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Research Article

Assessing Environmental Sustainability and Ensuring Thermal Comfort in Tiny Houses

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Keywords

Tiny house,
Environmental sustainability,
Thermal comfort,
Thermal bridge,
Insulation.

Abstract

Natural disasters, economic challenges, and the pressures of modern living conditions, characterized by the need for speed and adaptability, have increasingly led to the pursuit of more compact living arrangements. In this context, tiny house (TH) structures have emerged as a significant trend. THs are recognized for their potential to contribute to environmental sustainability due to their reduced footprint, lower material and energy consumption, and minimal waste generation. However, a review of the literature reveals a scarcity of case studies on THs, and the topic's significance is often underemphasized. This study examines seven TH buildings from different climate zones, analyzing their contributions to environmental sustainability across three primary dimensions: energy efficiency strategies, material selection, and thermal comfort. Additionally, a case study focused on thermal comfort was conducted. The findings indicate that on the coldest day of winter, the SIP system maintained an average indoor temperature that was 5.8% higher than the reference wooden system and demonstrated greater effectiveness with a 12.7% lower standard deviation in indoor temperatures compared to other alternatives. On the hottest summer day, the SIP system exhibited an 18.1% lower standard deviation in indoor temperatures relative to the other systems evaluated.

1. Introduction

The tiny house movement originated in America in the 1850s, driven by the ideals of individualism, simplicity, and freedom [1, 2]. Although there are stationary types, the mobile type is more commonly preferred. Unlike caravans, tiny houses were developed not only for travel purposes but also as a solution to ecological, economic, and political challenges [1]. Mobile spaces are living environments that can be relocated by means of a vehicle attached to them, according to the user's needs. These living spaces can serve various purposes beyond accommodation, such as work, education, or other necessities. They can be portable, relocatable, or removable [3].

In recent years, demand for mobile living spaces has increased, driven by economic factors as well as the desire to minimize the impacts of modern chaos, widespread epidemics, and natural disasters [4]. When discussing mobile spaces, one may encounter concepts such as motorized, towable, and alcove caravans [4], tiny houses (TH), and micro dwellings [5]. The term 'tiny house' (TH) typically refers to housing units with an area of less than 37 m² [6]. Three basic principles define THs: efficient use of space, good design that meets users' needs, and a means to achieve a desired lifestyle [7]. Mobile micro dwellings are characterized by their mobile spatial components, which are

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essential given the limited space. These structures prioritize minimizing environmental impacts and providing economic solutions. Micro dwellings generally have a maximum area of 28.5 m² [5]. In living units that are frequently on the move, such as boats and caravans, ergonomics, safety, and stability are paramount [8]. Flexibility, sustainability, energy efficiency, and comfort are crucial considerations in the design of these spaces [9].

The core principle of energy efficiency is to achieve more with less. Minimizing reliance on HVAC (Heating, Ventilation, and Air Conditioning) systems is particularly important, as they account for 50% of energy consumption in buildings [10]. In this respect, THs have the potential to play a significant role in addressing the current climate crisis and global warming. THs consume less energy, generate less waste, and require fewer materials throughout their life cycle compared to conventional buildings [1]. Due to their compact size and volume, cross ventilation and unidirectional ventilation techniques can be effectively implemented in THs based on wind direction and building orientation [6]. As a result, reliance on active cooling systems can be reduced through efficient natural ventilation methods. Moreover, reduced energy consumption lowers environmental impacts by decreasing carbon emissions.

Although limited, there are studies in the literature that explore environmental sustainability in the context of THs. These studies include comparisons with traditional houses [11], compliance with passive house standards [6], environmental impacts of building materials [7, 12], utilization of waste materials [13], and the effects of dynamic systems on thermal comfort [14]. However, a holistic evaluation of these aspects is necessary to fully understand the strengths and weaknesses of THs. This study aims to evaluate case studies of THs in different climate zones with a focus on environmental sustainability. By doing so, the study seeks to highlight the advantages of TH design, material selection, and applied systems in the context of global climate change and to demonstrate that more can be achieved for the environment with less spatial occupation. For this purpose, seven different buildings, each with an area of less than 37 m² and compliant with TH standards, were analyzed based on the use of passive systems, material selection, and user comfort, and the effects of these decisions on the natural environment were assessed.

Following the literature review, a case study was conducted on thermal bridging and thermal comfort, which are recognized as major challenges in TH design. The target audience for this study includes architects, TH owners, and all researchers, academics, and readers interested in this trend.

2. Impact Factors on Environmental Sustainability

2.1. Strategies for Energy Efficiency

Buildings in the built environment are among the primary contributors to environmental pollution. They emit harmful greenhouse gases and consume raw materials, energy, and water throughout their life cycle [15]. However, these impacts can be mitigated through various passive or hybrid strategies. Techniques such as natural ventilation, night cooling, insulation, appropriate window-to-wall ratios, and optimal building orientation, along with dynamic solutions that adapt to changing environmental conditions and user needs, play a crucial role in reducing environmental impacts.

A study on tiny houses (TH) in Australia found that THs produce 70% less carbon emissions over their lifetime compared to conventional homes. The study also revealed that the impact of climate on carbon emissions from heating and cooling is significantly lower in THs [11]. Similarly, an analysis of an award-winning TH in California showed that it emitted 96% less carbon and consumed 88% less energy compared to 24 homes that met California energy standards [16].

To prevent overheating of interior spaces in THs due to rapid changes in outdoor temperature, it is advisable to avoid large transparent surfaces in the design. High-performance windows and movable shading elements are recommended for such buildings [6]. Additionally, to conserve energy, it is recommended that THs be placed directly on the ground, rather than having crawl spaces under the slab. To prevent frost heave, additional insulation should be applied under the floor slab and at the corners using the so-called wing method (Figure 1) [6].

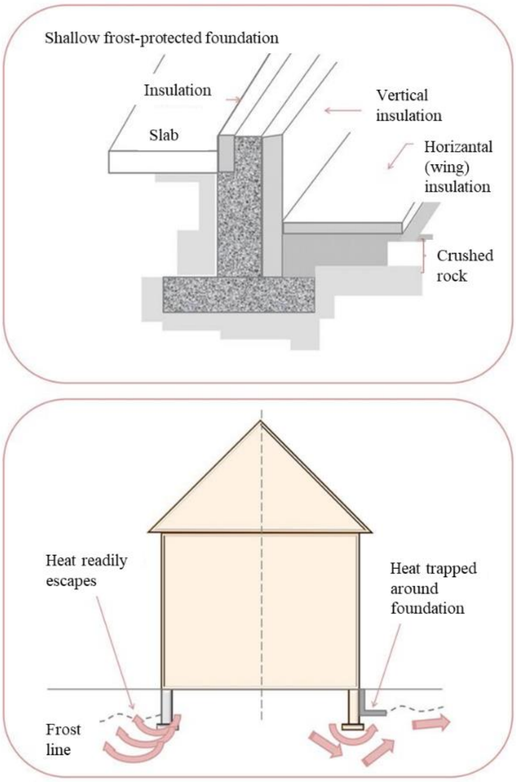


Figure 1. Additional insulation applied to reduce the freezing level of the foundation: ‘wing method’ [17]

Due to their low volume, passive methods such as cross ventilation and the chimney effect should be utilized to prevent heat buildup inside tiny houses (TH) [6]. It has been observed that thermal comfort can be achieved with minimal energy consumption when evaporative coolers are combined with fan-assisted night cooling. Consequently, the use of hybrid cooling systems is recommended for THs [6].

The limited living space in THs can pose challenges to the fulfillment of various functions. Therefore, mobile, versatile, technological, and innovative solutions may be necessary to overcome this limitation. In this context, the

POD THOW design introduces systems such as retractable verandas, terraces, and elevators, which increase the per capita area by approximately 5 m² and the total interior volume by approximately 27 m² (Figure 2). Although these design enhancements increase the total energy demand of the building by 210 kWh due to the expanded volume, this consumption can be mitigated through insulation and the use of passive energy sources [1].

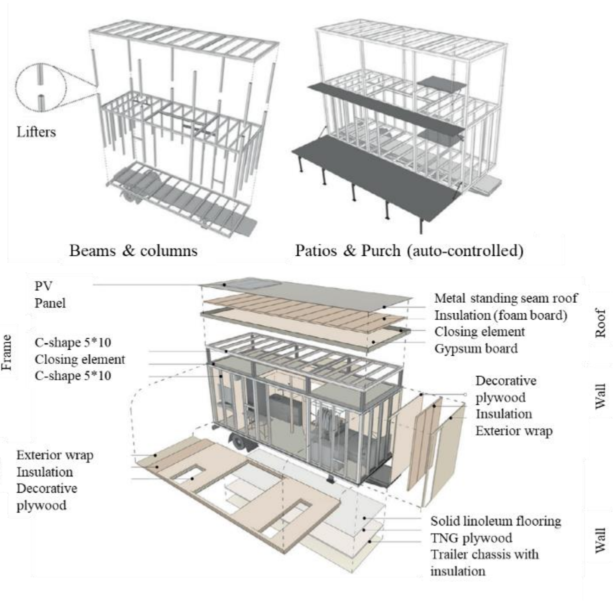


Figure 2. Components of the proposed POD THOW house [1]

2.2. Using Materials with Low Environmental Impact

When selecting materials for living spaces, it is crucial to consider not only user comfort and health but also the environmental impact of those materials. Building materials can emit various harmful gases and contribute to environmental pollution throughout their life cycle [18].

In one study, the environmental impact of coating and insulation materials used in a tiny house (TH) with a 25-year service life was evaluated according to the EN15978 standard [12]. The study compared 12 alternative designs across all impact classes and life cycle stages, finding that OSB (oriented strand board) and LVL (laminated veneer lumber) cladding materials exhibited the best environmental impact scores, while fiber cement performed the worst. This is largely due to the cement industry being one of the largest producers of carbon emissions [19]. Among insulation materials, EPS was found to have the best environmental impact. Additionally, PVC roofing membranes demonstrated better environmental performance compared to the other two options, bitumen and PVB (polyvinyl butyral). Among facade systems, composite stone showed the worst environmental impact, while wood, fiber cement, and basalt had similar environmental effects [12].

In another study examining the carbon emissions associated with structural and insulation materials used in the floors, walls, and roofs of THs, both new and reclaimed materials were considered. The study evaluated three different scenarios: the first using only new materials, the second using only reclaimed materials, and the third combining both types. The findings revealed that the second scenario, which used only reclaimed materials, resulted in 43.6% lower carbon emissions than the first scenario. Among the insulation materials analyzed—rock wool, sheep wool, PIR, glass wool, and flax—sheep wool was identified as the largest source of emissions [20].

In a comparison between a TH made of wood with a 50-year service life and an alternative TH made from wind turbine blades, it was found that the proposed option had up to 97% lower environmental impact across most impact classes. This significant reduction is attributed to the use of wind turbine blades, which have a service life of 20-25 years, as a ready-made building material (Figure 3). However, the proposed house showed high climate change and ozone depletion potentials during phases A1-5, likely due to the increased weight and additional processing required for joint details. Despite these challenges, the study serves as an important example of how environmental impacts can be reduced, the circular economy can be supported, and the use of raw materials can be minimized [13].

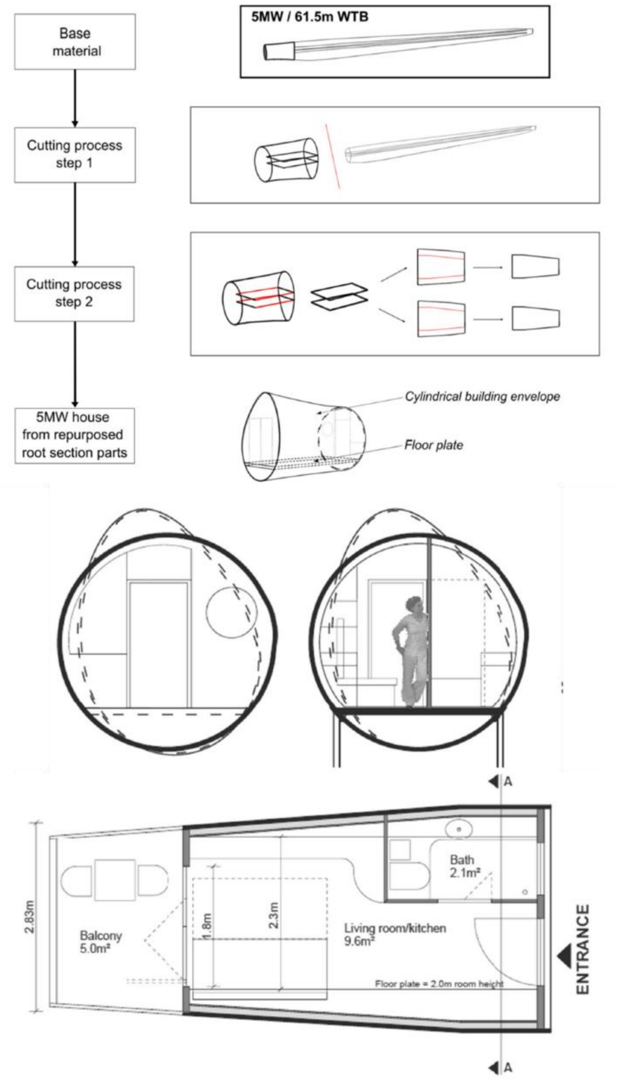


Figure 3. The process of using the root of a wind turbine blade in the production of a tiny house (above) and drawings of the house (below) [13]

2.3. Ensuring Thermal Comfort

Achieving indoor comfort through passive methods is crucial for reducing both energy consumption and environmental impacts. Among these passive systems, thermal energy storage systems can play a significant role. However, the excessive use of thermal energy storage materials, such as concrete, stone, and bricks, in tiny houses (THs) is not recommended, as it may lead to excessive indoor temperature increases, particularly during the summer months [6]. Instead, dynamic systems and appropriate ventilation methods can be employed to ensure effective thermal comfort.

He [14] conducted an experiment on a high-density concrete wall surrounding a TH with an area of 20.2 m², supported by insulation material on both sides, to assess its impact on thermal comfort. The ability to maintain thermal comfort without relying on any HVAC system in a building located in a hot desert environment presents a valuable case for economic, social, and environmental sustainability. To optimize the results, ventilation was provided through windows on the east and west facades, with shading elements added to these facades. For the north and south facades, dynamic insulation layers were incorporated on both the interior and exterior of the concrete wall. During the colder months, the dynamic insulation system operates by keeping the exterior layer closed and the interior layer active during the day. In warmer months, the exterior insulation layer remains closed during the day, while both the exterior and interior insulation layers are opened at night.

When examining the time delay between the concrete and insulation layers, it was found that a concrete wall with a thickness of 35-45 cm has a delay time of 10-12 hours; the use of XPS (extruded polystyrene) increases this delay time compared to EPS (expanded polystyrene). However, EPS was chosen in the combined model due to its environmental friendliness and cost-effectiveness. According to the final simulation results, when comparing comfort ranges for the entire year, it was found that the improved combined model provided thermal comfort for 70% of the year [14]. This outcome is significant in terms of reducing operational energy use and carbon emissions by enhancing thermal comfort through passive methods such as insulation and the utilization of thermal energy storage materials.

Overheating is considered one of the most significant challenges in THs [6]. This issue arises due to increased internal heat loads and the reduced thermal resistance of the building envelope, particularly when wood is used as the primary construction material [21]. Additionally, thermal bridges, air leaks, and moisture transmission due to thinner building envelopes can negatively impact thermal comfort [6]. Thermal bridges occur when building materials allow uncontrolled heat transfer at points where insulation is interrupted or compromised, preventing it from functioning effectively. These bridges are commonly found at panel junctions, roof-wall intersections, wall-floor connections, and window-wall joints, leading to increased energy consumption and carbon emissions.

Thermal bridges can be categorized into three types: repetitive, linear, and point. Repetitive thermal bridges occur in elements such as ceiling beams and wall studs, which are situated between insulation layers at regular intervals in the building envelope. Linear thermal bridges emerge at the intersection of two components, such as floor-wall or wall-window connections, while point thermal bridges occur at a single point, such as the area where electrical cables are located [22]. Linear thermal bridges can vary depending on material properties, geometry, and environmental temperature values [23]. The wooden construction system, frequently used in THs, can include details that create linear thermal bridges (Figure 4).

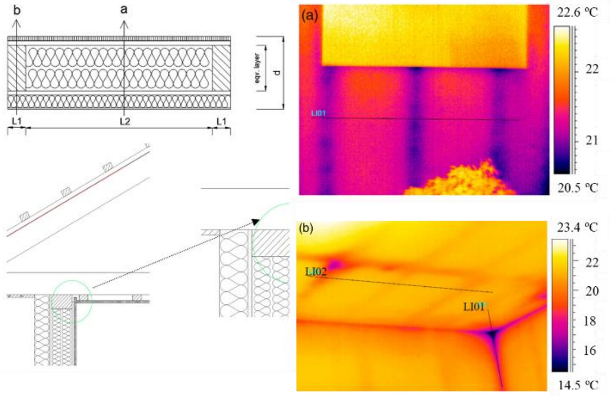


Figure 4. Details of the thermal bridge (left) and thermal camera images (right) [24]

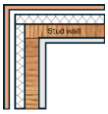
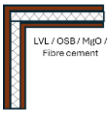
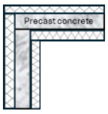
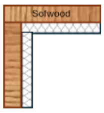
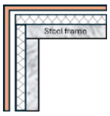
Table 1 summarizes the types of materials, climatic conditions, compared characteristics, and targeted issues across all the case studies reviewed. All the projects analyzed feature living spaces of less than 37 m², thereby fitting the definition of a tiny house (TH). These seven dwellings were designed primarily for residential use. While wood is the preferred main building material, other materials such as concrete, steel-framed systems, and even materials typically outside the construction sector are also utilized. The small footprint and surface areas of these structures offer various possibilities for material usage in TH design.

Thermal bridges are critically important in TH design due to their compact volume. Even if their occurrence is minimal, heat losses resulting from interrupted, damaged, or poorly constructed insulation can lead to overheating and a reduction in thermal comfort. To mitigate this issue, a Structural Insulated Panel (SIP) system placed between two plates is often employed.

Regarding façade systems, it is observed that THs in milder climates may not require an additional insulation layer, while in extreme climate regions, single or double insulation layers are applied. Furthermore, in harsh conditions such as hot desert climates, dynamic insulation systems are implemented to minimize the impact of outdoor temperature fluctuations between summer and winter, as well as between day and night.

A common thread among all these studies is a focus on environmental sustainability. While some studies approach this by examining the environmental impact of materials, others compare THs with standard houses, highlighting reduced material use and waste generation. The studies address a range of topics, including planning end-of-life scenarios for houses, analyzing operational and embodied carbon footprints, improving energy efficiency and thermal comfort, promoting the circular economy through material reuse, and ensuring harmonious coexistence between the natural and built environments through new TH proposals (Table 1).

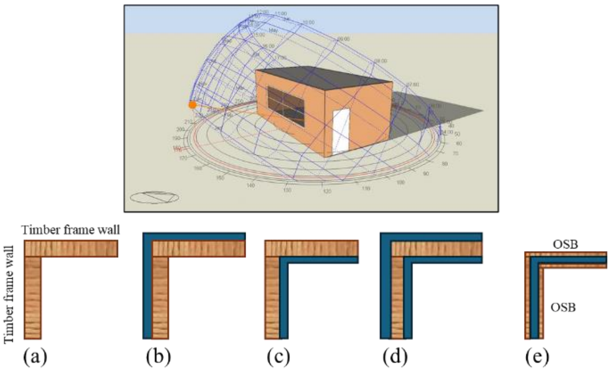
Table 1. Case studies and their characteristics

	TINY HOUSE CASE STUDIES			
Wall configuration				
Climate	Temperate and humid subtropical (Cfb, Cfa)	Cold and dry (Dfb)	Temperate oceanic (Cfb)	Temperate oceanic (Cfb)
Type	Mobile	Stable	Stable	Stable
Floor area	12.2 m²	17.4 m²	13 m²	33.6 m²
Materials	**Wall:** Cladding, timber frame, plasterboard **Floor:** Laminated timber flooring **Roof:** Corrugated steel roofing	**Wall:** Cladding insulation, timber frame, plywood, plasterboard **Floor:** VCT flooring **Roof:** Asphalt shingle, fiberglass insulation, plasterboard	**Wall:** Coating, wind türbine blade (root section) **Floor:** Shear webs **Roof:** Coating, wind türbine blade	**Wall:** SIP (Sheating, insulation (EPS), sheating) **Floor:** SIP **Roof:** Insulation, SIP
Comparison between	Traditional vs. tiny house	Passive and hybrid strategies	Wind turbine blade vs. wooden structure	Environmental impact
Focal point/s	Embodied and operational carbon	Energy efficiency and thermal comfort	End of life scenarios	Building materials
Reference	[11]	[6]	[13]	[12]
	TINY HOUSE CASE STUDIES			
Wall configuration				
Climate	Sub-tropical desert (BWh)	Temperate oceanic (Cfb)	Different climates	
Type	Stable	Stable	Mobile	
Floor area	20.2 m²	30.6 m²	29.5 m²	
Materials	**Wall:** Dynamic insulation, precast concrete, dynamic insulation (EPS / XPS) **Floor:** Precast concrete **Roof:** Precast concrete, insulation (EPS)	**Wall:** Softwood, insulation (sheep wool / rock wool / flax) **Floor:** Plywood, insulation **Roof:** Softwood, insulation	**Wall:** Cladding, insulation, steel frame, plywood **Floor:** Plywood, linoleum flooring **Roof:** Insulation, metal standing seam	
Comparison between	EPS, XPS and concrete	New vs. reclaimed materials	Standard tiny house vs.proposed tiny house	
Focal point/s	Thermal comfort	Global warming potential	Size and weight	
Reference	[14]	[7, 20]	[1]	

3. Case Study on Thermal Bridges

In timber-framed tiny houses (TH), the placement of insulation within the building envelope significantly affects thermal comfort. In these structures, the spaces between the studs are typically filled with insulation material. However, heat loss may occur at the points where the studs intersect, leading to repeated thermal bridges. To ensure thermal comfort, it is crucial to address this issue. Continuous insulation layers applied to the exterior walls, either from the inside or outside, can effectively prevent such heat losses. Additionally, if structurally insulated panels (SIPs) are used on the facade, it is possible to eliminate thermal bridges and avoid the need for additional insulation. These panels are constructed by sandwiching rigid insulation materials, such as expanded polystyrene (EPS), between two thin panels, such as oriented strand board (OSB) or laminated veneer lumber (LVL) . The lightweight nature of these panels also facilitates easier transportation, which in turn can reduce emissions associated with the transportation phase.

To assess the impact of insulation layer placement on thermal comfort, four different wall layer configurations were proposed for a TH building located in the Netherlands, a region where THs are widely adopted and the climate is mild. These configurations were compared with each other and with a baseline uninsulated timber-framed system (a). The simulations, which excluded the use of HVAC systems and considered only the passive heating and cooling effects of the materials, were conducted using the Design Builder software. The TH in question measures 8 meters in length, 4 meters in width, and 3 meters in height, with a total floor area of 32 m². The wall configurations of the TH are depicted in Figure 5.



(a)	Timber frame wall	%15 thermal bridging	0.13 m	0.41 W/m²K
(b)	Exterior insulation	%15 thermal bridging	0.16 m	0.30 W/m²K
(c)	Interior insulation	%15 thermal bridging	0.16 m	0.30 W/m²K
(d)	Double insulation	%15 thermal bridging	0.19 m	0.25 W/m²K
(e)	SIP	%0 thermal bridging	0.16 m	0.27 W/m²K

Figure 5. TH model (above) and wall alternatives (below)

The first wall alternative examined (a) is a timber-framed wall system filled with mineral wool. In the simulation program, the area occupied by the wooden studs on the wall surface was calculated, with thermal bridging assumed to occur in this area (15% bridging), and this was input into the program. The alternatives (b) and (c) consist of a 0.03 m EPS insulation layer applied on the interior and exterior of this wall system, respectively. Alternative (d) involves applying insulation on both surfaces of the wall, while option (e) is a SIP formed by placing 0.136 m of EPS between two 0.012 m thick OSB panels. In all alternatives, all parameters remain the same except for the wall layers. The wall alternatives were compared based on the hourly operative temperature values indoors for the hottest and coldest days—July 1 and January 23, respectively—according to the Dutch climate data. Operative temperature, which reflects thermal comfort, was used as the basis for comparison because it has been shown to correlate positively with users' thermal sensations [25, 26, 27, 28].

On the building's south façade, argon-filled double glazing with a transparency rate of 30% was applied. The east façade features a wooden entrance door, while the remaining façades are solid walls. The building is naturally ventilated, and the Dutch climate data was sourced from [29] (Appendix A).

4. Results and Discussion

According to the case study results, the SIP alternative (e) exhibited the highest indoor operative temperature values in the morning hours on the coldest day (January 23). Despite having a lower thermal transmittance value than the two-way insulation (d), the superior performance of option (e) during the coldest period can be attributed to the elimination of thermal bridging. However, after 9:00 pm, the two-way insulation application (d) surpassed the others in terms of thermal comfort, likely due to its faster response to the increasing outdoor temperature from 8:00 am onwards. Alternatives (b) and (c) demonstrated very similar thermal performance, reaching the highest indoor operative temperatures at noon when outdoor temperatures peaked, indicating their direct sensitivity to changes in the outdoor environment. As outdoor temperatures began to decline after 4:00 pm, SIP again showed superior performance with high indoor temperatures, proving its effectiveness in maintaining thermal comfort in cold climates (Figure 6).

The average temperature values recorded throughout the day were 15.3 ºC for (a), 15.9 ºC for (b) and (c), 16.1 ºC for (d), and 16.2 ºC for (e). The standard deviation values, reflecting temperature variations during the day, were 5.5 for (a), 5.4 for (b) and (c), 5.4 for (d), and 4.8 for (e). In this scenario, SIP exhibited the highest indoor mean temperature value (5.8% higher than the reference case) and the lowest standard deviation value (12.7% lower than the reference case) on the coldest day of the year. Detailed temperature data for January 23 can be found in Appendix B.

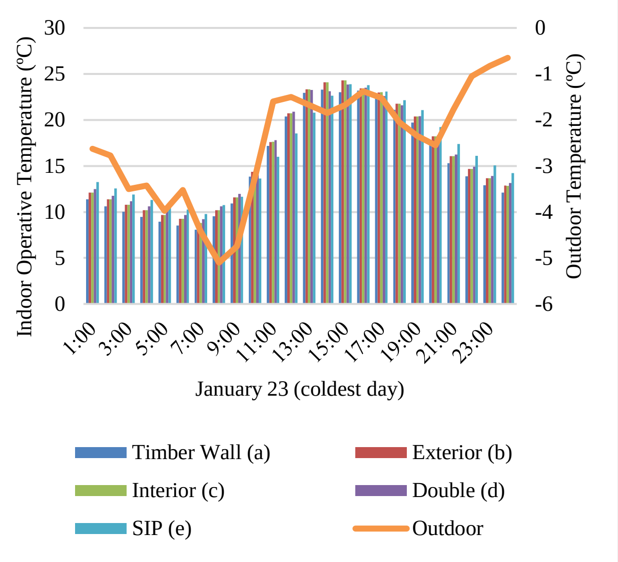


Figure 6. Operative indoor temperature changes of the wall alternatives in the coldest day of the year (January 23)

The issue of overheating in TH has been previously discussed. Therefore, it is crucial for indoor temperatures to remain within the thermal comfort range during periods of high outdoor temperatures. Since no mechanical systems were used in this study, none of the alternatives achieved indoor temperatures within the 19-28ºC range defined as thermal comfort by ASHRAE [30]. The absence of active systems necessitates a careful examination of how the building envelope influences indoor temperature fluctuations.

The results indicate that alternative (e) effectively manages the relationship between outdoor and indoor temperatures, similar to its performance during winter. While the outdoor temperature decreased between 18:00 and 03:00, the indoor operative temperature in alternative (e) increased gradually. This suggests that outdoor heat is transferred slowly into the indoor environment, providing a time lag and indicating high thermal resistance of the façade. During the peak heat hours between 10:00 and 16:00, alternative (e) maintained the lowest operative temperatures, whereas the reference system (a) exhibited the poorest thermal performance. This is because system (a) is directly affected by outdoor temperature fluctuations due to the lack of additional insulation beyond the mineral wool between the wooden studs. The temperature differences between alternatives (c), (b), and (d) were minimal (Figure 7).

The average temperature values recorded during the day were 34.3 ºC for (a), 34.5 ºC for (b) and (c), 34.6 ºC for (d), and 34.4 ºC for (e). The standard deviation values reflecting temperature variations throughout the day were 4.4 for (a), 4.3 for (b) and (c), 4.2 for (d), and 3.6 for (e). On the hottest day of the year, the reference case (a) exhibited the lowest indoor mean temperature, as it was most affected by the average outdoor temperature of 26.9 ºC. SIP demonstrated the lowest standard deviation throughout the day, which was 18.1% less than that of the reference case. Detailed temperature data for July 1 can be found in Appendix C.

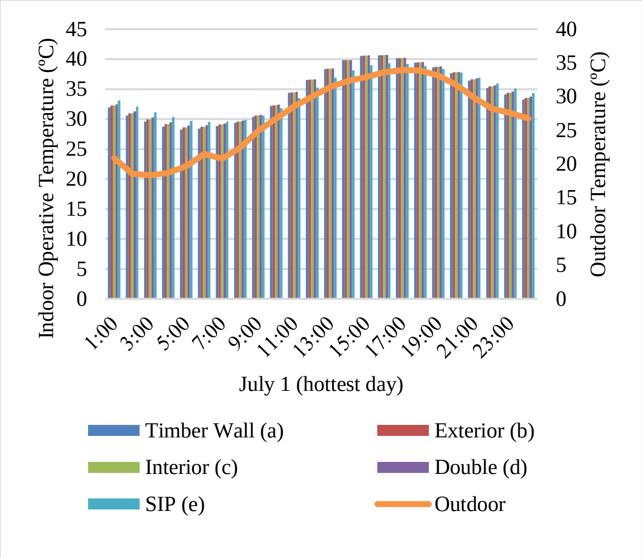


Figure 7. Operative indoor temperature changes of the wall alternatives in the hottest day of the year (July 1)

5. Conclusion and Recommendations

Recent trends indicate a growing demand for living spaces that feature movable, space-saving, and multifunctional furniture. Could this shift, driven by modern and fast-paced living, offer potential solutions for addressing the global climate crisis?

Due to their compact size, Tiny Houses (TH) require fewer materials and result in less waste production compared to traditional homes. While the embodied carbon values associated with their structures vary depending on the materials used, studies have demonstrated that these values are significantly lower than those of standard houses.

Additionally, THs equipped with dynamic systems can adapt to their environmental and climatic conditions and be tailored to meet user needs.

This study has presented factors and evaluations affecting environmental sustainability, including energy efficiency, material selection, and thermal comfort improvements, through an analysis of seven different TH structures. Energy-efficient strategies suggested include avoiding crawl spaces, employing the wing method, and utilizing high-performance windows and dynamic shading elements. Furthermore, passive ventilation systems should be complemented with fan coolers in THs.

In terms of material selection, it is crucial to consider user comfort and health, and to opt for natural materials with minimal environmental impact. The use of reclaimed materials should also be considered to conserve raw material resources. Thermal discomfort, which increases reliance on active systems, poses a threat to environmental sustainability. Therefore, it is essential to ensure that the building envelope is well-insulated, eliminate thermal bridges, and use thermal energy storage materials judiciously. Relocatable insulation layers should be considered, particularly in harsh climatic conditions.

One major issue observed in THs is overheating. The case study of a TH in the Netherlands, with a mild climate, assessed four façade alternatives in terms of operative indoor temperatures to determine thermal comfort on the hottest and coldest days of the year. The study found that Structural Insulated Panels (SIP) outperform the other alternatives by preventing thermal bridges and providing effective thermal inertia in the building envelope. SIP reduced the standard deviations in operative temperature during the day by up to 18% compared to the reference case.

Future research could focus on passive system applications for heating, cooling, ventilation, and air conditioning to address the limitations of THs. Investigating energy gains and changes in carbon emissions when THs are considered as hybrids with HVAC systems could provide valuable insights. Proposing innovative systems for THs, distinct from standard buildings, and ensuring economic sustainability—such as the system's ability to recover its cost in a short period—could both increase demand for THs and help reduce our global carbon footprint.

Conflict of Interest Statement

The authors declare no conflict of interest.

Appendices

Appendix A. Netherlands climate data

Month	Outside Dry-Bulb Temp.	Outside Dew-Point Temp.	Direct Normal Solar	Diffuse H. Solar	Wind Speed	Wind Direct.	Atmospheric Pressure	Solar Altitude	Solar Azimuth
	°C	°C	kWh	kWh	m/s	°	Pa	°	°
Jan.	4.4	2.0	39.4	12.6	5.8	213.7	101258.0	-18.3	171.3
Feb.	4.5	1.5	66.2	22.8	4.8	143.6	101735.0	-11.4	170.2
Mar.	6.7	3.3	112.2	37.4	4.6	212.7	102181.3	-1.8	171.3
Apr.	9.5	4.3	174.6	50.5	3.7	171.0	102004.1	8.5	173.3
May	13.9	9.3	165.8	64.6	3.7	201.1	101646.0	16.5	174.1
June	17.0	12.9	155.0	68.6	3.8	197.8	101930.2	20.2	173.3
July	18.4	13.4	169.6	58.4	4.5	218.8	101485.8	18.7	172.0
Aug.	18.4	13.8	160.7	54.3	3.2	198.2	101810.8	12.2	172.4
Sept.	15.5	11.2	104.4	42.0	3.9	176.1	102131.5	2.7	174.5
Oct.	11.9	9.7	65.3	26.5	4.5	172.3	101248.7	-7.5	176.7
Nov.	7.9	5.4	44.5	14.3	4.1	225.2	101491.8	-16.0	176.9
Dec.	5.3	3.8	40.1	11.3	4.0	189.5	102878.6	-20.2	174.5

Appendix B. Operative indoor temperature and outside dry-bulb temperature on January 23rd

Daily hours	Operative Temperature					January 23
	Timber Wall	SIP	Double	Exterior	Interior	Outdoor
01:00	11.37147	13.252	12.47098	12.12001	12.11726	-2.625
02:00	10.6244	12.54279	11.76289	11.37999	11.37733	-2.775
03:00	10.03112	11.9017	11.17085	10.77544	10.77276	-3.5
04:00	9.445577	11.29323	10.59935	10.18822	10.18568	-3.425

05:00	8.94259	10.74747	10.10487	9.682153	9.67969	-3.975
06:00	8.508276	10.26378	9.669286	9.240156	9.23782	-3.525
07:00	8.064935	9.784736	9.233239	8.796766	8.794549	-4.425
08:00	9.515391	10.74891	10.60314	10.19831	10.19485	-5.1
09:00	10.93052	11.64648	11.95969	11.57873	11.57734	-4.75
10:00	13.85841	13.61679	14.66825	14.38082	14.3797	-3.25
11:00	17.19487	15.98522	17.80693	17.61277	17.61389	-1.6
12:00	20.36281	18.53751	20.89627	20.73682	20.73981	-1.5
13:00	22.9545	20.78206	23.25021	23.33774	23.34226	-1.675
14:00	23.28236	22.64341	23.1099	24.09647	24.1023	-1.85
15:00	23.02843	23.87822	23.86194	24.29843	24.30231	-1.675
16:00	23.18703	23.7883	23.49626	23.41894	23.42326	-1.375
17:00	22.81579	23.09856	22.59087	22.99965	23.0021	-1.525
18:00	21.12283	22.13339	21.59574	21.77073	21.77194	-2.05
19:00	19.71835	21.08834	20.41316	20.37362	20.37342	-2.35
20:00	17.5108	19.23967	18.31722	18.21735	18.21743	-2.55
21:00	15.29639	17.40176	16.2433	16.06897	16.0673	-1.775
22:00	13.88496	16.10439	14.92482	14.66532	14.66237	-1.05
23:00	12.88746	15.06106	13.90117	13.66032	13.65732	-0.825
00:00	12.09359	14.22257	13.13654	12.85355	12.85065	-0.65
Average	15.3	16.2	16.1	15.9	15.9	-2.5
Average (%)	Base case	5.8	5.2	5.4	5.5	
Standard deviation (SD)	5.5	4.8	5.2	5.4	5.5	1.3
SD (%)	Base case	-12.7	-5.5	-1.8	-1.8	

Appendix C. Operative indoor temperature and outside dry-bulb temperature on July 1st

Daily hours	**Operative Temperature**					**July 1**
	Timber Wall	**SIP**	**Double**	**Exterior**	**Interior**	**Outdoor**
01:00	31.95374	33.11213	32.4748	32.23649	32.23495	20.875
02:00	30.58987	32.06551	31.26677	30.96951	30.9677	18.55
03:00	29.55217	31.11579	30.26303	29.94039	29.93798	18.325
04:00	28.73186	30.31402	29.47754	29.14967	29.14712	18.675
05:00	28.21955	29.70268	28.93842	28.62058	28.6179	19.7
06:00	28.41614	29.5064	28.96251	28.71651	28.71382	21.5
07:00	28.84595	29.56517	29.27126	29.0843	29.08239	20.8
08:00	29.33696	29.86438	29.73545	29.561	29.55976	22.425
09:00	30.39936	30.58213	30.71538	30.57392	30.57273	24.9
10:00	32.19326	31.81845	32.39624	32.30727	32.30667	26.775
11:00	34.39453	33.49455	34.52247	34.46656	34.46714	28.55
12:00	36.53903	35.24888	36.63627	36.59743	36.59924	29.975
13:00	38.35545	36.88382	38.44101	38.40829	38.41078	31.425
14:00	39.82634	38.14416	39.84221	39.85844	39.86143	32.325
15:00	40.54086	39.00628	40.6378	40.56601	40.56944	32.875
16:00	40.6363	39.30909	40.69417	40.66571	40.66903	33.6
17:00	40.14118	39.17979	40.21375	40.18445	40.18707	33.95
18:00	39.38896	38.8169	39.49918	39.4526	39.45422	33.85
19:00	38.63222	38.36382	38.77061	38.71048	38.71125	33.125
20:00	37.67344	37.74434	37.86538	37.78263	37.78296	31.7
21:00	36.44444	36.89615	36.76757	36.62806	36.6279	29.8
22:00	35.19479	35.96128	35.62317	35.43487	35.43396	28.175

23:00	34.13181	35.10346	34.61161	34.39859	34.39708	27.575
00:00	33.26764	34.31731	33.76915	33.54694	33.54515	26.75
Average	34.3	34.4	34.6	34.5	34.5	26.9
Average (%)	Base case	0.3	0.9	0.6	0.6	
Standard Deviation (SD)	4.4	3.6	4.2	4.3	4.3	5.5
SD (%)	Base case	-18.1	-4.5	-2.2	-2.2	

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