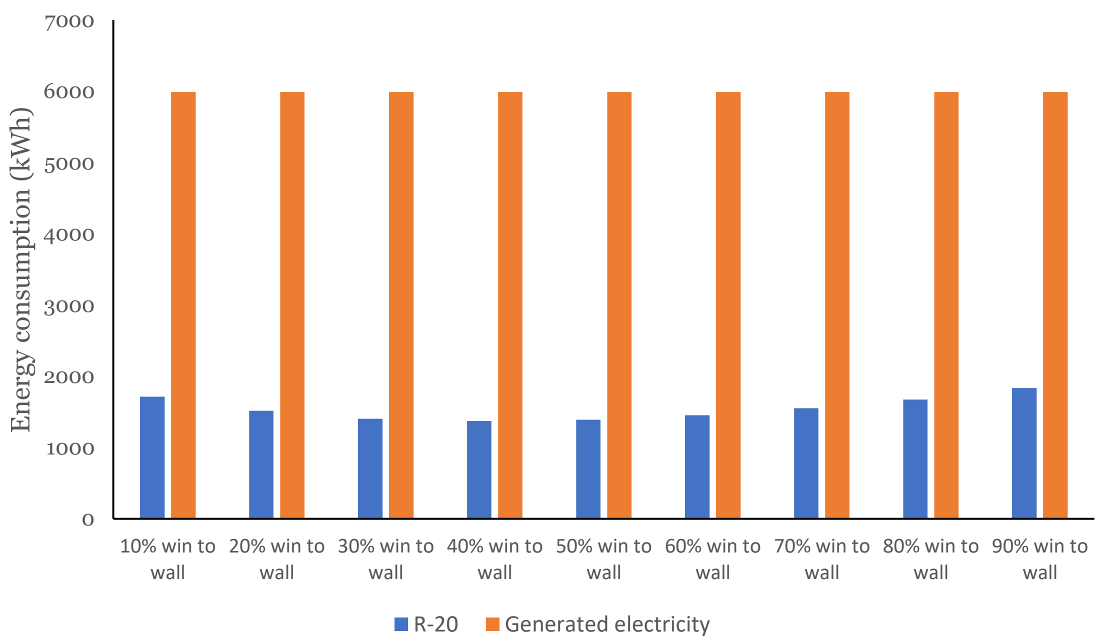


Figure 78- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in San Francisco.

Within the scope of Figure 79's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to 90% window-to-wall ratio is associated with the highest energy consumption, while the 40% ratio demonstrates the lowest annual consumption at 1302.296 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 1787.179 kWh, reflecting a notable 37% increase in energy consumption during the transition from a 40% to a 90% window-to-wall ratio. Just like the previous chart related to R-10 cases in east-west orientation, within 10%-40% increasing WWR leads to an increase in energy consumption, whereas, within the 50%-90% range the trend is opposite.

Additionally, the PV cells generate a total of 5988.185 kWh of electricity, surpassing the peak energy consumption recorded at 1787.179 kWh. Consequently, residents possess the potential to sell 4,201.006 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

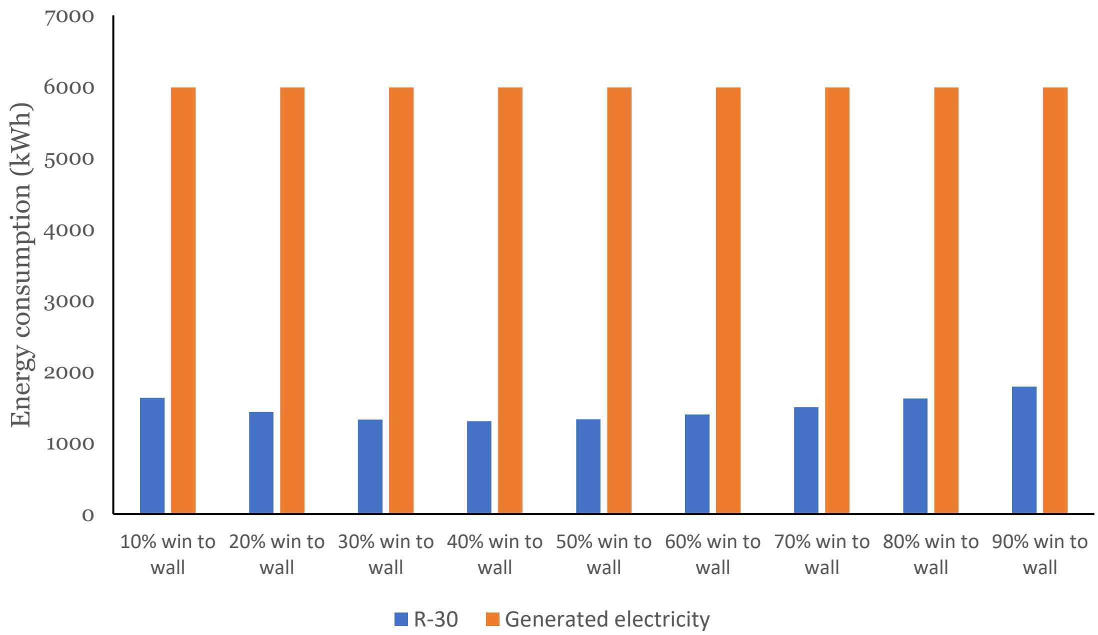


Figure 79- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in San Francisco.

Figure 80 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 2129.665 kWh, while the 30% ratio exhibits the lowest consumption, recording an annual total of 1562.757 kWh. The significant disparity between these extremes, revealing a 36% increase in energy consumption during the transition from a 30% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 5340.05 kWh of electricity, surpassing the peak energy consumption recorded at 2129.665 kWh. This surplus electricity generation implies a notable potential for residents to contribute to the energy grid, with the possibility of selling 3,210.385 kWh of excess electricity throughout the year. This dual revelation not only highlights the capability of PV cells to offset energy demand but also presents a tangible economic opportunity for residents. In essence, this detailed examination of the graph provides a holistic understanding of the intricate interplay between window-to-wall ratios and energy consumption, emphasizing the instrumental role of PV cells in meeting the diverse energy requirements inherent in various architectural contexts.

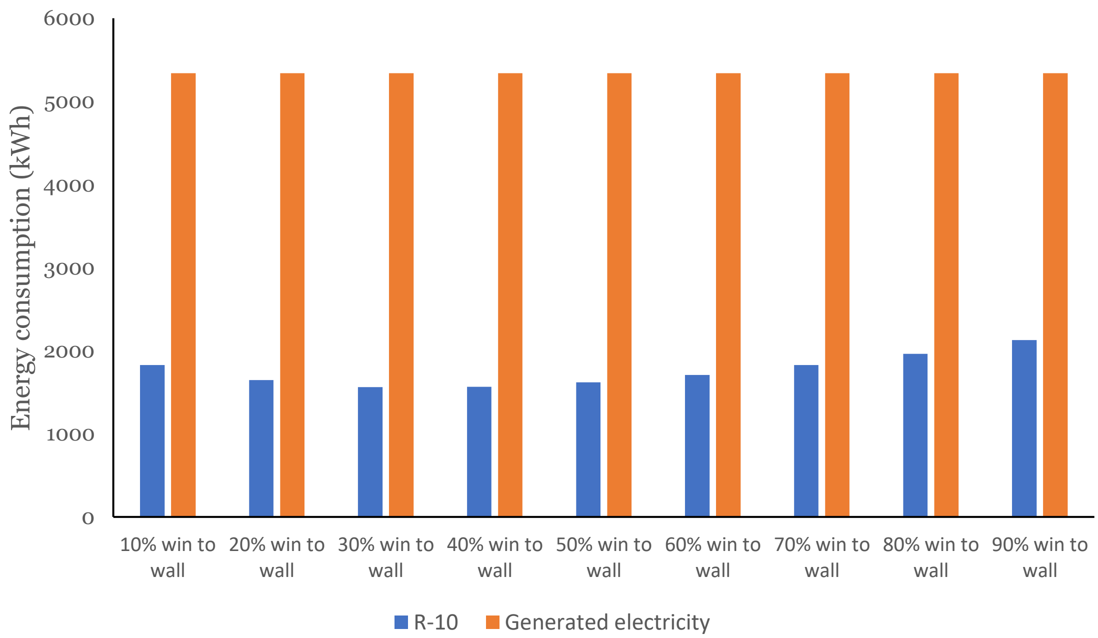


Figure 80- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in San Francisco.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 81. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 2080.367 kWh and the annual energy consumption for the best case 1453.456 kWh. It means increasing the window-to-wall ratio from 30% to 90% can increase energy consumption by 43%.

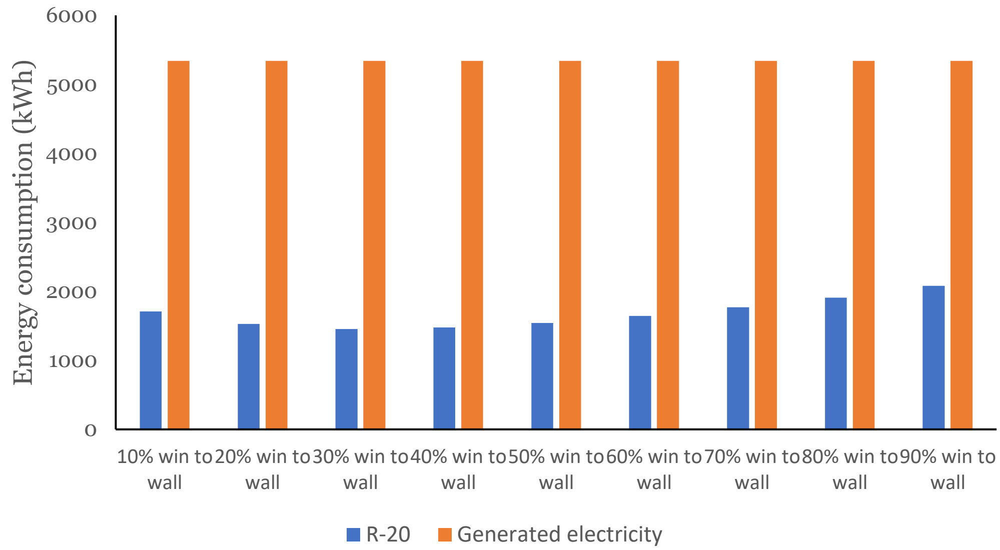


Figure 81- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in San Francisco.

Figure 82 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 30% ratio has the lowest energy consumption during the year. The annual energy consumption for a 30% window-to-wall ratio (best case) is 1374.818 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 2038.409 kWh. The difference between these two cases is significant: increasing the ratio from 30% to 90% results in a 48% increase in energy consumption.

The amount of electricity supplied by PV cells is 5340.05 kWh. As mentioned before, the highest energy consumption is 2038.409 kWh. This means that the residents can sell 3,301.641 kWh of electricity during the year.

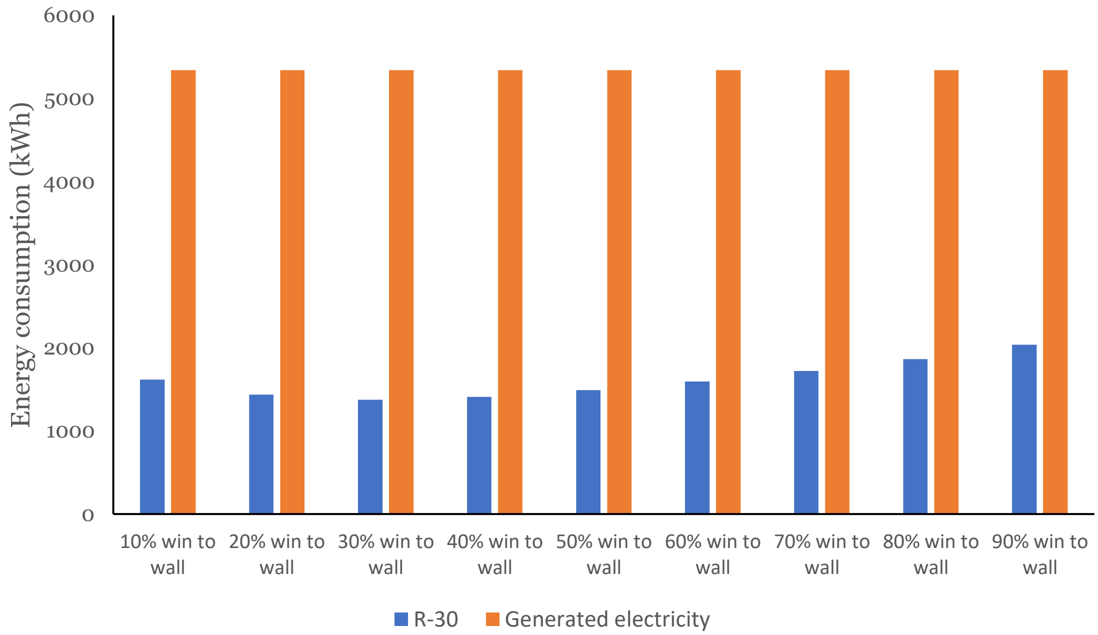


Figure 82- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in San Francisco.

Figure 83 shows the energy consumption of the building with R-10 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it’s clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 14.573 kWh (0.8%) in 10% window to wall, 149.498 kWh (10%) in 50% window to wall and 242.163 kWh (13%) in 90% WWR.

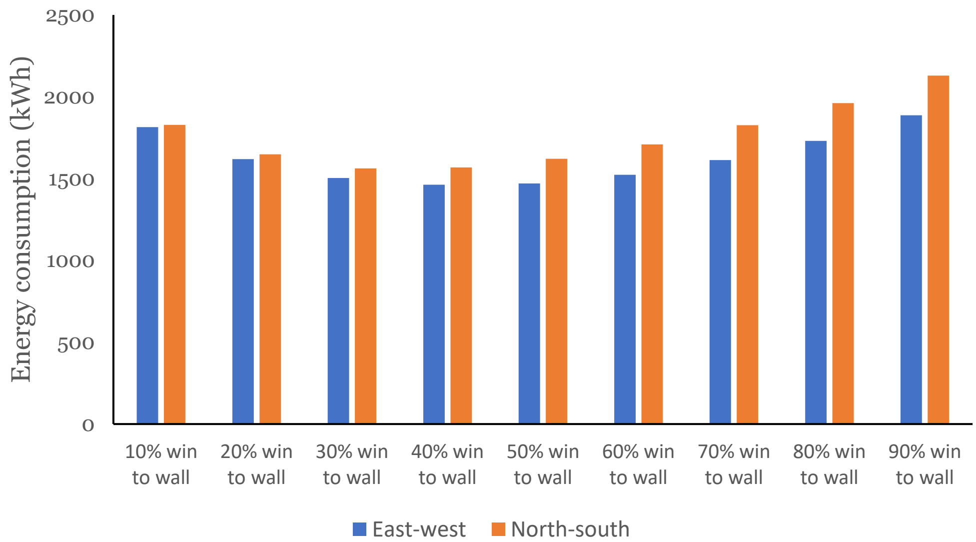


Figure 83- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in San Francisco.

Figure 84 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 5.421 kWh (0.31%) in 10% window to wall, 153.055 kWh (11%) in 50% window to wall and 246.228 kWh (13%) in 90% WWR.

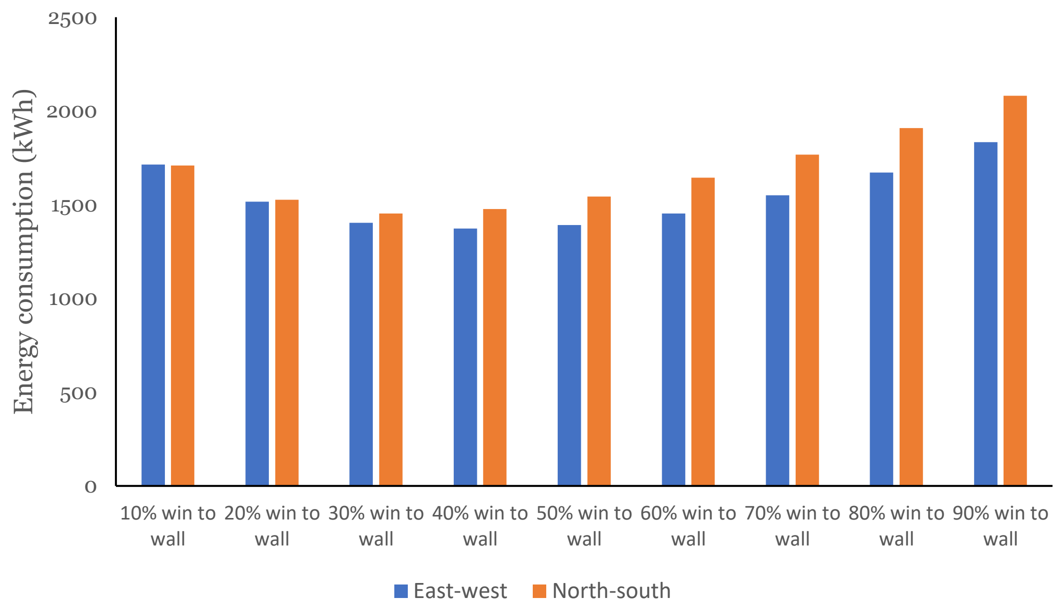


Figure 84- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in San Francisco.

Figure 85 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 15.598 kWh (0.9%) in 10% window to wall, 160.023 kWh (12%) in 50% window to wall and 251.23 kWh (14%) in 90%.

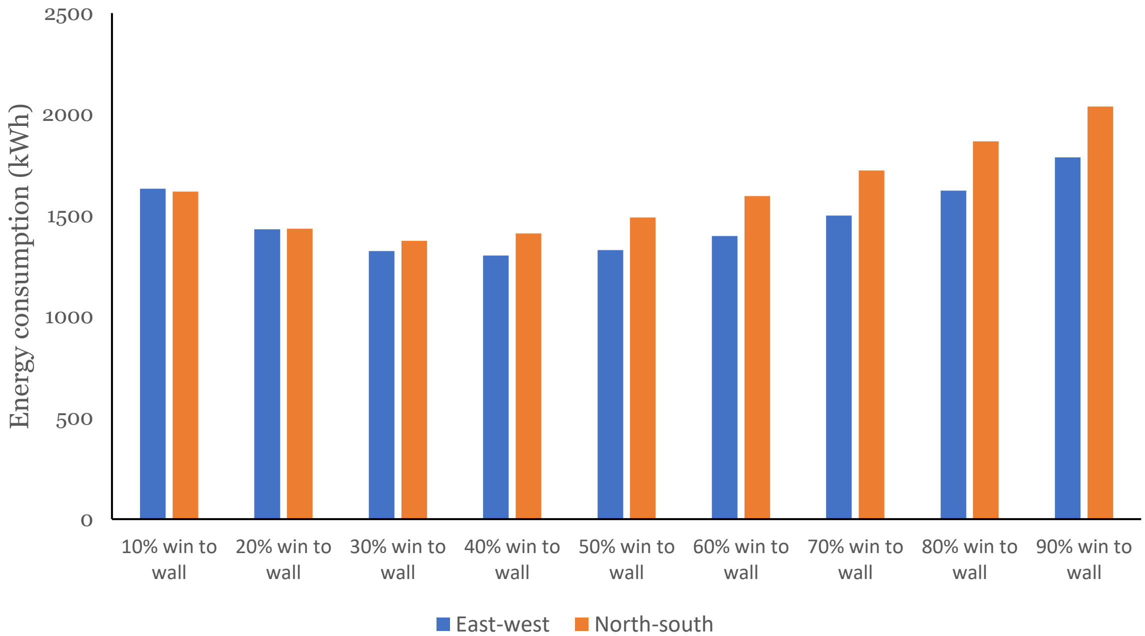


Figure 85- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in San Francisco.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 86 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5797.787 kWh and for north-south orientation is 5268.548 kWh. In other words, the generated electricity in east-west orientation is 12% more than the generated electricity in north-south condition.

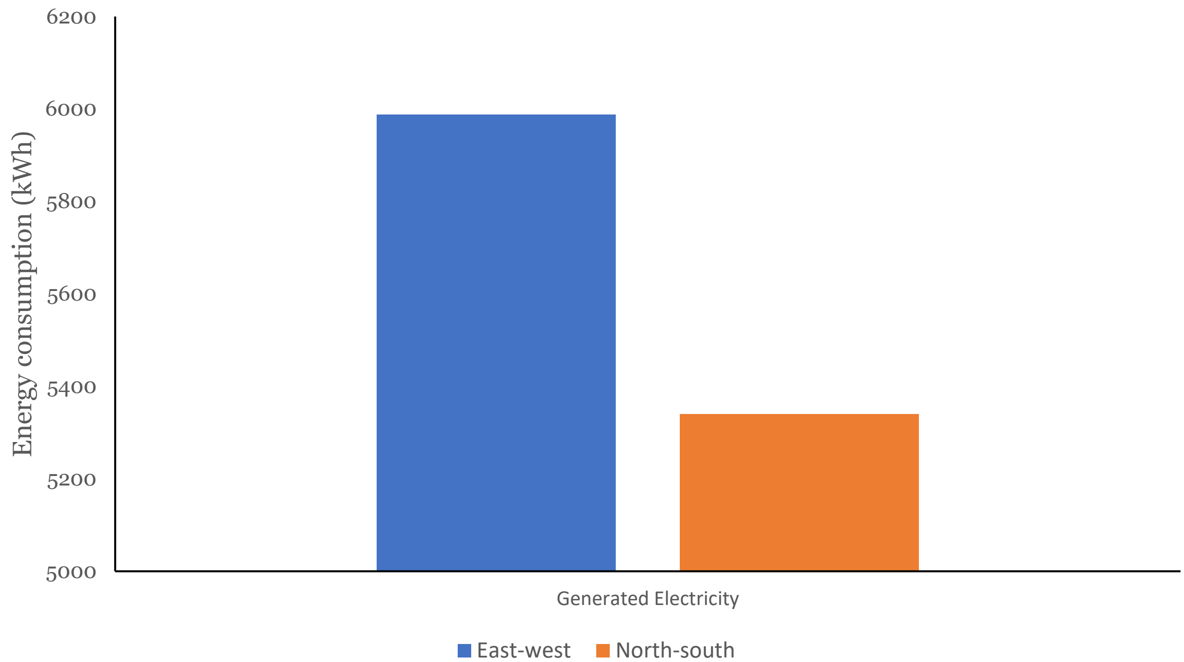


Figure 86- Generated electricity in different configurations of PV cells in San Francisco.

Figure 87 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10% -40% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 40% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.

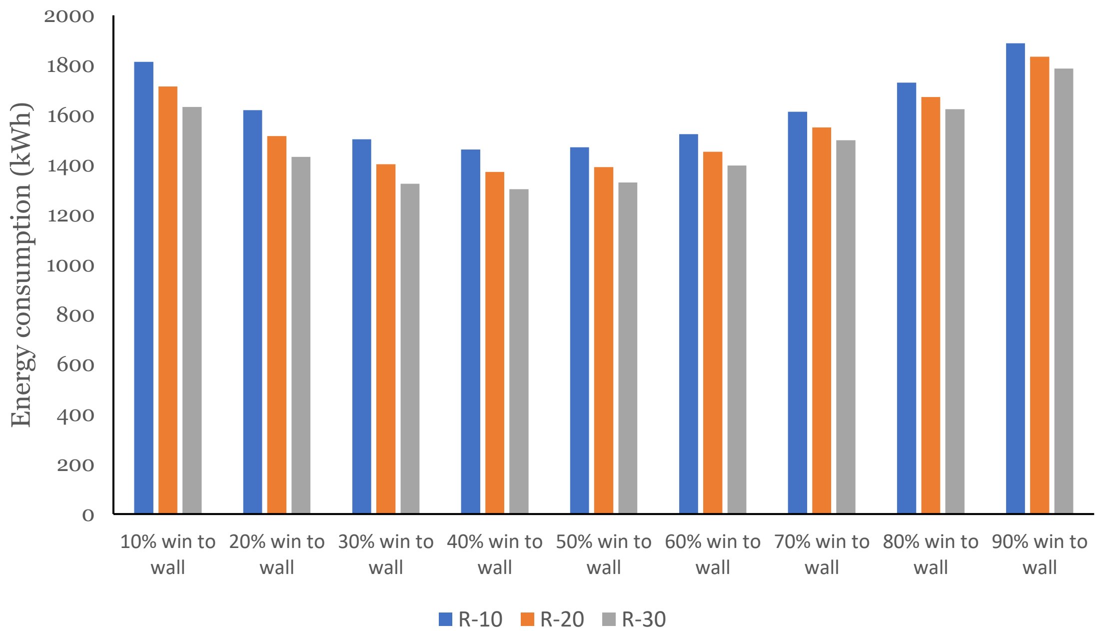


Figure 87- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in San Francisco.

Figure 88 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10% -30% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 30% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.

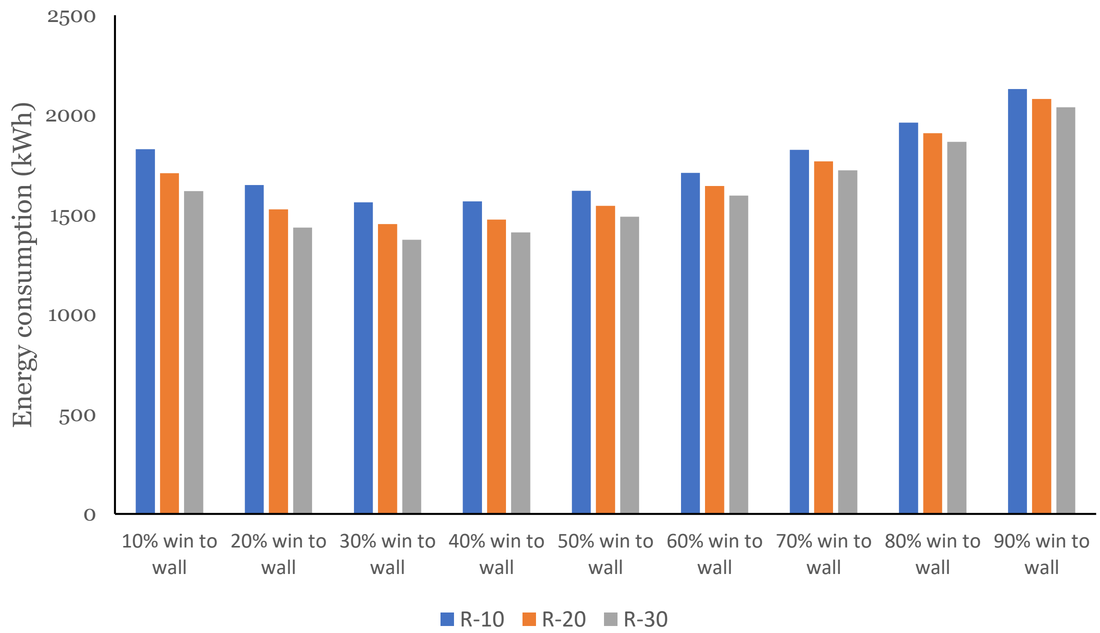


Figure 88- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in San Francisco.

CO2 Emissions for cases with east-west orientation is shown in figure 89 Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. Within the 40%-90% range, an increase in WWR causes an increase in CO2 emissions, whereas within 10%-40% the trend is adverse. Therefore, the lowest CO2 emissions is 40% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

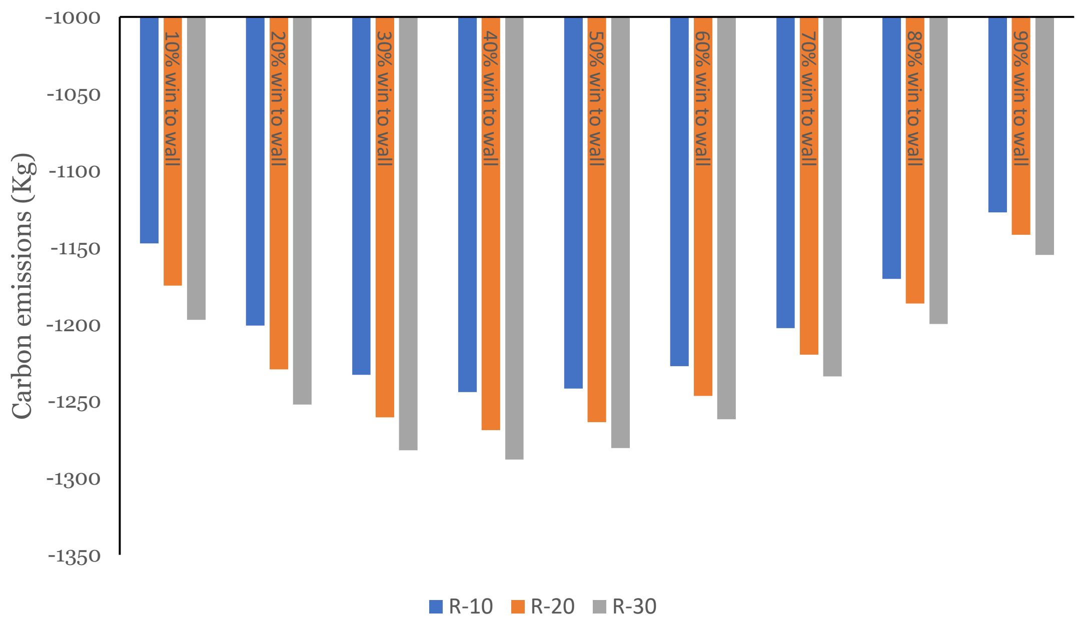


Figure 89- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in San Francisco.

Figure 90 shows CO2 emissions for cases with north-south orientation. Within the 30%-90% range, an increase in WWR causes an increase in CO2 emissions, whereas within 10%-30% the trend is adverse. Therefore, the lowest CO2 emissions is 30% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

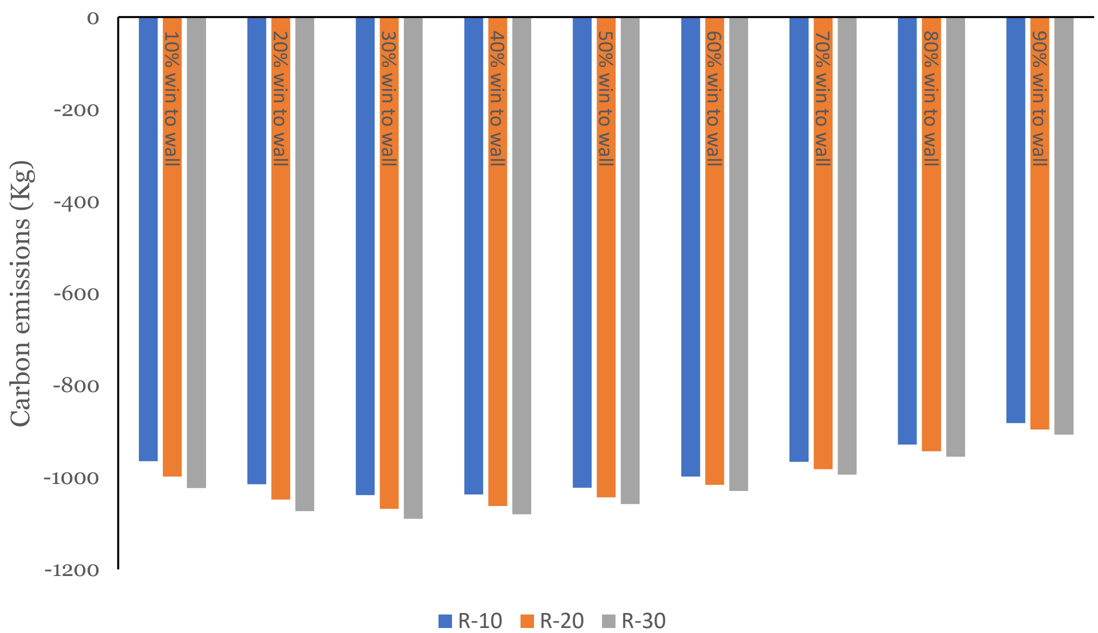


Figure 90- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in San Francisco.

11.7. 4A Washington, DC

Displayed in Table 15 are the energy consumption details for all 54 cases in Washington DC. The cells highlighted in green within the table signify instances where energy consumption falls below the generated electricity, indicating that the respective tiny houses have achieved a net-zero energy status. The unit of measurement for these values is kilowatt-hours (kWh), providing a standardized basis for assessing the energy dynamics of each case. The green-highlighted cells visually underscore the successful balance between energy generation and consumption, showcasing the potential for net-zero energy outcomes within the unique context of tiny houses living in the Washington DC region.

Table 15- Energy consumption (kWh) of all cases in Washington, DC.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	4135.04	3867.73	3659.421	4118.785	3802.237	3571.178
20	4163.991	3924.549	3736.418	4193.657	3913.674	3708.506
30	4231.63	4019.173	3851.5	4304.604	4060.192	3880.594
40	4325.517	4138.833	3991.257	4438.767	4227.25	4070.912
50	4412.047	4250.93	4121.965	4558.656	4379.859	4245.457
60	4502.195	4364.561	4253.207	4680.886	4531.244	4417.374
70	4603.365	4487.775	4392.061	4807.543	4683.146	4586.902
80	4703.256	4606.812	4524.528	4928.041	4826.776	4744.89
90	4829.451	4750.23	4680.379	5063.164	4982.706	4914.213
Generation	5113.79	5113.79	5113.79	4509.819	4509.819	4509.819

Table 16 details the CO_2 emissions across all cases. As the energy consumed in most cases is consistently less than the generated electricity, most numerical values in the table are negative. The incorporation of a green color scheme within the cells serves as a visual cue, highlighting instances where the cases exhibit zero-emission characteristics. This color-coded representation underscores the positive environmental impact of the tiny houses, emphasizing their contribution to a reduction in carbon footprint. The negative values, coupled with the green coloration, signify that the cases have effectively achieved a net-zero or even a carbon-negative status, reflecting a commendable commitment to sustainable and eco-friendly practices across the entirety of the cases examined.

Table 16- Carbon emissions (Kg) of all cases in Washington, DC.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-606.4409	-772.0676	-901.1373	-242.2873	-438.4225	-581.5886
20	-588.5022	-736.8623	-853.4294	-195.896	-369.3755	-496.4993
30	-546.5928	-678.2324	-782.1237	-127.1521	-278.5919	-389.872
40	-488.4197	-604.0901	-695.5295	-44.02434	-175.0815	-271.9497
50	-434.805	-534.6343	-614.5419	30.26007	-80.5238	-163.8005
60	-378.9488	-464.228	-533.2236	105.9945	13.27544	-57.2795
70	-316.263	-387.8833	-447.1888	184.4722	107.395	47.76146
80	-254.3696	-314.1275	-365.1111	259.1333	196.3889	150.5658
90	-176.1786	-225.264	-268.5443	342.8569	293.0042	145.652

Figure 91 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 4135.04 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 4829.451 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 16.8% increase in energy consumption.

The amount of electricity supplied by PV cells is 5113.79 kWh. As mentioned before, the highest energy consumption is 4829.451 kWh. This means that the residents can sell 284.339 kWh of electricity during the year.

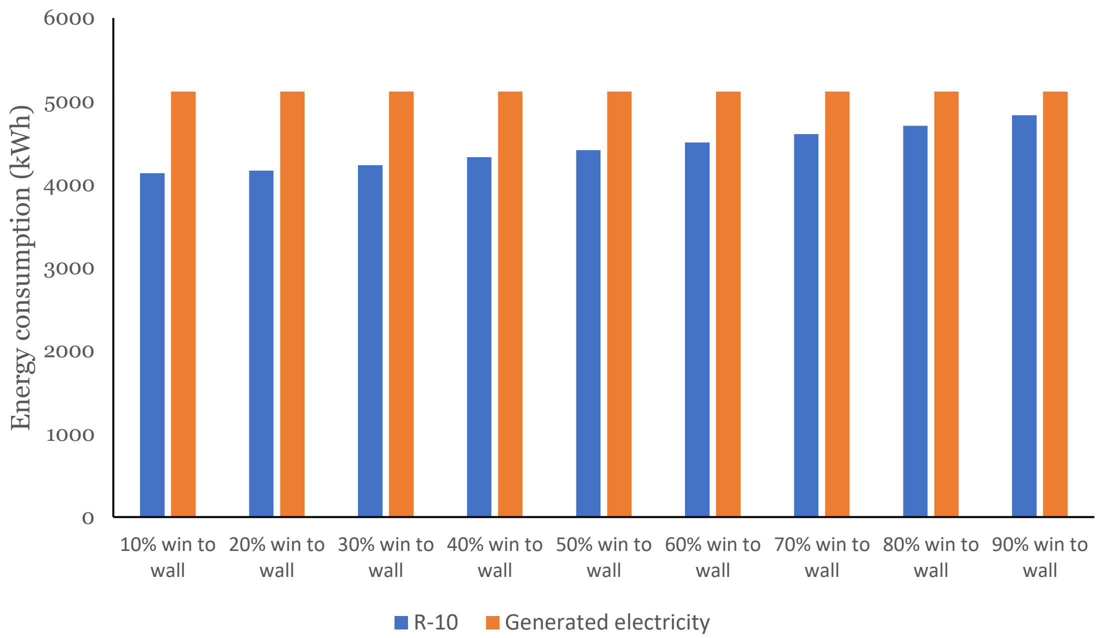


Figure 91- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Washington, DC.

In all scenarios examined in Figure 92, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 3867.73 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 4750.23 kWh, translating to a noteworthy 23% increase in energy consumption when transitioning from a 10% to a 90% window-to-wall ratio.

The PV cells generate a total of 5113.79 kWh of electricity, surpassing the highest recorded energy consumption of 4750.23 kWh. Consequently, residents have the potential to sell 363.56 kWh of surplus electricity throughout the year.

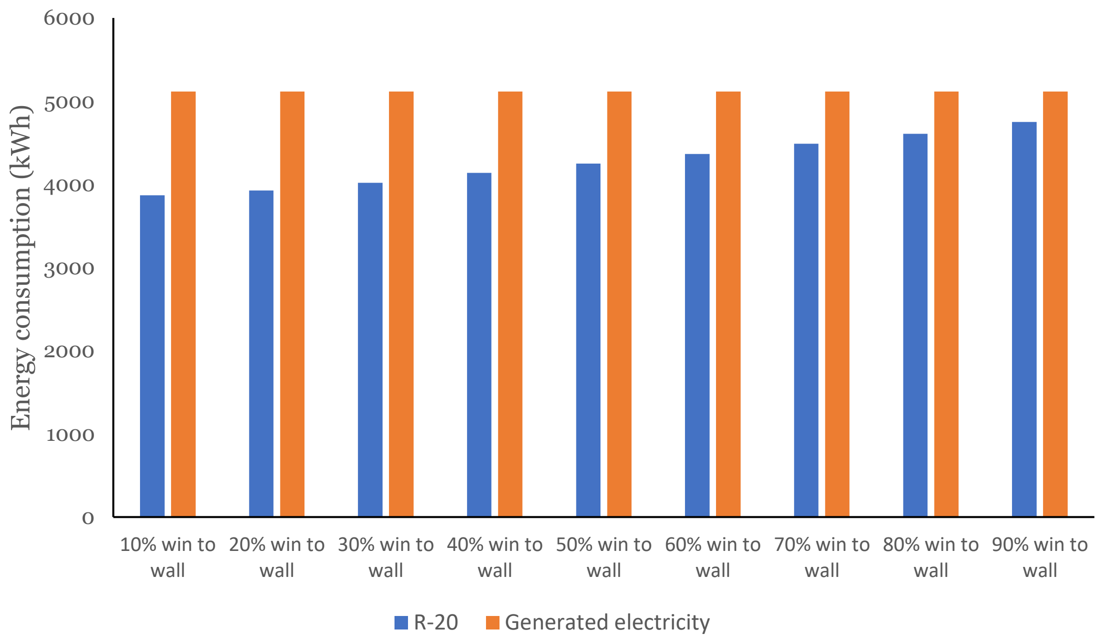


Figure 92- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Washington, DC.

Within the scope of Figure 93's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to effectively meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 3659.421 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 4680.379kWh,

reflecting a notable 28% increase in energy consumption during the transition from a 10% to an 80% window-to-wall ratio.

Additionally, the PV cells generate a total of 5113.79 kWh of electricity, surpassing the peak energy consumption recorded at 4680.379 kWh. Consequently, residents possess the potential to sell 433.411 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

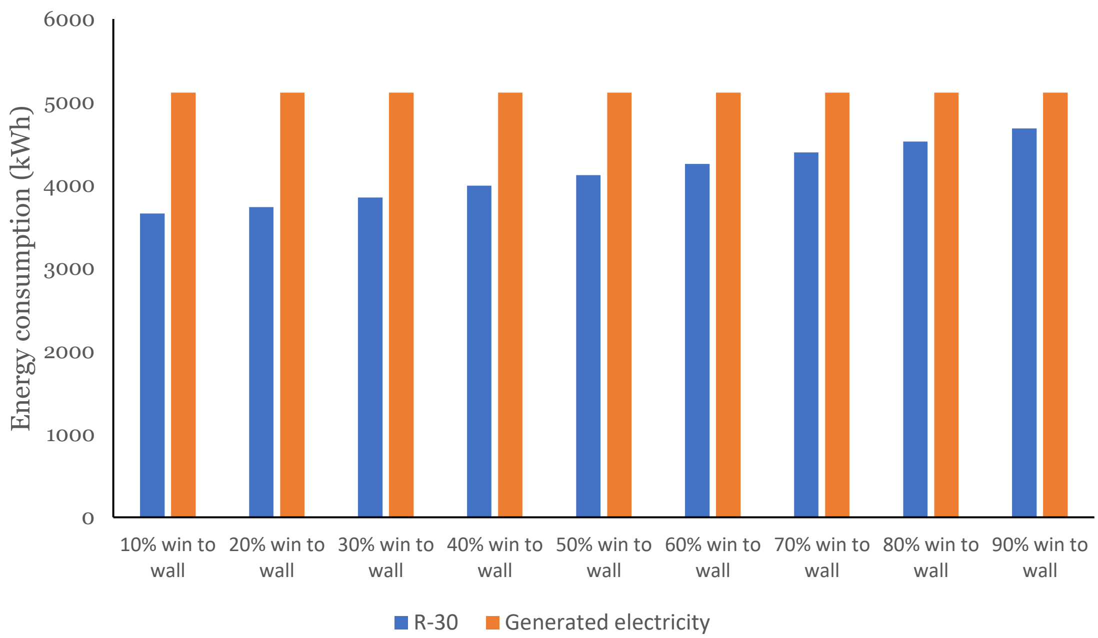


Figure 93- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Washington, DC.

Figure 94 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. The figure indicates that within 10%-30% PV cells are able to supply the required energy however, within 50%-90% range other sources are needed to supply it. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 5063.164 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 4118.785 kWh. The significant disparity between these extremes, revealing a 23% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 4509.819 kWh of electricity, surpassing the peak energy consumption recorded at 5063.164 kWh. Therefore, 553.345 kWh should be supplied in worse case by the grid.

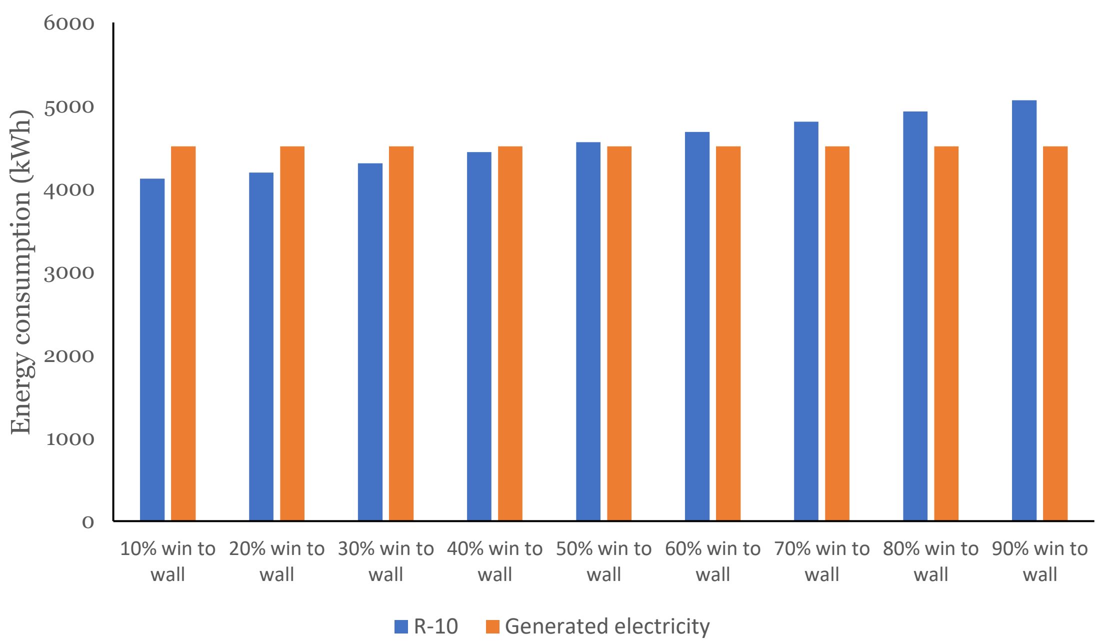


Figure 94- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Washington, DC.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 95. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 4982.706 kWh and the annual energy consumption for the best case 3802.237 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 23%.

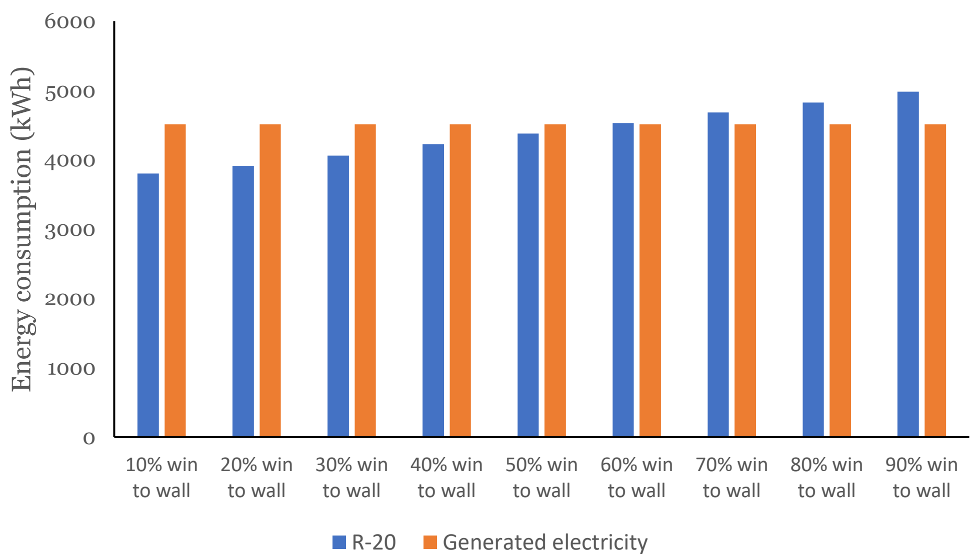


Figure 95- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Washington, DC.

Figure 96 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in the 10%-60% range, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 3571.178 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 4914.213 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 38% increase in energy consumption.

The amount of electricity supplied by PV cells is 4509.819 kWh. As mentioned before, the highest energy consumption is 4914.213 kWh. Therefore, in some cases another source is needed to supply the required electricity.

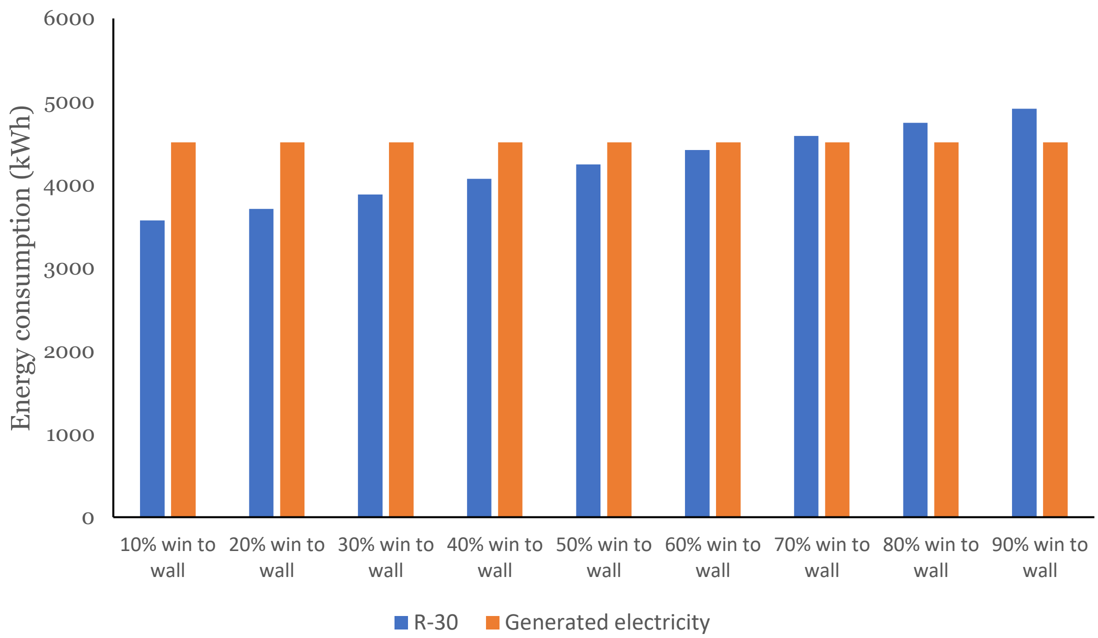


Figure 96- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Washington, DC.

Figure 97 shows the energy consumption of the building with R-10 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation (except for 10% WWR). As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 16.225 kWh (0.4%) in 10% window to wall, 146.609 kWh (3.3%) in 50% window to wall and 233.713 kWh (4.8%) in 90% WWR.

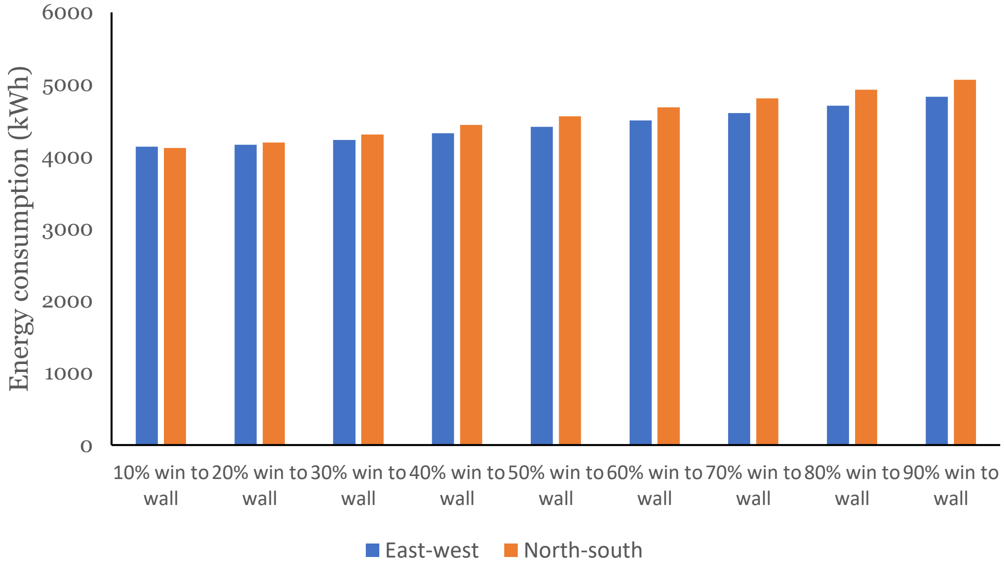


Figure 97- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Washington, DC.

Figure 98 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios (except for 10% and 20%) the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 65.493 kWh (1.7%) in 10% window to wall, 128.929 (3%) kWh in 50% window to wall and 232.476 kWh (4.9%) in 90% WWR.

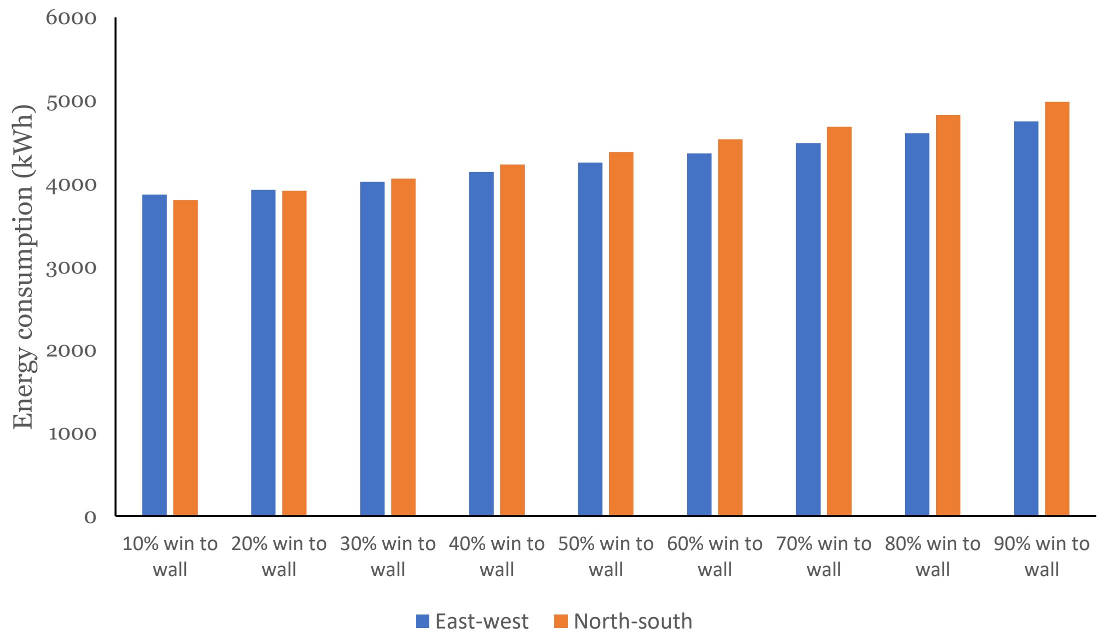


Figure 98- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Washington, DC.

Figure 99 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases (except for 10% and 20%) the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 88.243 kWh (2.4%) in 10% window to wall, 123.492 kWh (3%) in 50% window to wall and 233.834 kWh (5%) in 90%.

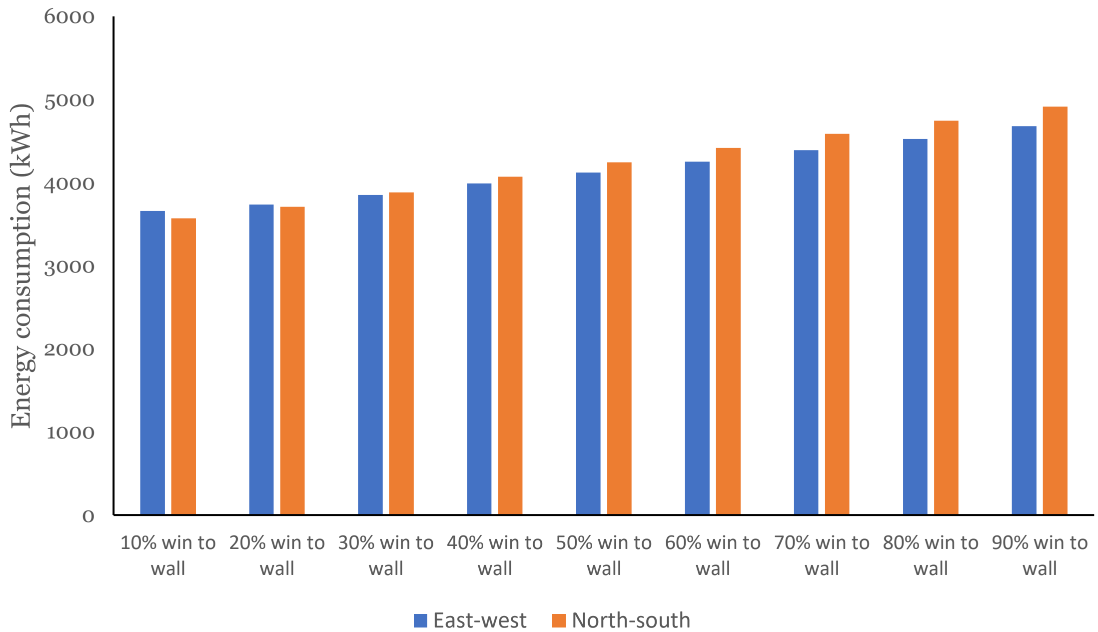


Figure 99- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Washington, DC.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 100 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5113.79 kWh and for north-south orientation is 4509.819 kWh. In other words, the generated electricity in east-west orientation is 13.4% more than the generated electricity in north-south condition.

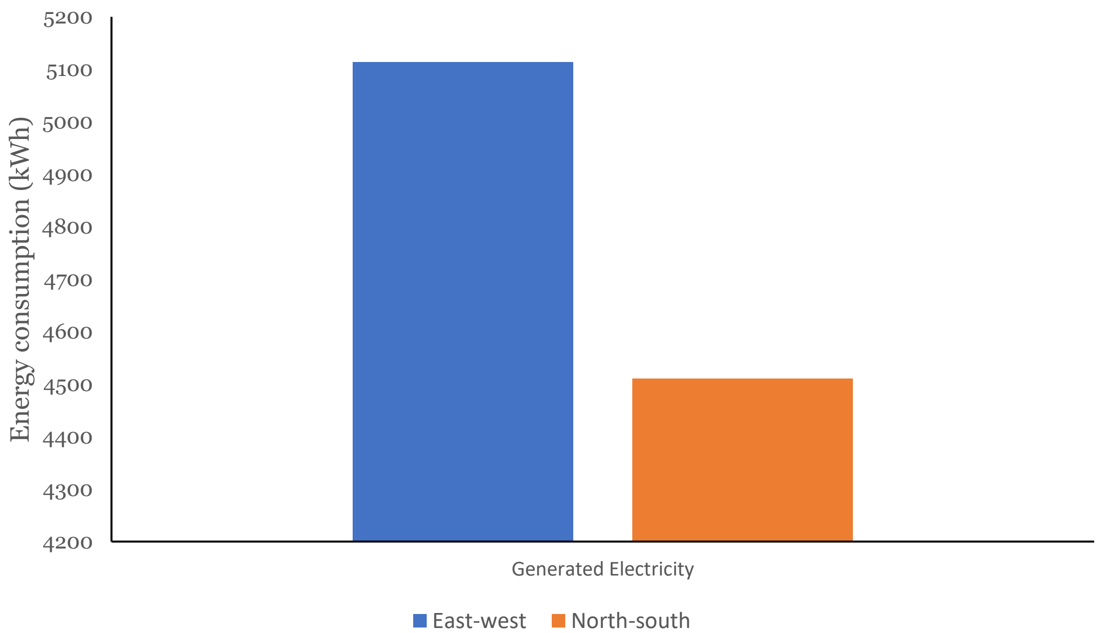


Figure 100- Generated electricity in different configurations of PV cells in Washington, DC.

Figure 101 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. In all ratios, an increase in R-value is associated with an increase in energy consumption.

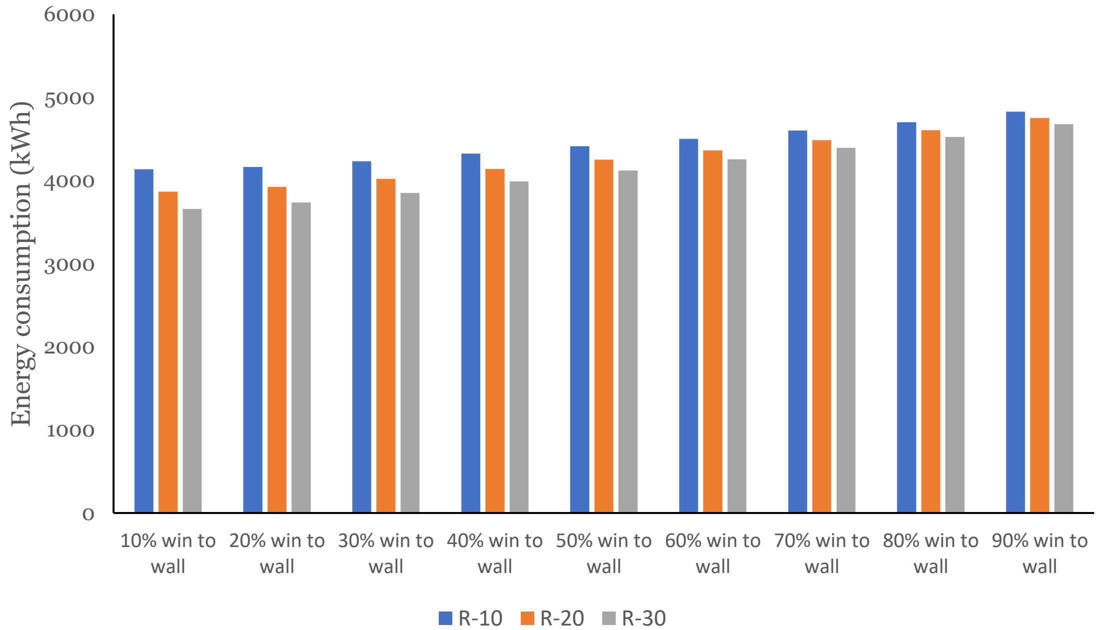


Figure 101- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Washington, DC.

Figure 102 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. In all ratios, an increase in R-value is associated with an increase in energy consumption.

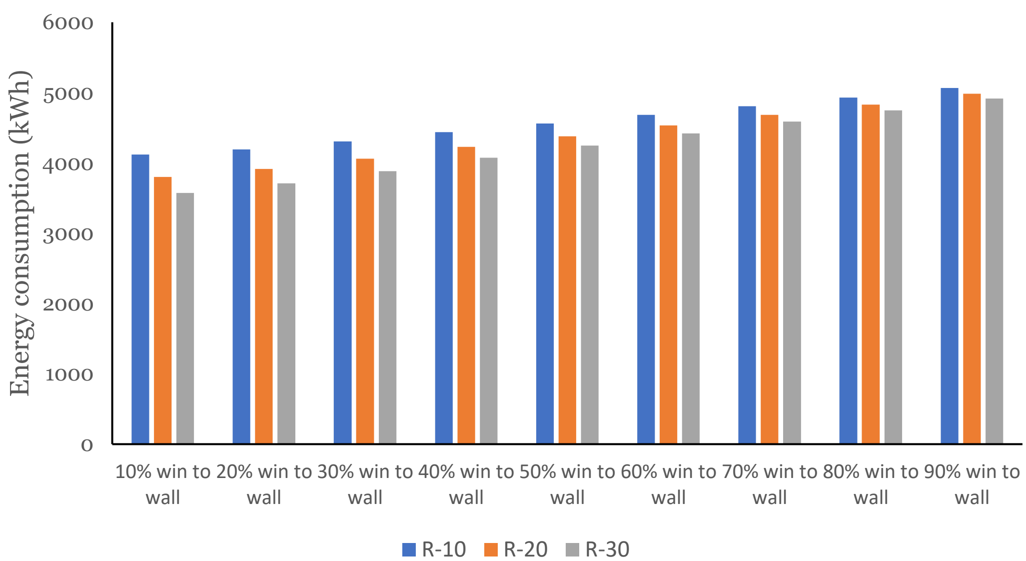


Figure 102- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Washington, DC.

The CO2 emissions for cases with east-west orientation is shown in figure 103 Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

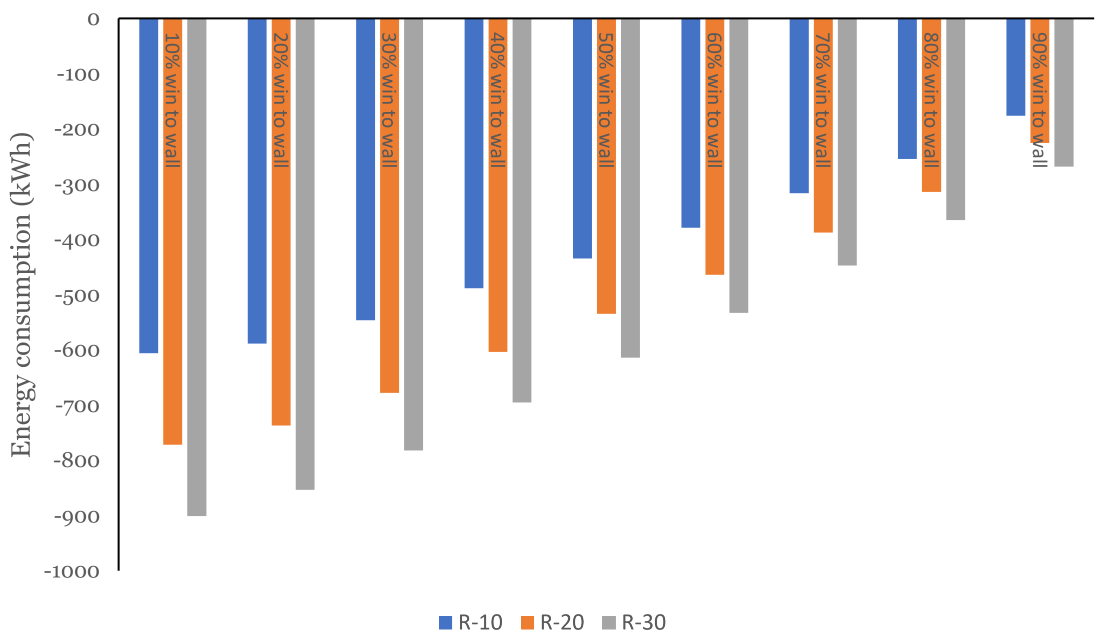


Figure 103- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Washington, DC.

Figure 104 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

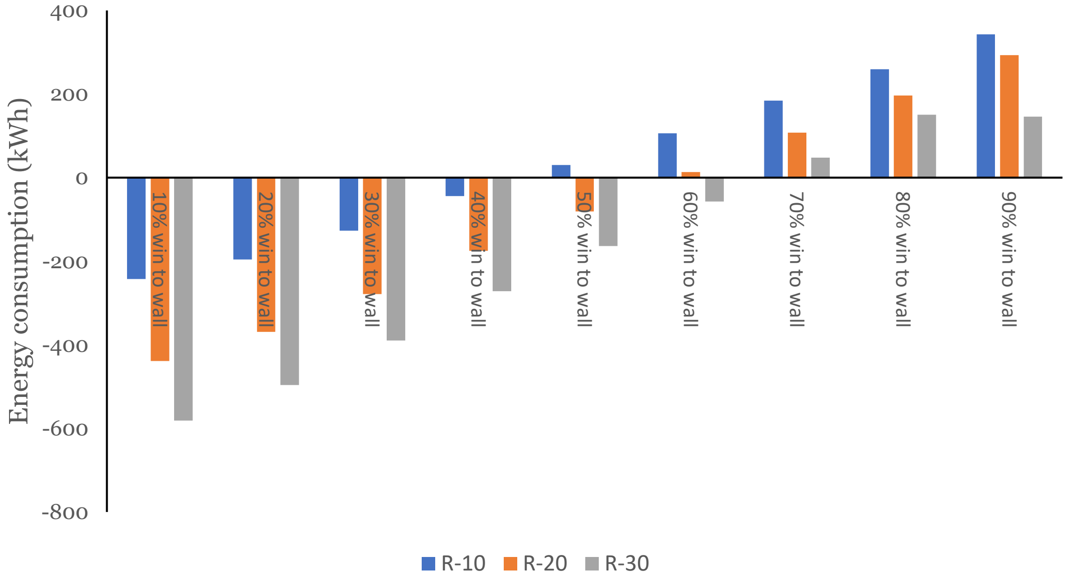


Figure 104- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Washington, DC.

11.8. 4B Albuquerque, NM

Table 17 shows the energy consumption of all 54 cases in Albuquerque. The Green color of cells indicates that energy consumption is less than generated electricity, so the tiny house is zero energy. The unit of these numbers is kWh.

Table 17- Energy consumption (kWh) of all cases in Albuquerque.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	3245.83	3035.214	2868.529	3285.436	3030.527	2842.091
20	3149.969	2951.739	2796.263	3255.963	3023.987	2853.846
30	3127.169	2948.175	2808.885	3298.177	3096.887	2948.878
40	3161.427	3003.946	2880.526	3394.6	3222.078	3095.409
50	3219.443	3082.994	2975.369	3510.1	3365.64	3259.243
60	3309.939	3192.345	3100.127	3649.973	3529.731	3439.445
70	3435.604	3334.617	3251.387	3813.583	3712.98	3634.85
80	3579.898	3492.649	3418.613	3990.289	3905.611	3837.409
90	3769.932	3695.226	3629.383	4195.741	4124.915	4065.073
Generation	6999.466	6999.466	6999.466	6227.568	6227.568	6227.568

Table 18 is about CO2 emissions in all cases. Because the consumed energy in all cases is less than the generated electricity all numbers are negative. The green color indicated that the cases are zero-emission, and the unit of numbers is Kg.

Table 18- Carbon emissions (Kg) of all cases in Albuquerque.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-3435.889	-3628.677	-3781.251	-2693.079	-2926.41	-3098.895
20	-3523.635	-3705.085	-3847.4	-2720.058	-2932.396	-3088.134
30	-3544.505	-3708.347	-3835.846	-2681.416	-2865.667	-3001.148
40	-3513.147	-3657.297	-3770.269	-2593.156	-2751.074	-2867.021
50	-3460.042	-3584.941	-3683.455	-2487.434	-2619.665	-2717.055
60	-3377.207	-3484.846	-3569.258	-2359.4	-2469.464	-2552.107
70	-3262.18	-3354.617	-3430.802	-2209.64	-2301.727	-2373.243
80	-3130.1	-3209.963	-3277.732	-2047.892	-2125.403	-2187.831
90	-2956.152	-3024.534	-3084.804	-1859.832	-1924.663	-1979.439

Figure 105 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 30% ratio has the lowest energy consumption during the year. The annual energy consumption for a 30% window-to-wall ratio (best case) is 3127.169 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 3769.932 kWh. The difference between these two cases is significant: increasing the ratio from 30% to 90% results in a 21% increase in energy consumption.

The amount of electricity supplied by PV cells is 6999.466 kWh. As mentioned before, the highest energy consumption is 3127.169 kWh. This means that the residents can sell 3,872.297 kWh of electricity during the year.

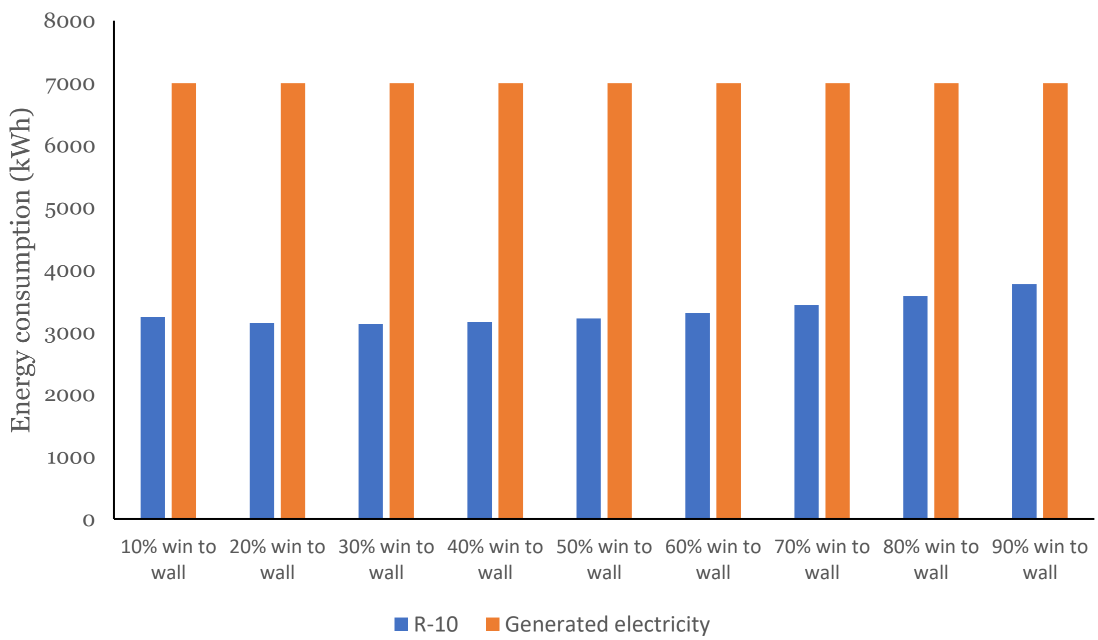


Figure 105- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Albuquerque.

In all scenarios examined in Figure 106, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 2948.175 kWh, is associated with a 30% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 3695.226 kWh, translating to a noteworthy 22% increase in energy consumption when transitioning from a 30% to an 90% window-to-wall ratio.

The PV cells generate a total of 6999.466 kWh of electricity, surpassing the highest recorded energy consumption of 3695.226kWh. Consequently, residents have the potential to sell 3,304.24 kWh of surplus electricity throughout the year.

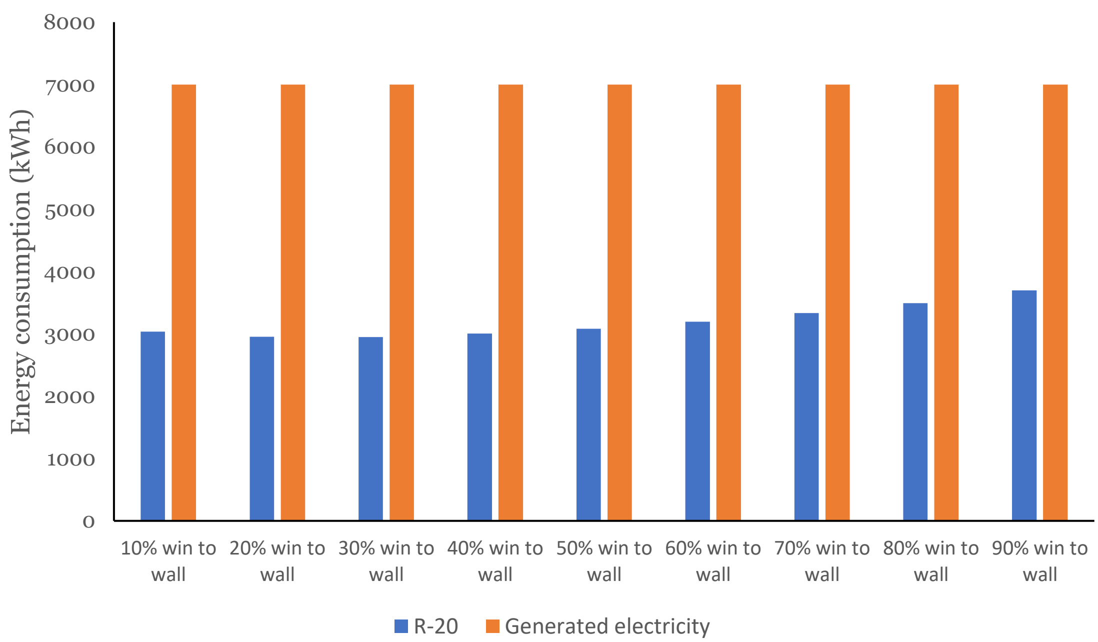


Figure 106- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Albuquerque.

Within the scope of Figure 107's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to effectively meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 20%

ratio demonstrates the lowest annual consumption at 2796.263 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 3629.383 kWh, reflecting a notable 30% increase in energy consumption during the transition from a 20% to a 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 6999.466 kWh of electricity, surpassing the peak energy consumption recorded at 3629.383 kWh. Consequently, residents possess the potential to sell 3,370.083 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

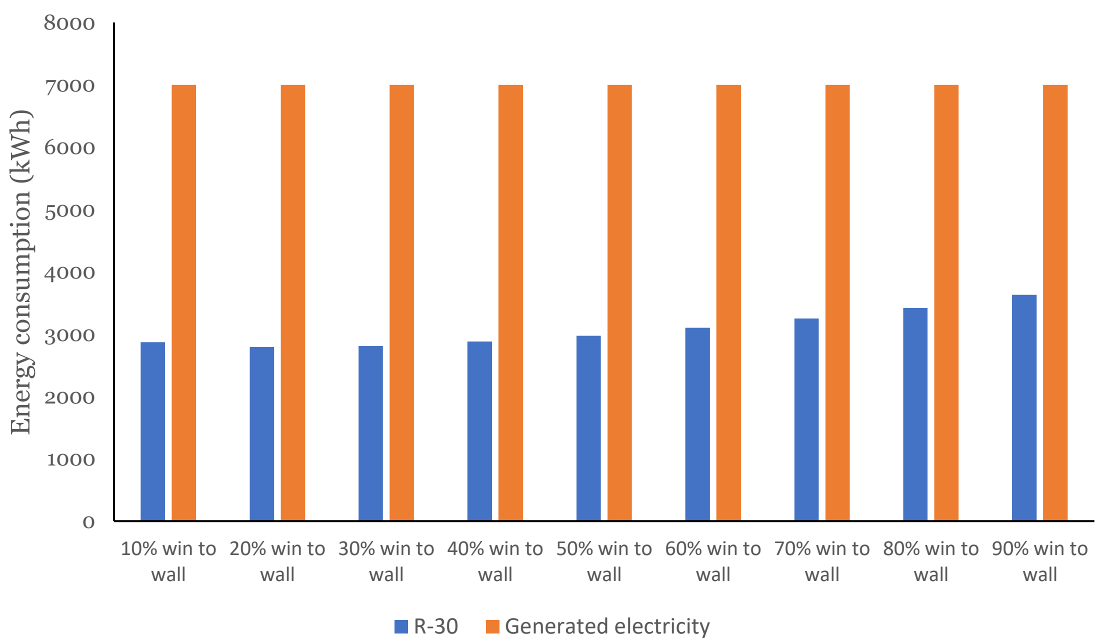


Figure 107- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Albuquerque.

Figure 108 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 4195.741 kWh, while the 20% ratio exhibits the lowest consumption, recording an annual total of 3255.963 kWh. The significant disparity between these extremes, revealing a 29% increase in energy consumption during the transition from a 20% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 6227.568 kWh of electricity, surpassing the peak energy consumption recorded at 4195.741 kWh. This surplus electricity generation implies a notable potential for residents to contribute to the energy grid, with the possibility of selling 2,031.827 kWh of excess electricity throughout the year. This dual revelation not only highlights the capability of PV cells to offset energy demand but also presents a tangible economic opportunity for residents. In essence, this detailed examination of the graph provides a holistic understanding of the intricate interplay between window-to-wall ratios and energy consumption, emphasizing the instrumental role of PV cells in meeting the diverse energy requirements inherent in various architectural contexts.

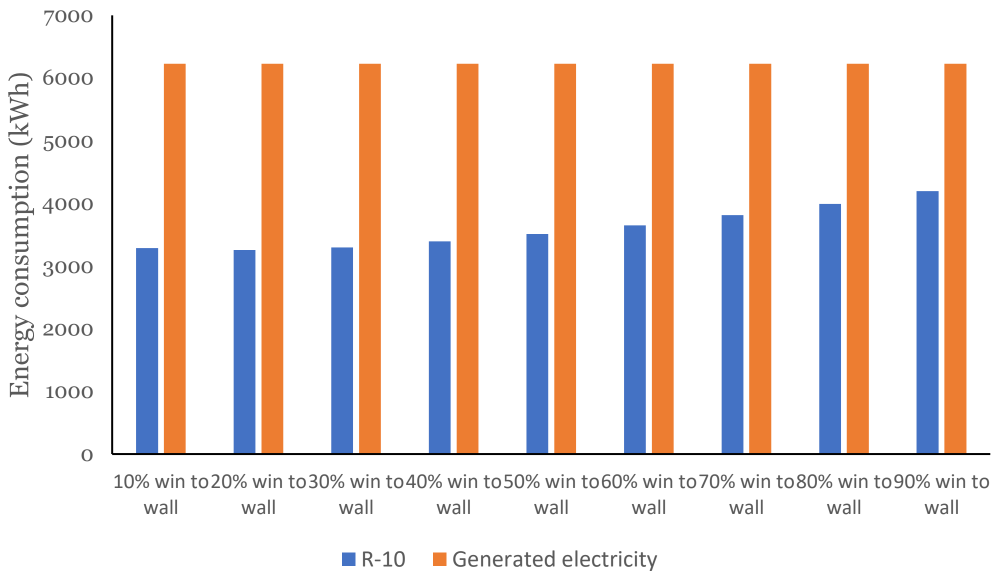


Figure 108- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Albuquerque.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 109. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 4124.915kWh and the annual energy consumption for the best case 3023.987 kWh. It means increasing the window-to-wall ratio from 20% to 90% can increase energy consumption by 36.4%.

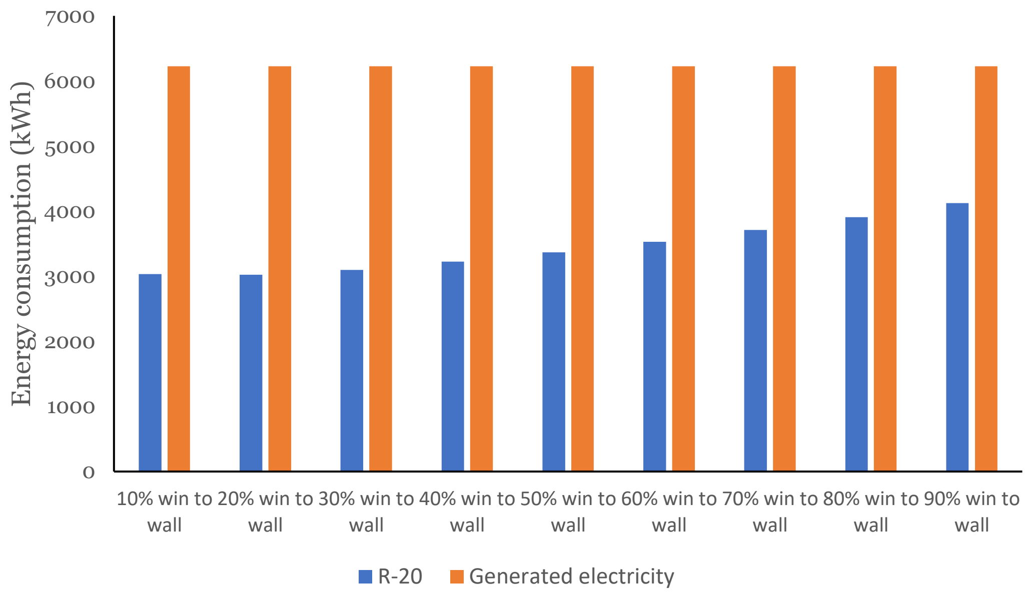


Figure 109- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Albuquerque.

Figure 110 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 2842.091 kWh, whereas for a 90% window-to-wall ratio (worst case), it is

4065.073 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 43% increase in energy consumption.

The amount of electricity supplied by PV cells is 6227.568 kWh. As mentioned before, the highest energy consumption is 4065.073kWh. This means that the residents can sell 2,162.495 kWh of electricity during the year.

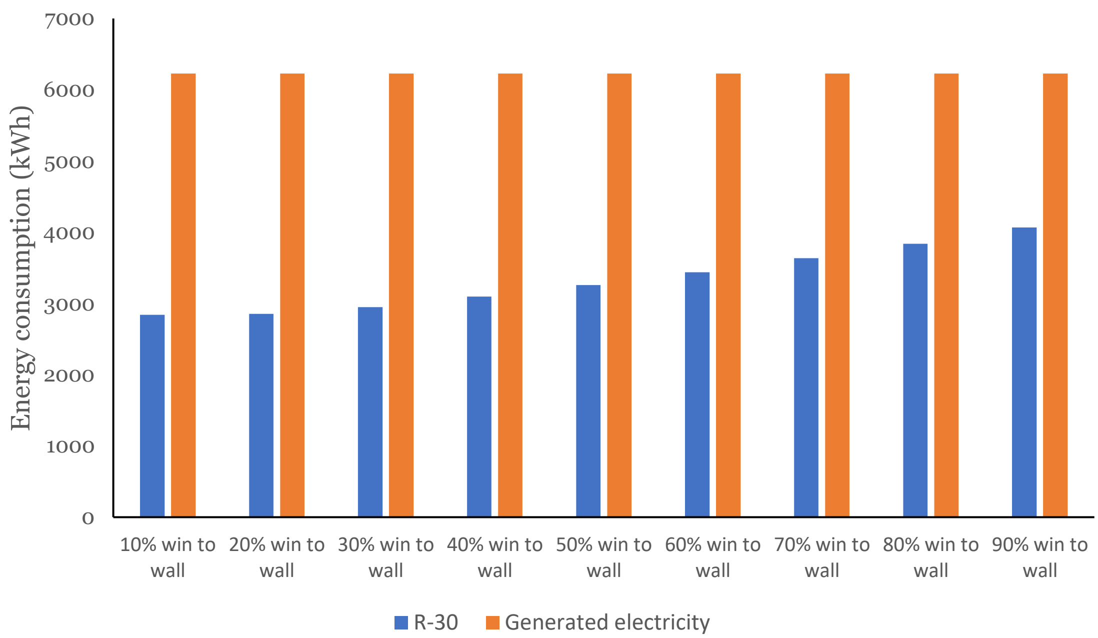


Figure 110- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Albuquerque.

Figure 111 shows the energy consumption of the building with R-10 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is

39.606 kWh (1.2%) in 10% window to wall, 290.657 kWh (9%) in 50% window to wall and 425.80 kWh (11.3%) in 90% WWR.

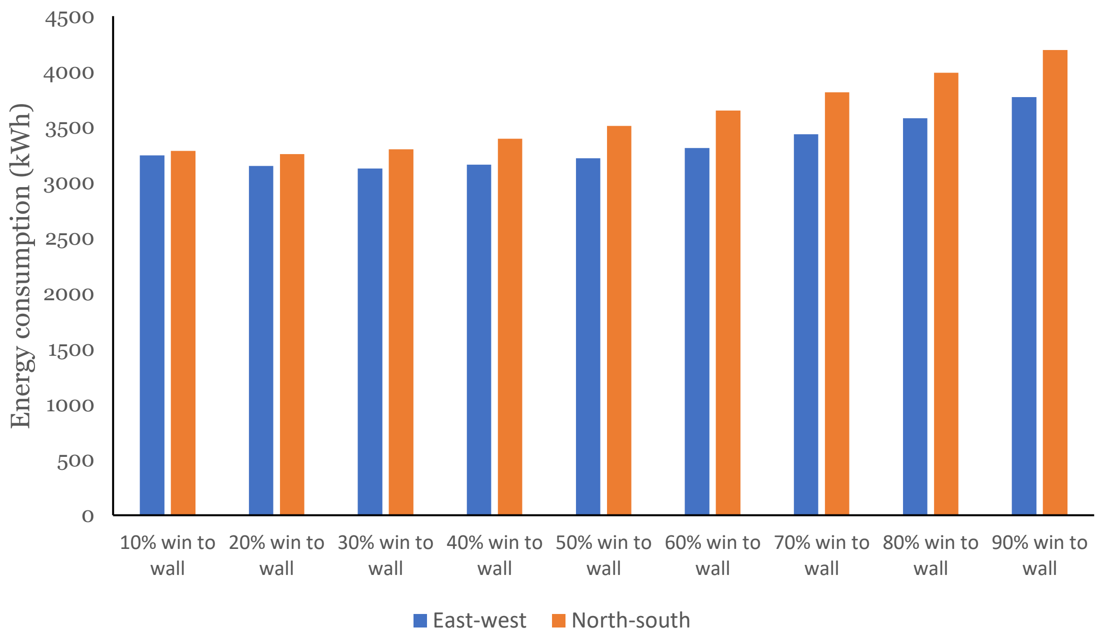


Figure 111- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Albuquerque.

Figure 112 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios the energy consumption of tiny houses with north-south orientation is higher (except for 10%). As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 4.687 (0.15%) kWh in 10% window to wall, 282646 (9%) kWh in 50% window to wall and 429.689 kWh (12%) in 90% WWR.

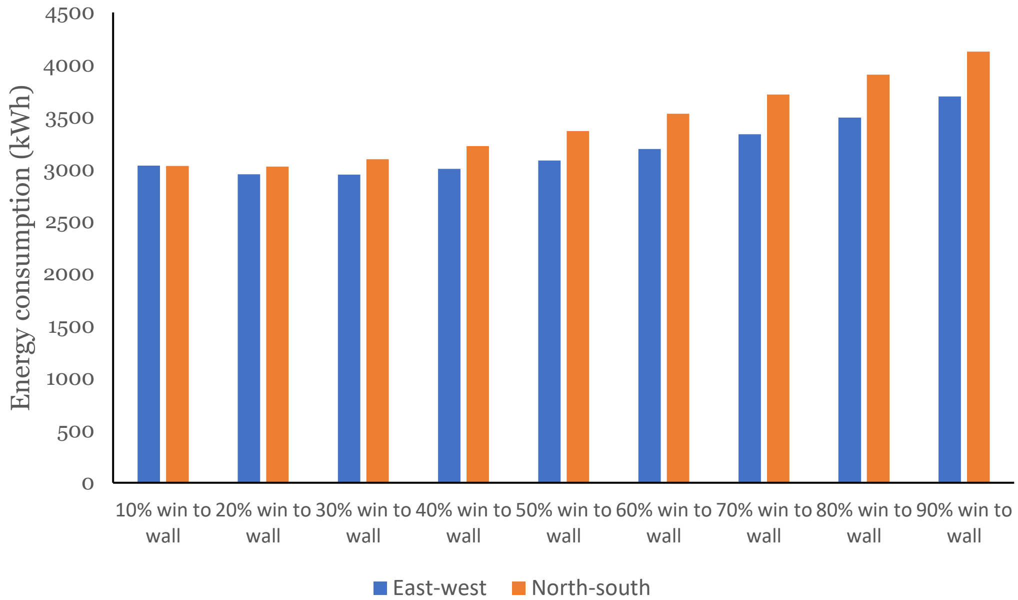


Figure 112- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Albuquerque.

Figure 113 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation (except for 10%). As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 26.438 kWh (0.9%) in 10% window to wall, 283.874 (9.5%) kWh in 50% window to wall and 435.69 (12%) kWh in 90%.

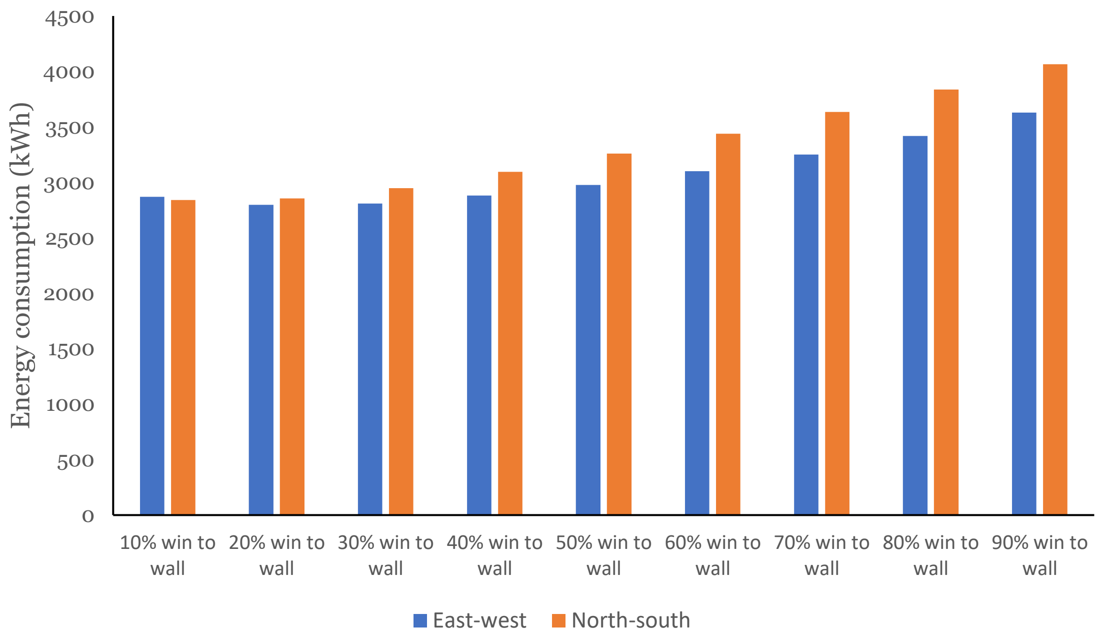


Figure 113- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Albuquerque.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 114 is about generated electricity in two orientations. The generated electricity for east-west orientation is 6999.466 kWh and for north-south orientation is 6227.568 kWh. In other words, the generated electricity in east-west orientation is 12.4% more than the generated electricity in north-south condition.

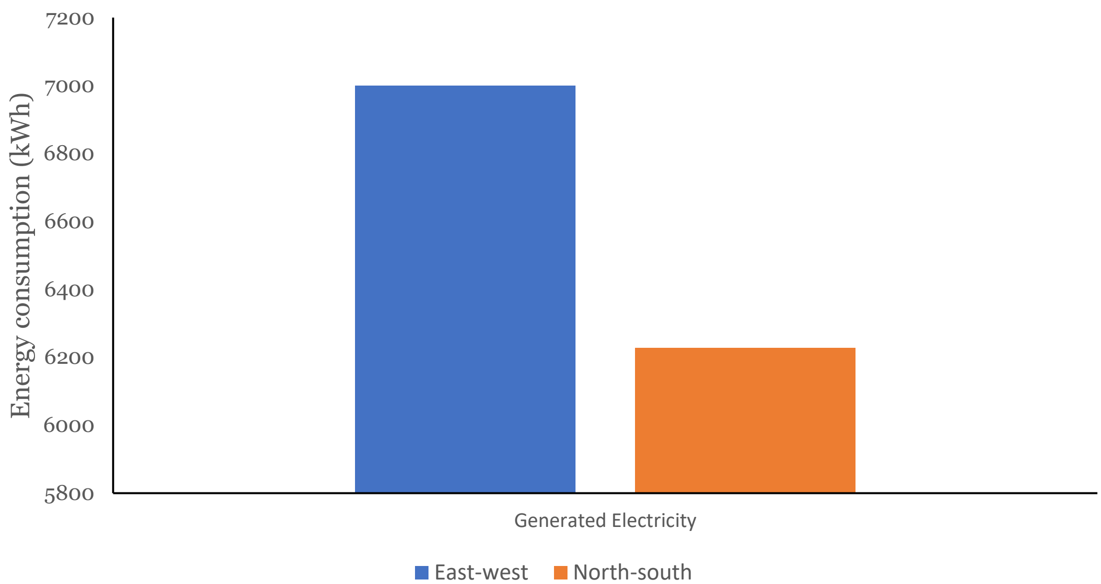


Figure 114- Generated electricity in different configurations of PV cells in Albuquerque.

Figure 115 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10%-30% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 30%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

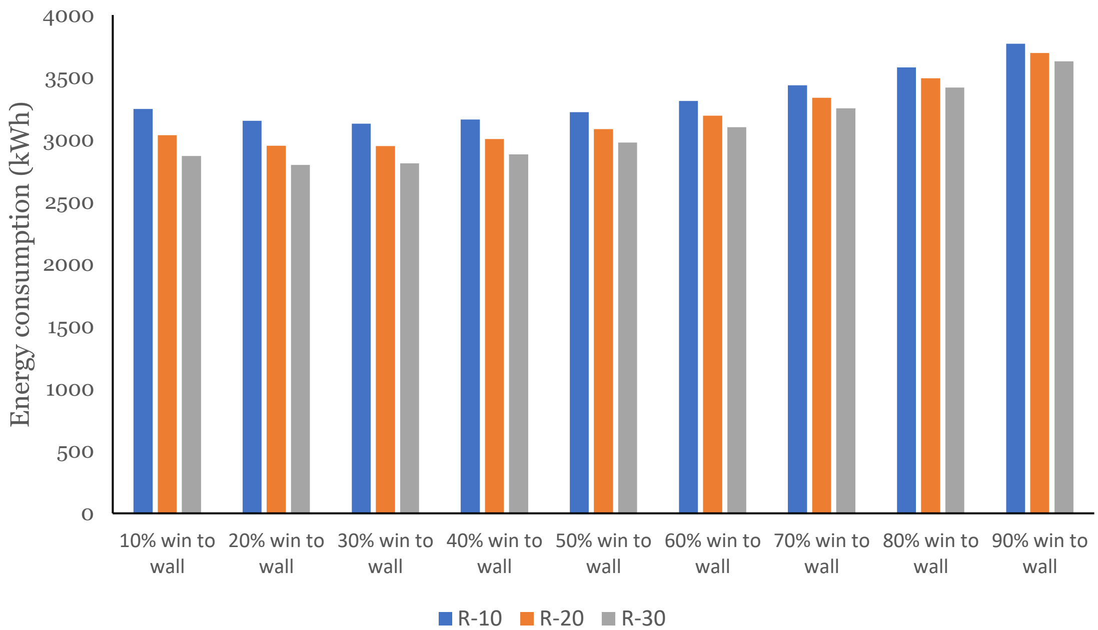


Figure 115- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Albuquerque.

Figure 116 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10% -20% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 20% -90% WWR range, an increase in R-value is associated with an increase in energy consumption.

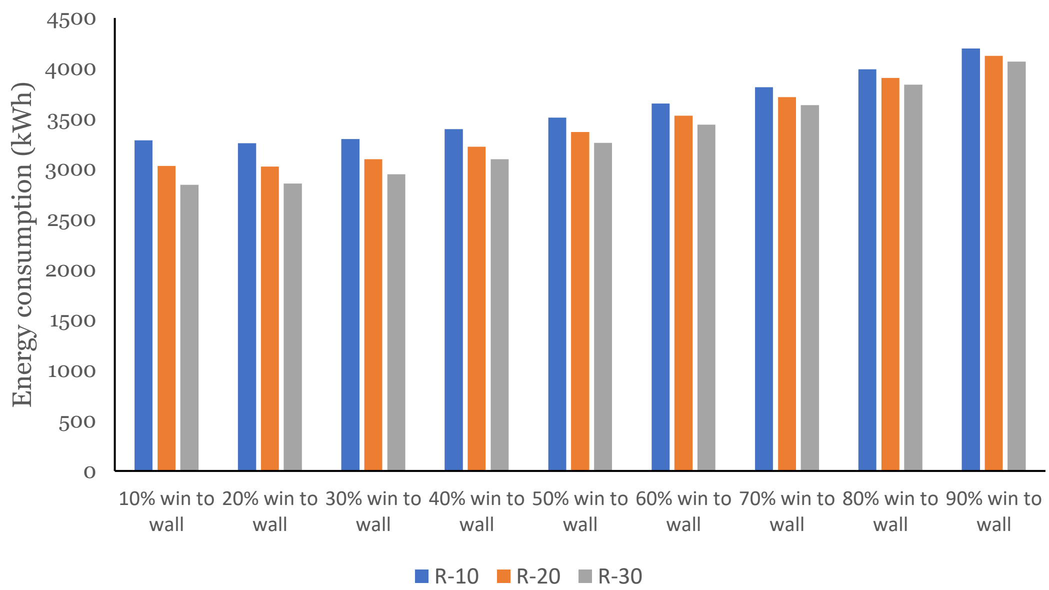


Figure 116- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Albuquerque.

CO2 emissions for cases with east-west orientation are shown in figure 117. Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. The lowest CO2 emissions is 30% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

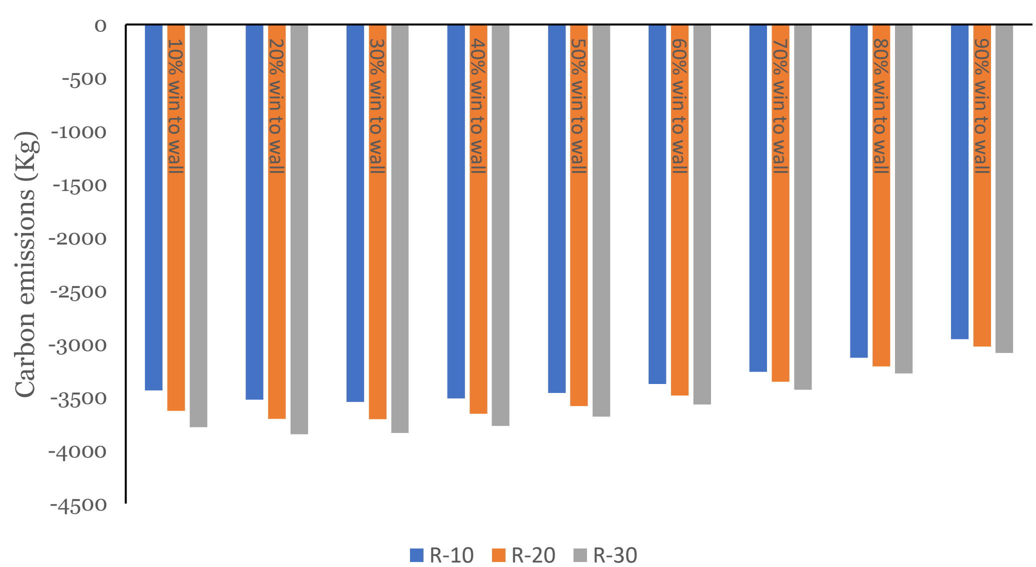


Figure 117- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Albuquerque.

Figure 118 shows CO_2 emissions for cases with north-south orientation. The trend of CO_2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO_2 emission is related to the 20% WWR.

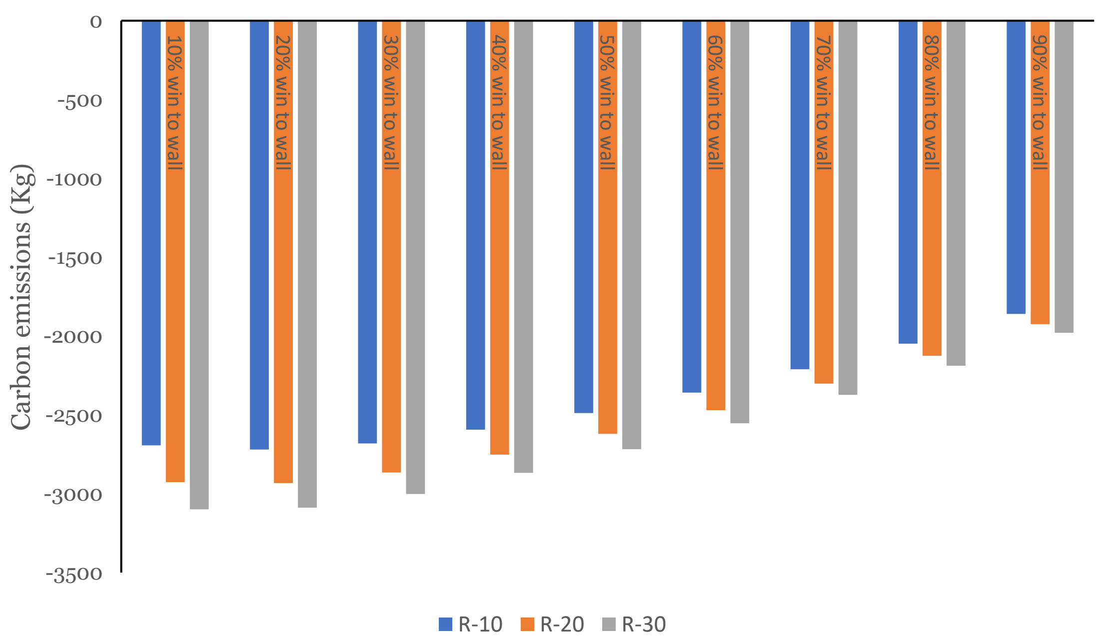


Figure 118- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south)

11.9. 4C Seattle, WA

Presented in Table 19 are the energy consumption details for all 54 cases in Seattle. Cells highlighted in green within the table indicate instances where energy consumption falls below the generated electricity, signifying a net-zero energy status for the respective tiny houses.

Conversely, cells highlighted in red indicate instances where energy consumption exceeds the generated electricity. The unit of measurement for these values is kilowatt-hours (kWh), providing a standardized basis for assessing the energy dynamics of each case.

Table 19- Energy consumption (kWh) of all cases in Seattle.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	3679.07	3449.583	3268.51	3635.868	3363.551	3162.99
20	3670.646	3459.17	3293.134	3661.959	3415.01	3233.896
30	3709.439	3518.832	3369.316	3739.465	3521.602	3361.624
40	3784.933	3616.547	3484.14	3852.72	3663.142	3523.928
50	3865.306	3718.721	3602.627	3967.207	3805.66	3685.708
60	3959.935	3834.15	3732.568	4089.992	3954.04	3850.587
70	4069.807	3962.89	3875.158	4223.015	4109.831	4021.595
80	4182.652	4092.896	4017.064	4355.089	4260.926	4185.694
90	4323.813	4250.096	4184.87	4508.553	4432.828	4368.909
Generation	4360.214	4360.214	4360.214	3811.319	3811.319	3811.319

Table 20 details the CO2 emissions across all cases. As the energy consumed in most cases is consistently less than the generated electricity, most numerical values in the table are negative. The incorporation of a green color scheme within the cells serves as a visual cue, highlighting instances where the cases exhibit zero-emission characteristics. This color-coded representation underscores the positive environmental impact of the tiny houses, emphasizing their contribution to a reduction in carbon footprint. The negative values, coupled with the green coloration, signify that the cases have effectively achieved a net-zero or even a carbon-negative status, reflecting a commendable commitment to sustainable and eco-friendly practices across

the entirety of the cases examined. However, there are cells with red color. The red color indicates that the CO_2 emission is positive, and the building is not zero-emission.

Table 20- Carbon emissions (Kg) of all cases in Seattle.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-76.00467	-101.6117	-121.8165	-19.57756	-49.9637	-72.34303
20	-76.94466	-100.5419	-119.0688	-16.66615	-44.22162	-64.4311
30	-72.61594	-93.88464	-110.5682	-8.017796	-32.32772	-50.17874
40	-64.1921	-82.98117	-97.75569	4.619611	-16.53423	-32.06825
50	-55.22372	-71.58026	-84.53441	17.39451	-0.631539	-14.01614
60	-44.66466	-58.70028	-70.03513	31.0953	15.92533	4.381588
70	-32.40471	-44.3349	-54.12444	45.93853	33.30902	23.46332
80	-19.81313	-29.82839	-38.28997	60.6758	50.16877	41.77409
90	-4.06187	-12.28749	-19.56557	77.79987	69.35023	62.21796

Figure 119 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 20% ratio has the lowest energy consumption during the year. The annual energy consumption for a 20% window-to-wall ratio (best case) is 3670.646 kWh, whereas for an 90% window-to-wall ratio (worst case), it is

4323.813 kWh. The difference between these two cases is significant: increasing the ratio from 20% to 90% results in an 18% increase in energy consumption.

The amount of electricity supplied by PV cells is 4360.214 kWh. As mentioned before, the highest energy consumption is 4323.813 kWh. This means that the residents can sell 36.401 kWh of electricity during the year.

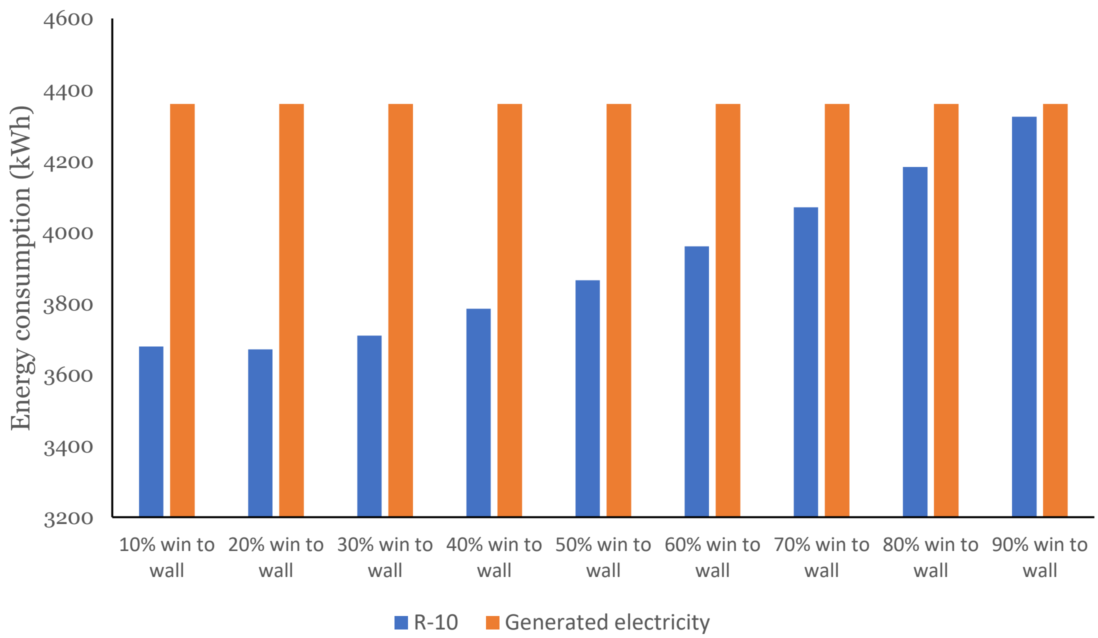


Figure 119- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Seattle.

In all scenarios examined in Figure 120, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 3449.583 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 4250.096 kWh, translating to a noteworthy 23% increase in energy consumption when transitioning from a 10% to a 90% window-to-wall ratio.

The PV cells generate a total of 4360.214 kWh of electricity, surpassing the highest recorded energy consumption of 4250.096 kWh. Consequently, residents have the potential to sell 110.118 kWh of surplus electricity throughout the year.

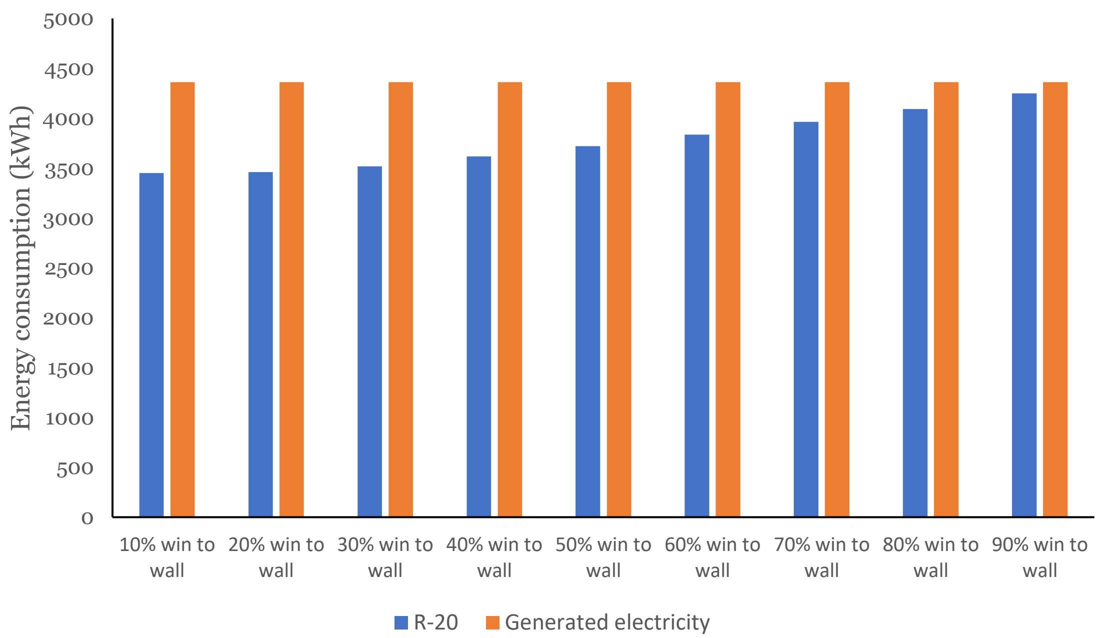


Figure 120- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Seattle.

Within the scope of Figure 121's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to effectively meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 3268.51 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 4184.87 kWh,

reflecting a notable 28% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 4360.214 kWh of electricity, surpassing the peak energy consumption recorded at 4184.87 kWh. Consequently, residents possess the potential to sell 175.344 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

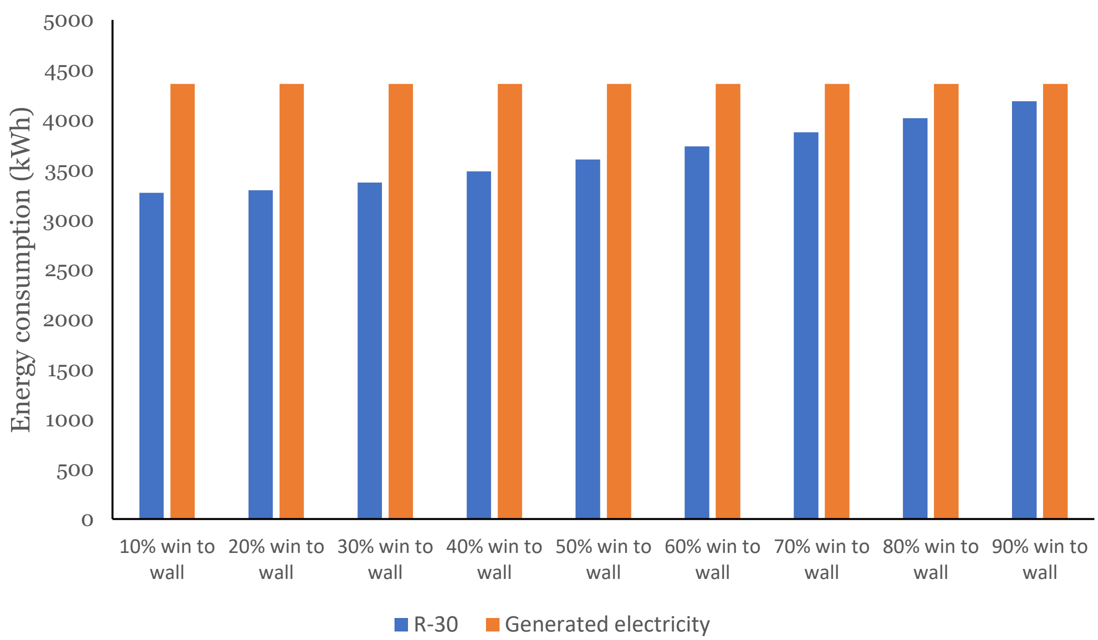


Figure 121- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Seattle.

Figure 122 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 4508.553 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 3635.868 kWh. The significant disparity between these extremes, revealing a 24% increase in energy consumption during the transition from a 10% to a 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 3811.319 kWh of electricity, surpassing the energy consumption in the 10%-30% range. However, in the 40%-90% range the energy consumption is more than the generated electricity.

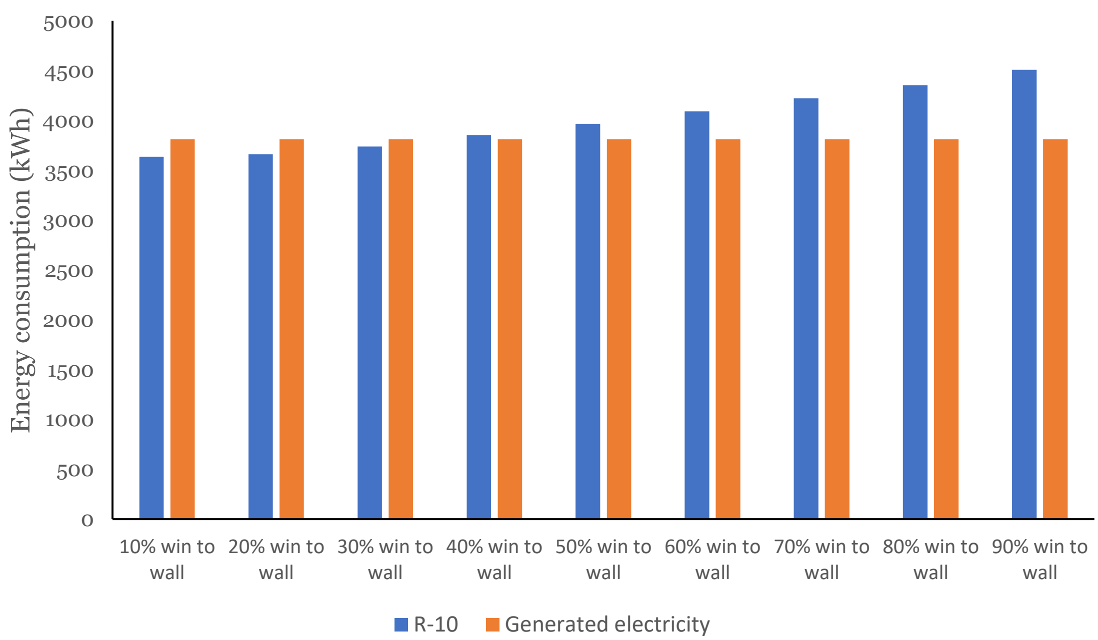


Figure 122- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Seattle.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 123. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window

to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 4432.828 kWh and the annual energy consumption for the best case 3363.551 kWh. It means increasing the window-to-wall ratio from 10% to 80% can increase energy consumption by 32%.

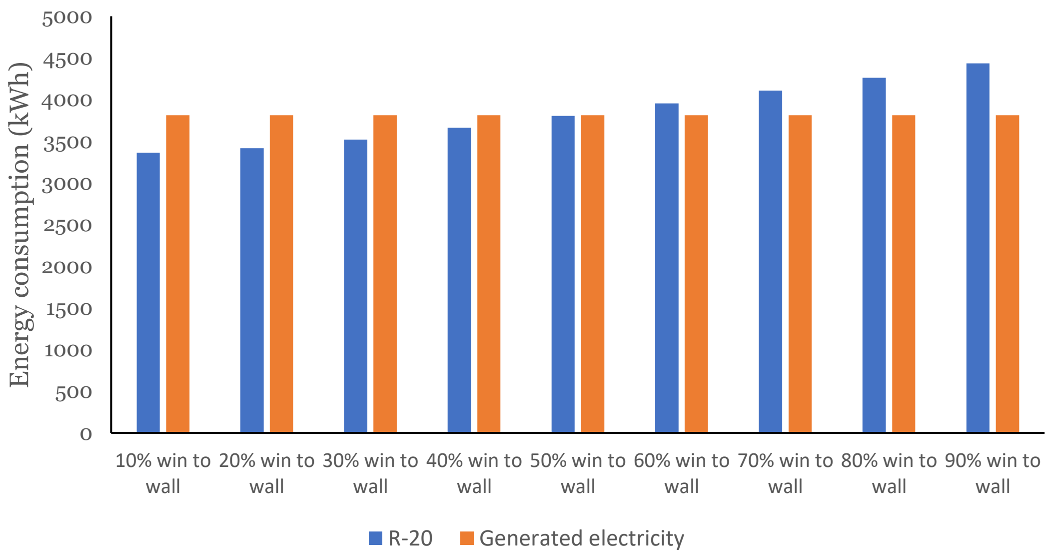


Figure 123- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Seattle.

Figure 124 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 3162.99 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 4368.909 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 38% increase in energy consumption.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 3811.319 kWh of electricity, surpassing the energy consumption in the

10%-40% range. However, in the 50%-90% range the energy consumption is more than the generated electricity.

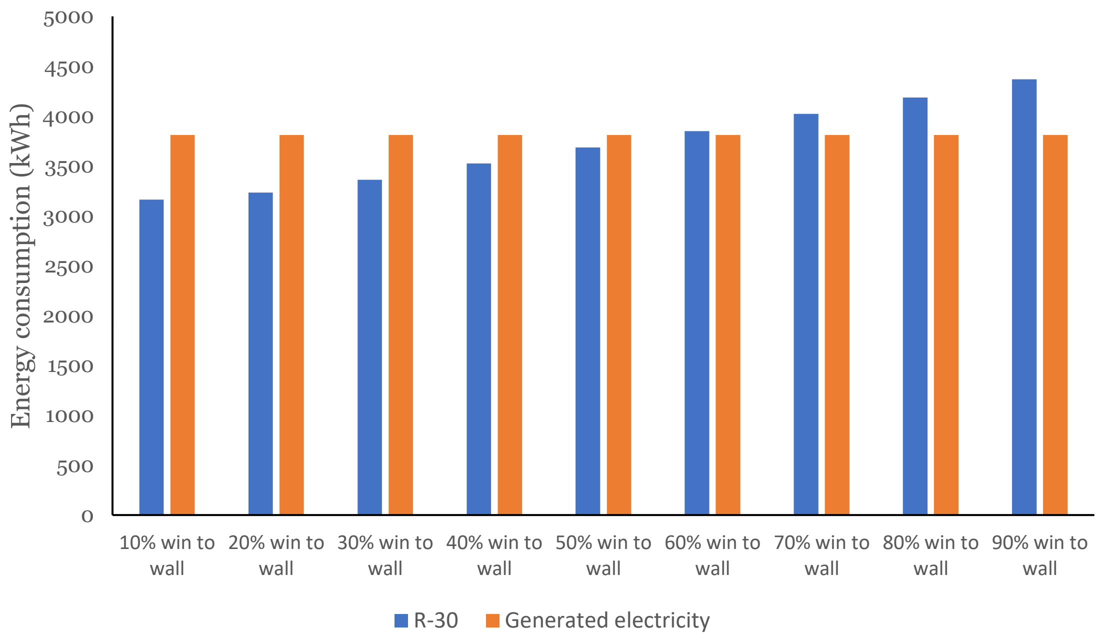


Figure 124- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Seattle.

Figure 125 shows the energy consumption of the building with R-10 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation (except for 10% and 20%). As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 43.202 kWh (1.1%) in 10% window to wall, 101.901 kWh (2.6%) in 50% window to wall and 184.74 kWh (4.2%) in 90% WWR.

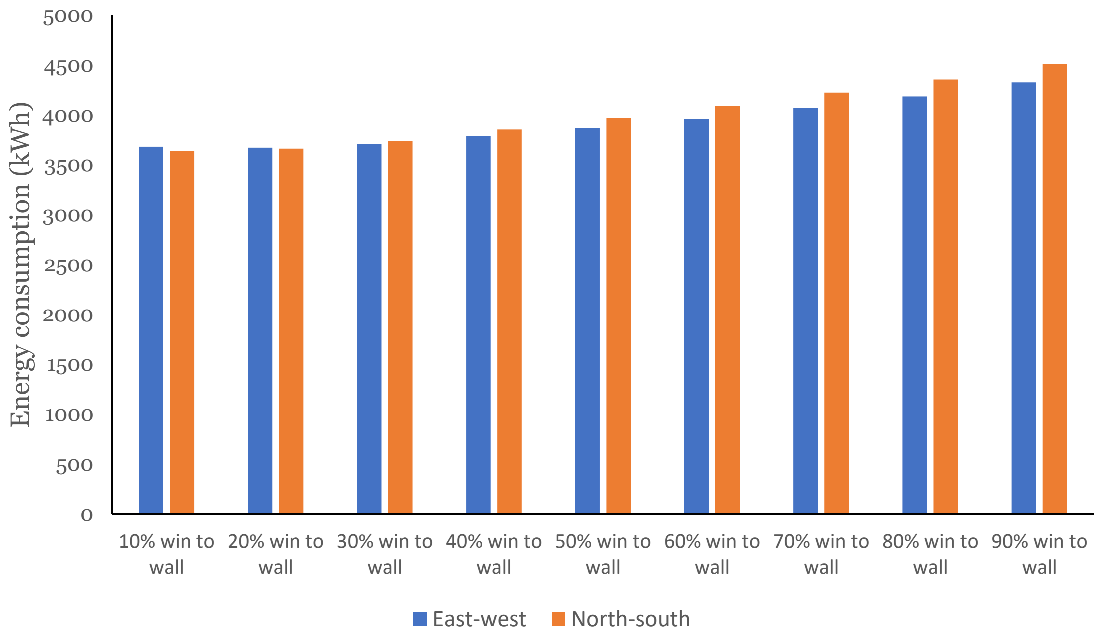


Figure 125- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Seattle.

Figure 126 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 86.032 kWh (2.5%) in 10% window to wall, 96.939 (2.3%) kWh in 50% window to wall and 182.732 kWh (4.2%) in 90% WWR.

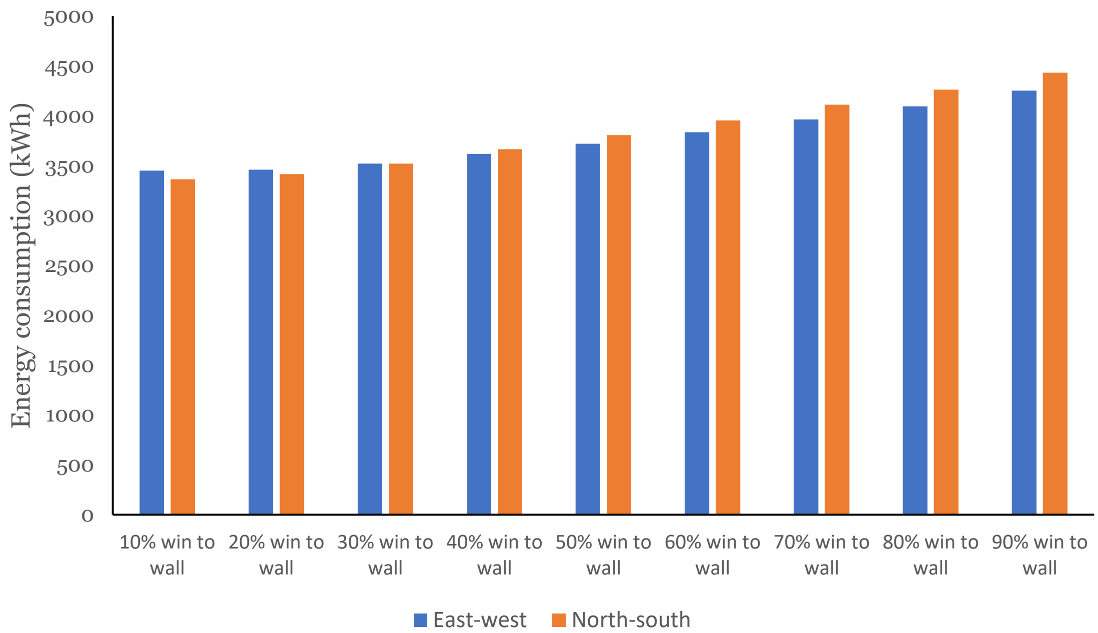


Figure 127- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Seattle.

Figure 127 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 105.52 kWh (3.2%) in 10% window to wall, 83.081 kWh (2.3%) in 50% window to wall and 184.039 kWh (4.4%) in 90%.

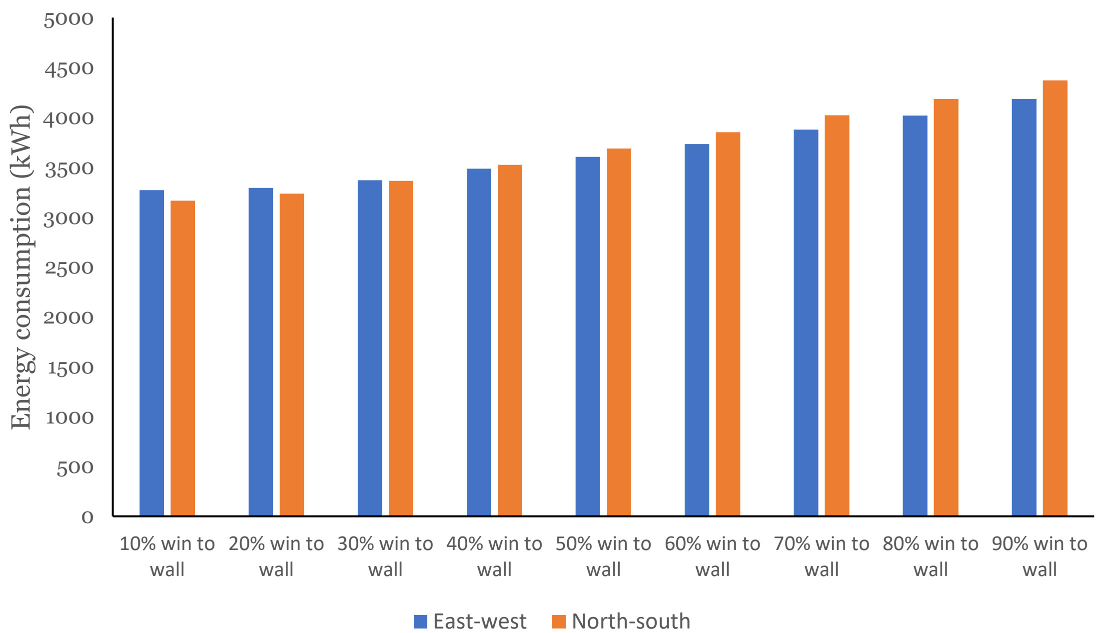


Figure 128- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Seattle.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 128 is about generated electricity in two orientations. The generated electricity for east-west orientation is 4360.214 kWh and for north-south orientation is 3811.319 kWh. In other words, the generated electricity in east-west orientation is 14.4% more than the generated electricity in north-south condition.

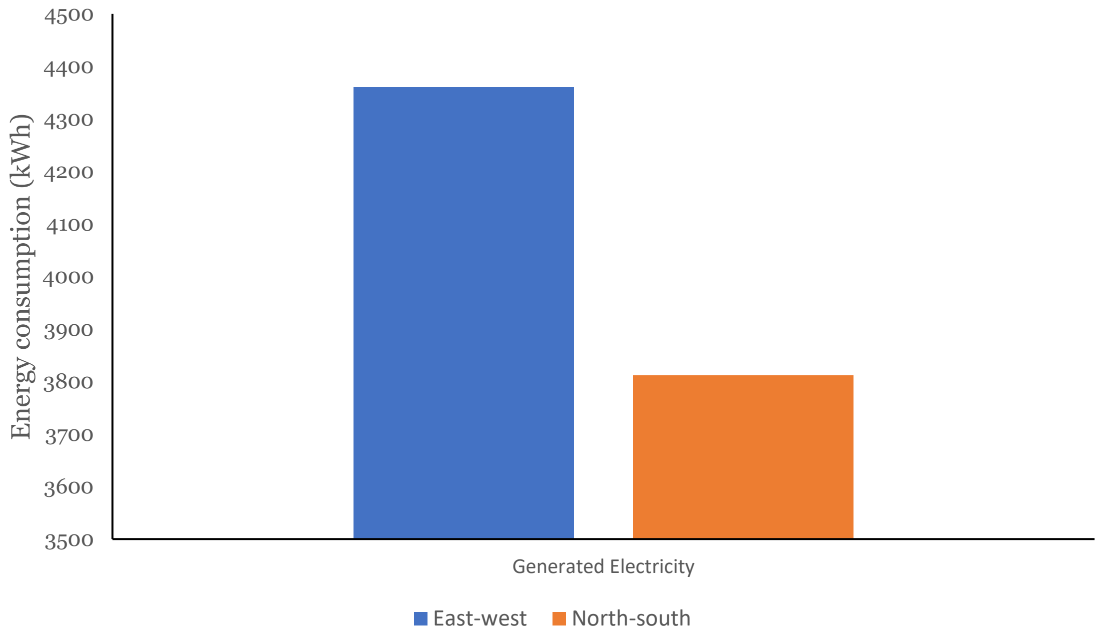


Figure 129- Generated electricity in different configurations of PV cells in Seattle.

Figure 129 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

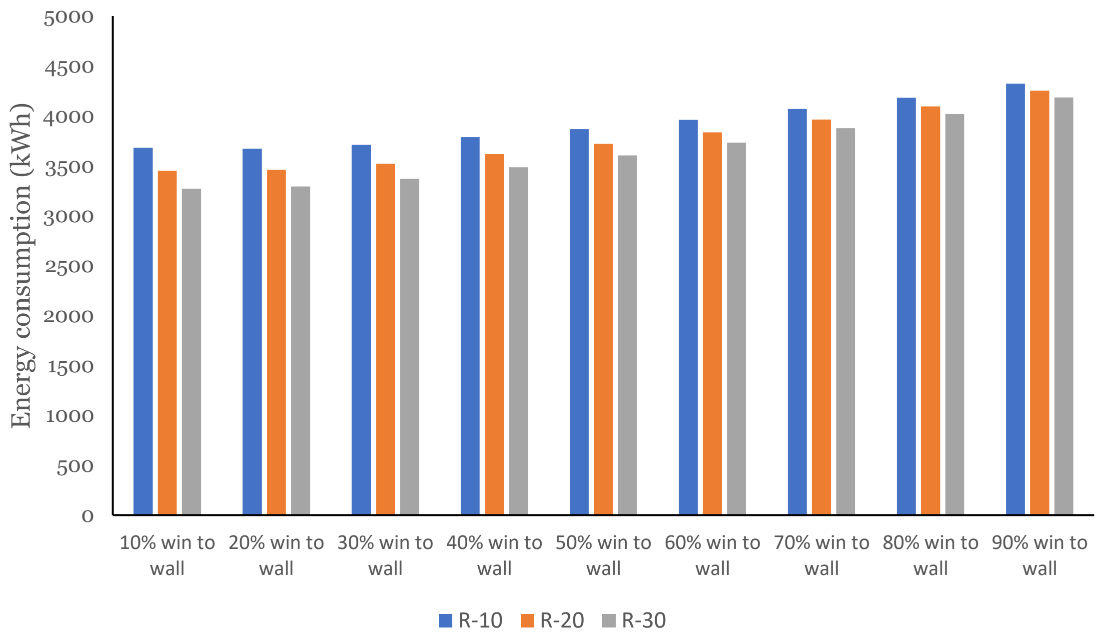


Figure 130- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Seattle.

Figure 130 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.

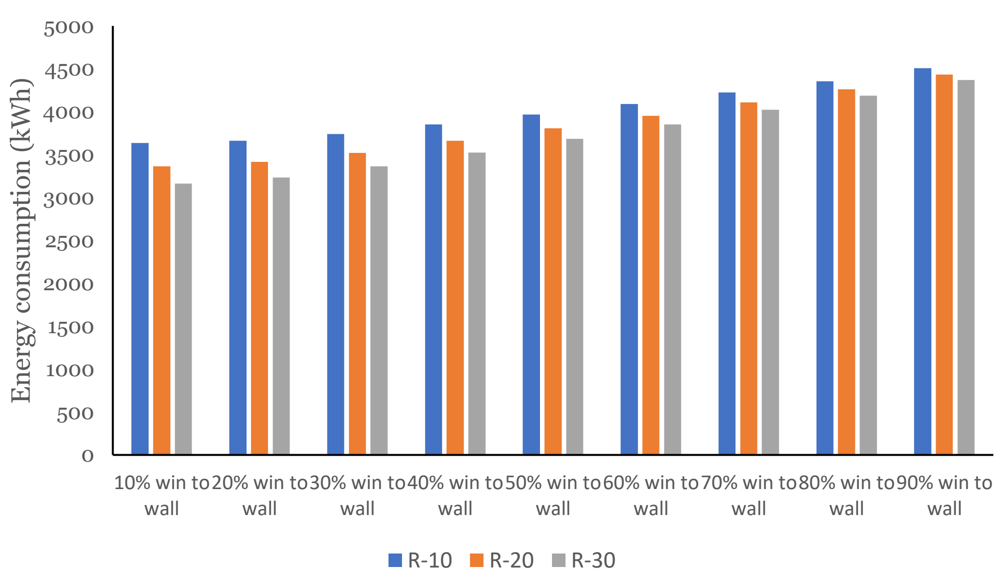


Figure 131- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Seattle.

The CO2 Emissions for cases with east-west orientation is shown in figure 131 Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

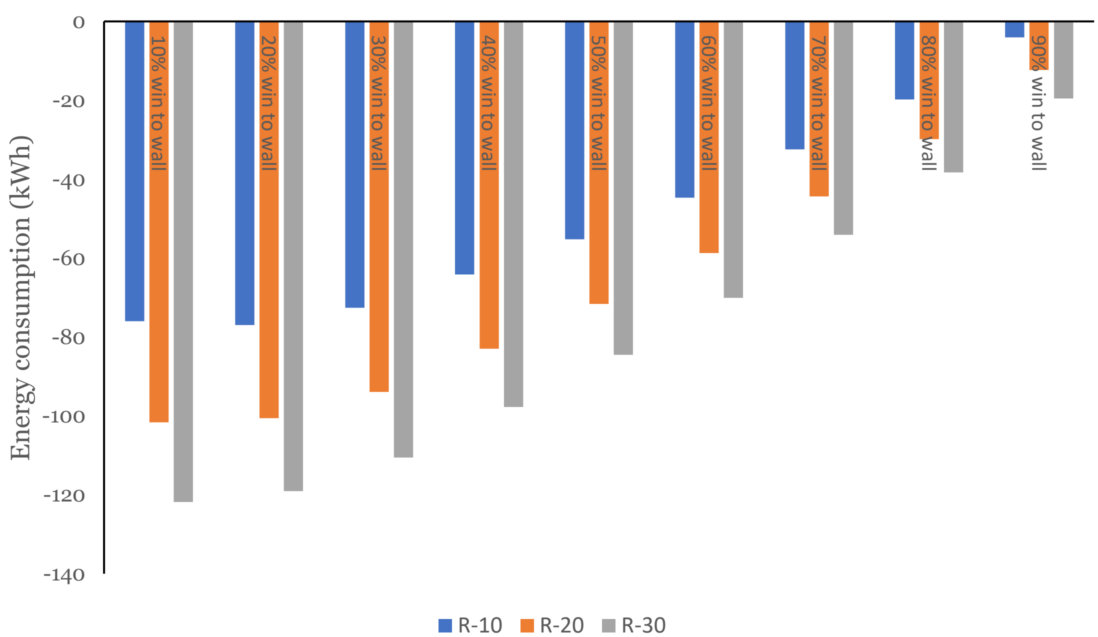


Figure 132- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Seattle.

Figure 132 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

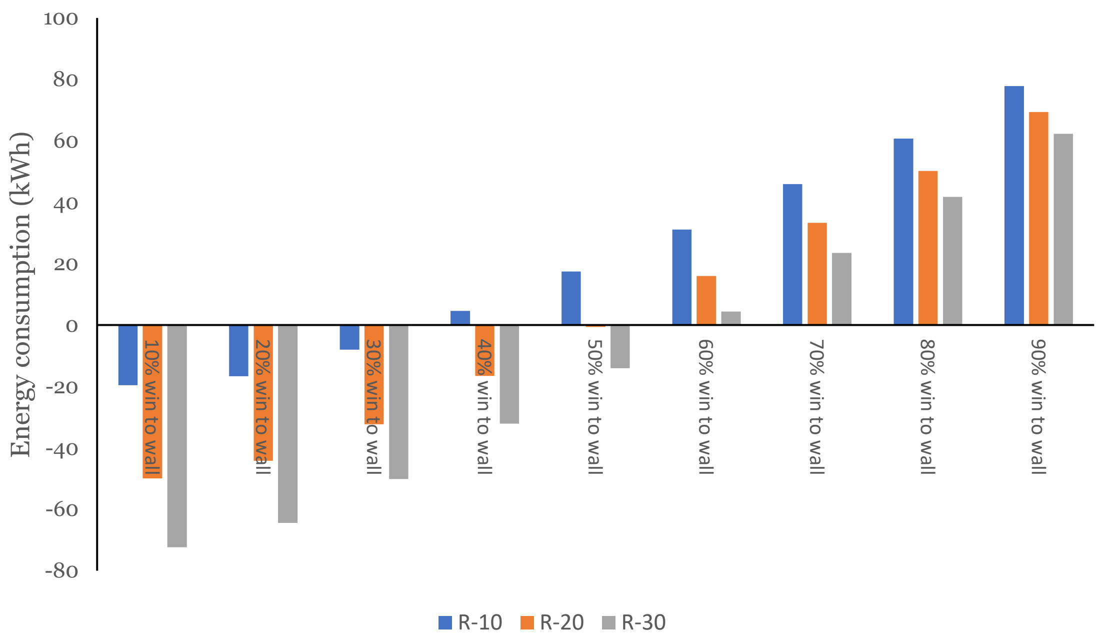


Figure 133- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Seattle.

11.10. 5A Boston, MA

Displayed in Table 21 are the energy consumption details for all 54 cases in Boston. Cells highlighted in green within the table indicate instances where energy consumption is lower than the generated electricity, signifying a net-zero energy status for the respective tiny houses. In contrast, cells highlighted in red indicate instances where energy consumption exceeds the generated electricity. The unit of measurement for these values is kilowatt-hours (kWh), offering a standardized basis for evaluating the energy dynamics of each case.

Table 21- Energy consumption (kWh) of all cases in Boston.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	4908.816	4561.15	4295.423	4848.586	4440.639	3162.99
20	4880.738	4569.633	4330.525	4874.442	4513.593	3233.896
30	4909.497	4632.697	4419.79	4954.271	4637.83	3361.624
40	4982.063	4738.866	4550.122	5071.729	4796.073	3523.928
50	5052.823	4841.577	4675.647	5181.662	4945.917	3685.708
60	5139.081	4958.155	4813.633	5301.154	5102.343	3850.587
70	5247.097	5093.743	4969.744	5436.45	5271.466	4021.595
80	5358.135	5231.058	5125.374	5570.326	5434.359	4185.694
90	5511.992	5409.725	5320.9	5738.289	5632.103	4368.909
Generation	5007.051	5007.051	5007.051	4366.909	4366.909	4366.909

Table 22 presents the CO2 emissions for all cases. Given that the energy consumed in some instances is consistently less than the generated electricity, corresponding numerical values in the table are negative. A green color scheme within the cells visually denotes instances where the cases exhibit zero-emission characteristics, emphasizing their positive environmental impact and contribution to reducing the carbon footprint. The negative values, paired with the green coloration, indicate the effective achievement of a net-zero or even a carbon-negative status, showcasing a commendable commitment to sustainable and eco-friendly practices across the examined cases. However, red-colored cells signify positive CO2 emissions, indicating that the building is not zero-emission.

Table 22- Carbon emissions (Kg) of all cases in Boston.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-56.94541	-258.4843	-412.5238	279.224	42.74062	-72.34303
20	-73.22201	-253.5671	-392.1759	294.2129	85.03191	-64.4311
30	-56.55093	-217.0093	-340.43	340.4891	157.0505	-50.17874
40	-14.4854	-155.464	-264.8773	408.5779	248.7829	-32.06825
50	26.53374	-95.92335	-192.1113	472.3054	335.646	-14.01614
60	76.5368	-28.34417	-112.1227	541.5736	426.3245	4.381588
70	139.1526	50.25501	-21.62656	620.0034	524.3637	23.46332
80	203.5206	129.855	68.591	697.6101	618.7915	41.77409
90	292.71	233.4266	181.9357	794.9767	733.4219	62.21796

Figure 133 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, only in four ratios (10%-40%), the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 20% ratio has the lowest energy consumption during the year. The annual energy consumption for a 20% window-to-wall ratio (best case) is 4880.738 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 5511.992 kWh. The difference between these two cases is significant: increasing the ratio from 20% to 90% results in a 13% increase in energy consumption.

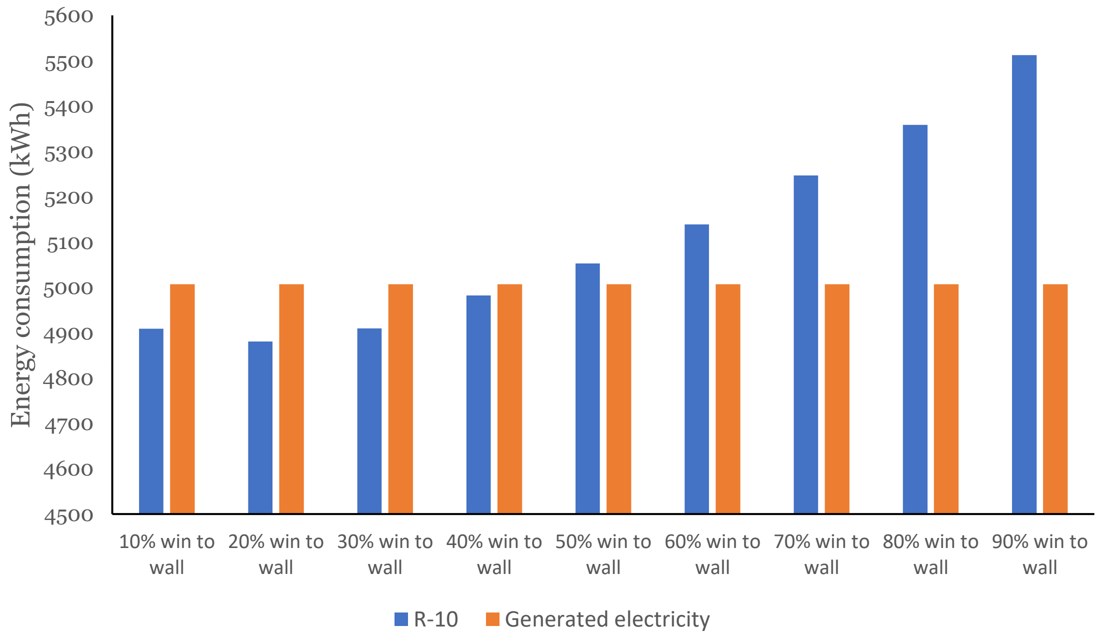


Figure 134- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Boston.

In all scenarios examined in Figure 134, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands in the 10%-60% range. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 4561.15 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 5409.725 kWh, translating to a noteworthy 19% increase in energy consumption when transitioning from a 10% to a 90% window-to-wall ratio.

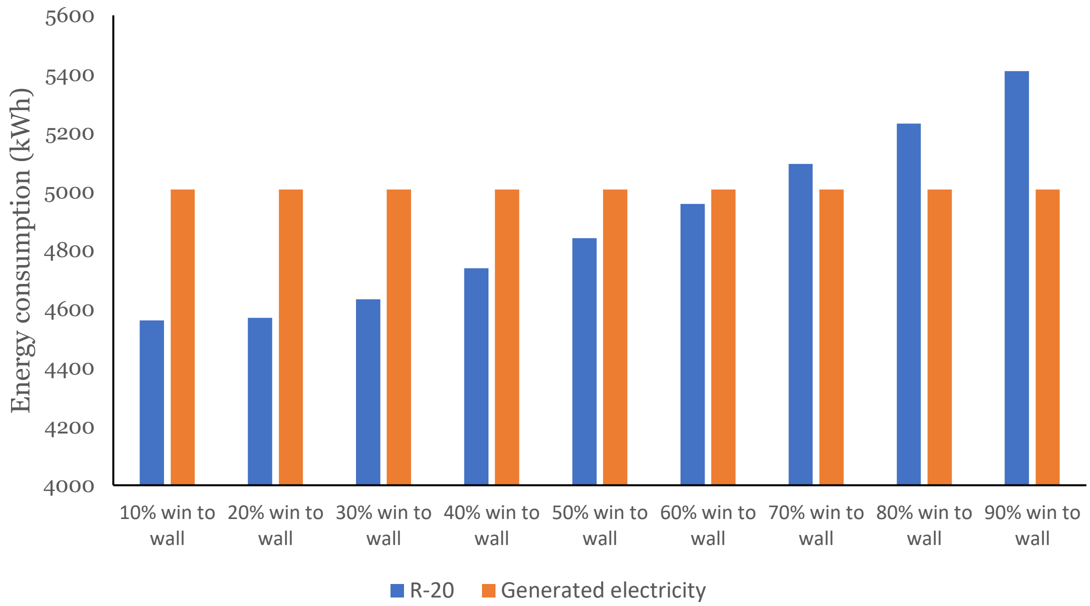


Figure 135- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Boston.

Within the scope of Figure 135's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to meet energy demands only in 10%-70% range. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 4295.423 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 5320.9 kWh, reflecting a notable 24% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio.

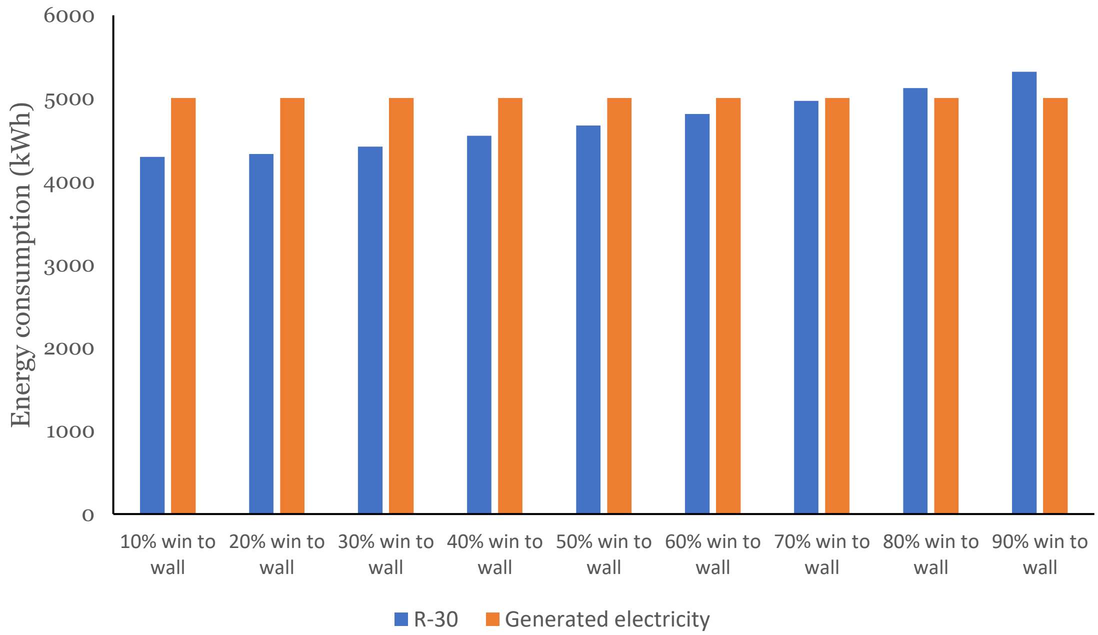


Figure 136- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Boston.

Figure 136 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 80% window-to-wall ratio is linked with the highest annual energy consumption, registering at 3454.773 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 1934.305 kWh. The significant disparity between these extremes, revealing a 79% increase in energy consumption during the transition from a 10% to an 80% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 5268.548 kWh of electricity, surpassing the peak energy consumption recorded at 3454.773 kWh. This surplus electricity generation implies a notable potential for residents to contribute to the energy grid, with the possibility of selling 1,813.775 kWh of excess electricity throughout the year. This dual revelation not only highlights the capability of PV cells to offset energy demand but also presents a tangible economic opportunity for residents. In essence, this detailed examination of the graph provides a holistic understanding of the intricate interplay between window-to-wall ratios and energy consumption, emphasizing the instrumental role of PV cells in meeting the diverse energy requirements inherent in various architectural contexts.

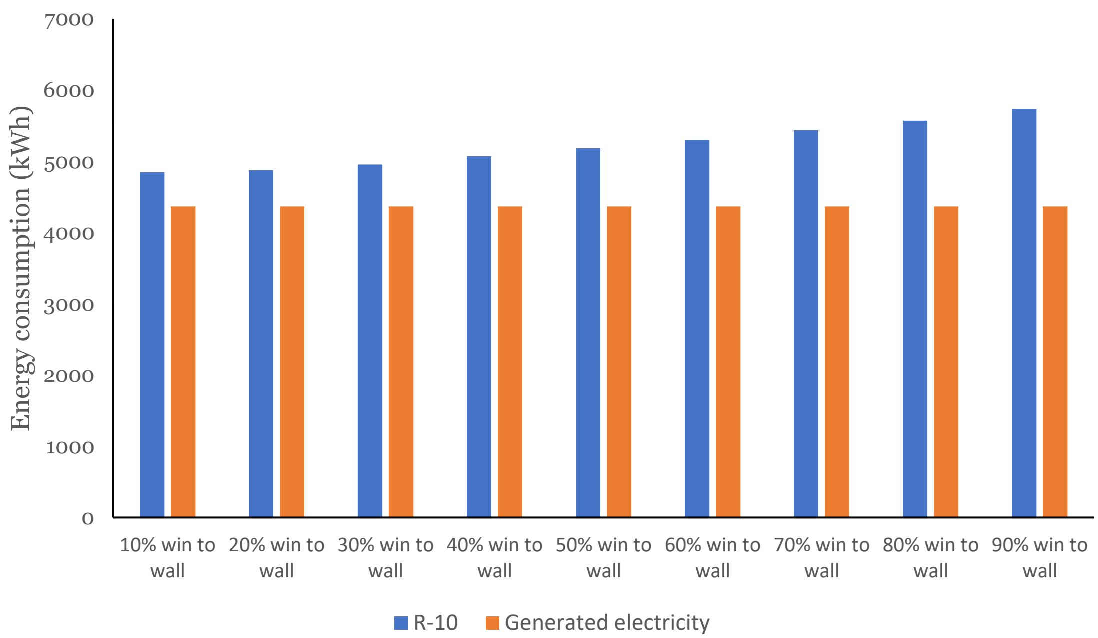


Figure 137- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Boston.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 137. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 5738.289 kWh and the annual energy consumption for the best case 4848.586 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 18%.

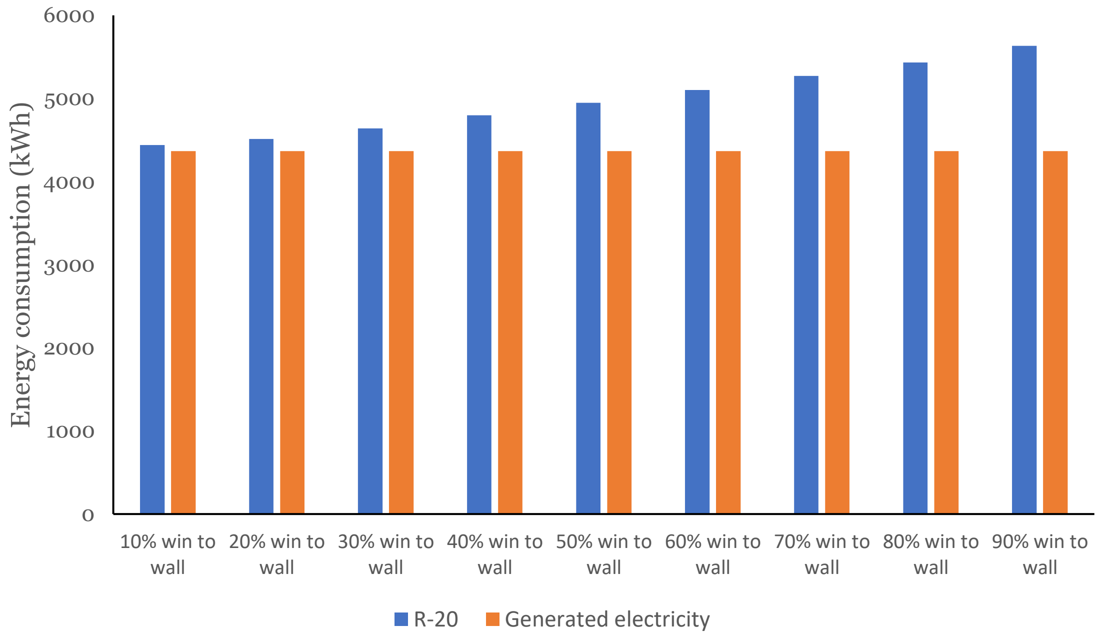


Figure 138- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Boston.

Figure 138 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, only in 10%-50% ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 3162.99 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 4368.909 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 38% increase in energy consumption.

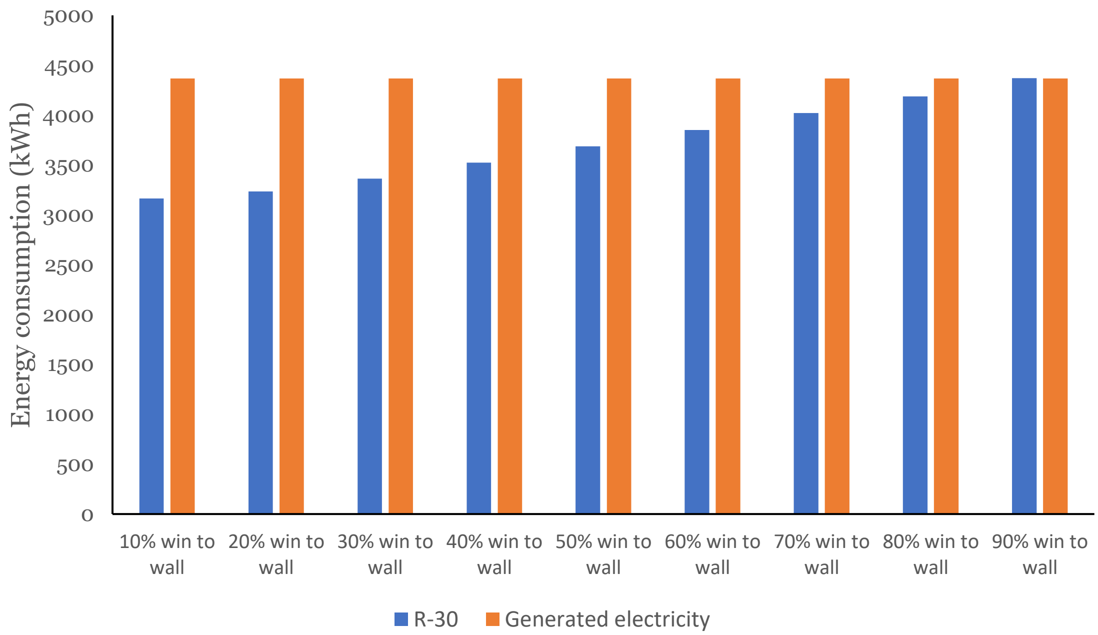


Figure 139- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Boston.

Figure 139 shows the energy consumption of the building with R-10 insulation in different orientations. Except for 10% and 20% WWRs, in other cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

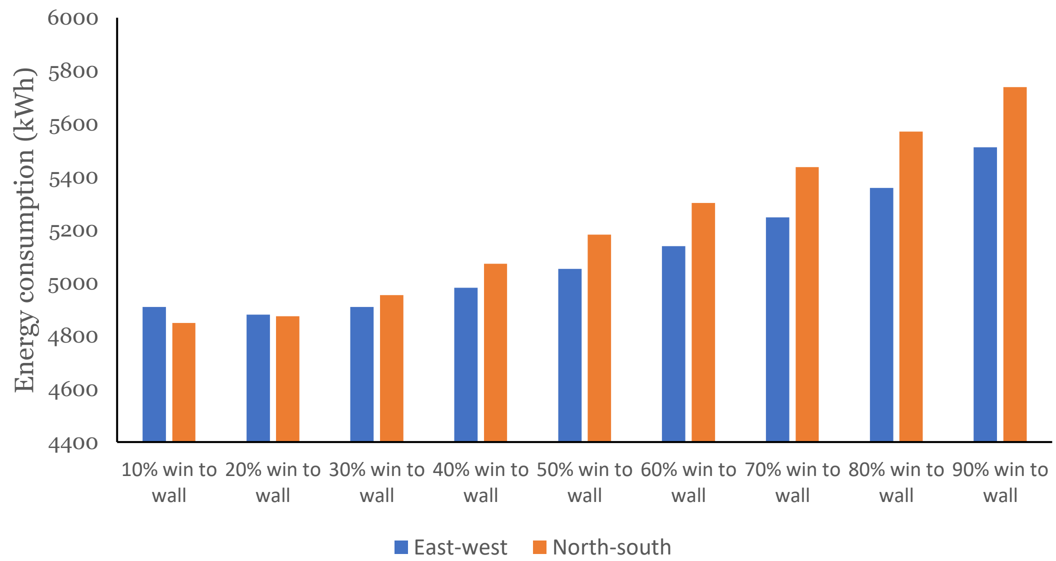


Figure 140- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Boston.

Figure 140 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In the 10%-20% range the energy consumption of cases with north-south orientation is less than cases with east-west orientation. However, in the 30%-90% the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

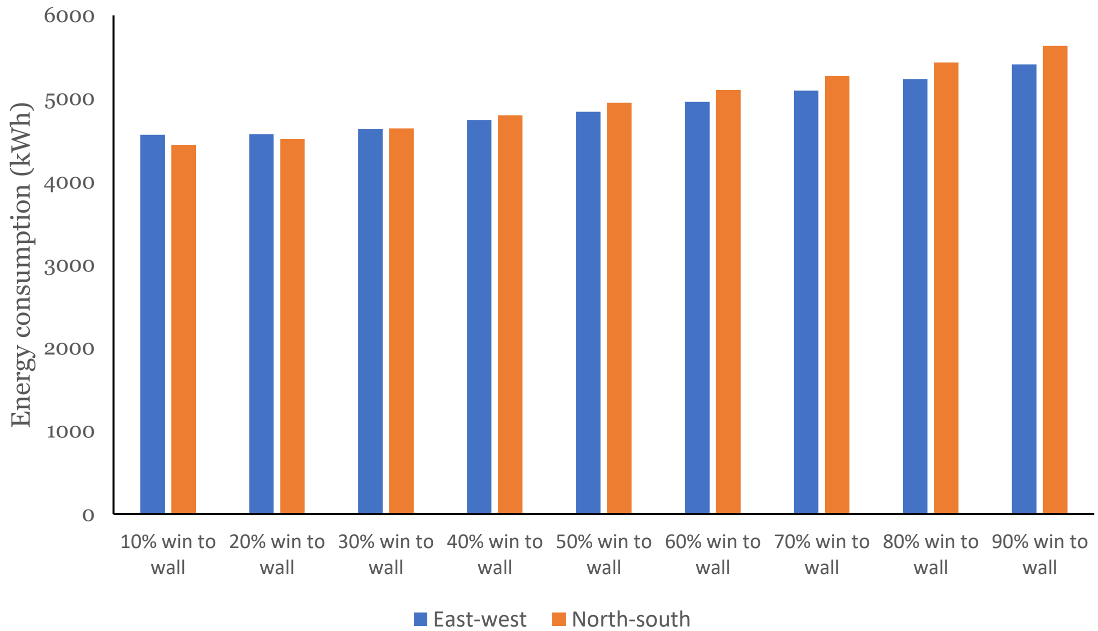


Figure 141- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Boston.

Figure 141 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation.

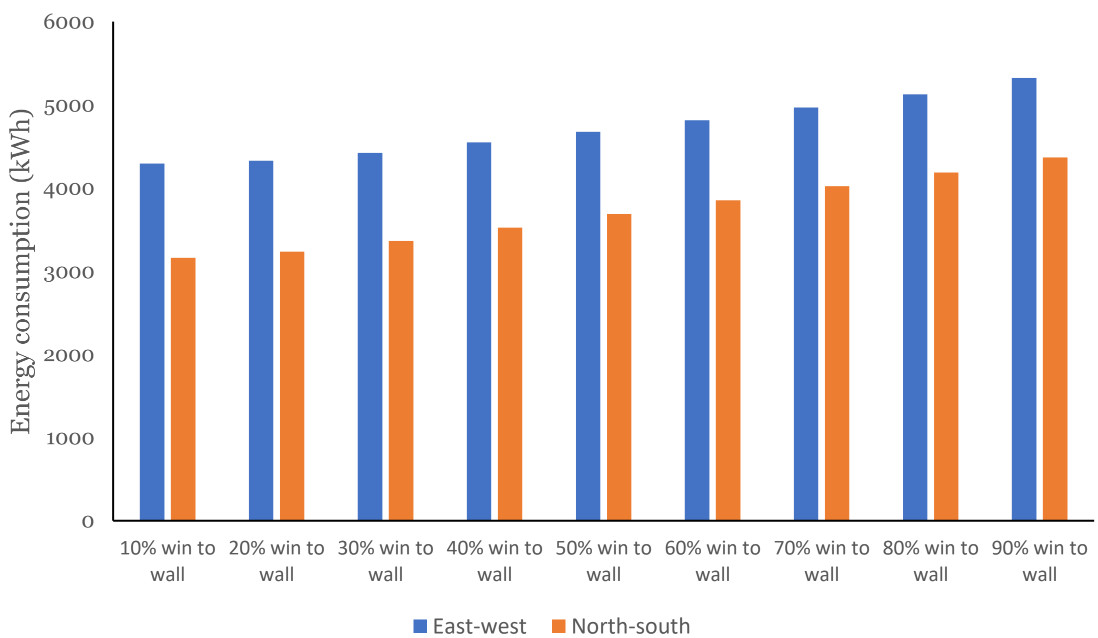


Figure 142- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Boston.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 142 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5007.051 kWh and for north-south orientation is 4366.909 kWh. In other words, the generated electricity in east-west orientation is 15% more than the generated electricity in north-south condition.

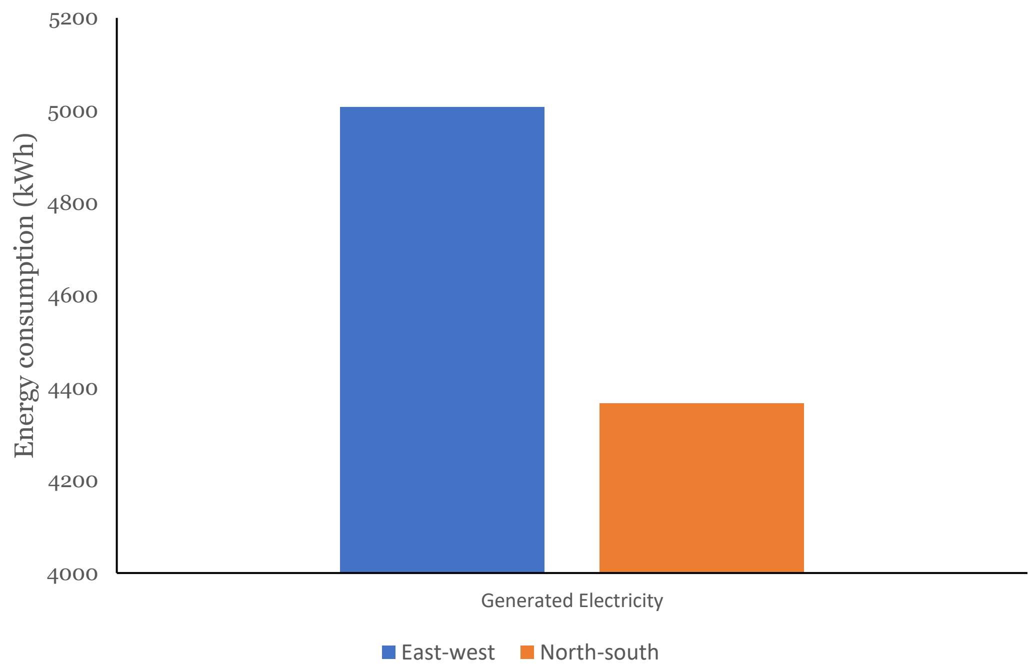


Figure 143- Generated electricity in different configurations of PV cells in Boston.

Figure 143 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

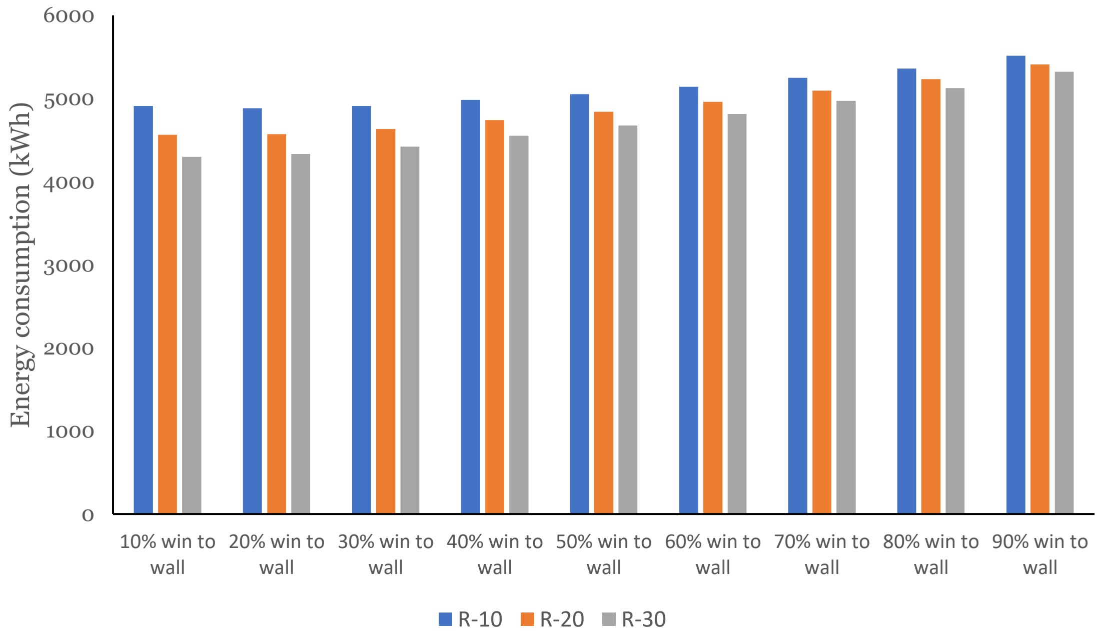
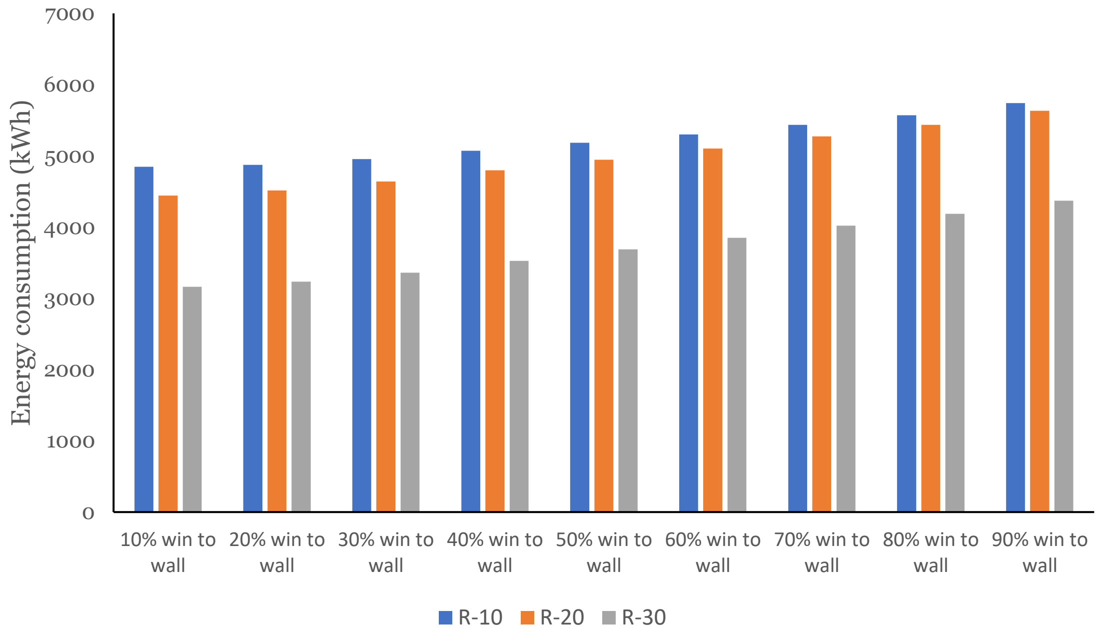


Figure 144- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Boston.

Figure 144 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 60% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.



The generated electricity in some ratios is less than energy consumption, CO2 emissions are negative for them, whereas, for the rest of the cases where the energy consumption is more than generated electricity, the CO2 emission is positive. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

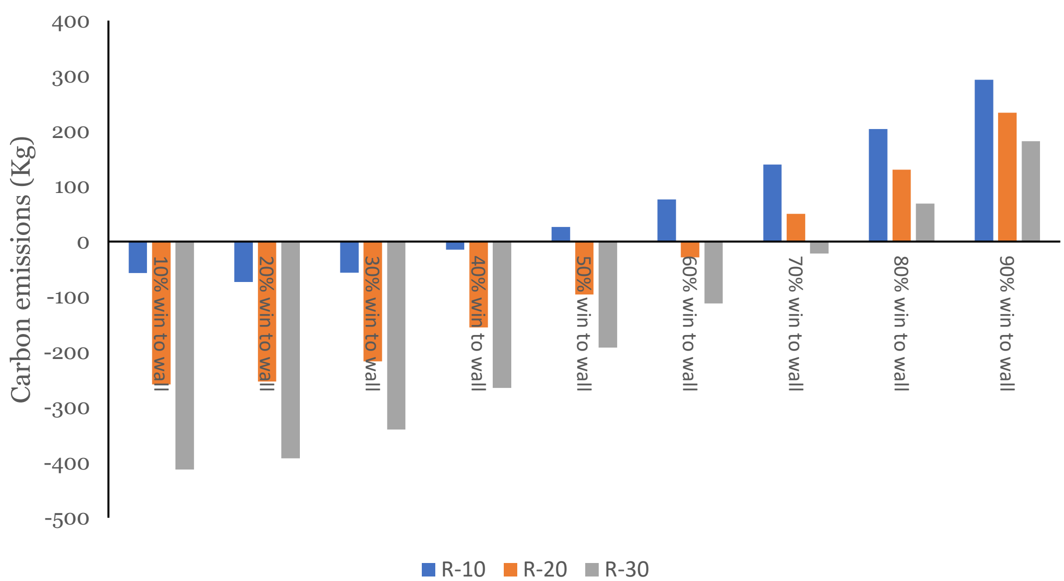


Figure 146- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Boston.

Figure 146 shows CO_2 emissions for cases with north-south orientation. The trend of CO_2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO_2 emission is related to the 10% WWR.

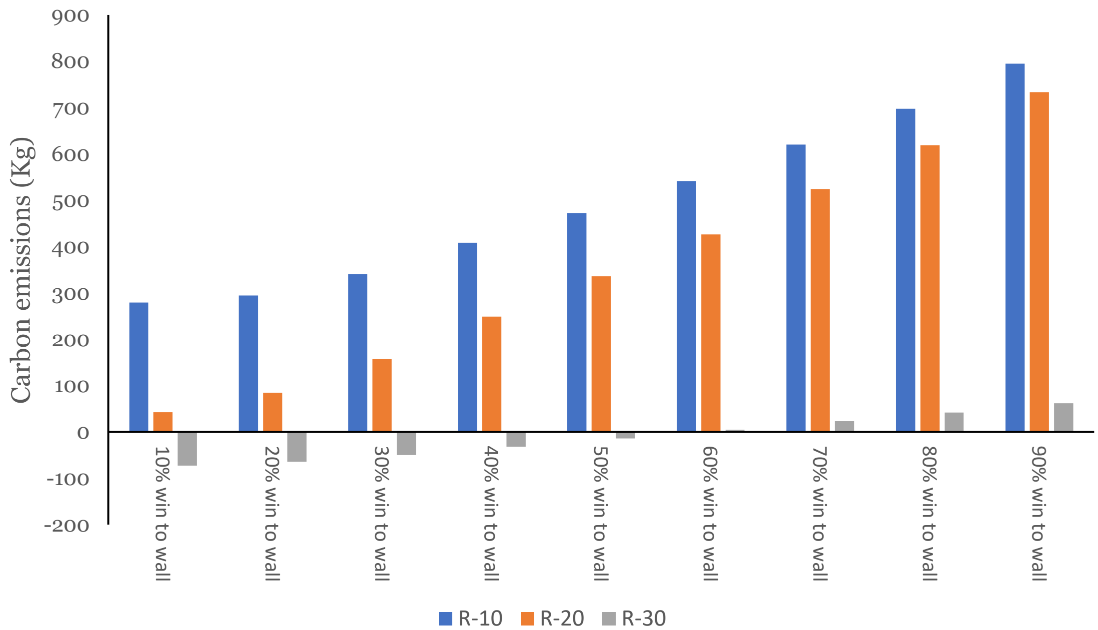


Figure 147- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Boston.

11.11. 5B Denver, CO

Table 23 displays the energy consumption details for all 54 cases in Denver. Green cells signify instances where energy consumption is less than generated electricity, indicating a net-zero energy status for the tiny house. Conversely, red cells indicate instances where energy consumption surpasses generated electricity. The unit of measurement for these values is kilowatt-hours (kWh).

Table 23- Energy consumption (kWh) of all cases in Denver.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	4292.528	3988.901	3753.927	4284.887	3924.401	3663.649
20	4217.215	3936.824	3719.477	4275.819	3949.312	3712.014
30	4215.53	3962.591	3766.361	4336.546	4047.636	3837.373
40	4270.859	4045.682	3870.143	4447.472	4194.377	4010.715
50	4340.338	4143.095	3988.218	4568.218	4351.272	4192.332
60	4439.974	4270.535	4134.719	4711.846	4528.621	4391.31
70	4576.924	4432.04	4313.735	4884.08	4730.429	4613.294
80	4730.939	4609.003	4506.848	5067.448	4940.942	4840.235
90	4944.401	4843.589	4753.82	5295.384	5193.411	5108.562
Generation	6050.004	6050.004	6050.004	5291.474	5291.474	5291.474

Table 24 details the CO_2 emissions across all cases. As the energy consumed in most cases is consistently less than the generated electricity, most numerical values in the table are negative. The incorporation of a green color scheme within the cells serves as a visual cue, highlighting instances where the cases exhibit zero-emission characteristics. This color-coded representation underscores the positive environmental impact of the tiny houses, emphasizing their contribution to a reduction in carbon footprint. The negative values, coupled with the green coloration, signify that the cases have effectively achieved a net-zero or even a carbon-negative status, reflecting a commendable commitment to sustainable and eco-friendly practices across the entirety of the cases examined. However, there are cells with red color. The red color indicates that the CO_2 emission is positive, and the building is not zero-emission.

Table 24- Carbon emissions (Kg) of all cases in Denver.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	-1535.364	-1800.619	-2005.896	-879.3732	-1194.3	-1422.099
20	-1601.159	-1846.114	-2035.993	-887.2949	-1172.538	-1379.846
30	-1602.631	-1823.603	-1995.034	-834.2429	-1086.64	-1270.33
40	-1554.295	-1751.014	-1904.368	-737.3358	-958.4445	-1118.895
50	-1493.597	-1665.912	-1801.216	-631.8497	-821.3779	-960.2314
60	-1406.553	-1554.578	-1673.23	-506.3735	-666.4423	-786.4003
70	-1286.91	-1413.484	-1516.838	-355.9071	-490.1397	-592.4708
80	-1152.36	-1258.886	-1348.13	-195.7128	-306.2311	-394.2108
90	-965.876	-1053.948	-1132.371	3.416125	-85.66957	-159.7952

Figure 147 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 30% ratio has the lowest energy consumption during the year. The annual energy consumption for a 30% window-to-wall ratio (best case) is 4215.53 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 4944.401 kWh. The difference between these two cases is significant: increasing the ratio from 30% to 90% results in a 17% increase in energy consumption.

The amount of electricity supplied by PV cells is 6050.004 kWh. As mentioned before, the highest energy consumption is 4944.401 kWh. This means that the residents can sell 1,105.603 kWh of electricity during the year.

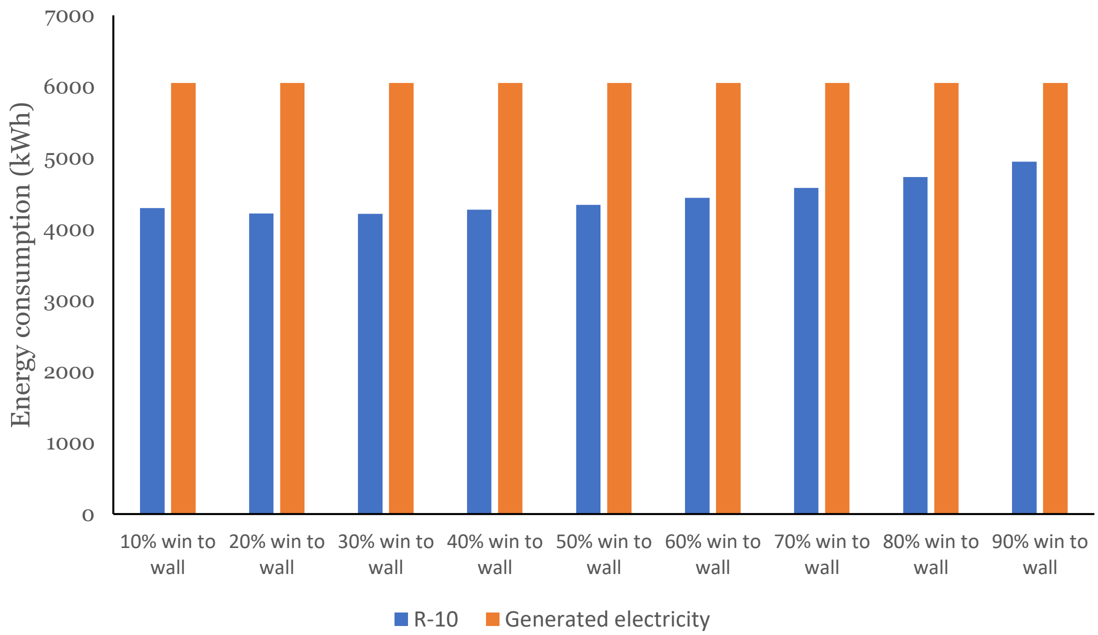


Figure 148- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Denver.

In all scenarios examined in Figure 148, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells prove capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 3936.824 kWh, is associated with a 20% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 4843.589 kWh, translating to a noteworthy 23% increase in energy consumption when transitioning from a 20% to an 90% window-to-wall ratio.

The PV cells generate a total of 6050.004 kWh of electricity, surpassing the highest recorded energy consumption of 4843.589 kWh. Consequently, residents have the potential to sell 1,206.415 kWh of surplus electricity throughout the year.

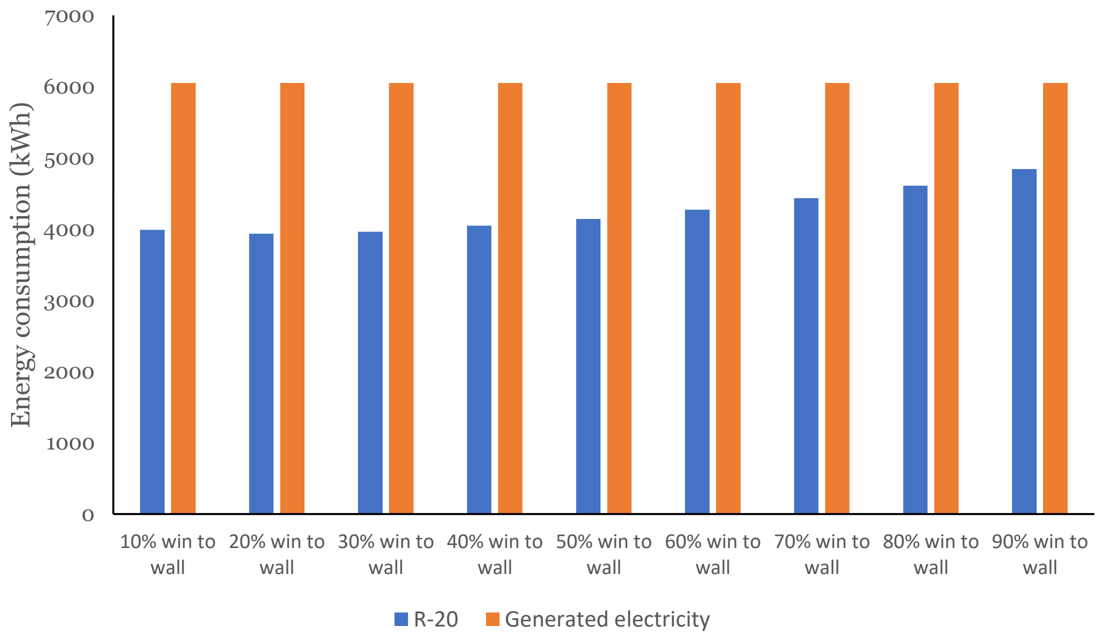


Figure 149- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Denver.

Within the scope of Figure 149's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to effectively meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 3719.477 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 4753.82 kWh, reflecting a notable 27% increase in energy consumption during the transition from a 20% to a 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 6050.004 kWh of electricity, surpassing the peak energy consumption recorded at 4753.82 kWh. Consequently, residents possess the potential to sell 1,296.184 kWh of surplus electricity throughout the year. This detailed examination of the graph sheds light on the intricate interplay between window-to-wall ratios

and energy consumption, underscoring the role of PV cells in meeting diverse energy requirements within architectural contexts.

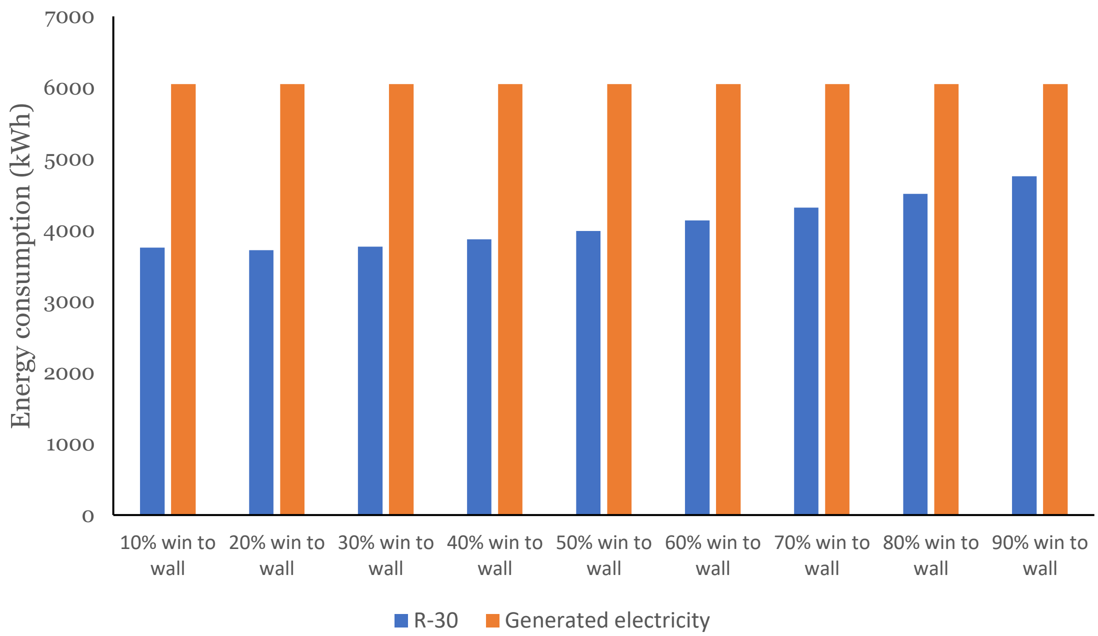


Figure 150- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Denver.

Figure 150 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results underscore the pivotal role played by photovoltaic (PV) cells in effectively meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 20% window-to-wall ratio is linked with the highest annual energy consumption, registering at 5295.384 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 4275.819 kWh. The significant disparity between these extremes, revealing a 24% increase in energy consumption during the transition from a 20% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals almost compelling insights into the performance of PV cells, which generate a total of 5291.474 kWh of electricity, surpassing the peak energy consumption 9after 90% WWR) recorded at 5067.448 kWh. However, 90% WWR PV cells are not capable of supplying the required electricity.

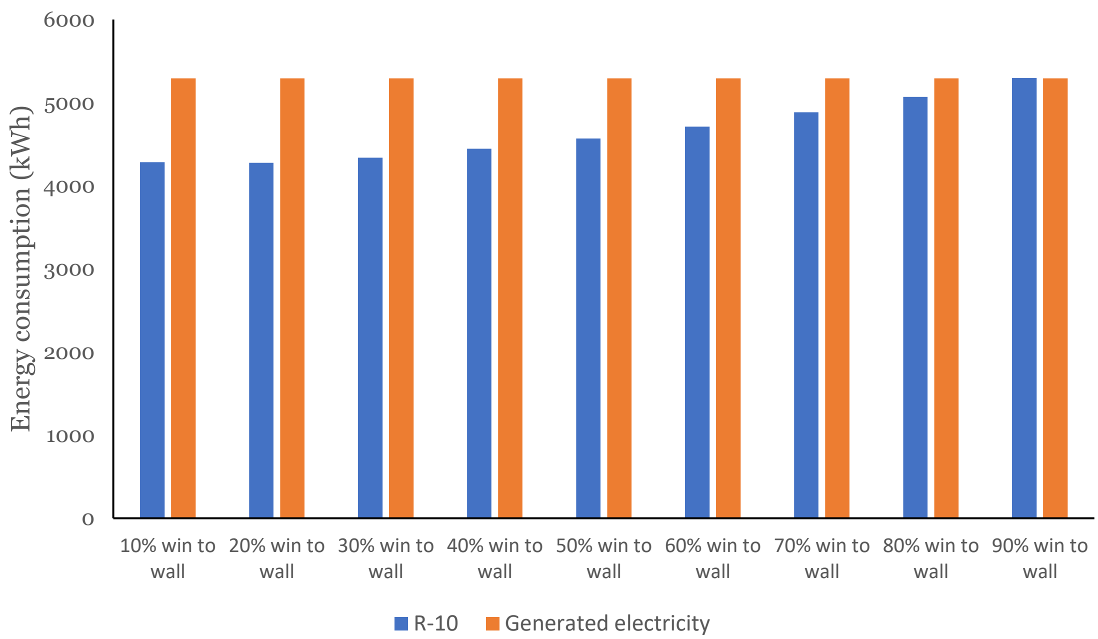


Figure 151- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Denver.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 151. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 5193.411 kWh and the annual energy consumption for the best case 3924.401 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 32%.

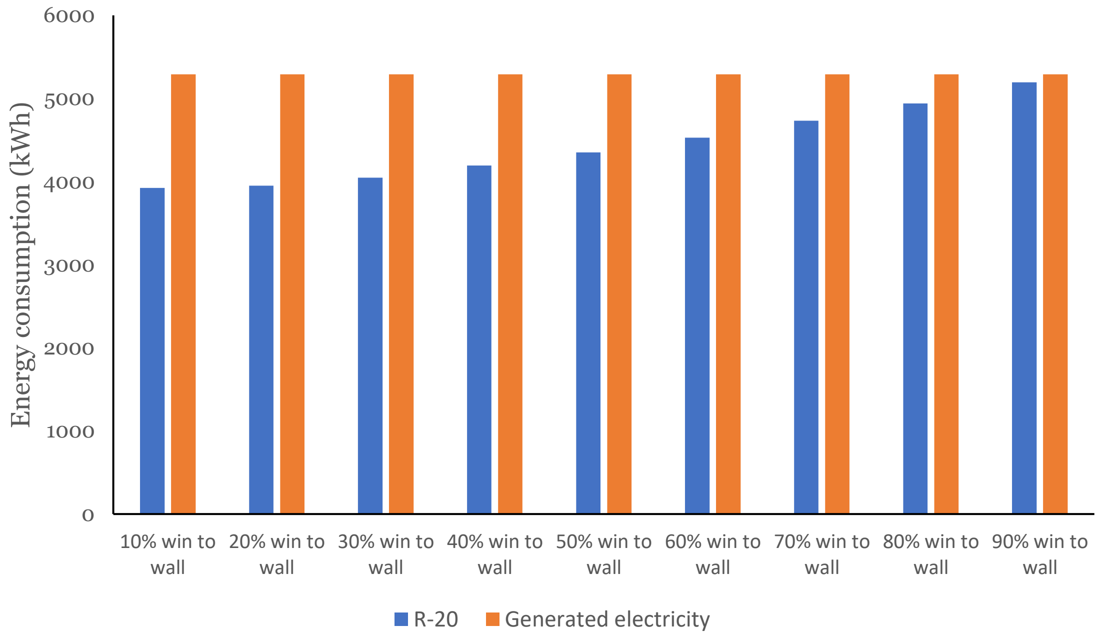


Figure 152- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Denver.

Figure 152 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 3663.649 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 5108.562 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 40% increase in energy consumption.

The amount of electricity supplied by PV cells is 5291.474 kWh. As mentioned before, the highest energy consumption is 5108.562 kWh. This means that the residents can sell 182.912 kWh of electricity during the year.

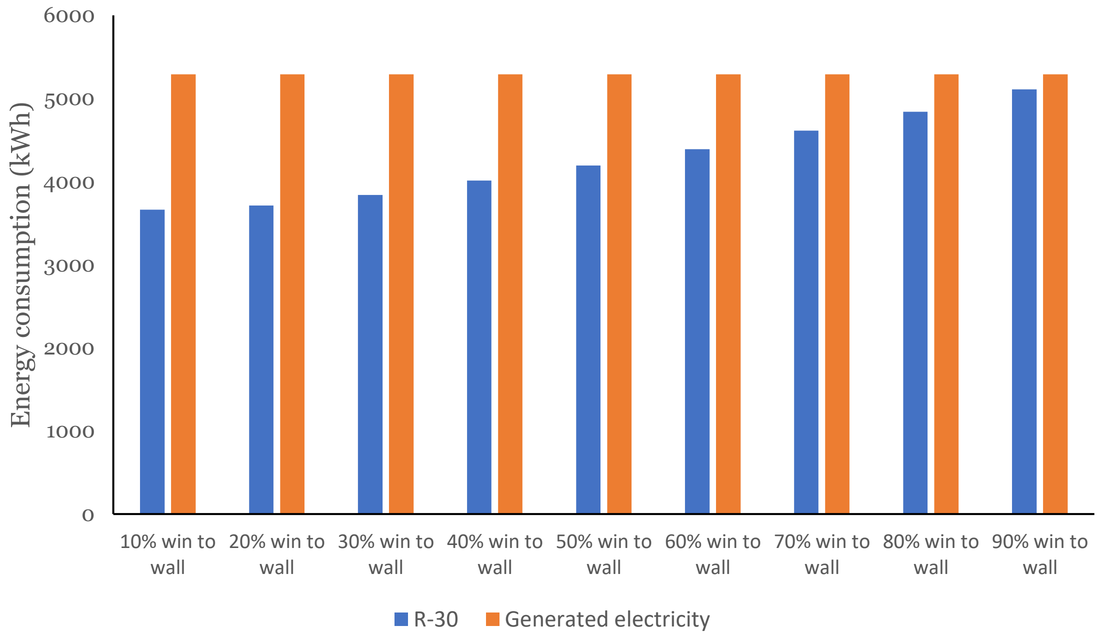


Figure 153- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Denver.

Figure 153 shows the energy consumption of the building with R-10 insulation in different orientations. Except for 10%, in other cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

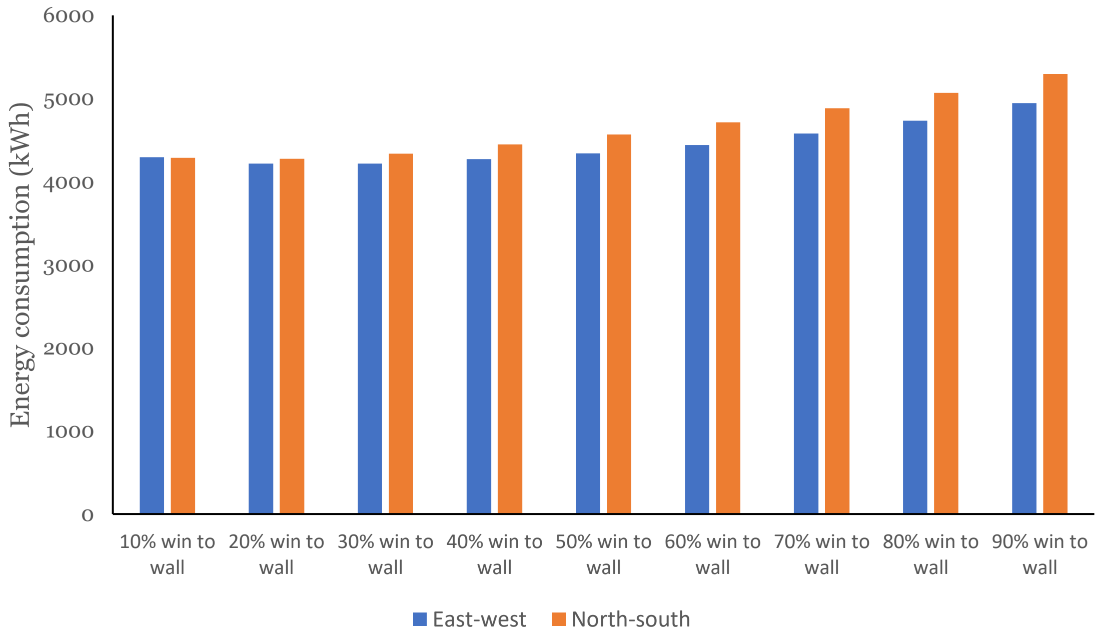


Figure 154- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Denver.

Figure 154 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. Except for 10% in other ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 64.5 kWh (1.6%) in 10% window to wall, 208.177 kWh (5%) in 50% window to wall and 349.822 kWh (7.2%) in 90% WWR.

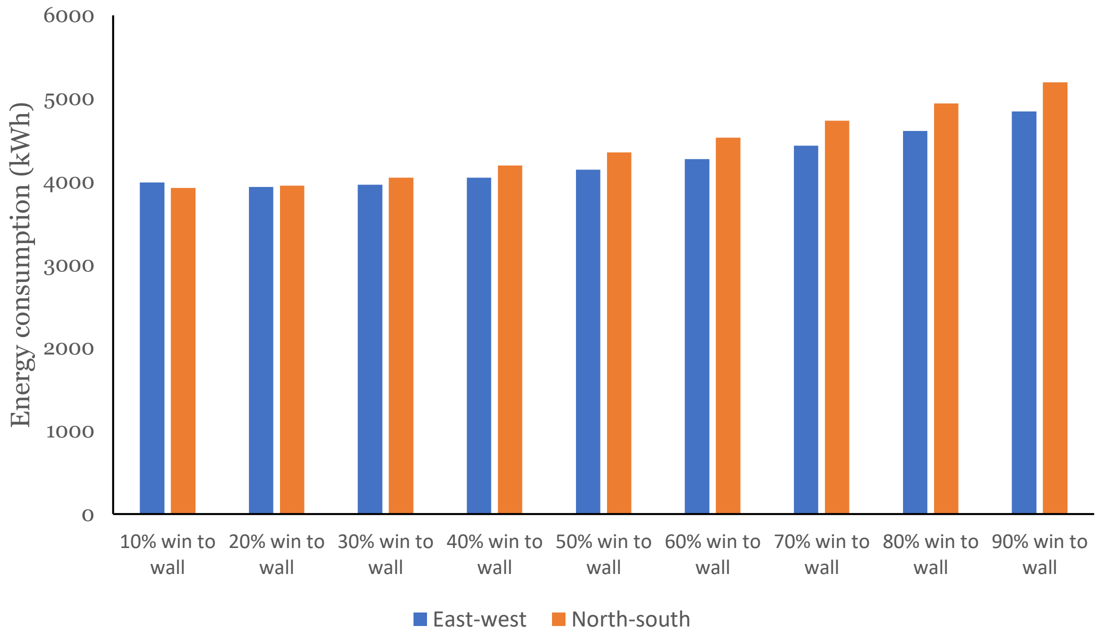


Figure 155- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Denver.

Figure 155 shows the energy consumption of buildings with R-30 insulation in different orientations. In all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it’s clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

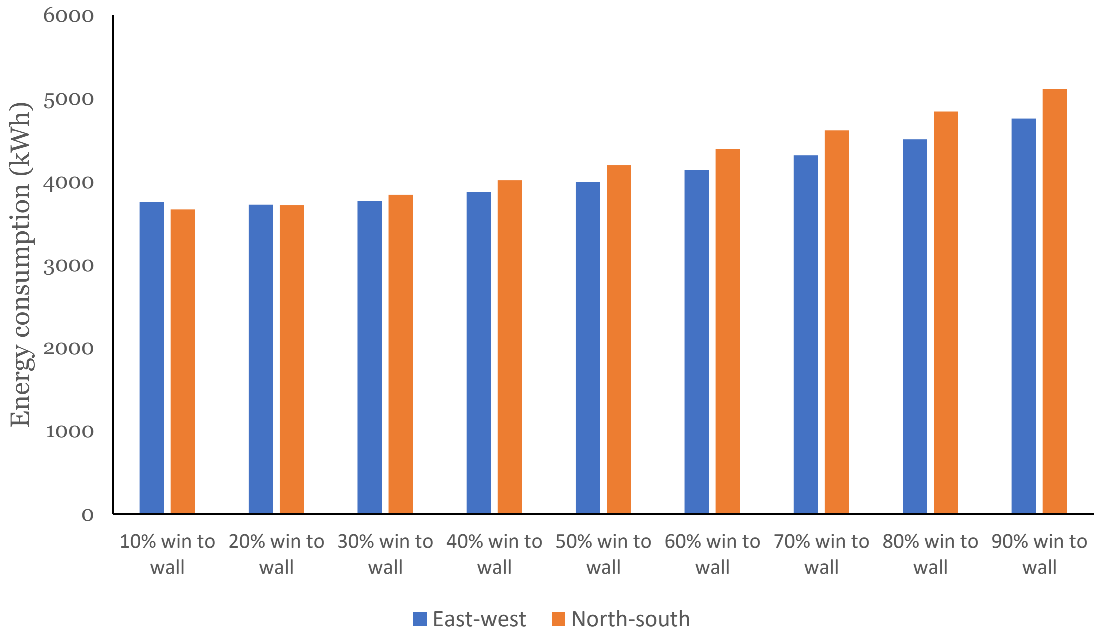


Figure 156- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Denver.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 156 is about generated electricity in two orientations. The generated electricity for east-west orientation is 6050.004 kWh and for north-south orientation is 5268.548 kWh. In other words, the generated electricity in east-west orientation is 14% more than the generated electricity in north-south condition.

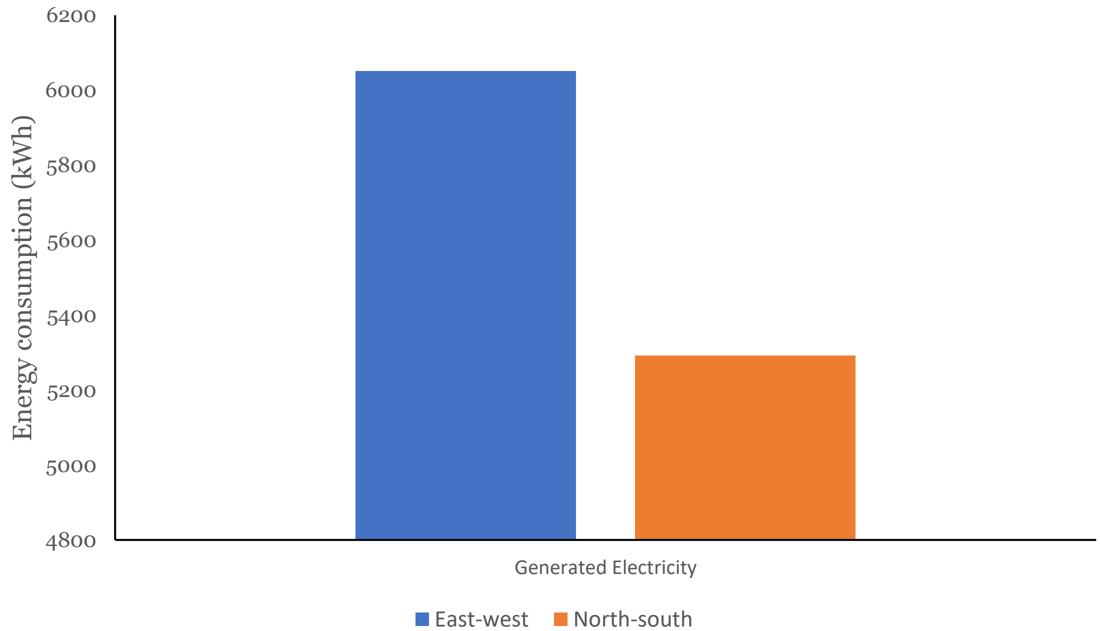


Figure 157- Generated electricity in different configurations of PV cells in Denver.

Figure 157 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10%-20% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 20%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

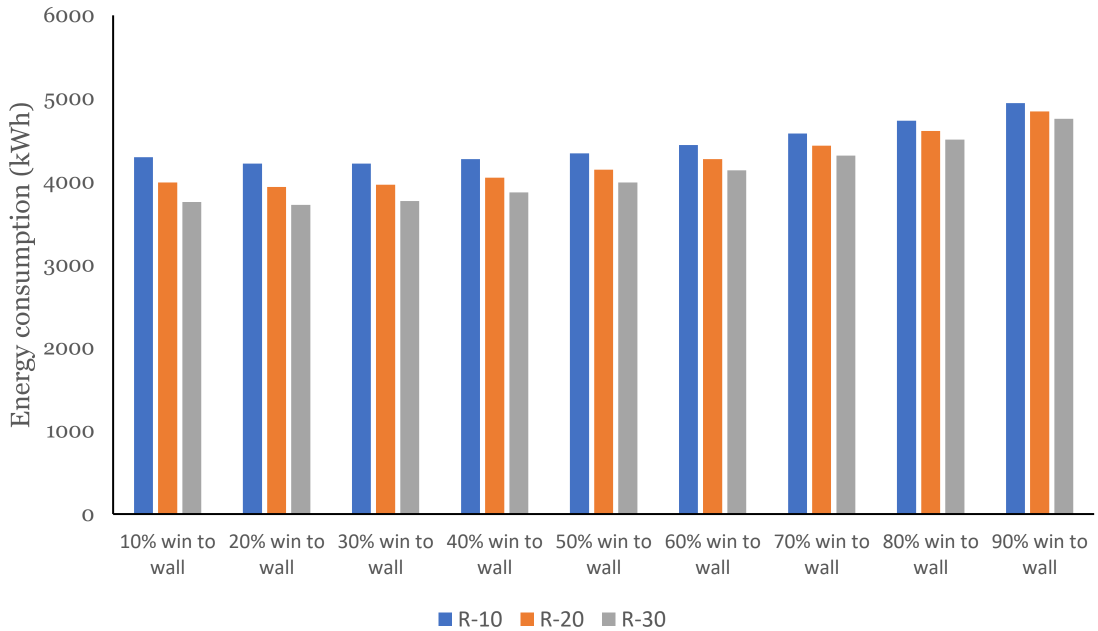


Figure 158- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Denver.

Figure 158 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.

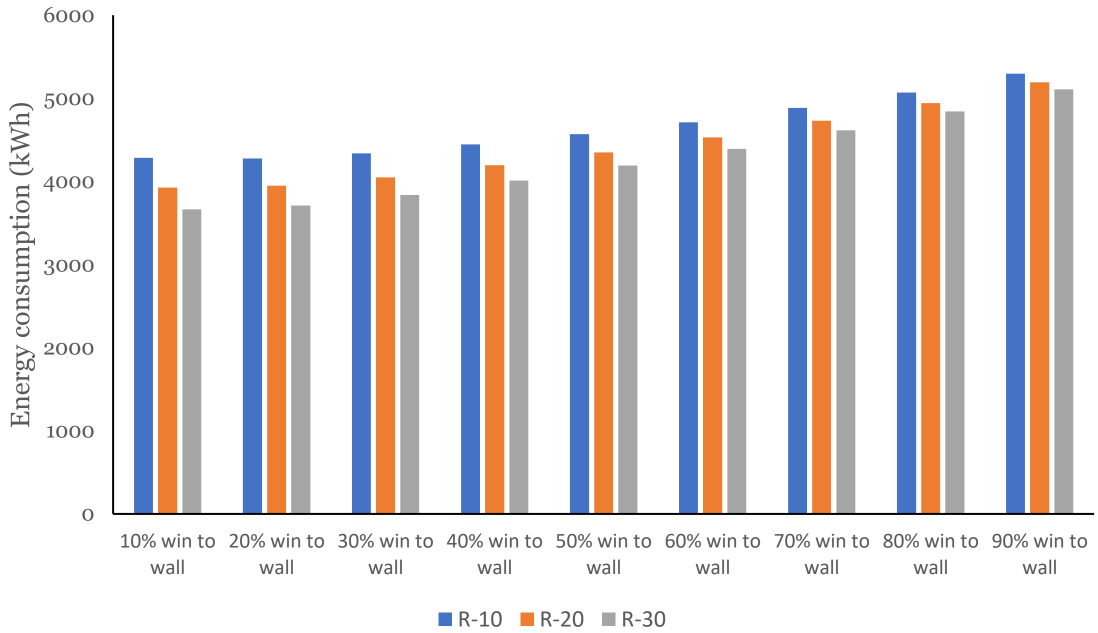


Figure 159- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Denver.

The CO2 emissions for cases with east-west orientation is shown in figure 159. Because the generated electricity is more than energy consumption, CO2 emissions are negative in all cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 20% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

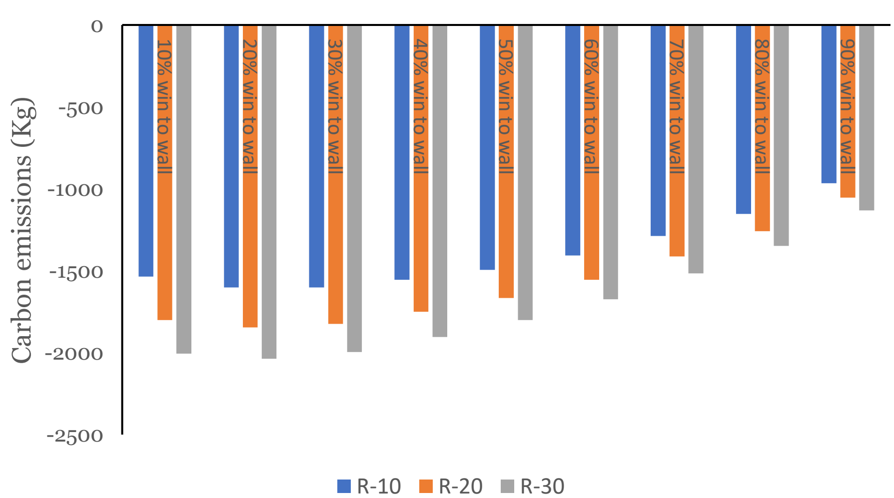


Figure 160- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Denver.

Figure 160 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

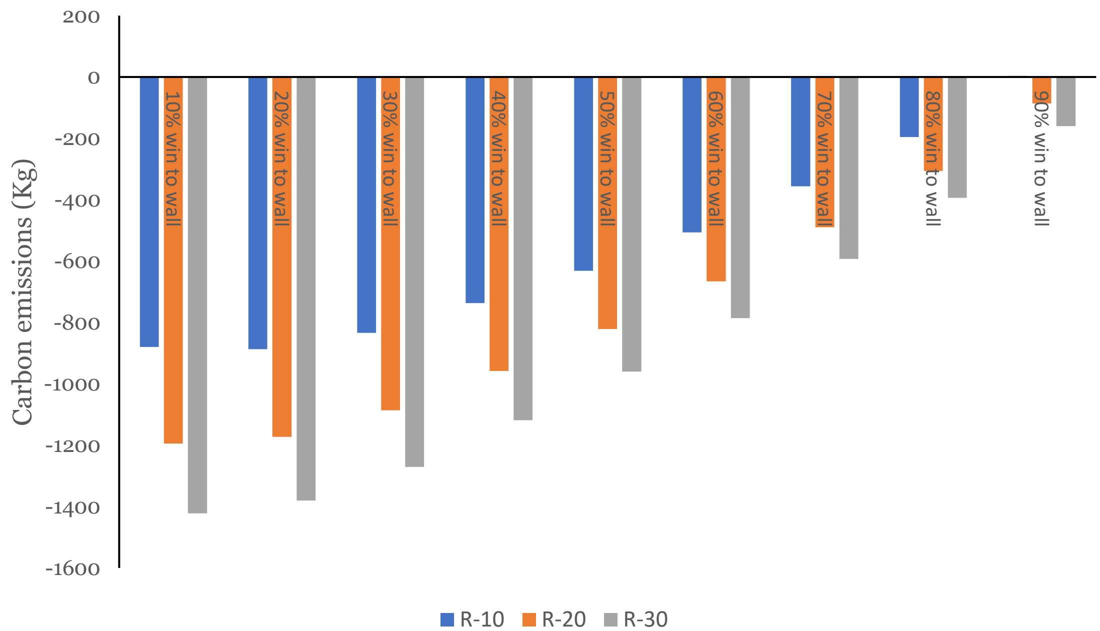


Figure 161- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Denver.

11.12. 6A Minneapolis, MN

Table 25 illustrates the energy consumption for all 54 cases in Minneapolis. Red cells signify instances where energy consumption exceeds the generated electricity, indicating that the tiny house cannot achieve a net-zero energy status. The unit of measurement for these values is kilowatt-hours (kWh).

Table 25- Energy consumption (kWh) of all cases in Minneapolis.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	6881.206	6360.285	5963.074	6775.266	6164.995	5733.506
20	6923.774	6459.701	6105.97	6897.083	6357.554	5975.108
30	7025.409	6616.549	6302.382	7067.66	6595.279	6258.797
40	7169.042	6809.729	6532.041	7270.178	6860.703	6565.088
50	7296.399	6986.021	6743.956	7454.246	7102.845	6847.892
60	7435.149	7172.321	6963.111	7640.692	7345.575	7127.152
70	7595.078	7374.837	7196.367	7840.234	7596.366	7411.502
80	7745.573	7564.79	7413.064	8020.744	7824.756	7671.158
90	7945.536	7803.121	7679.359	8241.579	8090.823	7965.797
Generation	5047.228	5047.228	5047.228	4373.821	4373.821	4373.821

Table 26 provides information on CO_2 emissions in all cases. Due to the fact that the consumed energy exceeds the generated electricity in all instances, all numerical values are positive, and consequently, all cells are marked in red. This red color indicates that the cases cannot achieve a zero-emission status.

Table 26- Carbon emissions (Kg) of all cases in Minneapolis.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	1076.451	770.6967	537.5543	1409.524	1051.327	798.0652
20	1101.436	829.0491	621.4271	1481.025	1164.349	939.873
30	1161.091	921.1106	736.7106	1581.145	1303.881	1106.384
40	1245.396	1034.498	871.5085	1700.012	1459.671	1286.161
50	1320.148	1137.971	995.892	1808.051	1601.796	1452.152
60	1401.587	1247.32	1124.525	1917.485	1744.266	1616.064
70	1495.457	1366.187	1261.434	2034.606	1891.468	1782.962
80	1583.79	1477.679	1388.624	2140.556	2025.521	1935.367
90	1701.158	1617.567	1544.925	2270.175	2181.689	2108.305

Figure 161 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy cannot be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 6881.206 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 7945.536 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 15% increase in energy consumption.

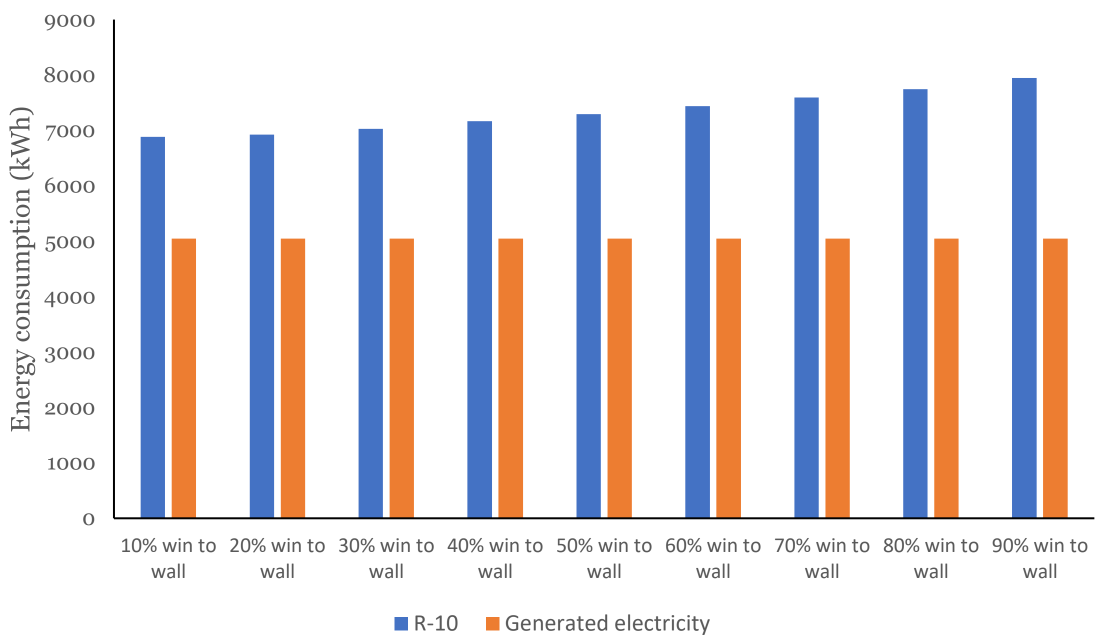


Figure 162- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Minneapolis.

In all scenarios examined in Figure 162, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells are not capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 6360.285 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 7803.121 kWh, translating to a noteworthy 23% increase in energy consumption when transitioning from a 10% to a 90% window-to-wall ratio.

The PV cells generate a total of 5047.228 kWh of electricity. It is less than energy consumption in all ratios. Therefore, using other resources to supply required energy is necessary.

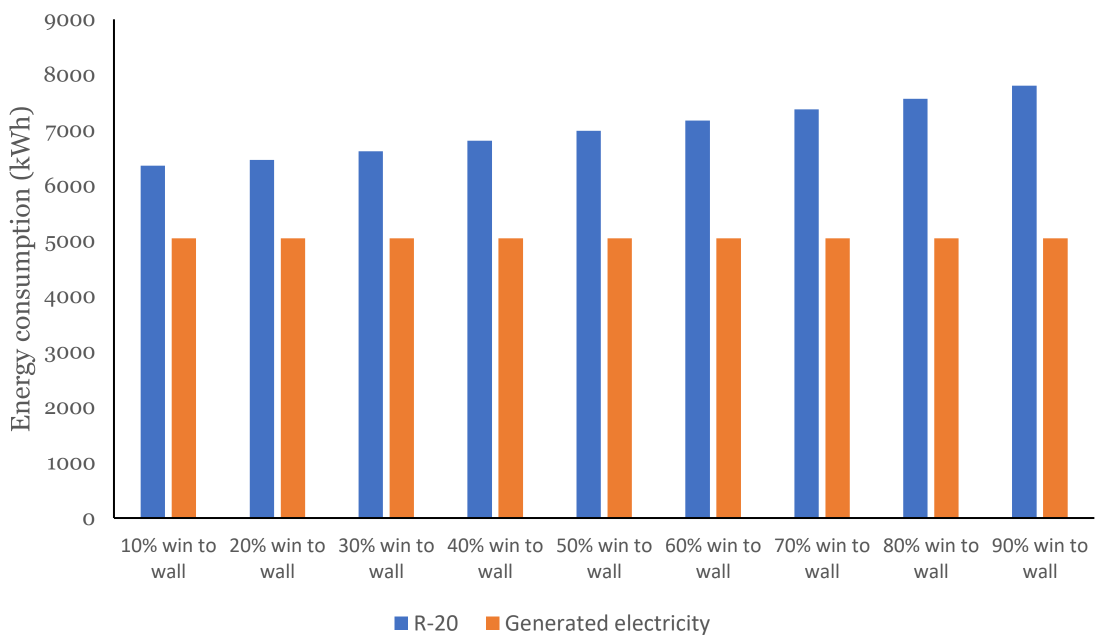


Figure 163- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Minneapolis.

Within the scope of Figure 163's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the incapability of photovoltaic (PV) cells to meet energy demands in these varied scenarios. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 5963.074 kWh. This disparity is significant, given that the 80% ratio exhibits a markedly higher annual consumption of 7679.359 kWh,

reflecting a notable 29% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio.

The PV cells generate a total of 5047.228 kWh of electricity. It is less than energy consumption in all ratios, in other words, the minimum energy consumption is 5963.074 kWh, and this amount is more than generated electricity. Therefore, using other resources to supply required energy is necessary.

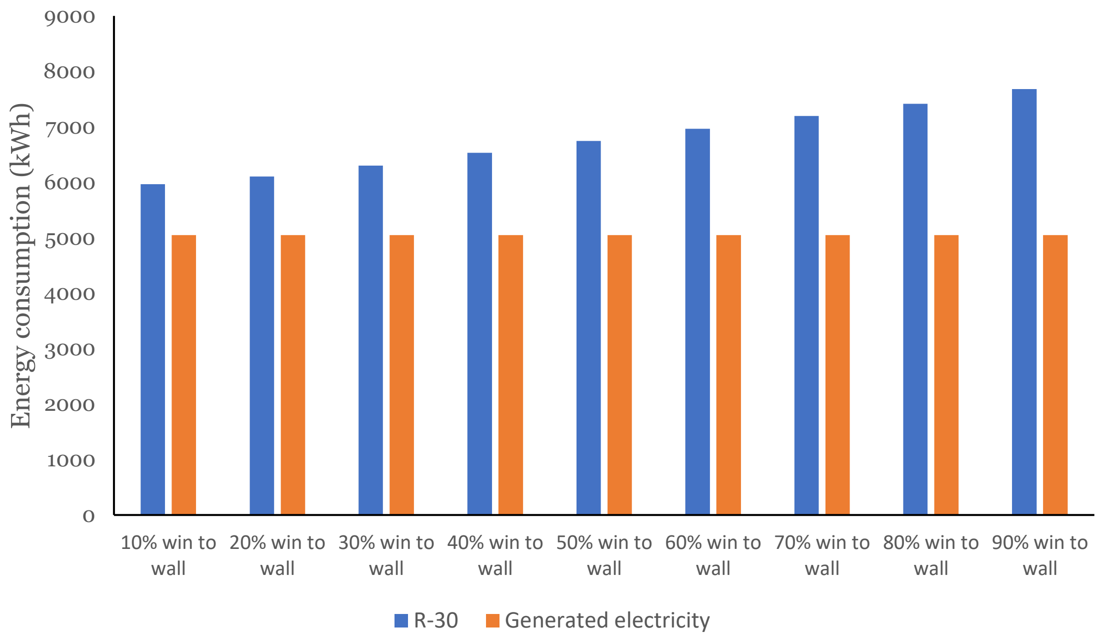


Figure 164- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Minneapolis.

Figure 164 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results indicate that photovoltaic (PV) cells cannot meet energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 8241.579 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 6775.266 kWh. The significant disparity between these extremes, revealing a 22% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

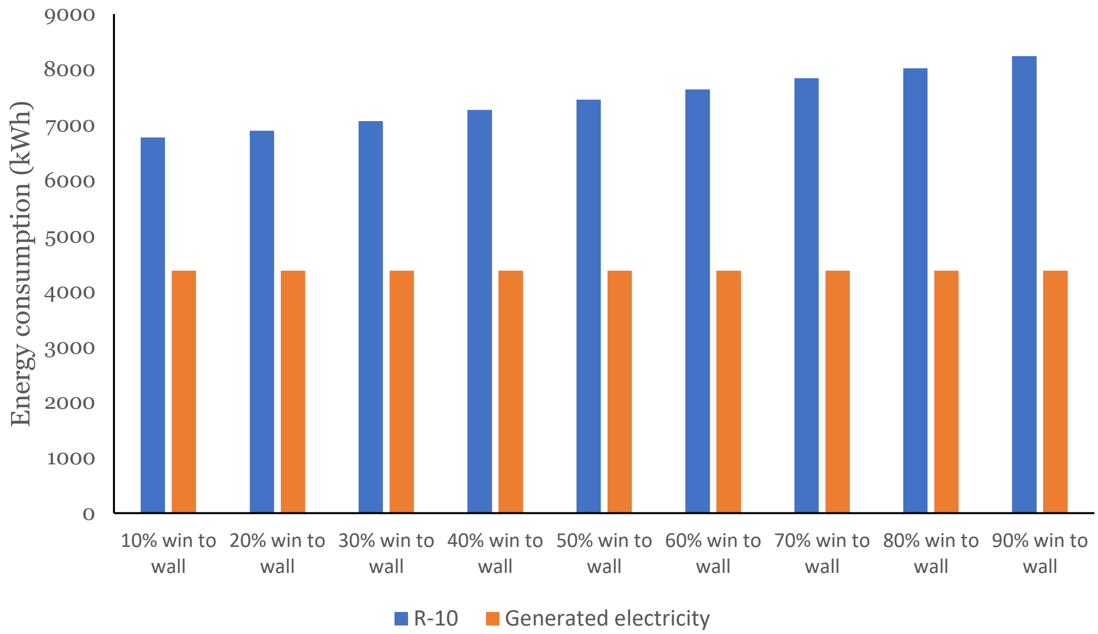


Figure 165- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Minneapolis.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 165. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 80% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 8090.823 kWh and the annual energy consumption for the best case 6164.995 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 31%.

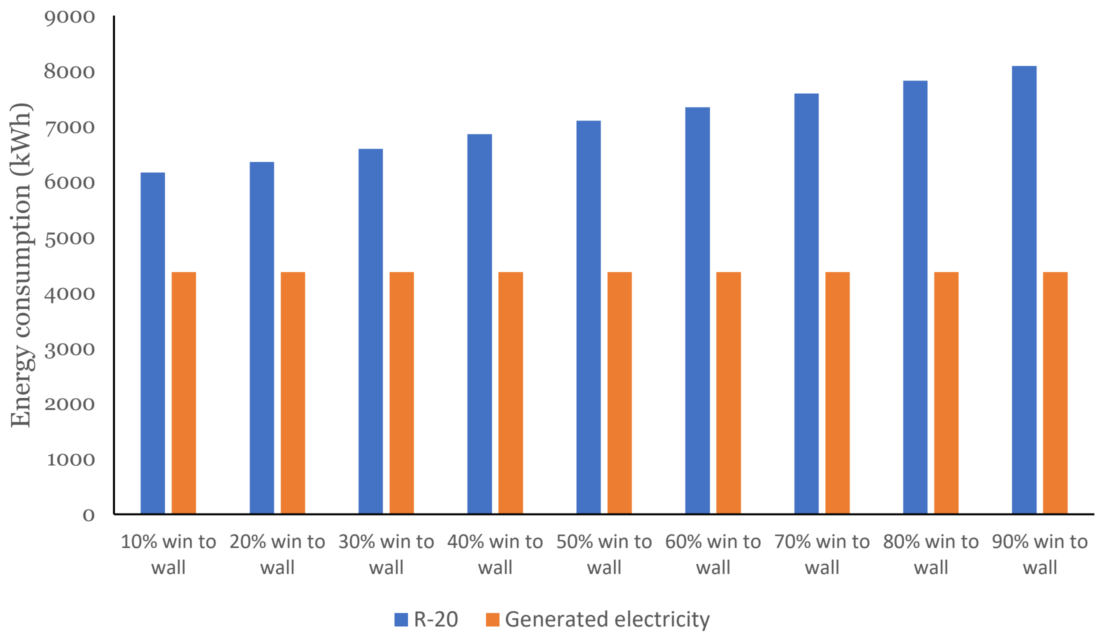


Figure 166- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Minneapolis.

Figure 166 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy cannot be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 5733.506 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 7965.797 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 39% increase in energy consumption.

The amount of electricity supplied by PV cells is 5268.548 kWh. As mentioned before, the lowest energy consumption is 5733.506 kWh, and this amount is more than generated electricity. Therefore, using PV cells for supplying required energy is not enough.

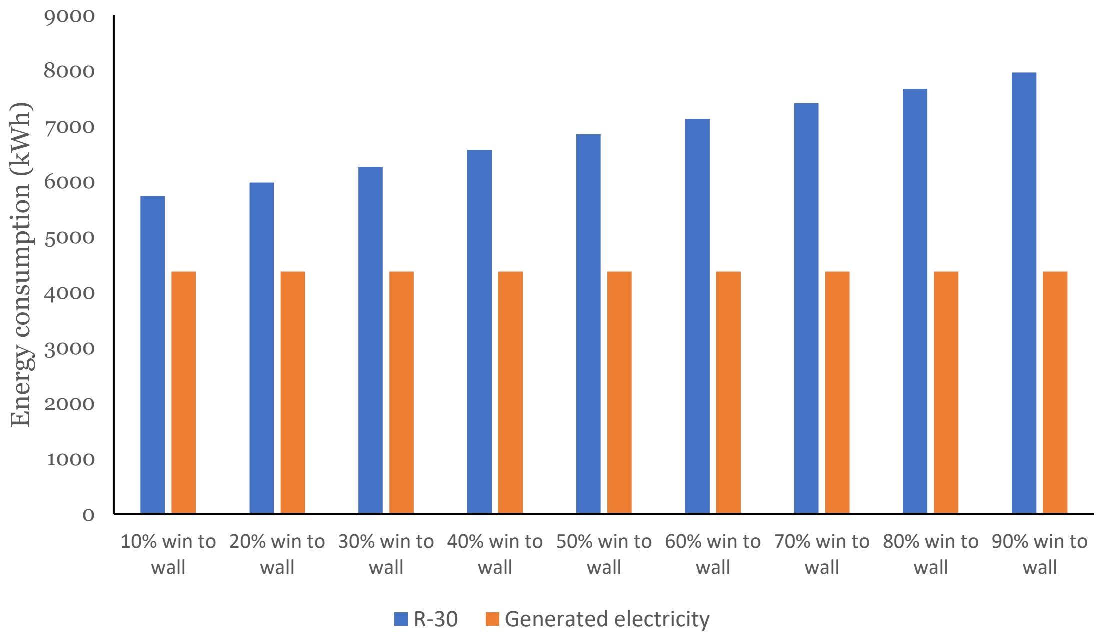


Figure 167- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Minneapolis.

Figure 167 shows the energy consumption of the building with R-10 insulation in different orientations. Except for 10% and 20% in other cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

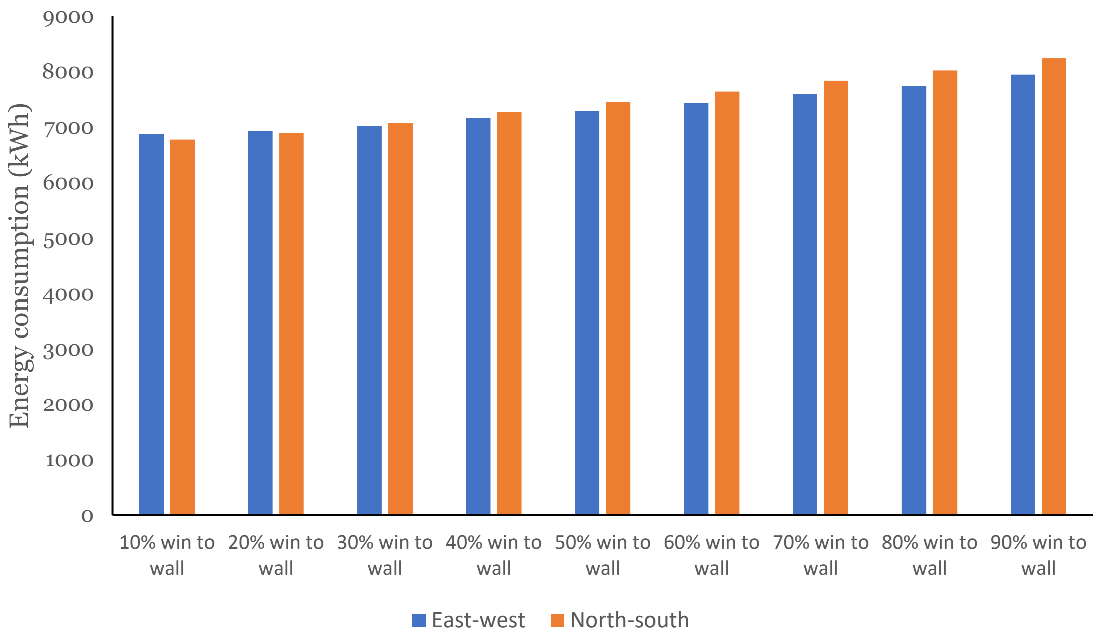


Figure 168- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Minneapolis.

Figure 168 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. In all ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

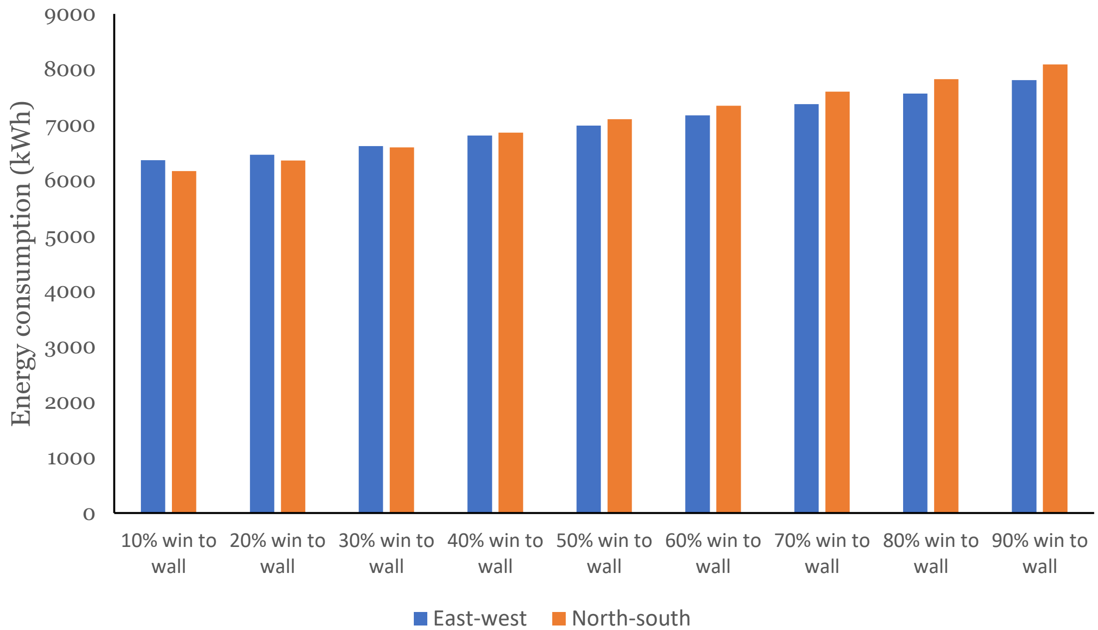


Figure 169- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Minneapolis.

Figure 169 shows the energy consumption of buildings with R-30 insulation in different orientations. Except for 10% and 20% WWR, in other cases energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

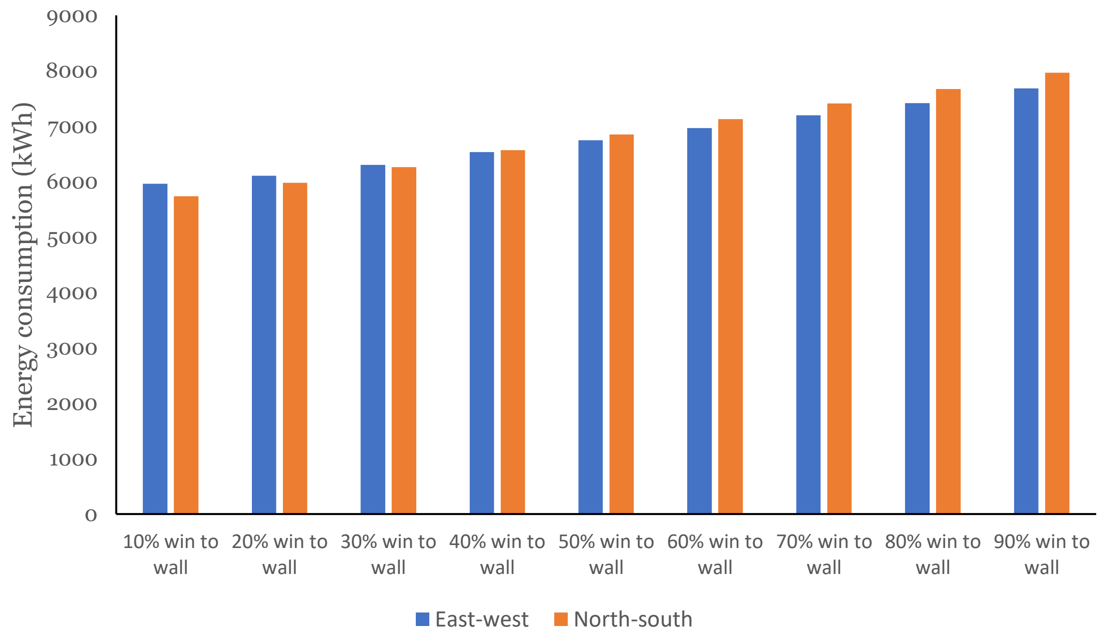


Figure 170- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Minneapolis.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 170 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5797.787 kWh and for north-south orientation is 5268.548 kWh. In other words, the generated electricity in east-west orientation is 15% more than the generated electricity in north-south condition.

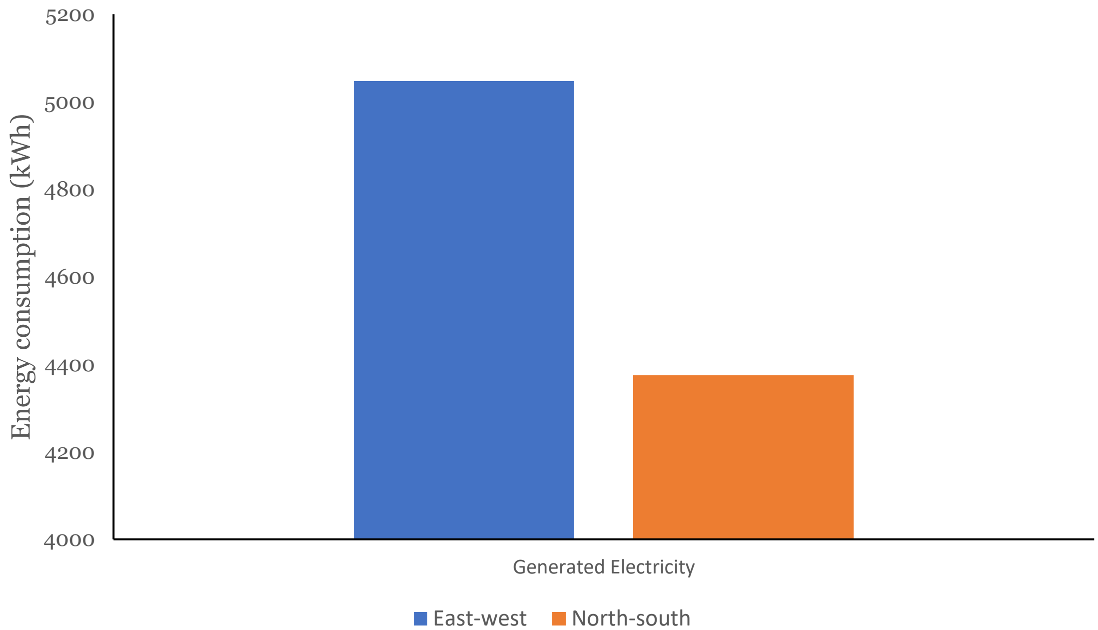


Figure 171- Generated electricity in different configurations of PV cells in Minneapolis.

Figure 171 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

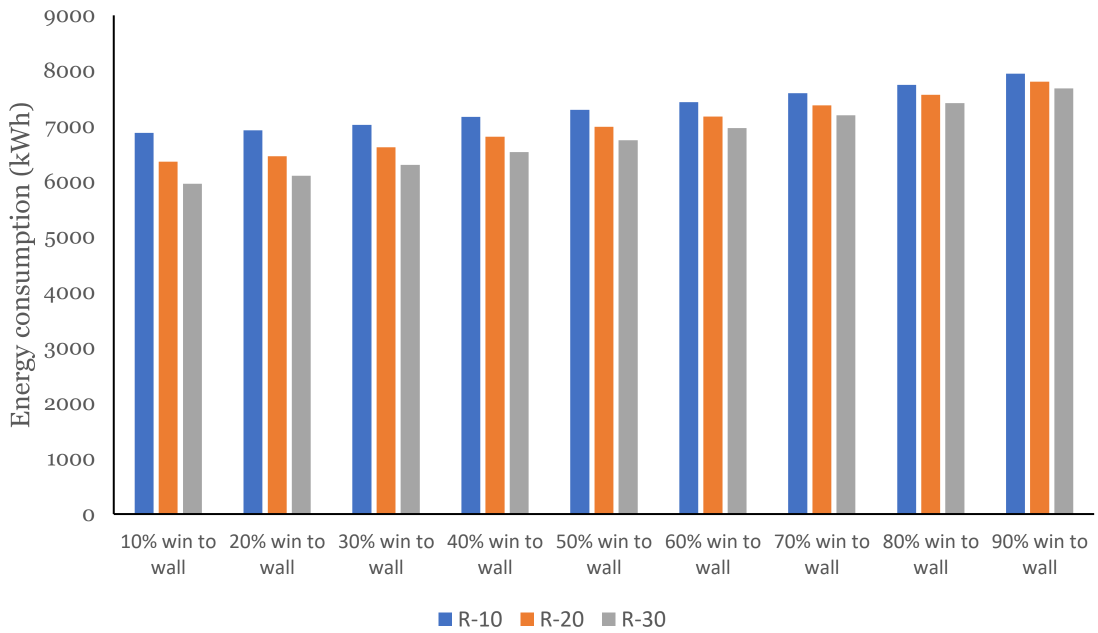


Figure 172- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Minneapolis.

Figure 172 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.

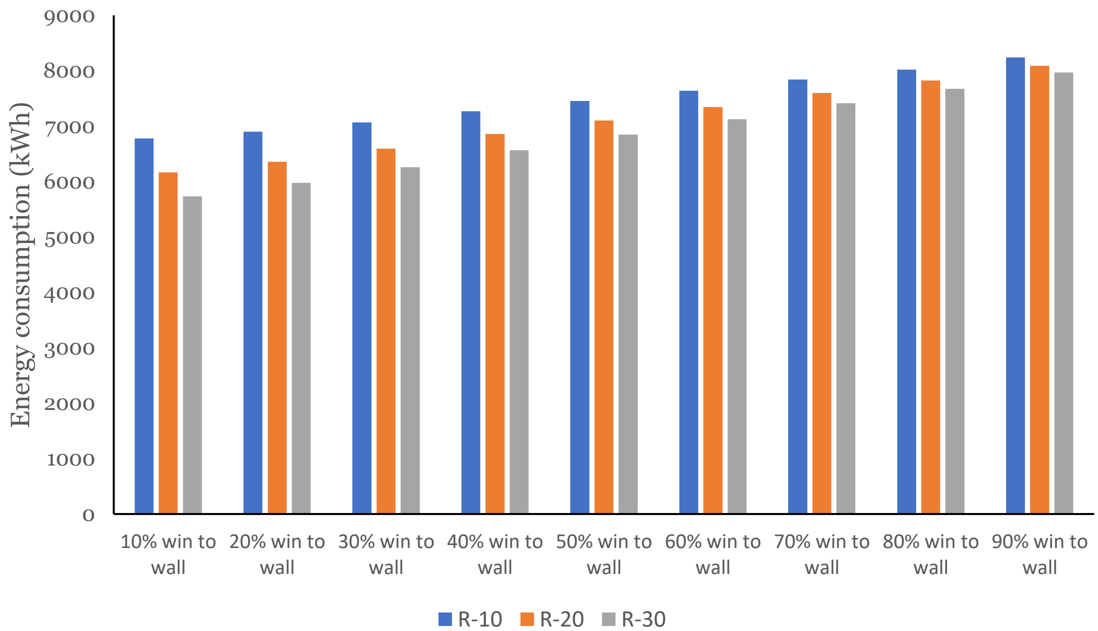


Figure 173- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Minneapolis.

The CO2 Emissions for cases with east-west orientation is shown in figure 173 Because the generated electricity is less than energy consumption, CO2 emissions are positive in all cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

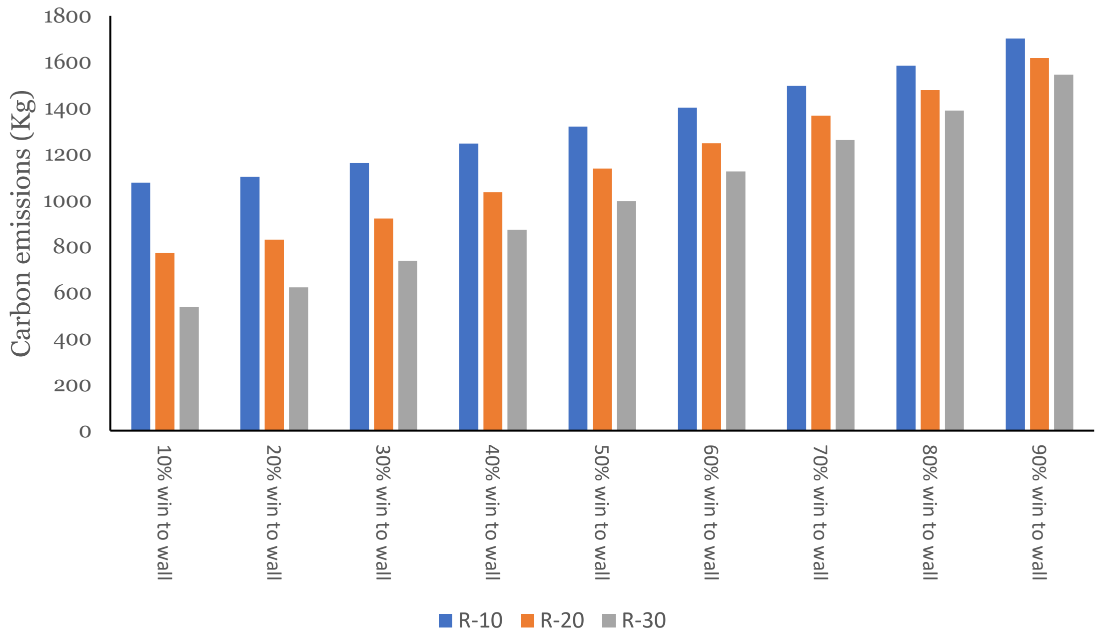


Figure 174- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Minneapolis.

Figure 174 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

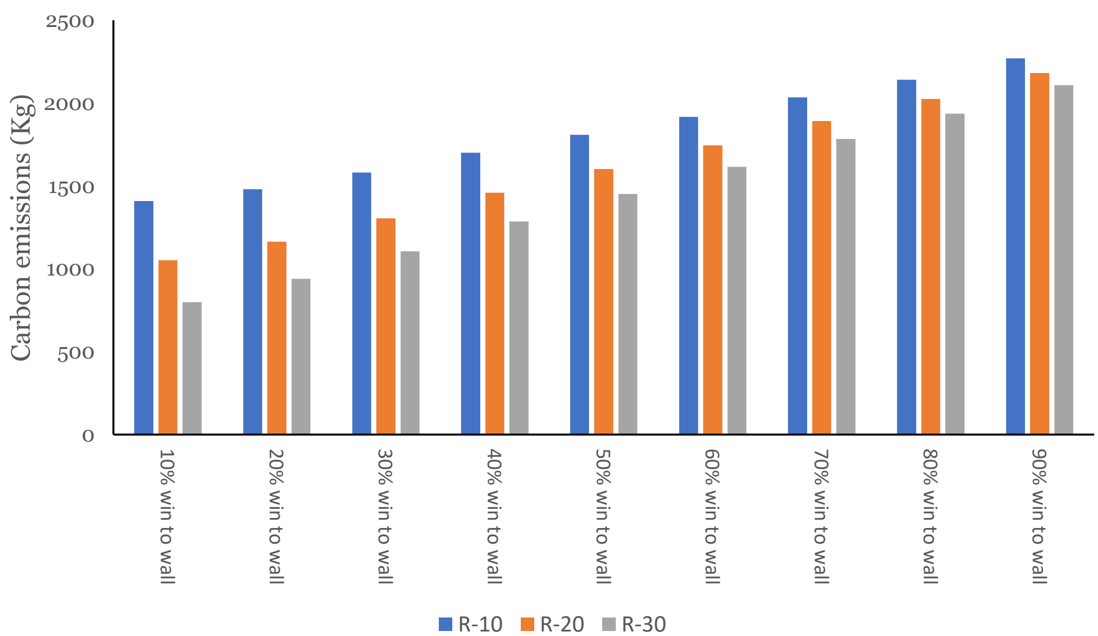


Figure 175- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Minneapolis.

11.13. 6B Billings, MT

Presented in Table 27 are the energy consumption details for all 54 cases in Billings. Cells highlighted in green within the table indicate instances where energy consumption falls below the generated electricity, signifying a net-zero energy status for the respective tiny houses. Conversely, cells highlighted in red indicate instances where energy consumption exceeds the generated electricity. The unit of measurement for these values is kilowatt-hours (kWh), providing a standardized basis for assessing the energy dynamics of each case.

Table 27- Energy consumption (kWh) of all cases in Billings.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	5510.452	5095.883	4779.919	5436.37	4950.42	4603.875
20	5494.309	5120.254	4833.716	5494.388	5059.857	4749.144
30	5546.472	5214.137	4959.269	5618.789	5237.754	4964.941
40	5652.624	5362.238	5136.77	5789.625	5460.116	5222.392
50	5761.032	5510.691	5315.035	5956.634	5676.877	5473.195
60	5891.527	5678.785	5509.799	6134.879	5901.699	5728.114
70	6046.652	5867.516	5722.845	6330.157	6138.015	5991.307
80	6202.67	6054.902	5932.242	6517.757	6361.957	6239.38
90	6403.598	6286.507	6184.662	6740.425	6619.175	6518.606
Generation	5458.25	5458.25	5458.25	4723.851	4723.851	4723.851

Table 28 details the CO2 emissions across all cases. As the energy consumed in most cases is consistently less than the generated electricity, most numerical values in the table are negative. The incorporation of a green color scheme within the cells serves as a visual cue, highlighting instances where the cases exhibit zero-emission characteristics. This color-coded representation underscores the positive environmental impact of the tiny houses, emphasizing their contribution to a reduction in carbon footprint. The negative values, coupled with the green coloration, signify that the cases have effectively achieved a net-zero or even a carbon-negative status, reflecting a commendable commitment to sustainable and eco-friendly practices across

the entirety of the cases examined. However, there are cells with red color. The red color indicates that the CO2 emission is positive, and the building is not zero-emission.

Table 28- Carbon emissions (Kg) of all cases in Billings.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	33.95469	-235.7024	-441.2215	463.4593	147.3727	-78.03825
20	23.45422	-219.8498	-406.229	501.1968	218.556	16.45205
30	57.38365	-158.7837	-324.5634	582.1135	334.2695	156.8175
40	126.4305	-62.45095	-209.1075	693.2346	478.9045	324.2767
50	196.9448	34.11047	-93.15446	801.8658	619.8978	487.4122
60	281.8257	143.4471	33.52993	917.8054	766.1329	653.2247
70	382.7268	266.2075	172.1062	1044.824	919.8451	824.4185
80	484.2088	388.0929	308.3089	1166.849	1065.509	985.7784
90	614.9025	538.741	472.4952	1311.684	1232.817	1167.401

Figure 175 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy cannot be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 20% ratio has the lowest energy consumption during the year. The annual energy consumption for a 20% window-to-wall ratio (best case) is 5494.309 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 6403.598 kWh. The difference between these two cases is significant: increasing the ratio from 20% to 90% results in a 17% increase in energy consumption.

The amount of electricity supplied by PV cells is 5458.25 kWh. As mentioned before, the highest energy consumption is 5510.452 kWh. This means that PV cells are not capable of supplying the required energy in all ratios.

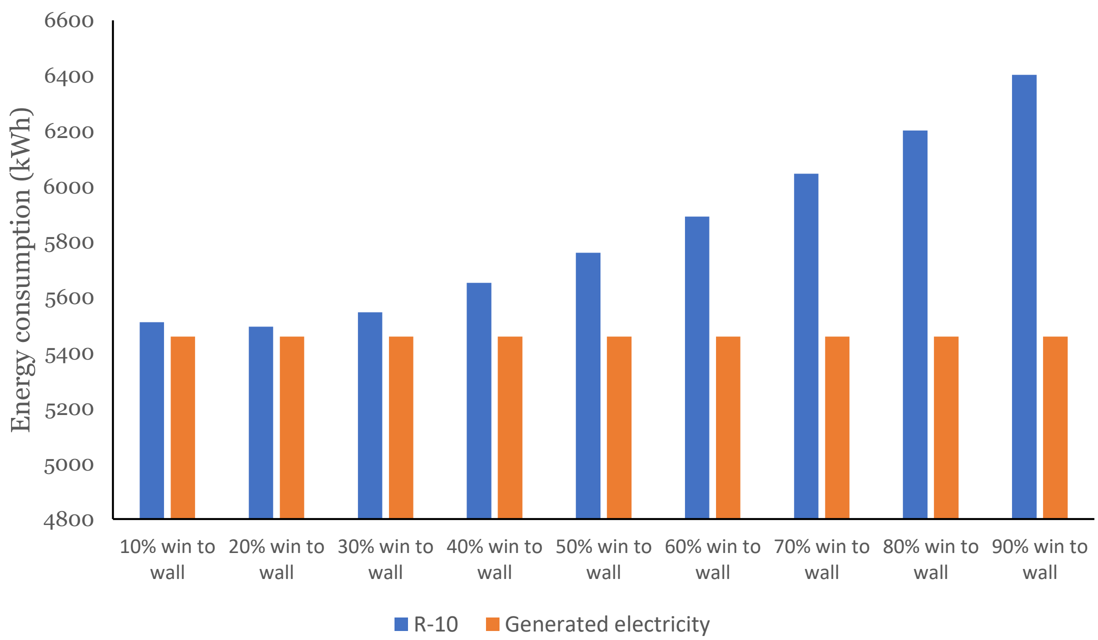


Figure 176- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Billings.

In all scenarios examined in Figure 176, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells are capable of satisfying energy demands only in 10%-40% WWR. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 5095.883 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 6286.507 kWh, translating to a noteworthy 23% increase in energy consumption when transitioning from a 10% to an 80% window-to-wall ratio.

The PV cells generate a total of 5458.25 kWh of electricity. As mentioned before, this amount is more than energy consumption in 10%-40% WWR and less than energy consumption in 50%-90% WWR.

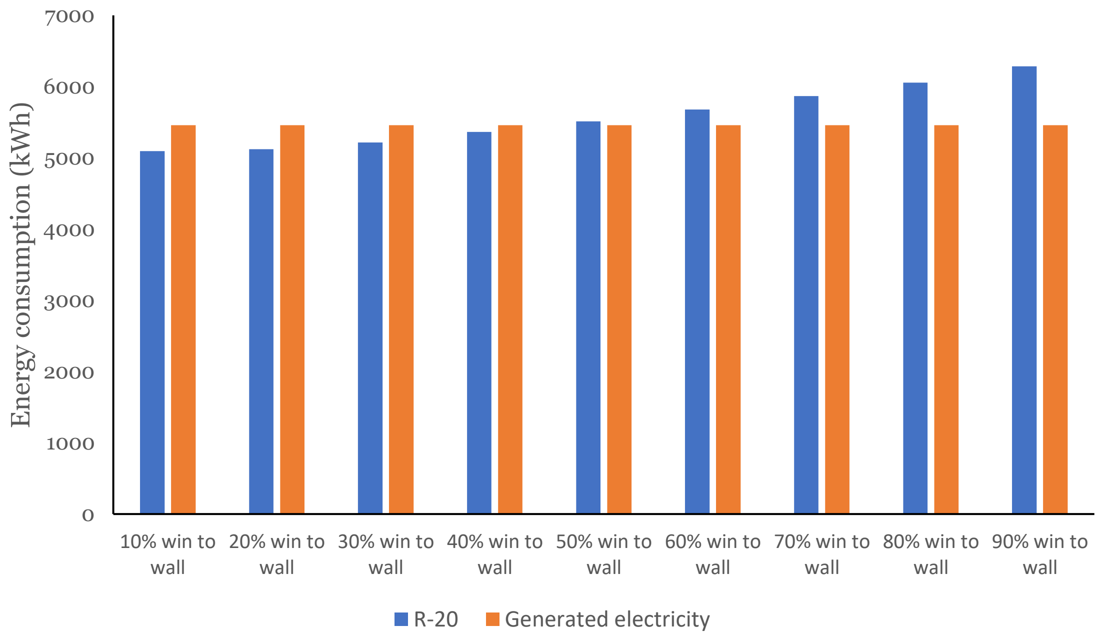


Figure 177- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Billings.

Within the scope of Figure 177's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the capability of photovoltaic (PV) cells to meet energy demands in 10%- 50% WWR. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 4779.919 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 6184.662 kWh, reflecting a notable 29% increase in energy consumption during the transition from a 10% to a 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 5458.25 kWh of electricity. As mentioned before, this amount is more than energy consumption in 10%-40% WWR and less than energy consumption in 50%-90% WWR.

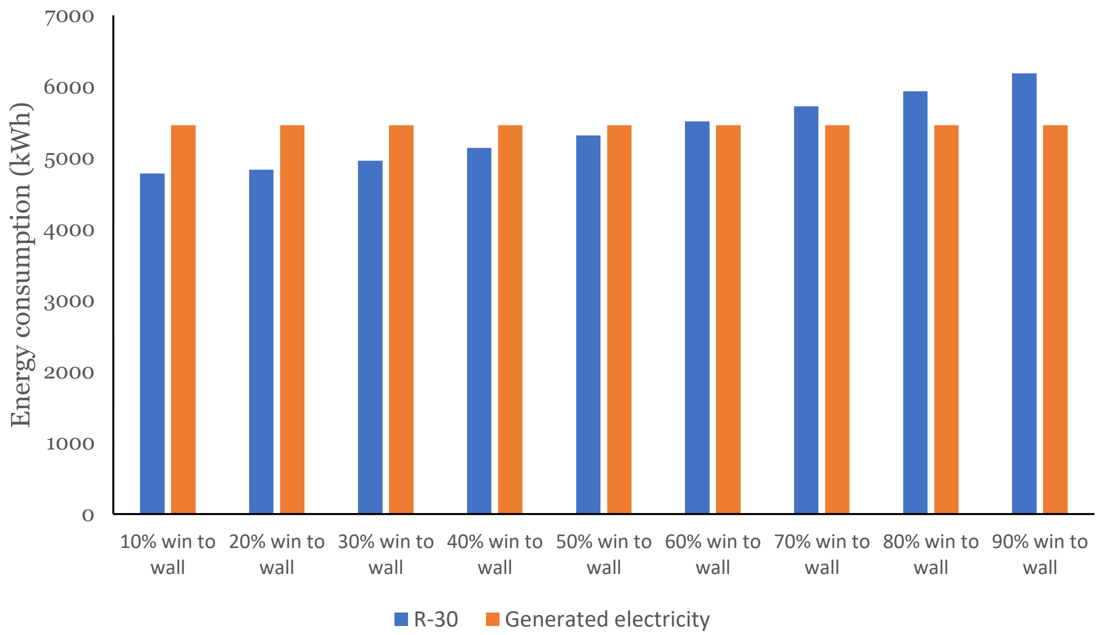


Figure 178- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Billings.

Figure 178 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results indicate that PV cells are not capable of meeting energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 6740.425 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 5436.37 kWh. The significant disparity between these extremes, revealing a 24% increase in energy consumption during the transition from a 10% to a 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals compelling insights into the performance of PV cells, which generate a total of 4723.851 kWh of electricity, less than the minimum energy consumption (5436.37 kWh). Therefore, using PV cells for achieving a net zero energy tiny house is not enough here.

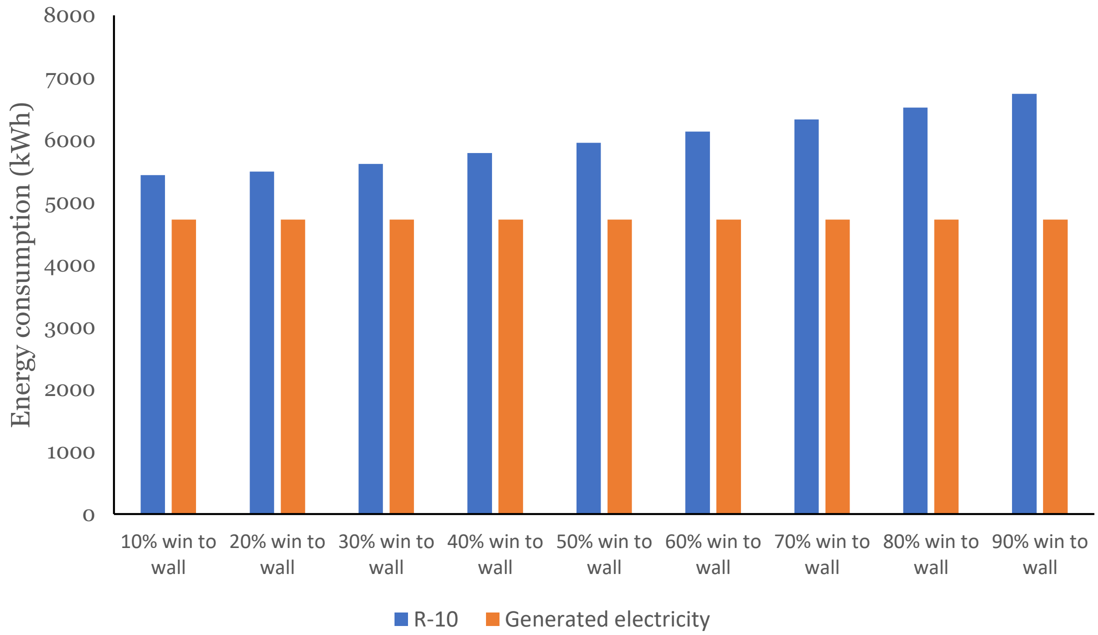


Figure 179- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Billings.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 179. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 80% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 6619.175 kWh and the annual energy consumption for the best case 4950.42 kWh. It means increasing the window-to-wall ratio from 10% to 80% can increase energy consumption by 34%.

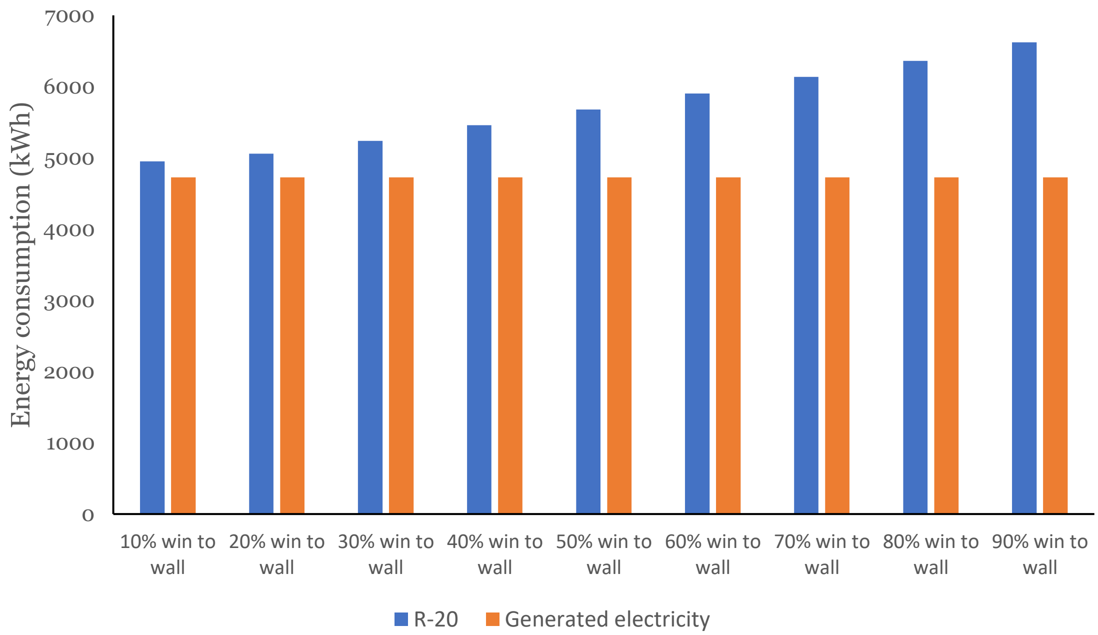


Figure 180- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Billings.

Figure 180 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in only one ratio (10%), the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 4603.875 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 6518.606 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 42% increase in energy consumption.

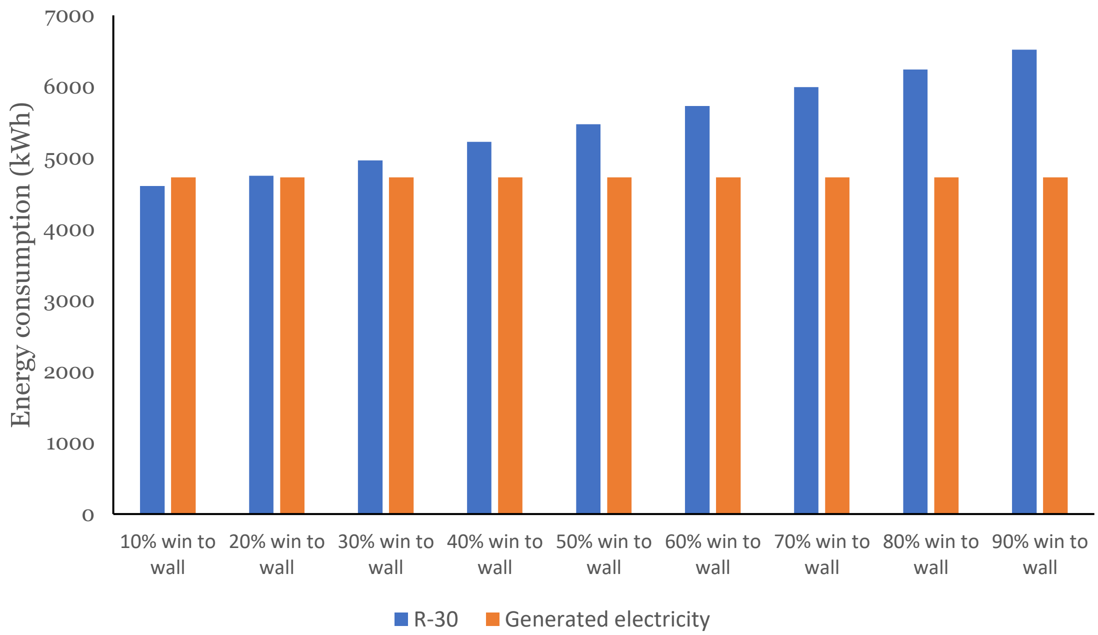


Figure 181- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Billings.

Figure 181 shows the energy consumption of the building with R-10 insulation in different orientations. Except for 10%, in other cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

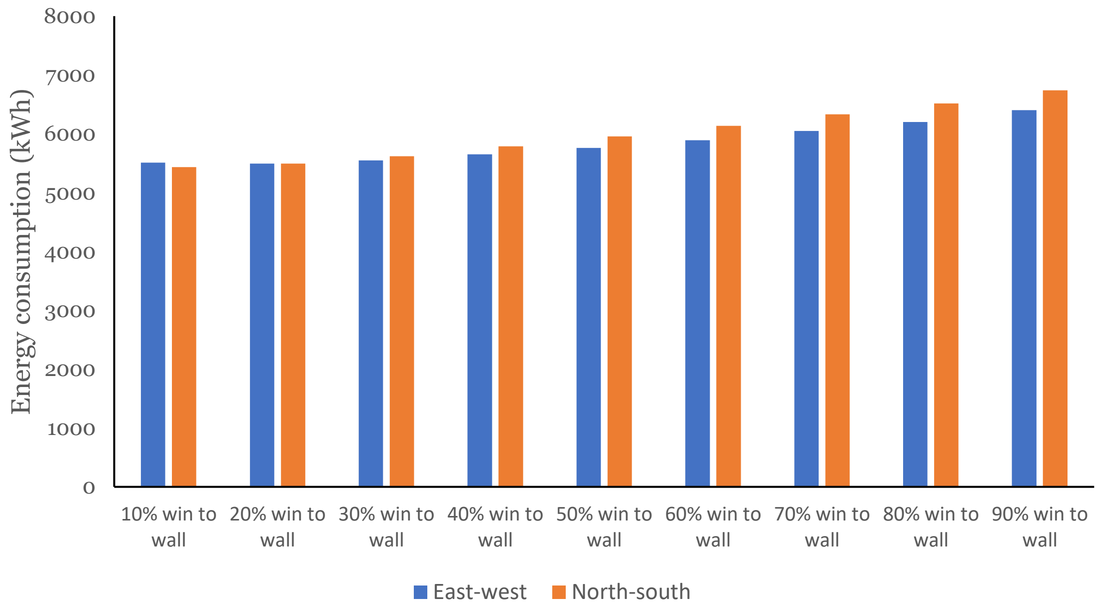


Figure 182- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Billings.

Figure 182 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. Except for 10% and 20%, in other ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

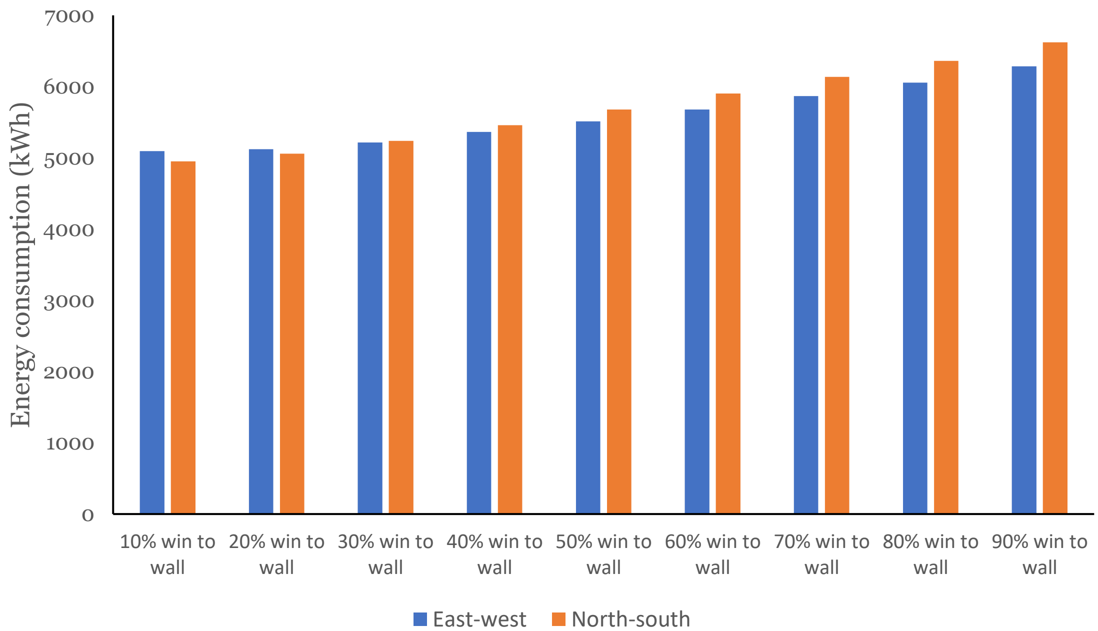


Figure 183- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Billings.

Figure 183 shows the energy consumption of buildings with R-30 insulation in different orientations. Except for 10%-20%, in other cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

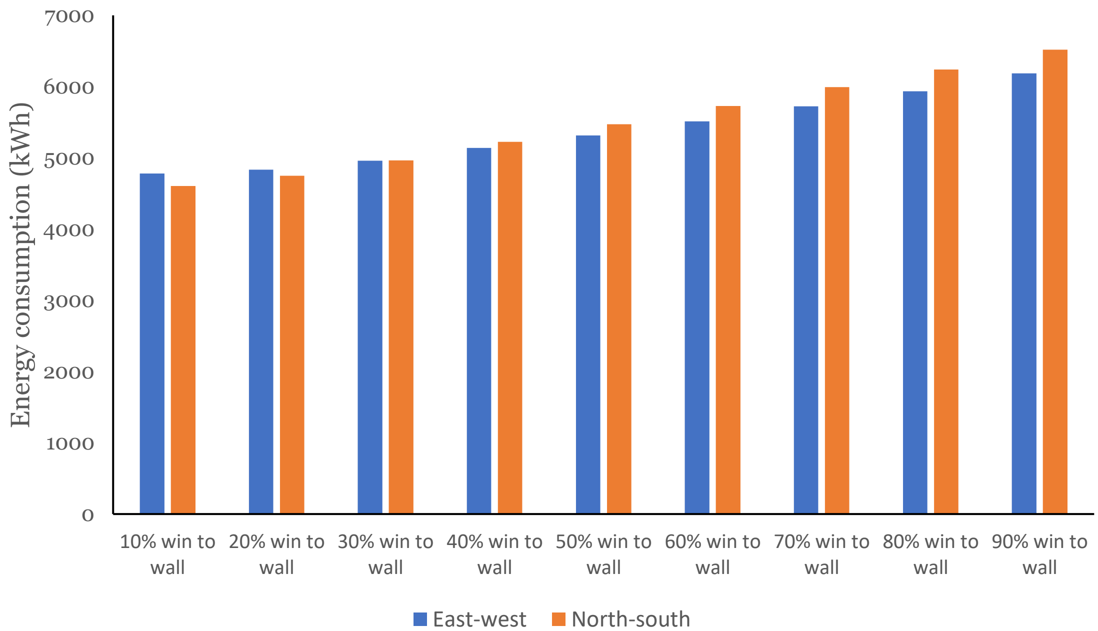


Figure 184- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Billings.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 184 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5458.25 kWh and for north-south orientation is 4723.851 kWh. In other words, the generated electricity in east-west orientation is 16% more than the generated electricity in north-south condition.

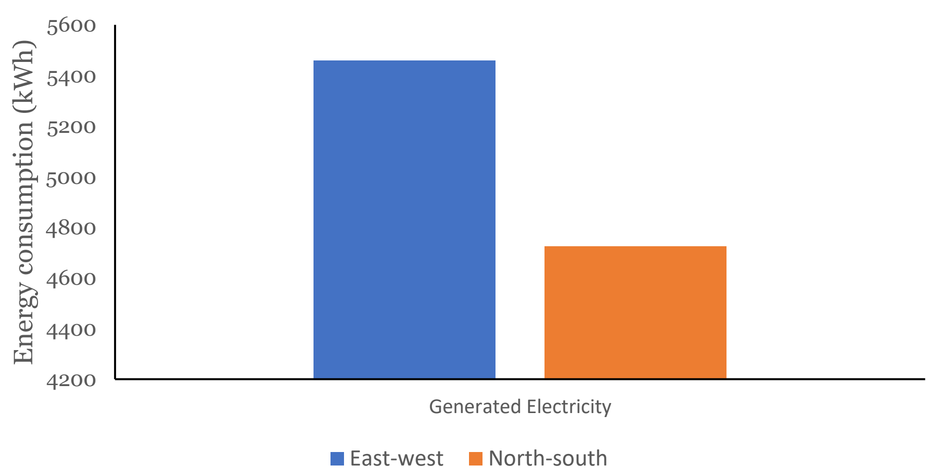


Figure 185- Generated electricity in different configurations of PV cells in Billings

Figure 185 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

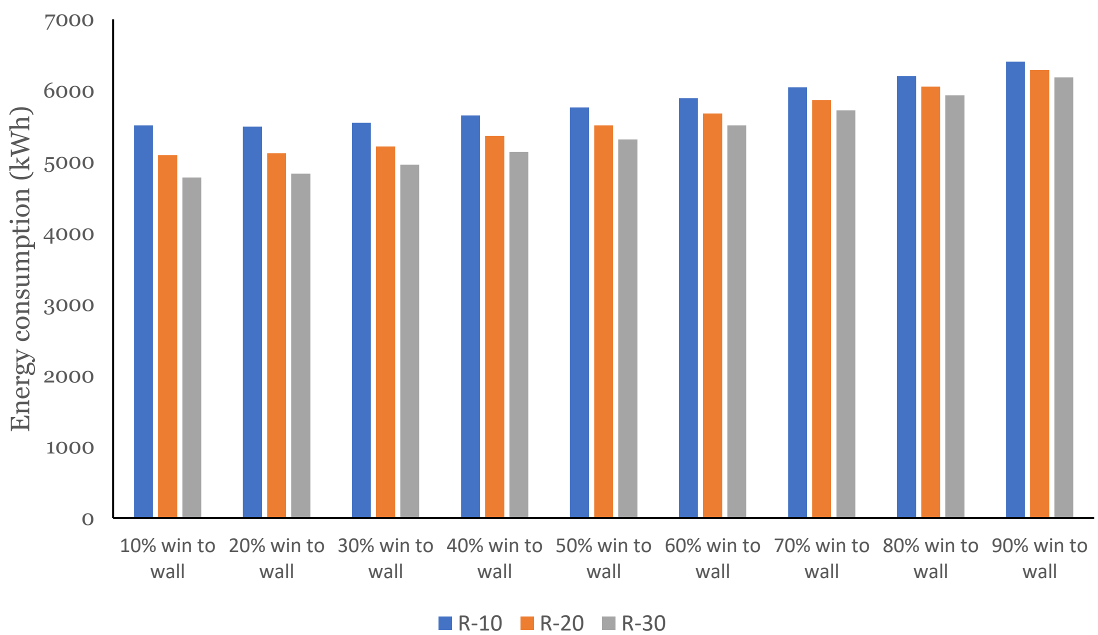


Figure 186- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Billings.

Figure186 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Within the 10% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.

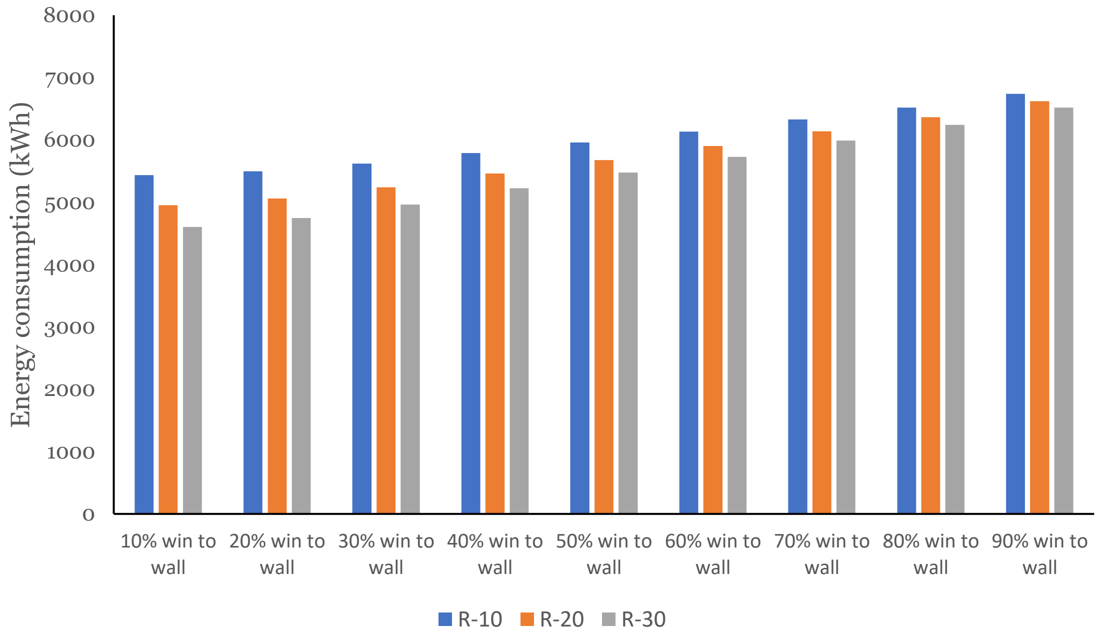


Figure 187- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Billings.

CO2 emissions for cases with east-west orientation is shown in figure 187 Because in most cases the generated electricity is less than energy consumption, CO2 emissions are positive in most cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

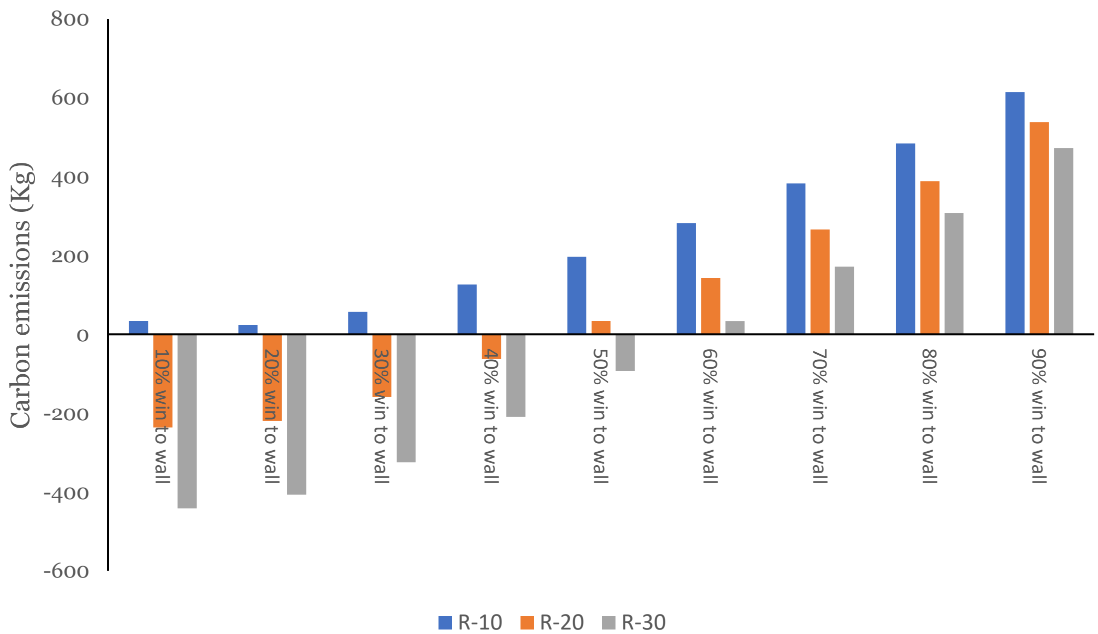


Figure 188- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Billings.

Figure 188 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

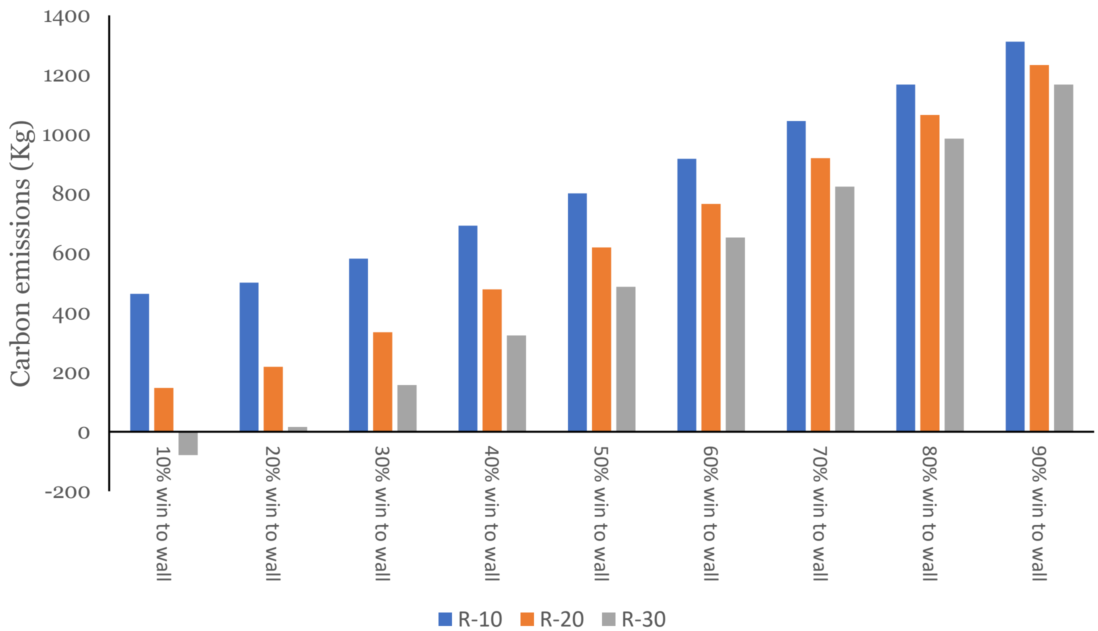


Figure 189- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Billings.

11.14. 7A Fargo, ND

Table 29 illustrates the energy consumption for all 54 cases in Fargo. Red cells signify instances where energy consumption exceeds the generated electricity, indicating that the tiny house cannot achieve a net-zero energy status. The unit of measurement for these values is kilowatt-hours (kWh).

Table 29- Energy consumption (kWh) of all cases in Fargo.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	8309.155	7658.184	7163.268	8153.666	7393.762	6856.826
20	8374.711	7791.721	7347.428	8309.035	7632.689	7153.099
30	8497.668	7982.906	7586.859	8520.395	7925.063	7499.108
40	8665.061	8214.393	7865.352	8765.425	8247.804	7875.23
50	8816.137	8429.201	8127.055	8985.721	8544.524	8223.258
60	8983.723	8657.06	8397.842	9208.051	8837.765	8563.592
70	9174.48	8902.761	8683.013	9441.02	9137.883	8908.046
80	9352.826	9131.633	8947.805	9652.268	9409.725	9219.695
90	9586.431	9413.702	9263.572	9910.333	9724.973	9572.256
Generation	5124.203	5124.203	5124.203	4410.195	4410.195	4410.195

Table 30 provides information on CO2 emissions in all cases. Due to the fact that the consumed energy exceeds the generated electricity in all instances, all numerical values are positive, and consequently, all cells are marked in red. This red color indicates that the cases cannot achieve a zero-emission status.

Table 30- Carbon emissions (Kg) of all cases in Fargo.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	3238.95	2576.942	2073.636	3806.938	3034.151	2488.112
20	3305.618	2712.743	2260.917	3964.942	3277.129	2789.407
30	3430.659	2907.169	2504.408	4179.884	3574.46	3141.283
40	3600.889	3142.581	2787.623	4429.068	3902.672	3523.782
50	3754.527	3361.031	3053.762	4653.1	4204.423	3877.71
60	3924.954	3592.753	3329.141	4879.199	4502.635	4223.813
70	4118.946	3842.62	3619.146	5116.117	4807.841	4574.108
80	4300.315	4075.373	3888.428	5330.947	5084.292	4891.042
90	4537.881	4362.224	4209.549	5593.388	5404.885	5249.579

Figure 189 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can't be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 8309.155 kWh, whereas for an 90% window-to-wall ratio (worst case), it is 9586.431 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 15% increase in energy consumption.

The amount of electricity supplied by PV cells is 5124.203 kWh. As mentioned before, the lowest energy consumption is 8309.155 kWh. This means that using PV cells for supplying the required energy is not enough.

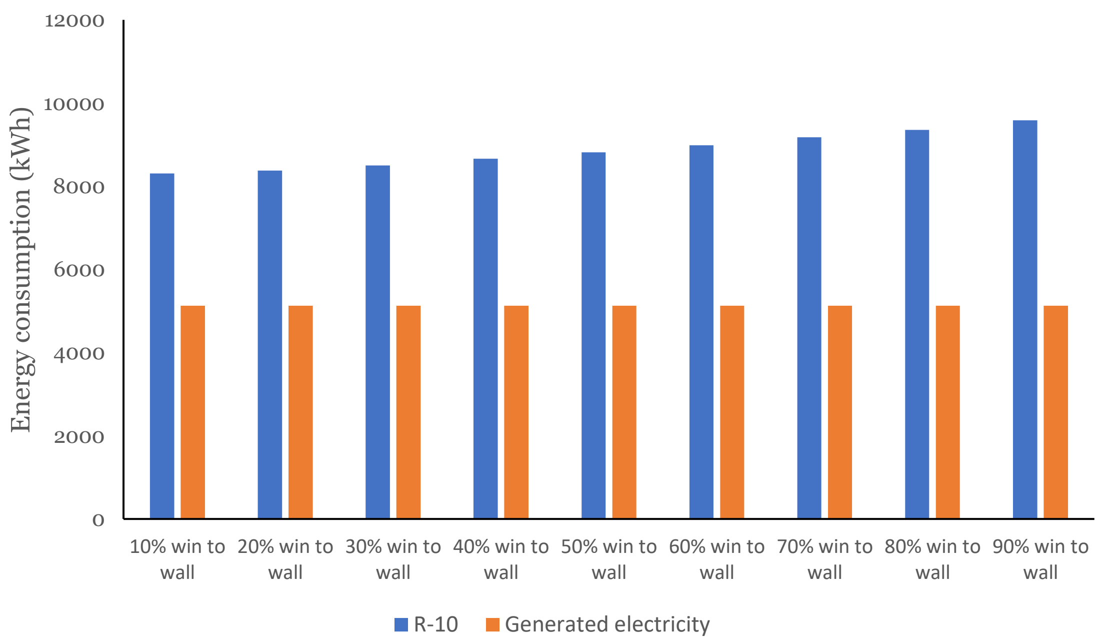


Figure 190- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Fargo.

In all scenarios examined in Figure 190, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated.

According to the findings, PV cells are not capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 7658.184 kWh, is associated with a 10% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 9413.702 kWh, translating to a noteworthy 23% increase in energy consumption when transitioning from a 10% to an 90% window-to-wall ratio.

The PV cells generate a total of 5124.203 kWh of electricity, whereas the lowest recorded energy consumption of 7658.184 kWh. Same as the previous case PV cells are not able to supply the minimum required energy.

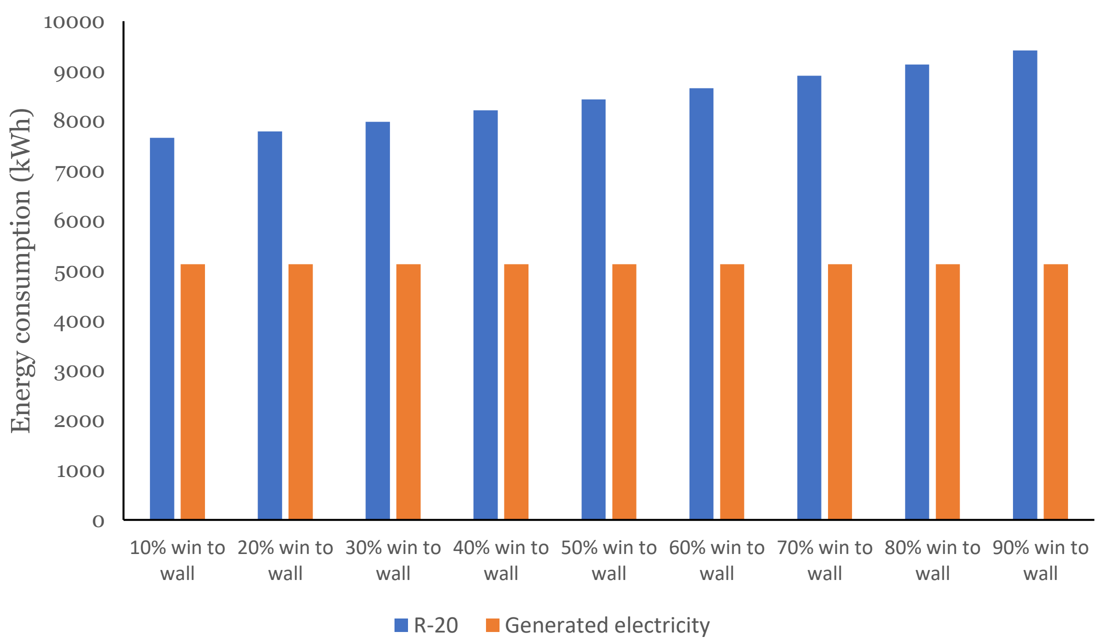


Figure 191- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Fargo.

Within the scope of Figure 191's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate the incapability of photovoltaic (PV) cells to meet energy demands in these varied scenarios. Noteworthy is the observation that the 90%

window-to-wall ratio is associated with the highest energy consumption, while the 10% ratio demonstrates the lowest annual consumption at 7163.268 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 9263.572 kWh, reflecting a notable 29% increase in energy consumption during the transition from a 10% to a 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 5124.203 kWh of electricity, less than the minimum energy consumption recorded at 7163.268 kWh. Therefore, supplying the required energy from other resources is necessary.

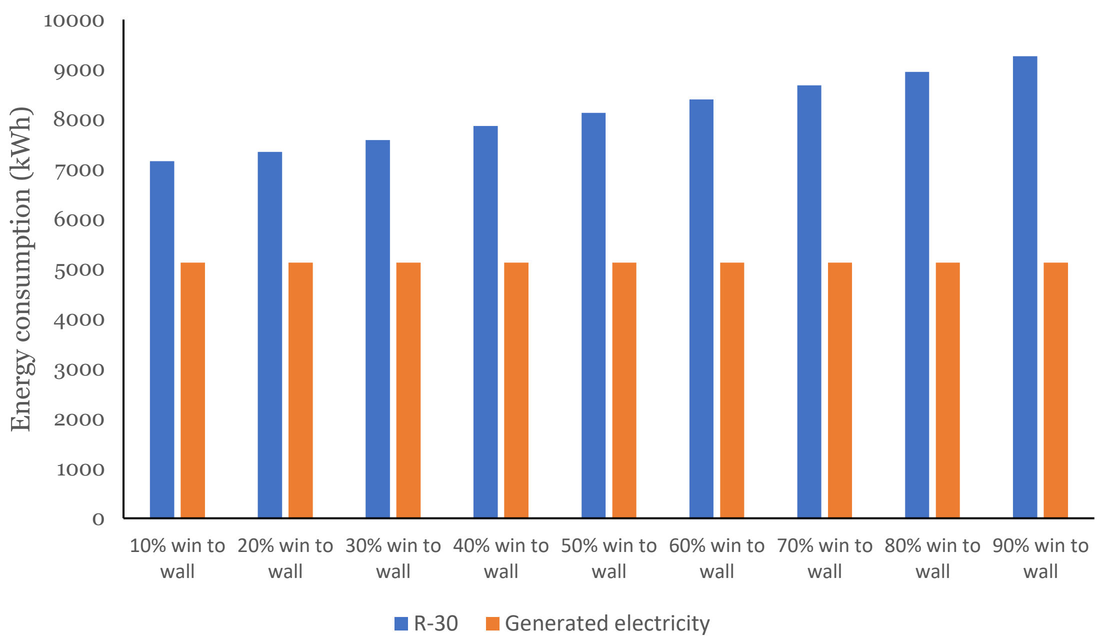


Figure 192- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Fargo.

Figure 192 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 9910.333 kWh, while the 10% ratio exhibits the lowest consumption, recording an annual total of 8153.666 kWh. The significant disparity between these extremes, revealing a 22% increase in energy consumption during the transition from a 10% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals that PV cells are not capable of meeting the needed energy. PV cells generate a total of 4410.195 kWh of electricity. This amount is less than the minimum energy consumption recorded at 8153.666 kWh.

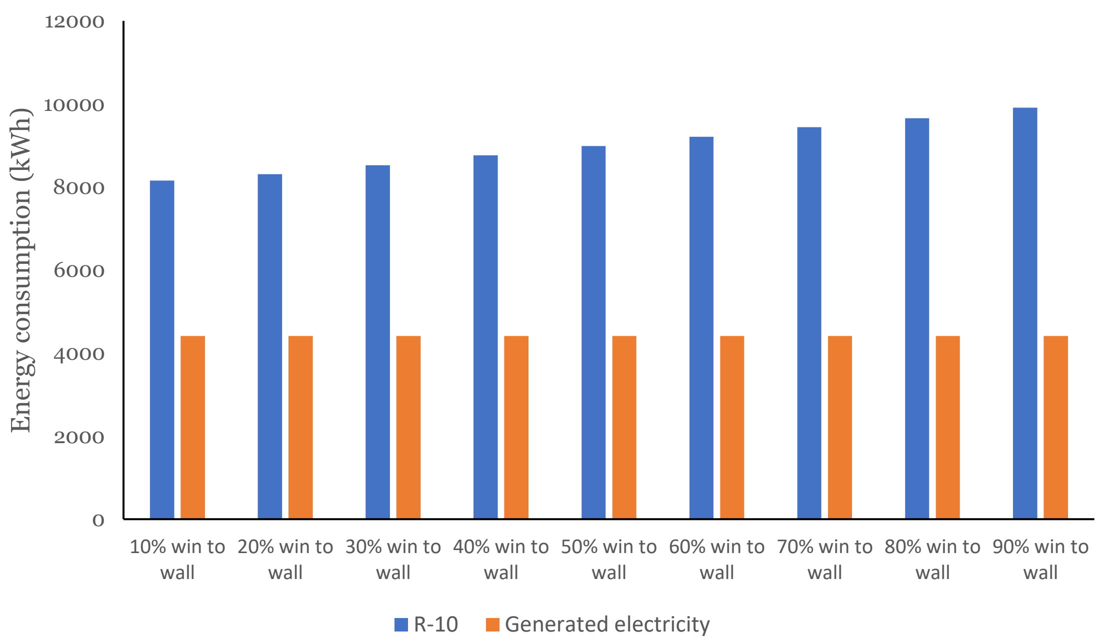


Figure 193- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Fargo.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 193. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 9724.973 kWh and the annual energy consumption for the best case 7393.762 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 32%.

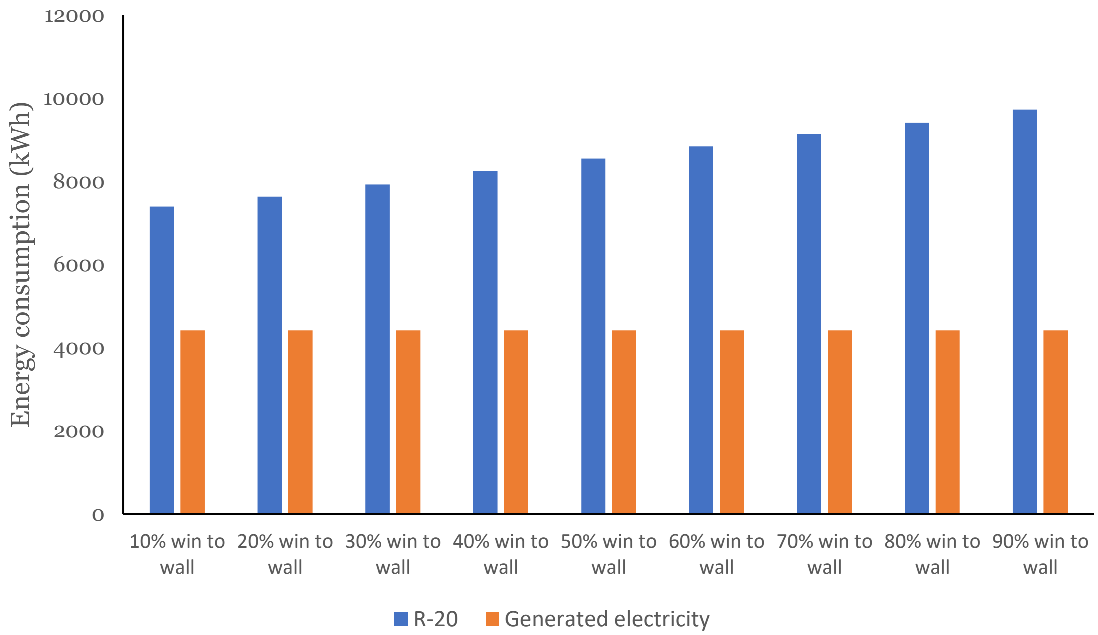


Figure 194- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Fargo.

Figure 194 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy cannot be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 6856.826 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 9572.256 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 40% increase in energy consumption.

The amount of electricity supplied by PV cells is 4410.195 kWh. As mentioned before, the lowest energy consumption is 6856.826 kWh. This means that the PV cells are only capable of supplying 64% of minimum energy consumption.

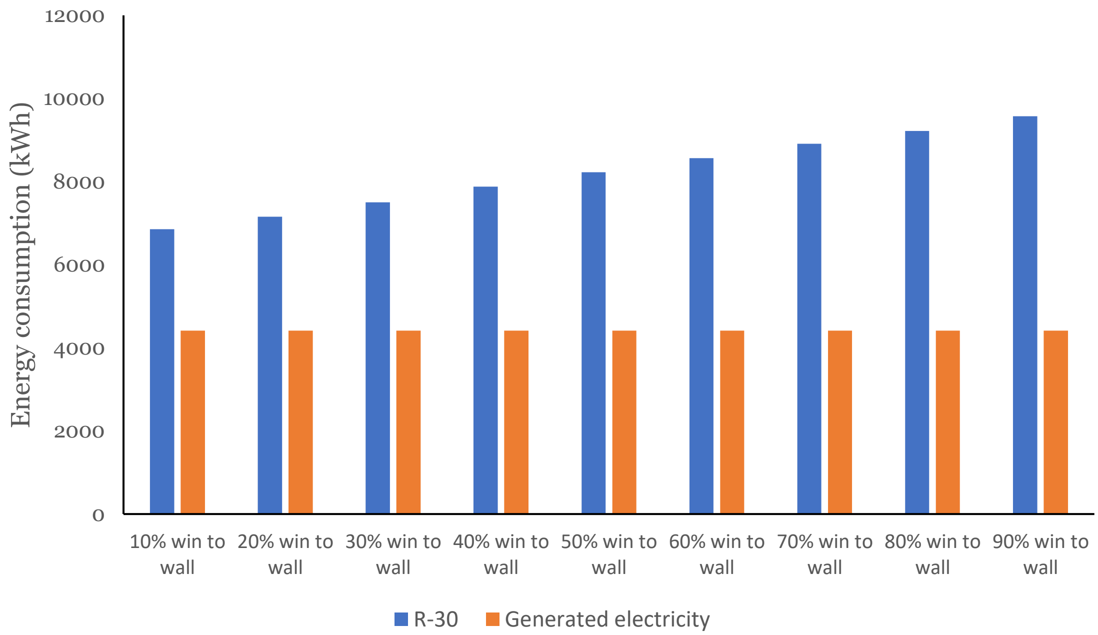


Figure 195- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Fargo.

Figure 195 shows the energy consumption of the building with R-10 insulation in different orientations. Except for two cases (10% and 20%) in all cases the energy consumption in the east-west orientation is less than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 155.5 kWh in 10% window to wall, 170 kWh in 50% window to wall and 323.90 kWh in 90% WWR.

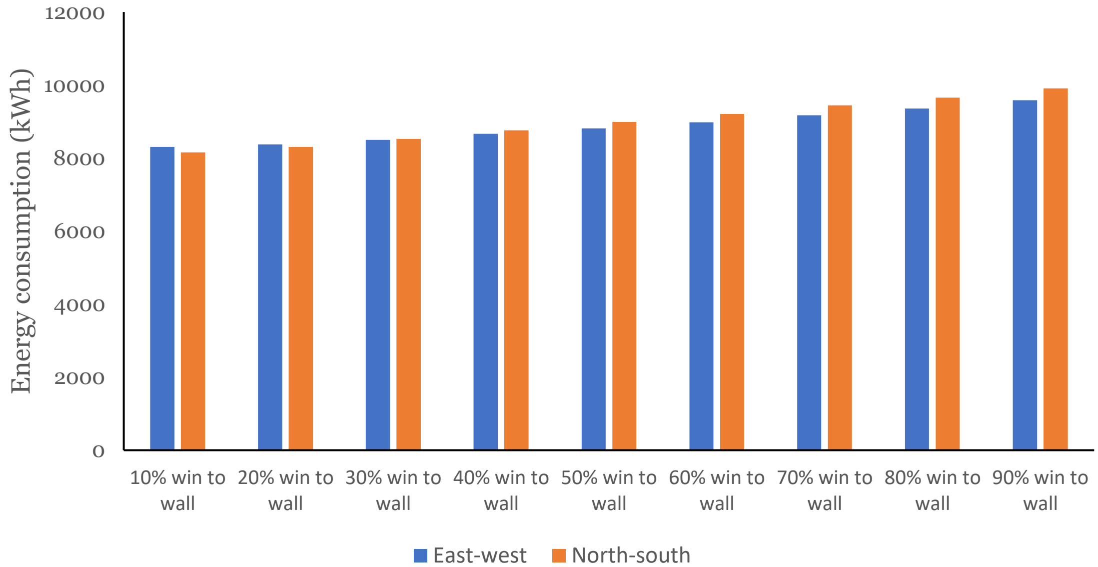


Figure 196- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Miami.

Figure 196 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. Except for the 10%-30% range, in other ratios the energy consumption of tiny houses with north-south orientation is higher. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 264.422 kWh in 10% window to wall and 311.271 in 90% WWR.

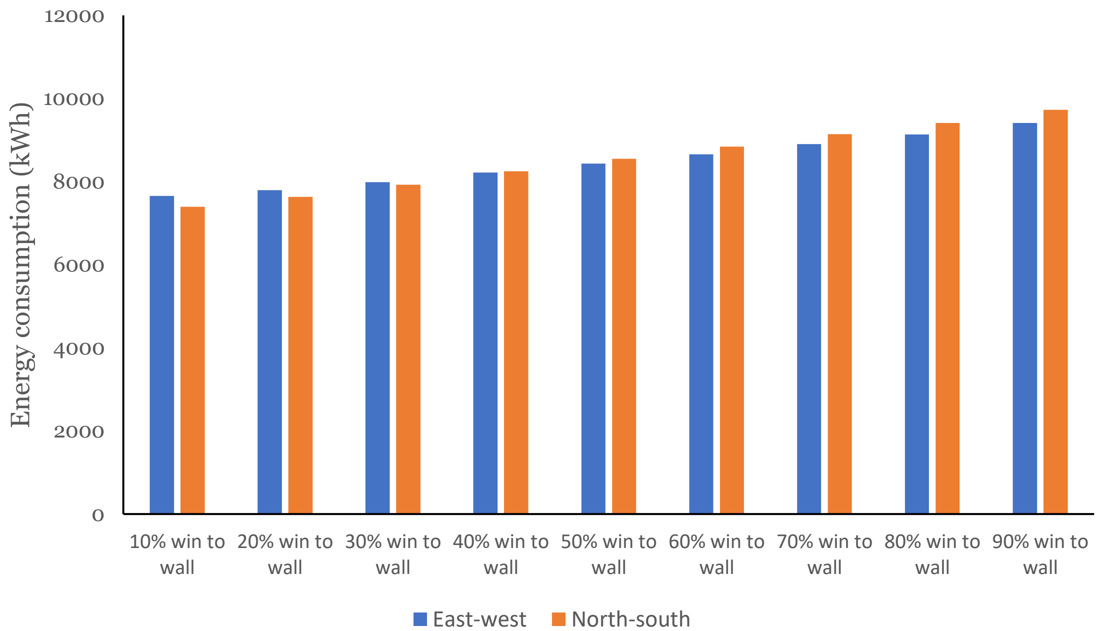


Figure 197- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Fargo.

Figure 197 shows the energy consumption of buildings with R-30 insulation in different orientations. Except for the 10%-30% range, in other ratios the energy consumption of tiny houses with north-south orientation is higher. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west.

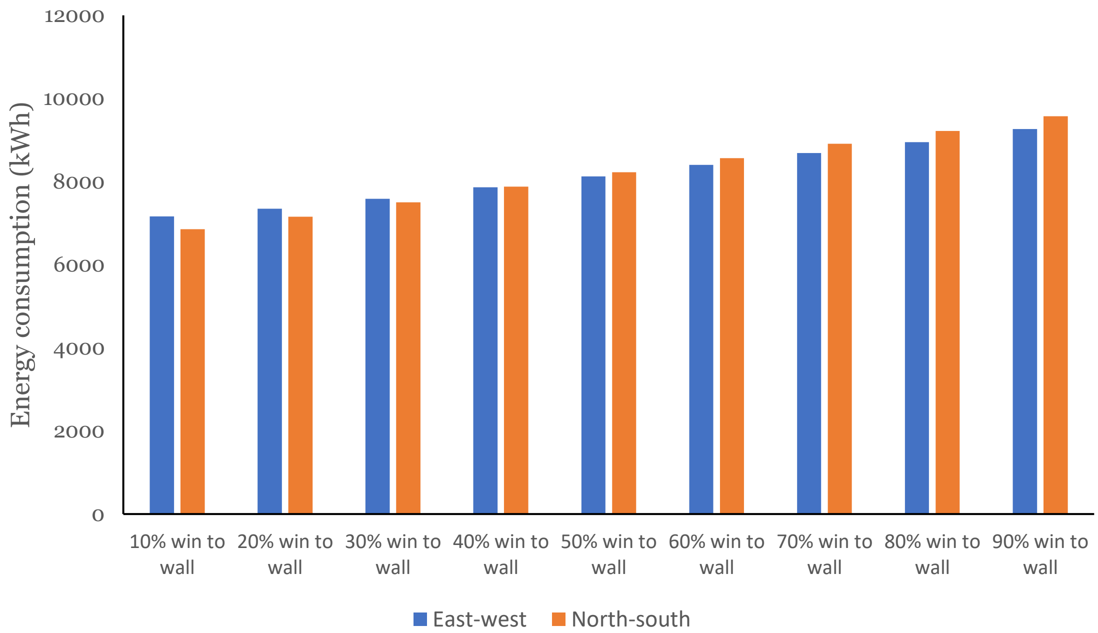


Figure 198- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Fargo.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 198 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5797.787 kWh and for north-south orientation is 5268.548 kWh. In other words, the generated electricity in east-west orientation is 16% more than the generated electricity in north-south condition.

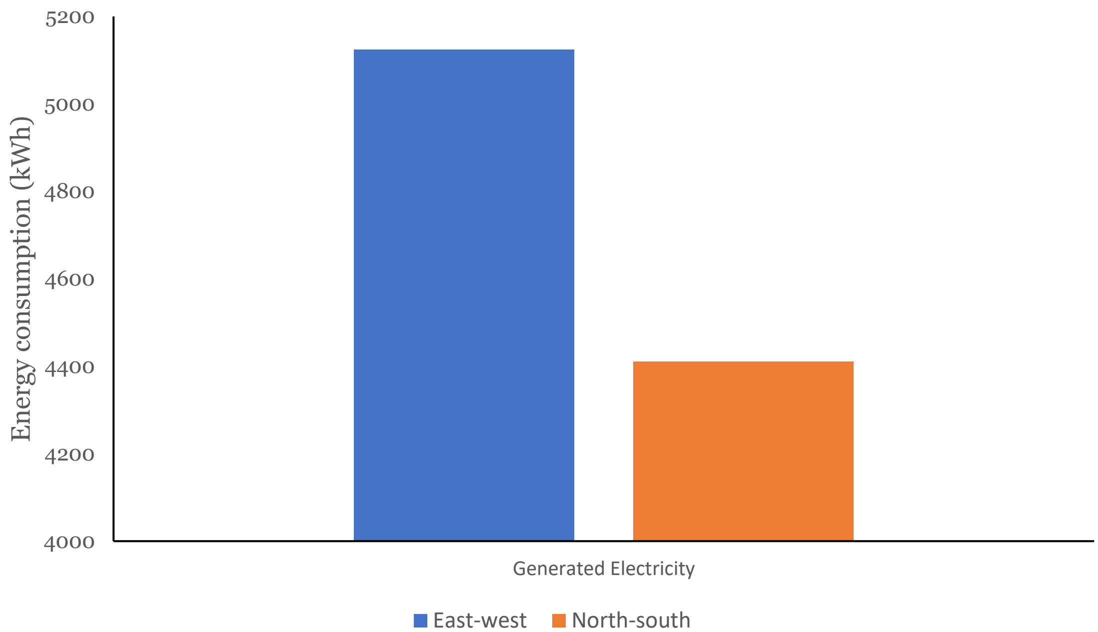


Figure 199- Generated electricity in different configurations of PV cells in Fargo.

Figure 199 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Generally, an increase in R-value is associated with an increase in energy consumption.

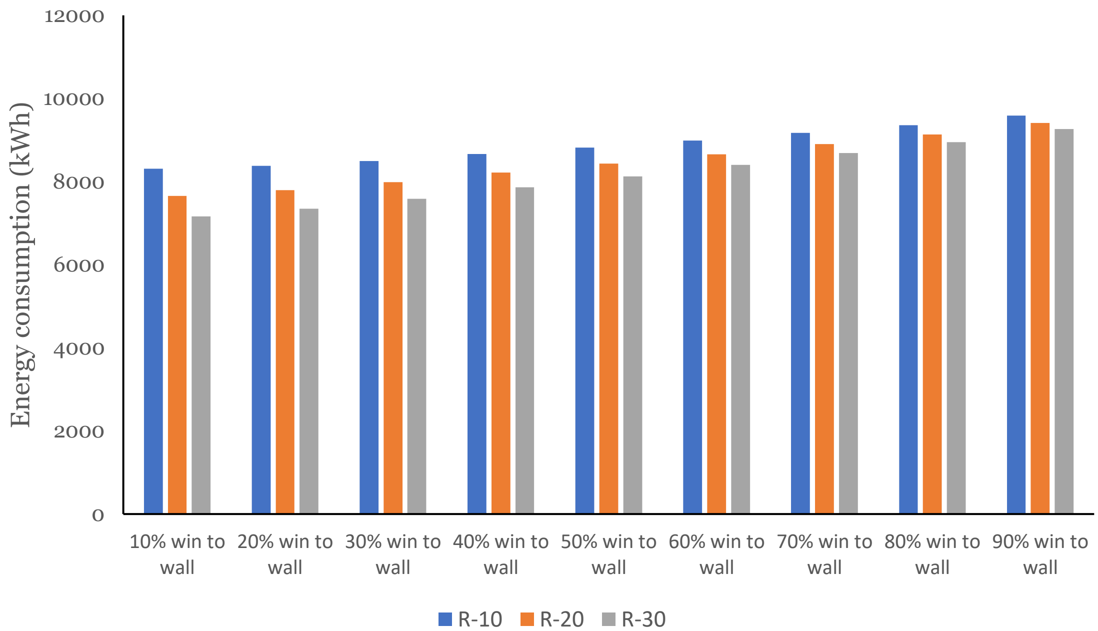


Figure 200- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Fargo.

Figure 200 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs.

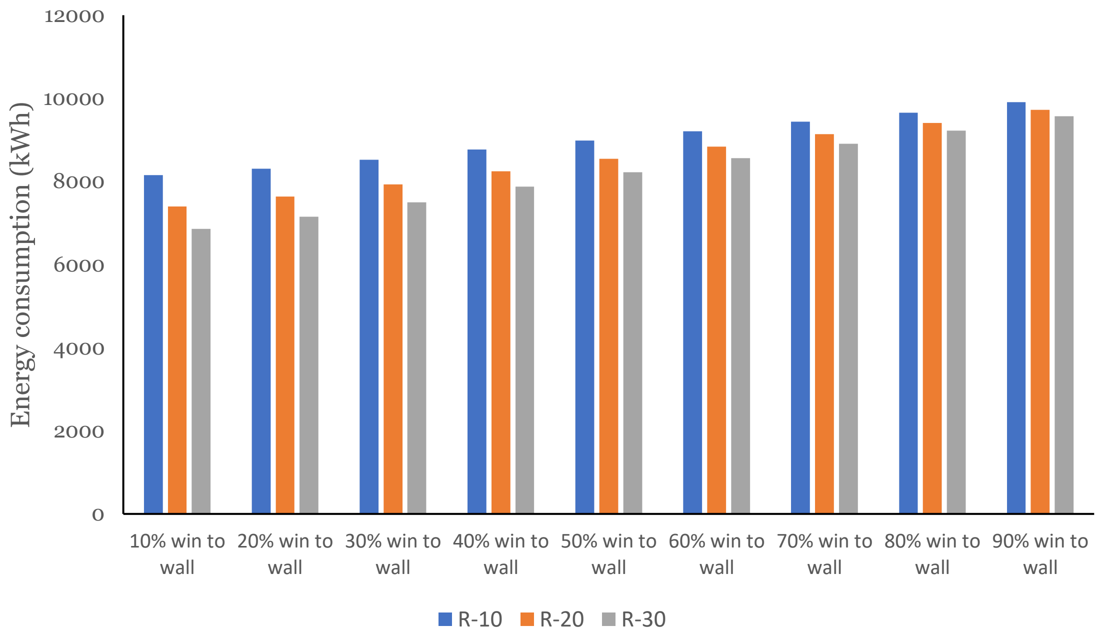


Figure 201- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Fargo.

CO2 Emissions for cases with east-west orientation is shown in figure 201 Because the generated electricity is less than energy consumption, CO2 emissions are positive in all cases. Generally, an increase in WWR causes an increase in CO2 emissions, therefore the lowest CO2 emissions is 10% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

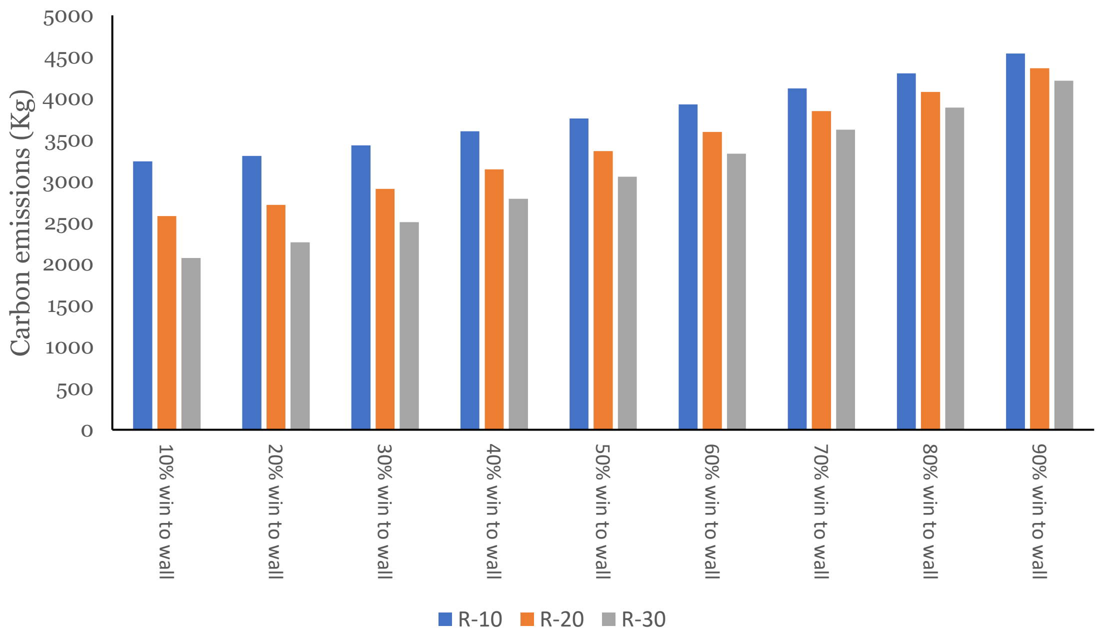


Figure 202- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Fargo.

Figure 202 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 10% WWR.

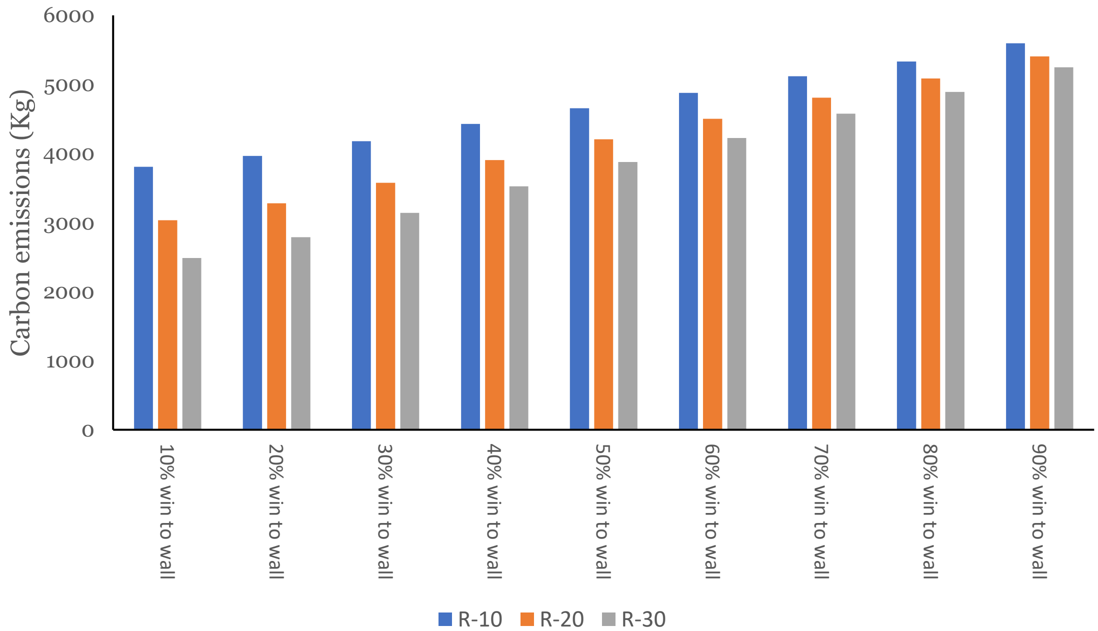


Figure 203- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Fargo.

11.15. 7B Jackson, WY

Presented in Table 31 are the energy consumption details for all 54 cases in Jackson. Cells highlighted in green within the table indicate instances where energy consumption falls below the generated electricity, signifying a net-zero energy status for the respective tiny houses. Conversely, cells highlighted in red indicate instances where energy consumption exceeds the generated electricity. The unit of measurement for these values is kilowatt-hours (kWh), providing a standardized basis for assessing the energy dynamics of each case.

Table 31- Energy consumption (kWh) of all cases in Jackson.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	6409.268	5920.837	5546.602	6252.691	5679.458	5274.002
20	6302.036	5862.346	5525.63	6206.594	5696.758	5336.119
30	6295.564	5904.864	5605.517	6268.136	5821.928	5505.104
40	6362.575	6019.927	5756.6	6398.824	6011.669	5735.532
50	6444.875	6147.724	5916.312	6537.596	6207.0765	5967.951
60	6561.25	6307.261	6106.462	6703.125	6424.112	6218.915
70	6719.379	6504.499	6332.157	6899.544	6667.75	6493.096
80	6894.376	6716.252	6568.866	7106.316	6916.871	6768.708
90	7138.616	6995.504	6871.596	7371.709	7221.854	7098.701
Generation	5609.322	5609.322	5609.322	4923.016	4923.016	4923.016

Table 28 details the CO2 emissions across all cases. As the energy consumed in most cases is consistently less than the generated electricity, most numerical values in the table are negative. The incorporation of a green color scheme within the cells serves as a visual cue, highlighting instances where the cases exhibit zero-emission characteristics. This color-coded representation underscores the positive environmental impact of the tiny houses, emphasizing their contribution to a reduction in carbon footprint. The negative values, coupled with the green coloration, signify that the cases have effectively achieved a net-zero or even a carbon-negative status, reflecting a commendable commitment to sustainable and eco-friendly practices across

the entirety of the cases examined. However, there are cells with red color. The red color indicates that the CO2 emission is positive, and the building is not zero-emission.

Table 32- Carbon emissions (Kg) of all cases in Jackson.

Window to wall ratio (%)	Orientation					
	East-west			North-south		
	Insulation			Insulation		
	R-10	R-20	R-30	R-10	R-20	R-30
10	778.6746	303.232	-61.05264	1294.318	736.3282	341.653
20	674.294	246.2958	-81.46687	1249.447	753.168	402.1182
30	667.9945	287.6832	-3.703733	1309.353	875.0093	566.6099
40	733.2234	399.6866	143.361	1436.565	1059.705	790.9106
50	813.3348	524.0853	298.8264	1571.647	1249.916	1017.149
60	926.6151	679.3799	483.9209	1732.774	1461.181	1261.44
70	1080.54	871.3735	703.614	1923.971	1698.341	1528.331
80	1250.883	1077.496	934.0291	2125.245	1940.837	1796.614
90	1488.629	1349.322	1228.709	2383.581	2237.71	2117.832

Figure 203 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-10 insulation. According to this figure, in all ratios, the required energy can't be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 30% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 6295.564 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 7138.616 kWh. The difference between these two cases is significant: increasing the ratio from 30% to 90% results in a 13% increase in energy consumption.

The amount of electricity supplied by PV cells is 5609.322 kWh. As mentioned before, the highest energy consumption is 7138.616 kWh. This means that the residents should supply 1,529.294 kWh of electricity during the year from the grid.

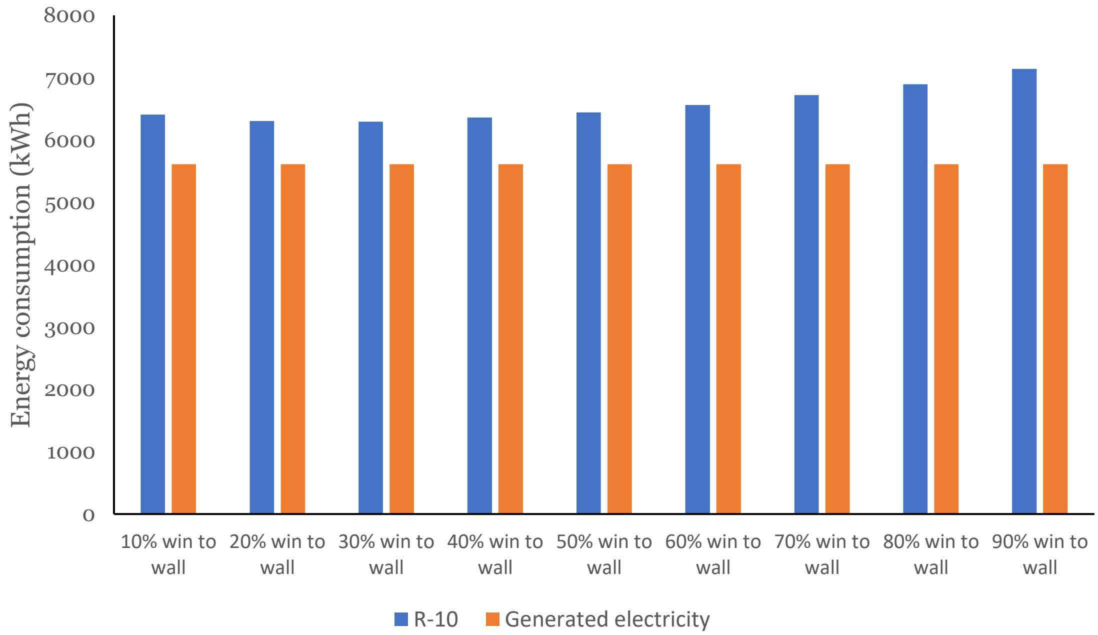


Figure 204- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 insulation (East-west) in Jackson.

In all scenarios examined in Figure 204, variations in energy consumption across different window-to-wall ratios, east-west orientations, and R-20 insulation levels are illustrated. According to the findings, PV cells are not capable of satisfying energy demands across these diverse scenarios. Notably, the highest energy consumption is observed with a 90% window-to-wall ratio, whereas the lowest annual consumption, amounting to 5862.346 kWh, is associated with a 20% ratio. This difference is substantial, with the 90% ratio exhibiting a significantly higher annual consumption of 6995.504 kWh, translating to a noteworthy 19% increase in energy consumption when transitioning from a 20% to a 90% window-to-wall ratio.

The PV cells generate a total of 5609.322 kWh of electricity, surpassing the highest recorded energy consumption of 6995.504 kWh. Consequently, residents should supply 1,386.182 kWh from other resources.

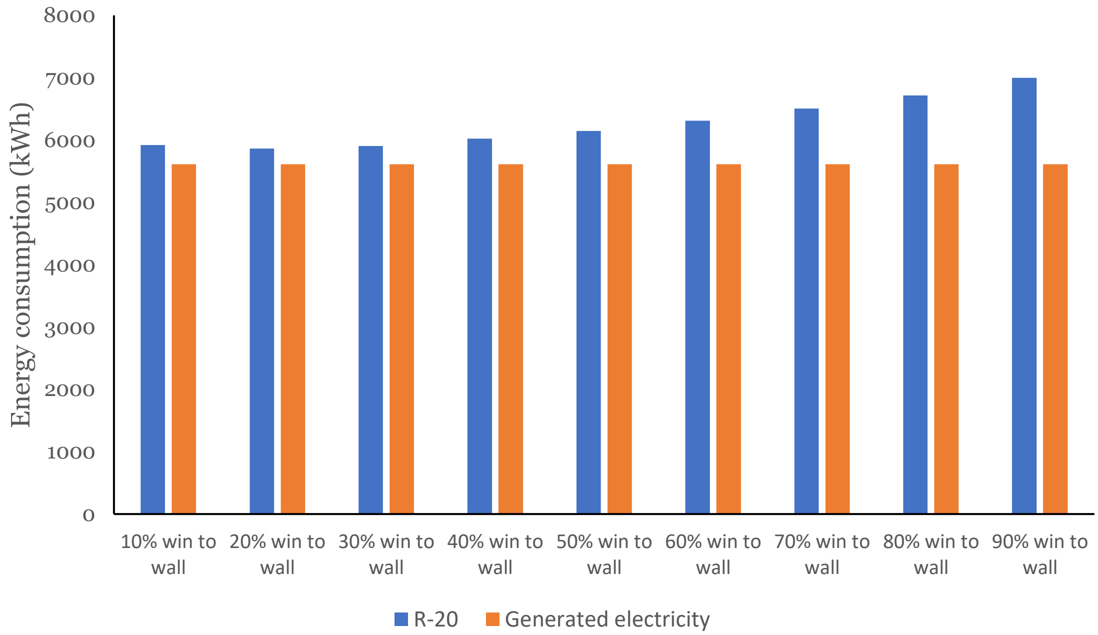


Figure 205- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (East-west) in Jackson.

Within the scope of Figure 205's analysis, various scenarios are considered to delineate energy consumption variations concerning diverse window-to-wall ratios, east-west orientations, and R-30 insulation levels. The study's results indicate photovoltaic (PV) cells are capable of meeting energy demands only in three cases. Noteworthy is the observation that the 90% window-to-wall ratio is associated with the highest energy consumption, while the 20% ratio demonstrates the lowest annual consumption at 5525.63 kWh. This disparity is significant, given that the 90% ratio exhibits a markedly higher annual consumption of 6871.596 kWh, reflecting a notable 24% increase in energy consumption during the transition from a 20% to an 90% window-to-wall ratio.

Additionally, the PV cells generate a total of 5609.322 kWh of electricity, surpassing the peak energy consumption recorded at 6871.596 kWh. Consequently, residents should supply 1,262.274 kWh from the grid.

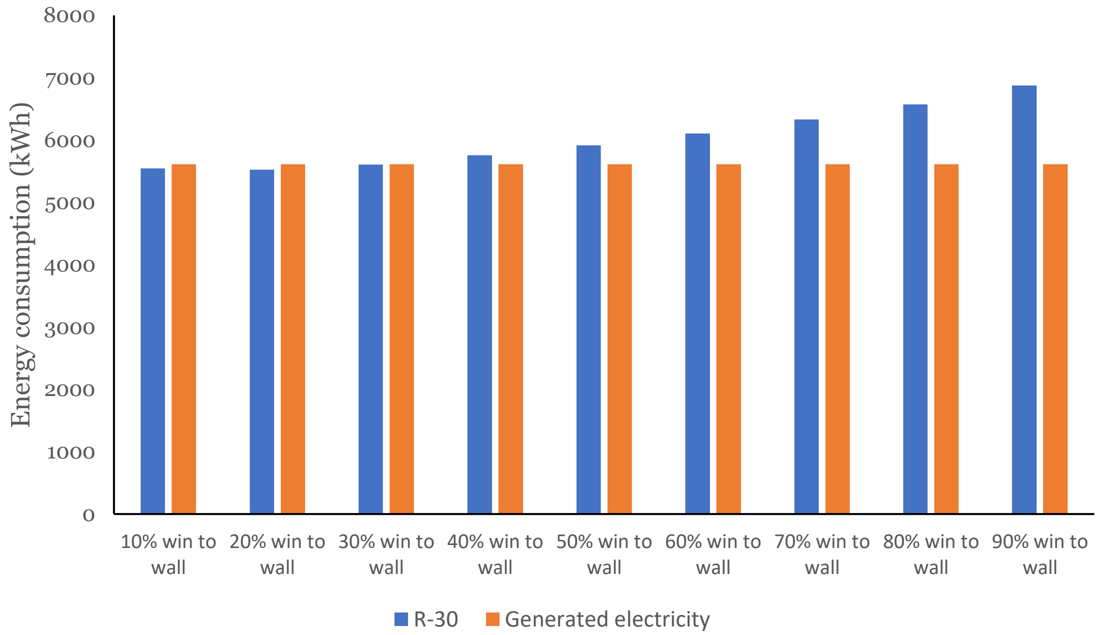


Figure 206- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (East-west) in Jackson.

Figure 206 meticulously explores the impact of varying window-to-wall ratios, north-south orientations, and R-10 insulation levels on energy consumption patterns. Notably, the results indicate that photovoltaic (PV) cells are not able to meet energy demands across these diverse scenarios. A noteworthy observation emerges as the 90% window-to-wall ratio is linked with the highest annual energy consumption, registering at 7371.709 kWh, while the 20% ratio exhibits the lowest consumption, recording an annual total of 6206.594 kWh. The significant disparity between these extremes, revealing a 19% increase in energy consumption during the transition from a 20% to an 90% window-to-wall ratio, accentuates the critical influence of architectural design choices on energy efficiency.

Furthermore, the analysis reveals that PV cells, which generate a total of 4923.016 kWh of electricity, less than the minimum energy consumption recorded at 6206.594 kWh, are not able to supply the required electricity.

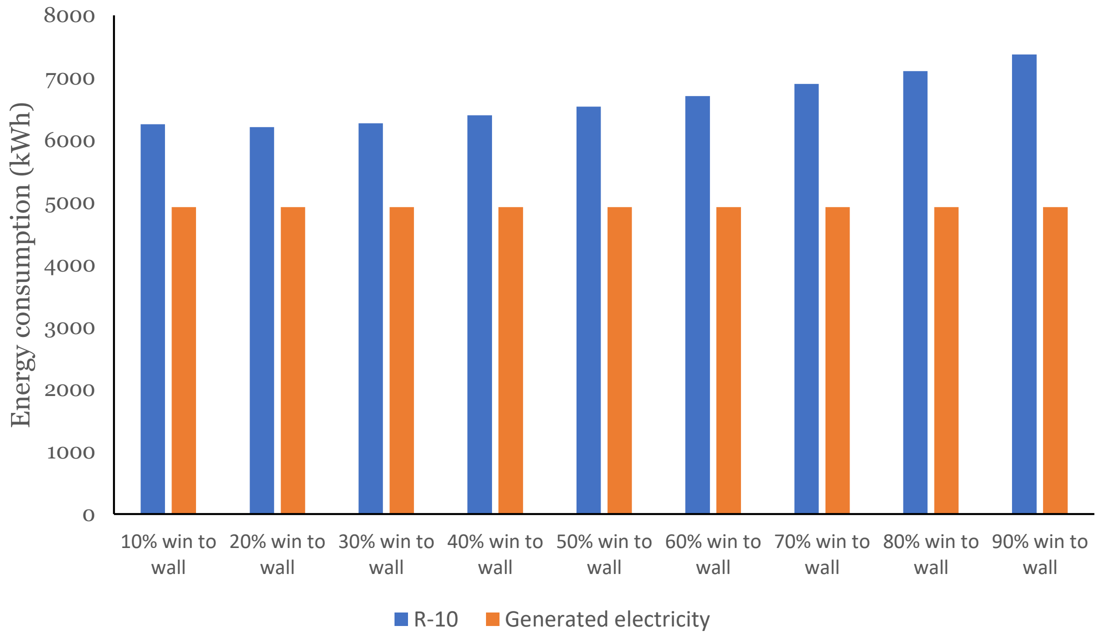


Figure 207- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-10 of mycelium-based insulation (north-south) in Jackson.

The annual energy consumption of the proposed tiny house, north-south orientation and R-20 insulation is shown in Figure 207. In this orientation photovoltaic panels are still facing south. According to this figure the highest annual energy consumption occurs in 90% of window to wall ratio. In other words, the trend of changes in energy consumption is the same as the previous orientation. The annual energy consumption in the worst case is 7221.854 kWh and the annual energy consumption for the best case 5679.458 kWh. It means increasing the window-to-wall ratio from 10% to 90% can increase energy consumption by 27%.

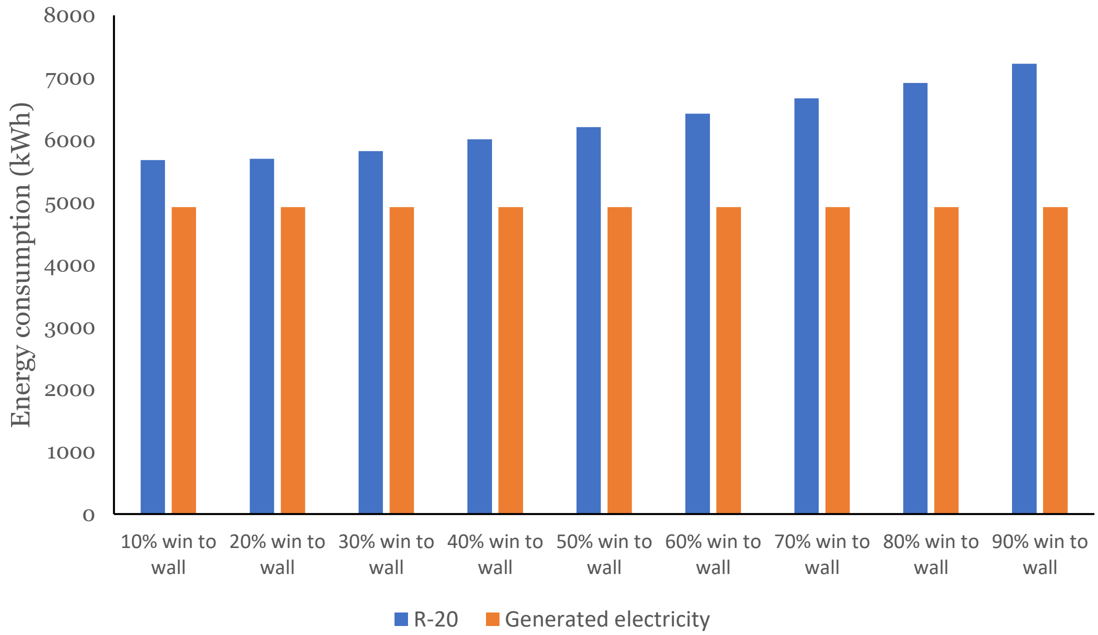


Figure 208- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-20 of mycelium-based insulation (north-south) in Jackson.

Figure 208 compares the amount of energy consumed in different window-to-wall ratios, east-west orientation, and R-30 insulation. According to this figure, in all ratios, the required energy can be supplied by PV cells. Moreover, according to the results, the highest energy consumption occurs with a 90% window-to-wall ratio. Additionally, the 10% ratio has the lowest energy consumption during the year. The annual energy consumption for a 10% window-to-wall ratio (best case) is 5274.002 kWh, whereas for a 90% window-to-wall ratio (worst case), it is 7098.701 kWh. The difference between these two cases is significant: increasing the ratio from 10% to 90% results in a 35% increase in energy consumption.

The amount of electricity supplied by PV cells is 4923.016 kWh. As mentioned before, the lowest energy consumption is 5274.002 kWh. This means that the residents should supply the required electricity from the grid.

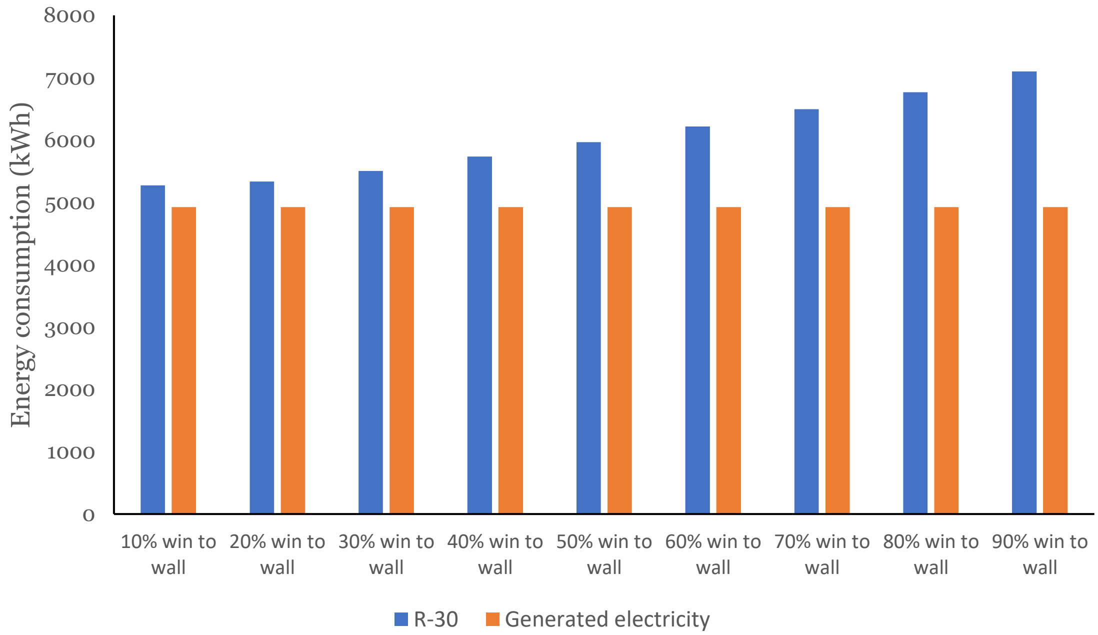


Figure 209- Comparing the annual generated electricity and annual energy consumption in different window to wall ratios and R-30 of mycelium-based insulation (north-south) in Jackson.

Figure 209 shows the energy consumption of the building with R-10 insulation in different orientations. Only in the 10%-30% range the energy consumption in the east-west orientation is more than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 92.721 kWh (1.4%) in 50% window to wall and 233.093 kWh (3.2%) in 90% WWR.

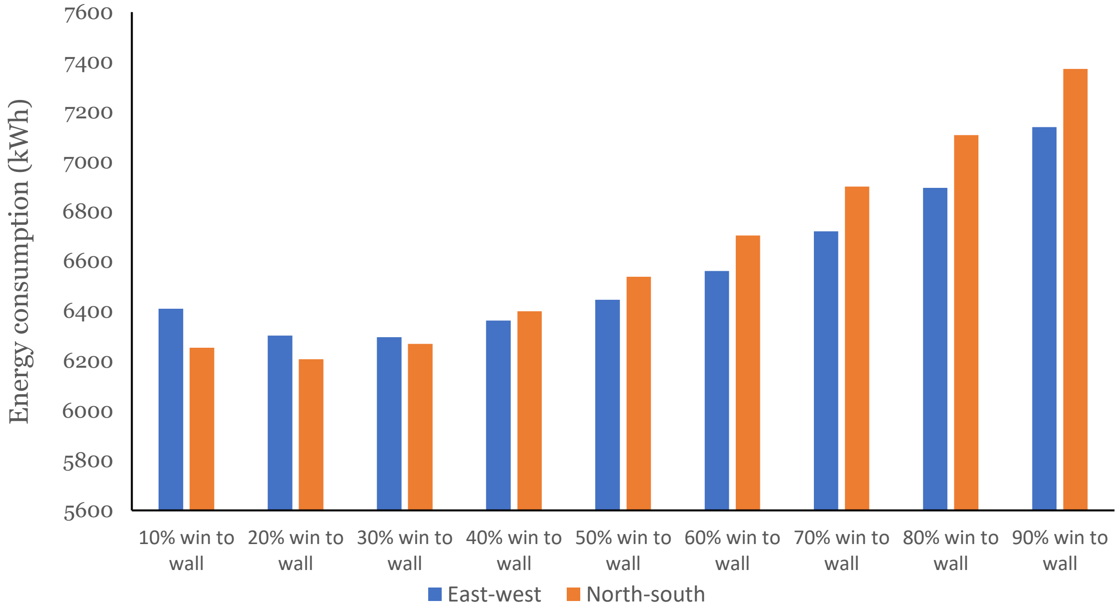


Figure 210- The influence of orientation on annual energy consumption in cases with R-10 insulation and varying window-to-wall ratios in Jackson.

Figure 210 is about comparing the annual consumption of tiny houses with R-20 insulation in different orientations. Only in the 10%-40% range the energy consumption in the east-west orientation is more than in the north-south orientation. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. The difference between these two orientations is 59.35 kWh (0.9%) in 50% window to wall and 226.35 (3.2%) in 90% WWR.

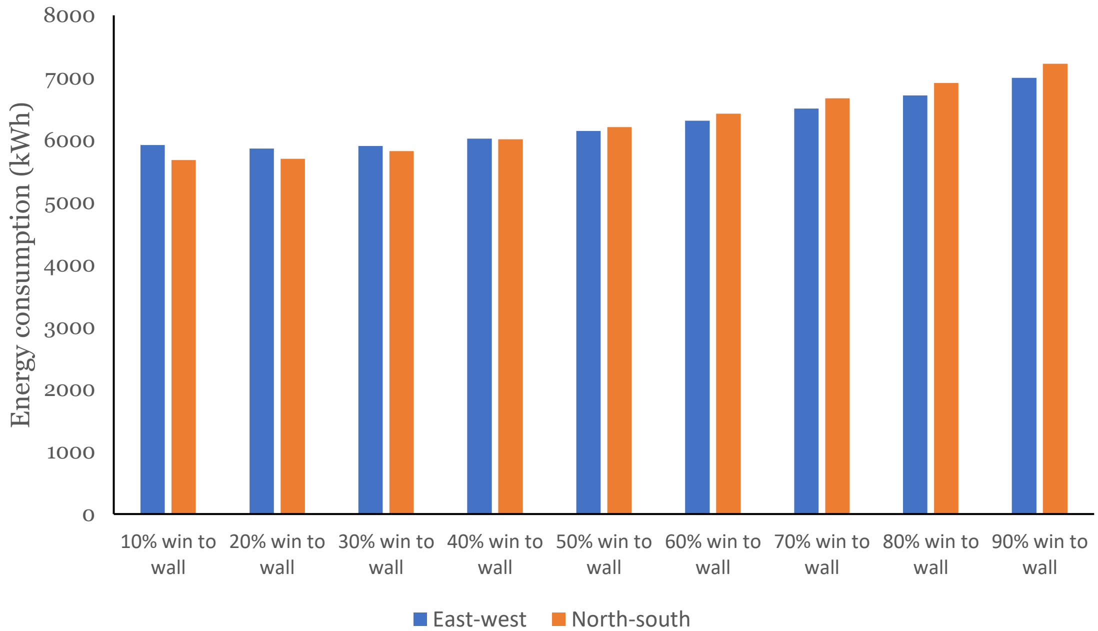


Figure 211- The influence of orientation on annual energy consumption in cases with R-20 insulation and varying window-to-wall ratios in Jackson.

Figure 211 shows the energy consumption of buildings with R-30 insulation in different orientations. Only in the 10%-40% range the energy consumption in the east-west orientation is more than in the north-south orientation. As it's clear in the figure the difference is higher in some ratios. As the ratio of window to wall increases, the difference in energy consumption increases in the direction of north to south and east to west. For example, the difference between these two orientations is 51.639 kWh (0.8%) in 50% window to wall and 227.105 kWh (3.3%) in 90%.

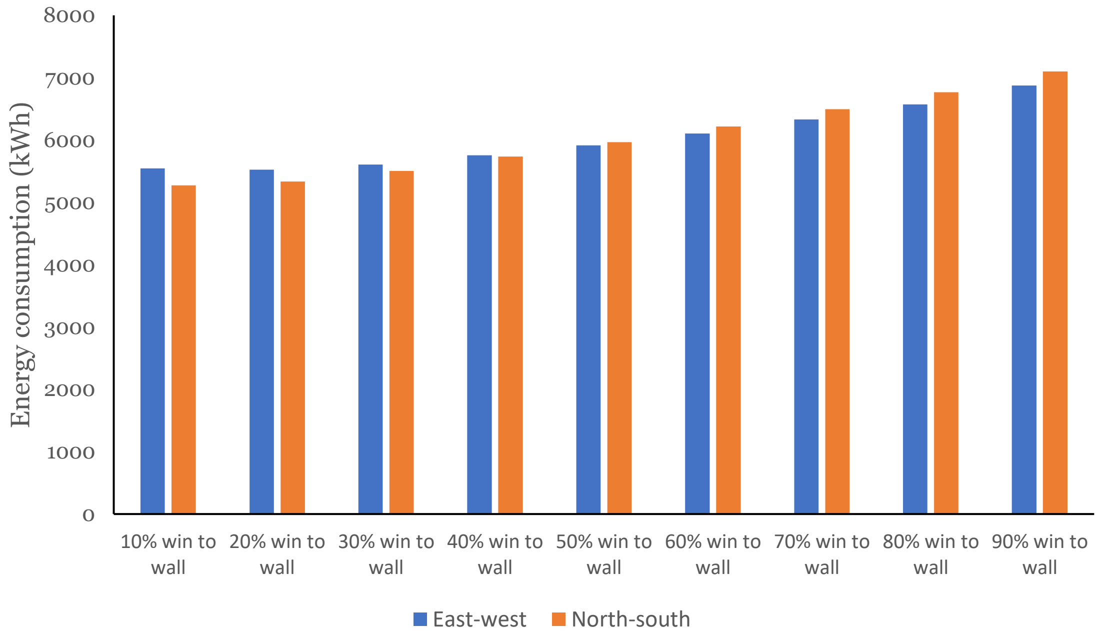


Figure 212- The influence of orientation on annual energy consumption in cases with R-30 insulation and varying window-to-wall ratios in Jackson.

Orientation is an important factor for generating electricity through PV cells. In this project PV cells in all cases face south. But the forms of them are different. Figure 212 is about generated electricity in two orientations. The generated electricity for east-west orientation is 5609.322 kWh and for north-south orientation is 4923.016 kWh. In other words, the generated electricity in east-west orientation is 14% more than the generated electricity in north-south condition.

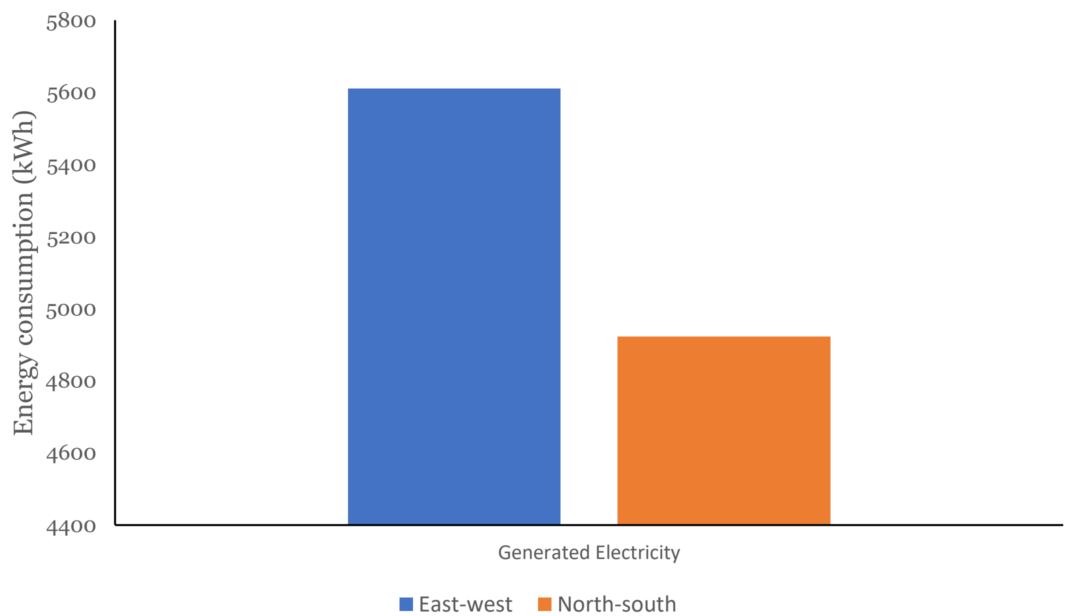


Figure 213- Generated electricity in different configurations of PV cells in Jackson.

Figure 213 illustrates the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10%-20% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 20%-90% WWR range, an increase in R-value is associated with an increase in energy consumption.

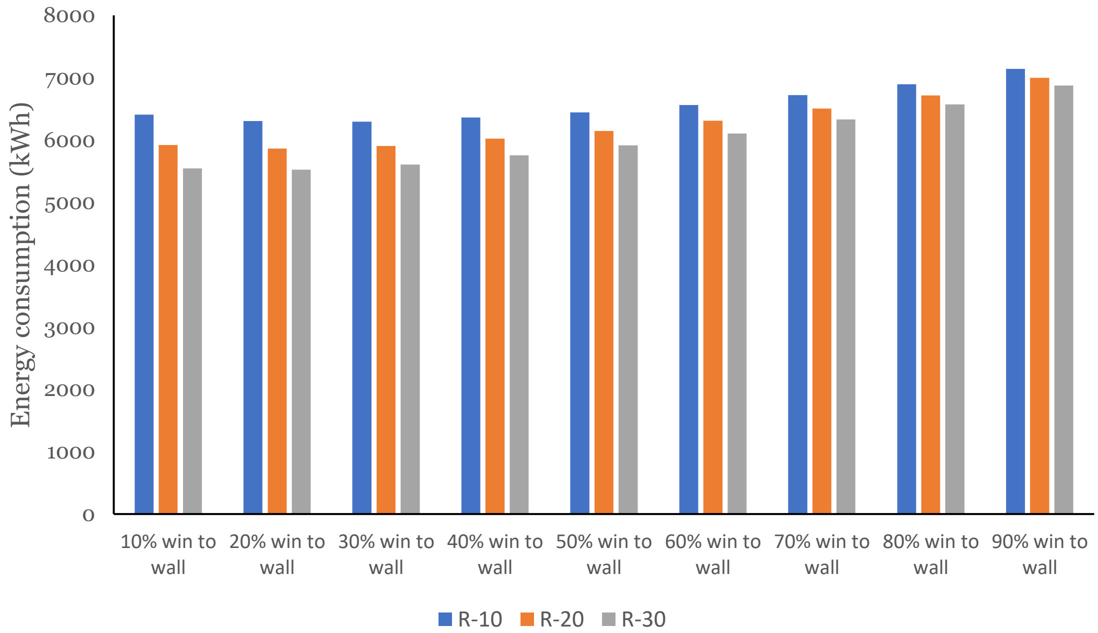


Figure 214- Comparing the annual energy consumption in different window to wall ratios and different R-values (east-west) in Jackson.

Figure 214 shows the energy consumption of cases with varying Window-to-Wall Ratios (WWRs) and R-values. It is evident from the figure that as same as the previous graph the disparities in energy consumption among different R-values are more pronounced in lower WWRs compared to higher WWRs. Specifically, within the 10% -20% WWR range, an increase in R-values correlates with a reduction in energy consumption. Conversely, within the 20% - 90% WWR range, an increase in R-value is associated with an increase in energy consumption.

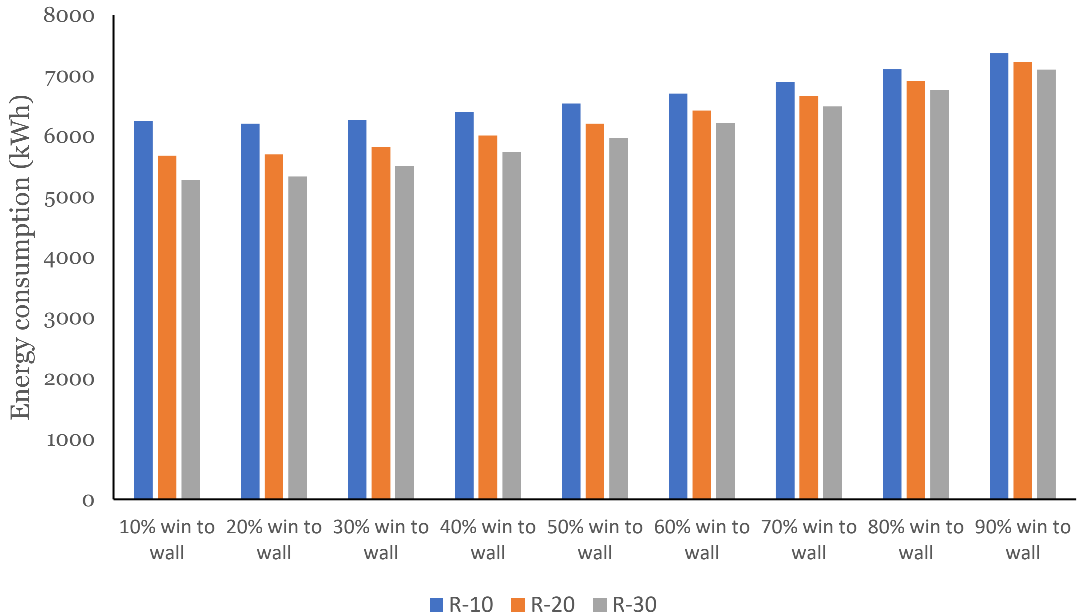


Figure 215- Comparing the annual energy consumption in different window to wall ratios and different R-values (north-south) in Jackson.

The CO2 Emissions for cases with east-west orientation is shown in figure 215 Because the generated electricity is not enough in most cases, CO2 emissions are positive for them. Generally, an increase in WWR causes an increase in CO2 emissions, however the lowest CO2 emissions is 20% WWR. Moreover, insulation thickness has a direct relationship with CO2 emissions.

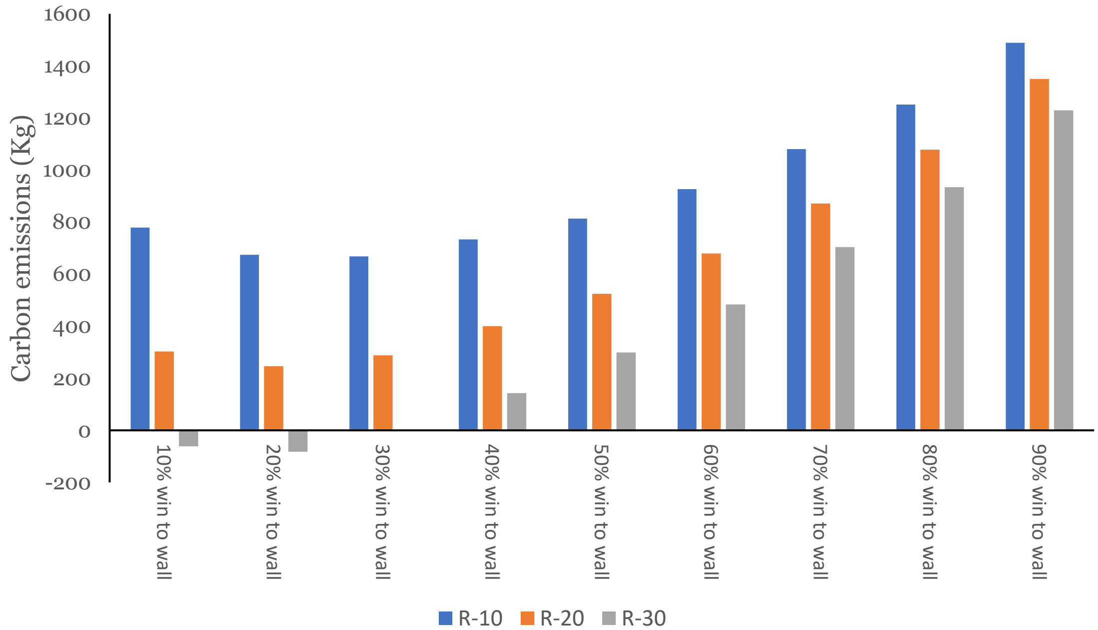


Figure 216- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (east-west) in Jackson.

Figure 216 shows CO2 emissions for cases with north-south orientation. The trend of CO2 emission for these cases is the same as the trend of cases with east west orientation. That means the lowest CO2 emission is related to the 20% WWR.

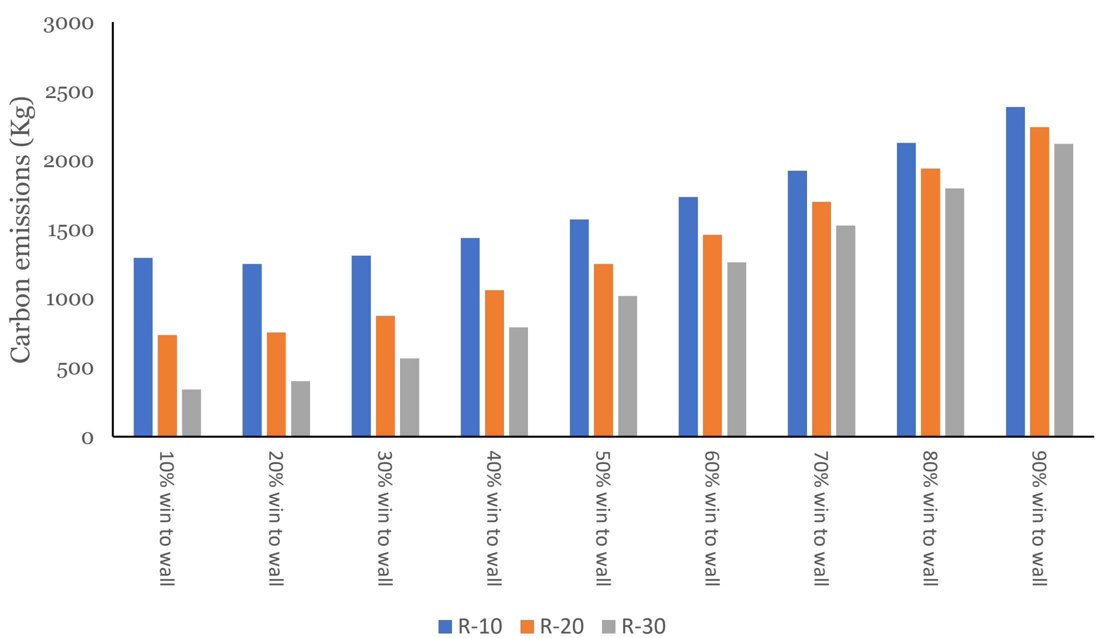


Figure 217- Comparing the annual CO2 emissions in different window to wall ratios and different R-values (north-south) in Jackson.

11.16. Energy consumption in different cities

Table 33 presents the average energy consumption across various orientations in the investigated cities. This data holds valuable insights for selecting optimal locations to construct net-zero energy buildings. Within this chapter, the average energy consumption of all cases serves as a crucial metric for comparing and evaluating these cities. The findings from this table contribute essential information to guide decisions related to sustainable and energy-efficient building practices, aiding in the strategic planning and selection of cities conducive to net-zero energy construction.

Table 33- Average energy consumption across various orientations in the investigated cities.

Climate-City	East-West	North-south	Total
1A Miami, FL	2763.92	2964.11	2864.014
2A Houston, TX	2872.63	2992.76	2932.70
2B Pheonix, AZ	3192.70	3523.37	3358.04
3A Charlotte, NC	3290.28	3461.02	3375.65
3B Los Angeles, CA	1085.45	1268.10	1176.78
3C San Francisco, CA	1550.29	1685.55	1617.92
4A Washington, DC	4278.80	4394.12	4336.46
4B Albuquerque, NM	3202.41	3458.60	3330.51
4C Seattle, WA	3776.88	3850.20	3813.54
5A Boston, MA	4908.44	4635.04	4771.74
5B Denver, CO	4261.79	4448.21	4355.00
6A Minneapolis, MN	7039.40	7137.13	7088.27
6B Billings, MT	5595.35	5737.62	5666.49
7A Fargo, ND	8493.48	8580.42	8536.95

7B Jackson, WY	6286.55	6325.56	6306.06

Figure 217 provides a comparative analysis of different cities, focusing on their average energy consumption. Notably, Fargo, characterized by a very cold climate, stands out with the highest energy consumption among the cities examined. In stark contrast, Los Angeles, with its warm and dry climate, showcases significantly lower energy consumption, approximately 10% of Fargo's. Following Los Angeles, San Francisco, known for its warm and marine climate, presents the lowest energy consumption among the cities considered. This visual representation emphasizes the distinct energy consumption patterns across cities with varying climates, highlighting the profound impact of climatic conditions on energy needs. Additionally, Minneapolis, representing a cold and dry climate, secures the second-highest position in terms of energy consumption, further emphasizing the role of climate in shaping energy demands.

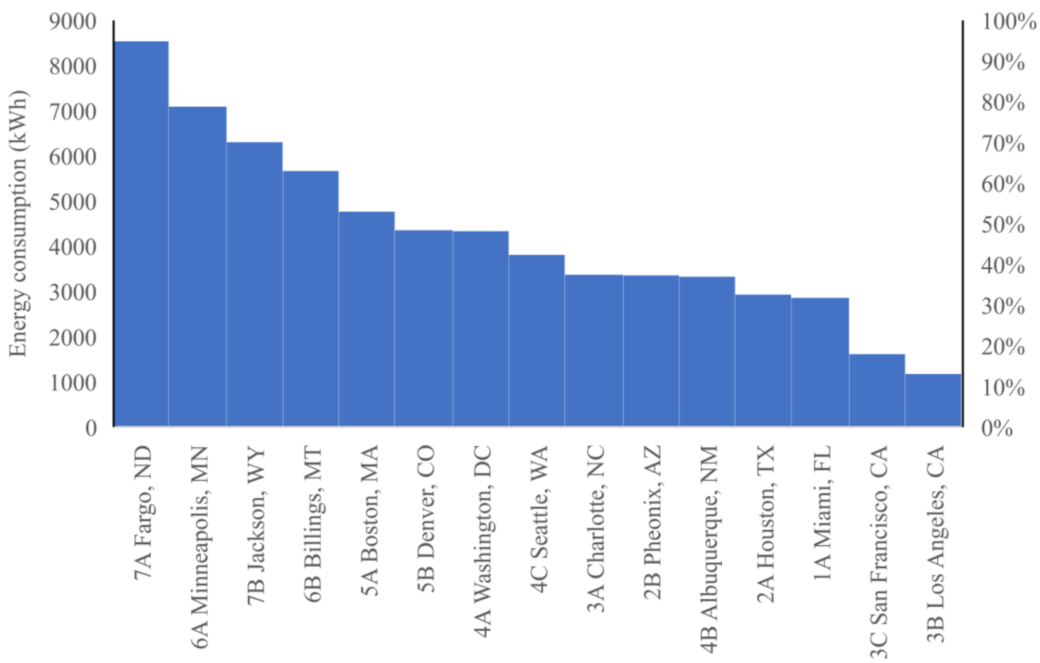


Figure 218- Average energy consumption across various orientations in the investigated cities.

11.17. Generated electricity in different cities

Table 34 presents the generated electricity and sensitivity of various cities to shading. In the east-west orientation, PV cells are positioned on a monolithic frame, ensuring no shadowing among them. Conversely, in the north-south orientation, PV cells face south but are structured with smaller frames, introducing the potential for shadows. To quantify this sensitivity, dividing the generated electricity in the east-west orientation by the generated electricity in cases with a north-south direction provides a clear measure.

Table 34- Comparing generated electricity in different cities.

Climate-City	East-West	North-south	East-west/North-south	Average
1A Miami, FL	5797.787	5268.548	1.100453	5533.168
2A Houston, TX	5224.847	4863.32	1.074337	5044.084
2B Pheonix, AZ	7295.075	6544.478	1.114692	6919.777
3A Charlotte, NC	5665.917	5045.056	1.123063	5355.487
3B Los Angeles, CA	6290.622	5641.418	1.115078	5966.02
3C San Francisco, CA	5988.185	5340.05	1.121372	5664.118
4A Washington, DC	5113.79	4509.8190	1.133924	4811.805
4B Albuquerque, NM	6999.466	6227.568	1.123949	6613.517
4C Seattle, WA	4360.214	3811.319	1.144017	4085.767
5A Boston, MA	5007.051	4366.909	1.146589	4686.98
5B Denver, CO	6050.004	5291.474	1.143349	5670.739
6A Minneapolis, MN	5047.228	4373.821	1.153963	4710.525
6B Billings, MT	5458.25	4723.851	1.155466	5091.051

7A Fargo, ND	5124.203	4410.195	1.161899	4767.199
7B Jackson, WY	5609.322	4923.016	1.139408	5266.169

Figure 218 depicts a comparison of the average generated electricity in the investigated cities. The chart is organized in descending order, indicating the most to the least produced energy. This arrangement provides a clear view of each city's position in terms of energy generation. Notably, Phoenix stands out with the highest energy generation, while Seattle, positioned at the lowest end, generates approximately half the energy produced in Phoenix. This visual representation underscores the significant variations in energy generation among the cities under consideration.

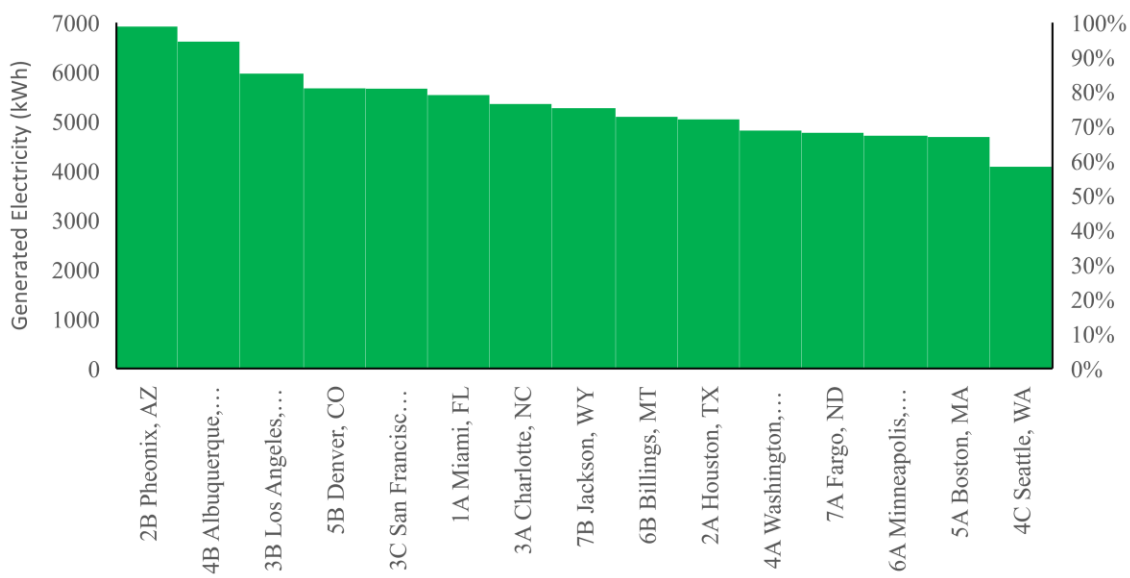


Figure 219- Generated electricity in different cities.

11.18. Sensitivity of PV cells to shading in different cities.

As previously discussed, a method to assess sensitivity to shading involves dividing the generated electricity in the east-west orientation by the generated electricity in cases with a north-south direction. Figure 219 provides a comparative analysis of the sensitivity of various cities to shading. The chart ranks cities based on their sensitivity, with Fargo exhibiting the highest sensitivity and Houston demonstrating the lowest sensitivity to shading. This visual representation offers insights into how different cities respond to shading conditions, emphasizing Fargo's heightened sensitivity and Houston's comparatively low sensitivity in the context of electricity generation.

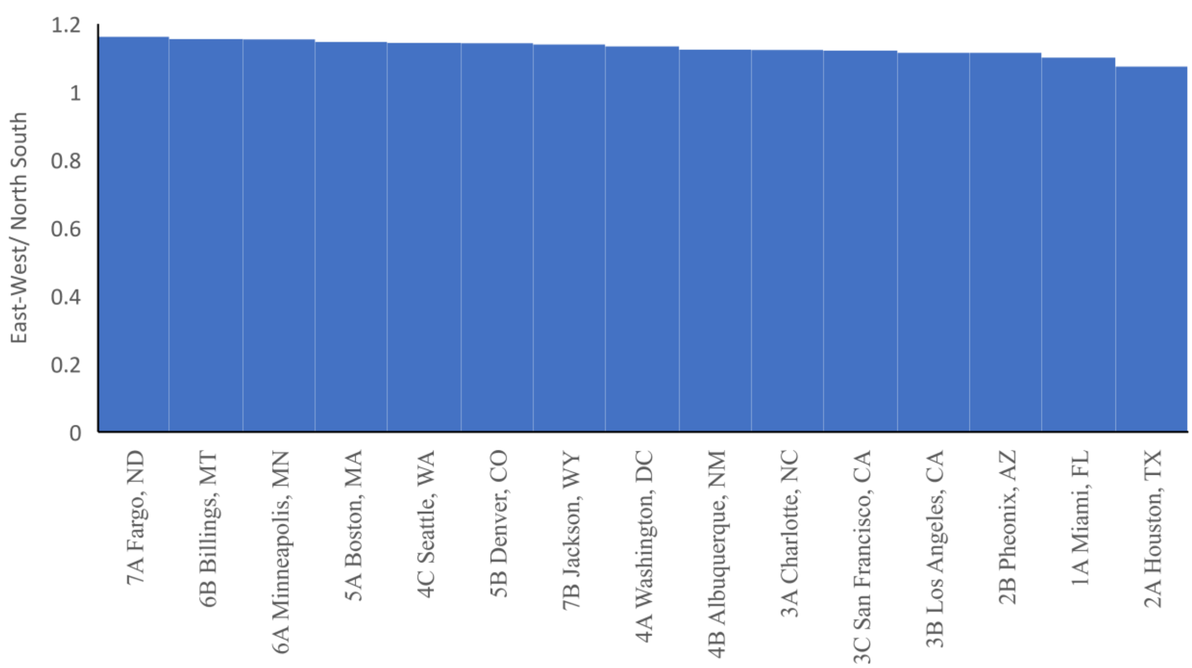


Figure 220- Sensitivity of PV cells to shading in different cities.

11.19. Potential of designing net zero energy buildings in different cities.

Figure 220 provides a visual representation of the count of cases that have the potential to achieve zero energy status. In these scenarios, the generated electricity surpasses the consumed energy, designating them as potential net-zero energy buildings. Notably, the chart reveals that across all 54 cases, there are seven cities where generated electricity consistently exceeds consumed energy. However, in two cities, Fargo and Minneapolis, PV cells cannot supply the required electricity in any of the cases. The chart is organized in descending order, offering a clear perspective on the cities with the highest to the lowest number of cases where PV cells can meet the necessary energy demand.

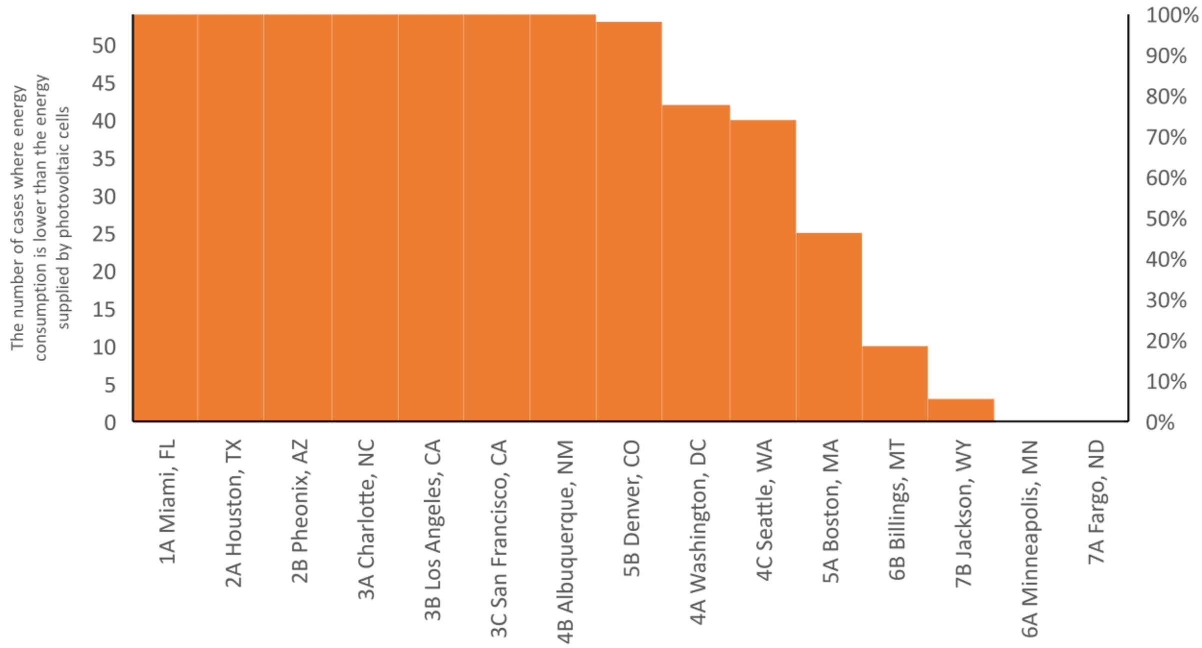


Figure 221- count of cases that the generated electricity surpasses the consumed energy.

Indicating that the generated electricity falls short of meeting the consumed energy. This ratio, visually represented by the color-coded chart, provides valuable insights into the energy dynamics of different cities. Los Angeles and San Francisco, with ratios above 100%, showcase a notable surplus in generated electricity, underlining their advantageous positions. On the other hand, Fargo and Minneapolis, with ratios below 100%, highlight challenges in achieving a surplus of generated electricity relative to their energy consumption. The observation underscores variations in the ability of cities to generate sufficient electricity to meet their consumption needs.

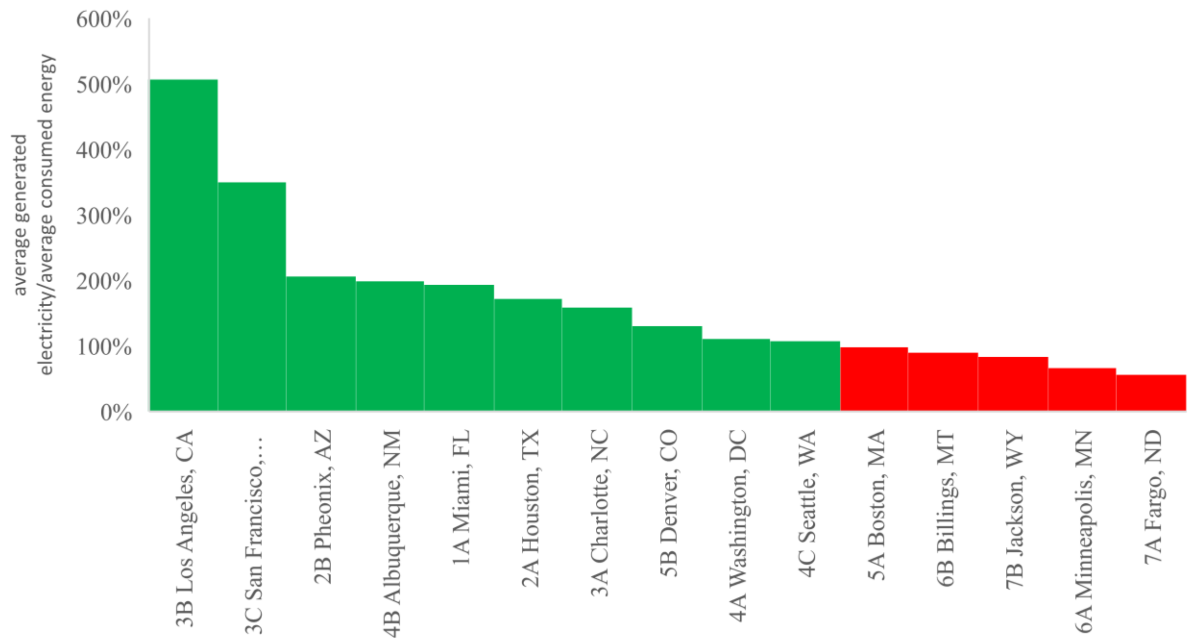


Figure 222- comparing generated electricity/consumed energy in different cities.

Table 35 serves as a crucial reference point by unveiling the optimal configurations for energy efficiency and environmental sustainability in various cities. In this context, the term "best case" encapsulates scenarios characterized by the lowest energy consumption and minimal carbon dioxide emissions within each specific urban context. What sets this table apart is its holistic portrayal of the factors contributing to superior performance, encapsulating not only the best insulation practices but also the most effective building orientations and window-to-wall ratios for each city. By delineating these key parameters, the table provides a nuanced understanding of the tailored strategies required to achieve peak sustainability in diverse geographical and climatic settings. As such, it becomes an invaluable resource for urban planners, architects, and policymakers seeking localized insights to inform conscientious decision-making in the pursuit of energy-efficient and eco-friendly urban landscapes.

Table 35- The optimum cases in different cities.

Climate zone/ City	Orientation	Insulation	WWR (%)
1A Miami, FL	East-West	R-30	10
2A Houston, TX	North-South	R-30	10
2B Pheonix, AZ	East-West	R-30	10
3A Charlotte, NC	North-South	R-30	10
3B Los Angeles, CA	East-West	R-30	10
3C San Francisco, CA	North-South	R-30	10
4A Washington, DC	North-South	R-30	10
4B Albuquerque, NM	East-West	R-30	20
4C Seattle, WA	North-South	R-30	10
5A Boston, MA	North-South	R-30	10
5B Denver, CO	North-South	R-30	10
6A Minneapolis, MN	North-South	R-30	10
6B Billings, MT	North-South	R-30	10
7A Fargo, ND	North-South	R-30	10
7B Jackson, WY	North-South	R-30	10

12. CONCLUSION

In conclusion, the analysis of various climates and cities has revealed key patterns and considerations in the realm of net-zero energy tiny houses:

Climate Impact on Energy Consumption: It is evident that cold climates, including very cold humid, cold and humid, and very cold and humid, exhibit the highest energy consumption, while warm climates, such as warm dry and warm marine, demonstrate the lowest energy consumption. This highlights the substantial influence of climate on the energy needs of tiny houses.

City Variability in Electricity Generation Potential: Among different cities, Phoenix stands out with the highest potential for generating electricity, while Seattle, due to its limited sunny days, has the lowest potential. This underscores the importance of considering local climatic conditions when evaluating the feasibility of net-zero energy solutions.

PV Cell Sensitivity in Cold Climates: PV cells in cold and very cold climates display higher sensitivity to shading, attributed to the sun's angle. Understanding this sensitivity is crucial for optimizing the performance of solar installations in these climates.

Promising Potential for Net-Zero Energy Houses: Remarkably, among the 15 investigated cities, all cases in seven cities achieved zero energy status. This high prevalence indicates a significant opportunity for designing and implementing net-zero energy tiny houses, showcasing the viability of sustainable practices across diverse urban landscapes.

Los Angeles Leading in Generation/Consumption Ratio: Los Angeles emerges as a frontrunner among the investigated cities, boasting the highest generation-to-consumption ratio. This underscores the city's capacity to generate surplus electricity, potentially contributing to a more sustainable and energy-efficient urban environment.

In essence, these findings emphasize the importance of tailoring net-zero energy solutions to the unique climatic and geographical characteristics of each city. The successful implementation of sustainable practices in certain cities sets a positive precedent for the broader adoption of net-zero energy tiny houses, contributing to a more environmentally conscious and energy-efficient future.

The results underscore the significance of the window-to-window-to-wall ratio in influencing energy consumption and carbon dioxide emissions. The positive correlation observed indicates that as this ratio escalates, there is a concurrent increase in both energy demands and CO2 emissions. This association is closely tied to the inherent properties of windows, which typically exhibit lower insulation values compared to walls, leading to heightened heat transfer, and necessitating greater reliance on heating or cooling systems to maintain interior comfort.

In contrast, the simulations affirm the positive influence of insulation thickness on energy efficiency and environmental sustainability. The data highlights that augmenting insulation thickness acts as a formidable barrier against heat exchange, resulting in reduced energy consumption and, consequently, lower CO2 emissions. This emphasizes the importance of prioritizing insulation as a fundamental component of building design and construction, presenting a tangible avenue for mitigating the ecological footprint of structures.

Moreover, the simulations affirm the role of building orientation as a crucial factor in optimizing energy performance. Specifically, structures oriented along a north-south axis exhibit lower energy consumption and CO2 emissions. This orientation allows for effective utilization of natural light, minimizing the need for artificial lighting, and strategically mitigates direct exposure to intense sunlight, thereby reducing the reliance on cooling systems. These findings reinforce the holistic approach required in architectural decision-making, where considerations of window-to-wall ratio, insulation thickness, and building orientation collectively contribute to creating more sustainable and environmentally responsible built environments.

In this study, the research emphasis is deliberately directed towards heating and cooling, with the energy consumption for lighting being excluded from the analysis. This decision stems from the unique lifestyle of the building's occupants—a young couple—who are frequently outdoors from 6 AM to 5 PM throughout the week. Given their extended absence, the study prioritizes the more impactful aspects of energy consumption related to heating and cooling, aligning the investigation with the occupants' daily patterns and ensuring a nuanced examination of their energy needs.

Furthermore, the acknowledgment of the diverse climate zones in the United States adds depth to the research approach. The decision to avoid studying just one city as a representative of a climate zone recognizes the substantial variations in climatic conditions across the country. While studying a single city may provide insights, a comprehensive understanding necessitates consideration of the specific challenges posed by each climate zone. This nuanced approach aims to offer more tailored and applicable recommendations for energy-efficient building design across diverse geographical contexts.

Despite the conscious decisions made in focusing on heating and cooling and considering multiple climate zones, it is important to note that the validation process has been overlooked due to constraints in time and the number of cases. While this study recognizes the importance of validation for research rigor, the limitations in resources have prompted this omission. Acknowledging this gap, future research endeavors are encouraged to incorporate validation processes to fortify the credibility and robustness of findings in line with established research standards.

In future studies, there is a compelling need to expand upon the current research framework to encompass a more holistic understanding of energy consumption in buildings designed for specific lifestyles. Recognizing the constraints that led to the exclusion of the validation process, forthcoming investigations should prioritize the integration of rigorous validation methodologies to enhance the reliability and credibility of findings. Additionally, a broader geographical scope must be considered, acknowledging the diverse climate zones across the United States. By extending the study to multiple representative cities or regions, future research endeavors can capture the nuanced influences of varying climatic conditions on energy usage, providing more comprehensive insights into sustainable building design. This evolution in research methodology will not only enrich our understanding of energy dynamics in diverse contexts but also contribute valuable insights for the development of targeted and effective strategies to promote energy-efficient building practices.

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