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Systematic Review

A Systematic Review on the Risk of Overheating in Passive Houses

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Abstract: The rise in energy-efficient building strategies, driven by the intensifying energy crisis, has encouraged the development of the passive house (PH) approach. However, existing research highlights a potential downside, the perception of the overheating risk in hot periods, particularly when design and construction methods fail to incorporate adequate mitigation strategies. This study examines the pressing necessity of addressing overheating risks in PHs through a systematic review. The aim is to identify key factors reported as contributing to overheating, to evaluate recommended solutions across diverse global regions, and to identify methods to reduce the risk. This review indicates that PHs are considered at risk of overheating in the hot periods of the year across many climatic regions, exacerbated by the impacts of climate change. Architectural features, climate conditions, inhabitants' behaviors, and perceptions of the quality of indoor spaces are important factors affecting PH overheating and should be considered at the design stage. It is concluded that the urban context, building envelope characteristics, and their impacts require greater attention. Based on the knowledge gaps identified, green walls are proposed as a nature-based solution with good potential for mitigating overheating in PHs. More integrated consideration of all factors and solutions can minimize current and future risks.

Keywords: passive houses; overheating risk; indoor air temperature; thermal comfort

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1. Introduction

Extreme weather and warming trends have resulted from global climate change [1]; subsequently, people are more frequently subjected to heat stress due to growing urbanization and climate change [2]. Buildings are required to meet more stringent and advanced standards: specifically, hey should be sustainable, consume no more than zero net energy, create comfortable and healthy surroundings for residents, and be grid-compatible while being affordable to build and maintain [3]. Accordingly, due to the need for high thermal comfort and low energy consumption, architects and researchers across the globe are increasingly favoring passive house (PH) design [4]. The purpose of this paper is to draw together and review extant information relating to a specific concern sometimes associated with passive house buildings: the potential to cause overheating. The authors believe this review will be of value to the wider research and practitioner community, especially as PH buildings are being increasingly promoted for use in hot climates. It thus provides a suitable collation of material for those planning future developments of PHs. At the same time, it should be noted that the use of PH design approaches does not preclude the use of cooling systems if required by the climate, but it does attempt to minimize the need to match an adjusted cooling energy criterion.

In cold climates, PH design aims to reduce heat loss and optimize potential to use solar and other heat gains through a focus on the building envelope. In regions with higher ambient temperatures, the insulation standards also need to be high to minimize conduction heat gains from windows, walls, and roofs. In regions with hot and humid weather, the humidity level should be controlled. The design principles for PHs differ according to the climate zone. In both cold and hot regions, it is better to have a compact building shape that maximizes the ratio of exterior surface area to living space [4].

Providing "an adequate and even enhanced interior environment concerning indoor air quality and thermal comfort" is one of the goals of the PH concept [5]. Although several standards that use adaptive comfort models would suggest that the sense of overheating in buildings is not as extreme as in other models, there are ambiguities regarding how these standards will be used [6]. It is crucial to have the right tools to foresee this risk during the design process to create comfortable, healthy homes that can survive both the current climate and hotter ones in the future [7]. The passive house or passive building design approach might be summarized as an approach to constructing buildings that utilize natural energy sources and passive techniques to achieve energy efficiency, comfort, and sustainability, taking into consideration climatic conditions in both summer and winter seasons. Initially, there was a focus on minimizing heat losses [5], but over a number of years, there have been examples showing dissatisfaction with internal thermal comfort during hot periods, prompting this review [7,8].

It should be noted that the terms "Passivhaus" and "Passive House" are interchangeable in the literature; in this study, PH replaces both for efficiency. A rising number of studies demonstrate that, given the current climatic circumstances, overheating during hot periods is becoming a significant issue in both new and existing homes [7,9]. Consequently, achieving high energy efficiency in PHs whilst simultaneously offering appropriate thermal comfort in all locations and seasons is becoming more complex [10]. In addition to the threats to health and thermal comfort, overheating can also result in higher electricity consumption due to an increased use of air conditioning [11]. New buildings need to be constructed to adapt to a warmer environment, as the risk of hot period overheating may increase [12]. If policymakers quickly implement adaptation actions, the risk of overheating in new and existing buildings can be reduced [6]. Otherwise, passive modifications cannot completely prevent overheating; therefore, by the 2080s, active cooling will probably be needed to keep a pleasant temperature inside a PH, not only in warm regions but also in more moderate climate areas.

The energy-efficient passive house concept also needs review and/or modification due to dynamic climate changes in different regions. Whilst PH design calculations already incorporate some of these concerns, this study aims to review research studies relating to the overheating risk in PHs to identify the primary factors, address the gaps, and propose a new strategy to minimize this risk. We therefore conduct a review and analysis of previous research on the overheating risk in PHs across diverse global regions. By examining the timeline of existing research, this study emphasizes the critical need to integrate overheating risk considerations into PH design. The main aims are as follows:

- Highlight the potential problems and the need to address these in a timely manner and quantify the impact of the overheating risk and its potential consequences.
- Highlight regional variations in overheated PHs considering the regional diversity of the risk associated with overheating PHs.
- Identify influencing factors and explore the numerous factors that contribute to the frequency and intensity of overheating in PHs.
- Identify and evaluate the effectiveness of existing solutions for the overheating risk in PHs and conduct a comprehensive overview of currently available strategies, analyzing the influence and effectiveness of each solution in addressing thermal comfort challenges within PHs.
- Identify knowledge gaps and highlight areas where further research and development are needed.

Through a multifaceted approach, this systematic review paper can provide a novel contribution to the knowledge of the risk of overheating in PHs. This study uses a stage-based development trajectory to identify three aspects of research on the risk of overheating in PHs. It assesses studies based on relevance and reliability, highlighting gaps in the existing literature and the time-dependent nature of climate change. The analysis identifies significant areas of knowledge and provides recommendations for future research. This knowledge will be valuable to various stakeholders including designers and can be incorporated into strategies to mitigate overheating risks during the initial design phase. Occupants can gain a deeper understanding of their important role in maintaining thermal comfort. Also, other stakeholders like policymakers and industry professionals can utilize the findings to develop guidelines and implement solutions. It is not, however, designed to be a review of PH design manuals or the Passive House Planning Package in detail (though the latter is referred to in Section 3).

2. Materials and Methods

This study reviewed the research on the overheating risk in PHs by emphasizing the timeline over which this occurred and investigating the number of studies based on the time and issues addressed across several geographical regions. By focusing on the cases considering climate factors, building design and construction, and the degree of the overheating risk, features associated with this issue have been categorized. Sources and references were categorized through searching the keywords 'Passive House', 'Passivhaus', 'overheating risk', and 'post-occupancy evaluation', along with related fields such as 'energy performance' and 'thermal comfort.' This study extracted what could be classified as reliable data from ISI Web of Science, ScienceDirect, Scopus, and PubMed digital libraries. In addition, related research theses, conferences, government documents, reports, and items from passive house institutions and trusts were also collected. The strategy for the searching of information was based on the publication date from 1988 to 2024, language, study type, including reviews, experimental studies, observational studies, simulation studies, survey studies, case studies, comparative studies, policy analysis studies, technical reports, and intervention studies, and full-text availability. Data were extracted and categorized based on climate factors, building design and construction, and overheating risk factors. European studies are classified into three stages due to the number of studies and methodologies applied in each phase.

2.1. Inclusion and Exclusion Criteria

The PH concept originated in Germany and subsequently gained traction in Austria, Sweden, and Switzerland. This review focuses primarily on research published in English with readily available full text. To broaden the scope, a limited number of relevant studies were included after translation from German, Swedish, Dutch, Norwegian, and Chinese. It should be noted that this study excludes documents in native languages due to the diversity of local sources, which may limit the comprehensiveness of this review. Additionally, as the primary focus of this study is on passive houses (PHs), the overheating risk in common buildings and energy-efficient buildings is only considered in comparative studies. The conceptual framework of this study is illustrated in Figure 1.

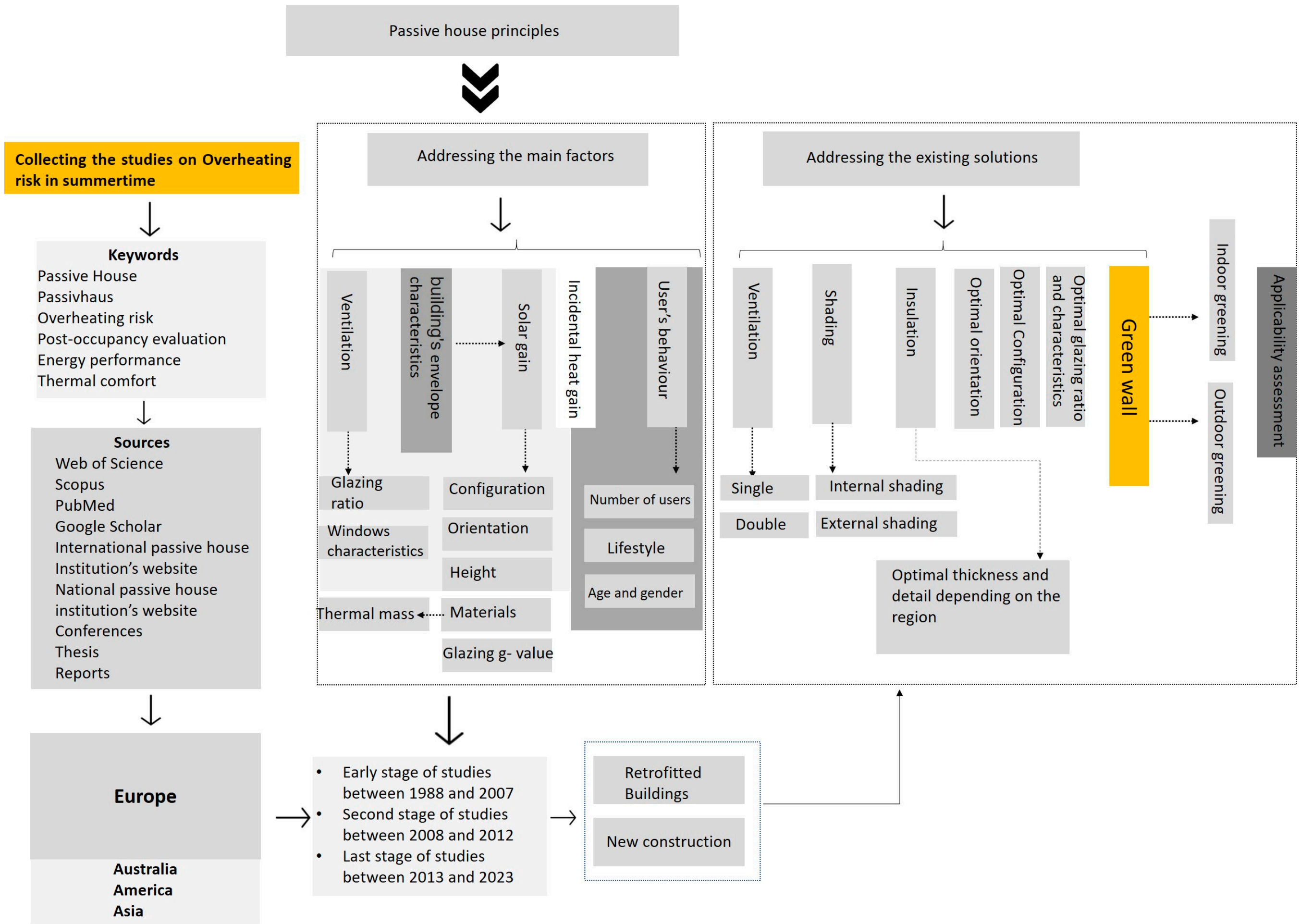

Figure 1. Conceptual framework of study.

2.2. Study Selection

The study selection process adhered to the PRISMA 2020 guidelines for assessing the overheating risk in PHs. Initially, 1984 records were identified through database searches, with an additional 55 records identified from other sources, totaling 2039 records. After removing duplicates, 1966 records remained. These were then screened, resulting in 312 records. Out of these, 114 records were excluded based on the initial screening criteria. The remaining 198 full-text articles were assessed for eligibility, and 18 were excluded for several reasons. Ultimately, 75 studies were included in the qualitative synthesis, and 105 studies were included in the quantitative synthesis (meta-analysis), as depicted in the PRISMA flow diagram in Figure 2.

Main Study Characteristics: Studies are categorized based on geographical region, time period, and methodological approaches. This review highlights three distinct stages of research from 1991 to 2024.

Main Limitations: this review acknowledges limitations in the study methodologies, the impact of technological advancements, and language barriers in accessing relevant studies.

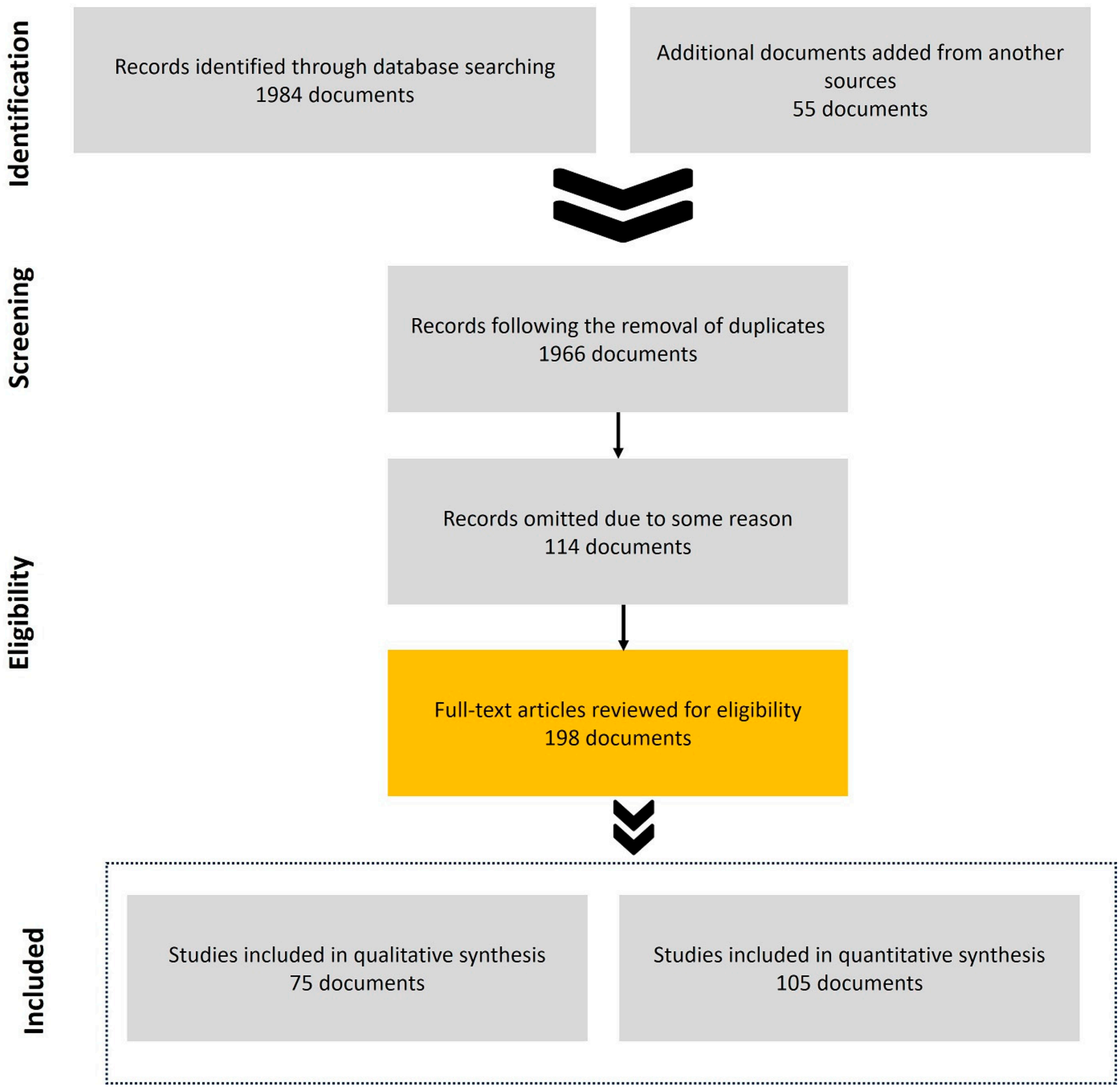

Figure 2. Database diagram constructed according to PRISMA approach (used under terms of CC BY 4.0 License) [13].

3. Overheating Risk in Passive Houses

The PH standard employs a predetermined threshold temperature that remains constant regardless of the weather outside and the vulnerability of the building's occupants to assess the risk of overheating. According to the guidelines, dwelling spaces cannot have temperatures above 25 °C for more than 10% of the time they are occupied [14]. Planning for less than 5% overheating is encouraged, according to the Passive House Institute, taking future climate changes into account [15]. In some countries, such as Belgium, the Passive House Platform standard sets 5% over a year as the allowable limit for PHs [16]. The overheating evaluation uses the same PHPP inputs as those used to calculate the building's thermal envelope, such as insulated opaque elements, thermal mass, glazing system performance, and ventilation systems [8]. Heat stress directly affects human thermoregulation, which is determined by the interaction of two independent variables, clothing and metabolic rate, with four external parameters, including the effects of air temperature, radiant temperature, humidity, and air speed, and the body when coupled [17].

3.1. Overheating Prediction Tools

It is crucial to have the right tools to foresee the overheating risk during the design process to create livable, healthy homes that can withstand both the current climate and warmer ones in the future [18]. To simulate the performance of a specified PH, the PH Institute developed a conformance tool called PHPP. It was carefully created using contrasting dynamic simulations to validate measurements in finished passive house projects, so it is considered an accurate tool in the PH community [19]. Although there are simulation tools to anticipate the overheating risk of dwelling in hot periods, the choice of the airflow modeling strategy is crucial for PH buildings to predict overheating accurately. Goncalves et al. stated that the method of BEM airflow modeling is unlikely to appropriately predict the extent and frequency of overheating incidence for PHs in warmer climates [20].

On the other hand, PHPP's overheating frequency evaluation has limitations, although its capability for overheating risk prediction was confirmed by Ridley et al. [21]. However, the limitation of PHPP for estimating the overheating risk in hot periods has been addressed in numerous studies; for instance, Hopfe and McLeod [22] declared that although PHPP is a reliable and well-validated tool, it is insufficient to determine the total amount of overheating danger. Similarly, Morgan et al., [23] concluded that popular prediction systems do not seem to be able to predict overheating with sufficient accuracy. The energy performance gap through the simulation and monitoring of PHs in the North of England was proved [8]. This study showed inaccurate predictions of indoor temperatures by PHPP. Finegan et al. [24] determined the precise difference between the measured indoor temperature and PHPP simulations by comparing the PHPP simulated annual overheating frequency with that measured through a comparative study. In addition, the study on certified PHs of Australian student accommodation revealed the inaccuracy of PHPP's ability to predict potential overeating frequency [25]. Through post-occupation evaluation, inadequate simulation reality results were identified [26].

3.2. Three Stages of Studies in Europe on PHs

In this study, taking account of the time dependency of climate change and climate-resilient strategies, the timeline illustrates the occurrence of the overheating process in the first certified PHs in Germany in 1988. Not surprisingly, as this concept was started in Germany and then accepted in Sweden and Austria in the early-stage studies that span 1991–2007, most of the studies have been conducted in central and northern European countries. During this time, studies were scarce and primarily presented in German, Swedish, Norwegian, and Dutch. It was the first stage of the post-occupancy evaluation that highlighted occupancy satisfaction in most of the case studies. Since PHs were still a novel idea for cold regions, residents were more concerned about their inability to heat than their need for cooling [27]. The research on overheating in PHs has seen a steady rise, particularly during three distinct stages:

- Stage 1 (1991–2007): this initial stage witnessed a moderate increase in research, primarily concentrated in northern Europe, and the instances of overheating are minimal.
- Stage 2 (2008–2012): Notably, the first UK study on overheating emerged just three years after the UK's first PH construction. Climate change was also recognized as a contributing factor. The number of overheated case studies increased in this stage.
- Stage 3 (2013–2024): This period marked a significant expansion in research, with a growing body of studies conducted across diverse regions including Europe, Australia, and Asia. Importantly, UK-based research joined the global effort during this stage.

3.2.1. The Early Stage of Studies in Europe between 1991 and 2007

In a preliminary study conducted in Stadtwerke Hannover from October 2000 to May 2001, a socio-scientific assessment of the PH "Lummerlund", built in 1999, was performed. High indoor temperatures and the lack of room temperature control were reported in the bedroom [28]. Ebel et al. [29] compared PHs and low-energy buildings in Germany and concluded that the temperature conditions in hot periods were rated worse on average than those in winter. A slightly higher frequency of overheating was measured in low-energy homes (on average, 7.5% of the time above 25 °C) than in the PH dwellings (6.5%).

A study on the first multi-storey PH, located in Kassel, Germany, in 2003, showed a high satisfaction of tenants during hot periods [30]. However, in 2005, another study on PH dwellings conducted by Berndgen-Kaiser [31] in Aachen (Germany) showed that thermal comfort is negatively rated in the hot period due to overheating. This was often due to a lack of sun-shading devices, and 38% of residents complained of excessively high temperatures in the hot period.

The row of houses in Lindås, which was completed in 2001, was the first Swedish project [27] to be investigated. The mean internal temperature for the four PHs in Lindås, analyzed by the Technical Research Institute of Sweden in a study of 20 terraced PHs, was 25.2 °C in the hot period [32]. Moreover, Schnieders [33] indicated that the majority of residents (88%) expressed satisfaction or extreme satisfaction with the hot period indoor air quality through an evaluation of 11 PH projects within the EU-funded demonstration project CEPHEUS (Cost Efficient Passive Houses as European Standards) [33,34]. Likewise, in a post-occupancy study by Feist et al. in 2005, great satisfaction with the hot period indoor climate was observed [5]. A PH survey in Hamburg–Lurup, Germany [31], established in 2005 found that 33% of the respondents were delighted with their housing after regulated winter operations, although 36% of the apartments experienced hot period overheating.

3.2.2. The Second Stage of Studies in Europe between 2008 and 2012

In the second stage, the number of overheating studies increased remarkably in Europe, with southern European cases reported for the first time based on the first PH constructed. A brief version of the PH study was provided as part of the 8th Vienna Housing Research Days on 17 November 2009, with a focus on "Energy Efficiency in Residential Construction", and the significance of the total energy efficiency consideration was heavily debated for the hot period.

Samuelsson and Lüddeckens [27] studied the indoor climate in PHs in their master's thesis. They surveyed three PHs in Frillesås, Oxtorget, and Gumsløv in Sweden to investigate user satisfaction, employing a questionnaire about temperature variations, draughts, and perceived indoor climate. More than half of the residents complained that it was too cold in the winter and extremely hot in the hot period, especially in one of the three projects.

The POE in Vienna discovered that issues with humidity and temperature were comparable to those in older buildings, but they were becoming more obvious. Since the first large passive residential buildings were built, such issues have increasingly been considered. Any high-rise building is believed to have some weaknesses in terms of controlling temperature and moisture, especially during the first winter after moving in (the "drying phase"). Still, PHs draw attention because their residents concentrate on this area ("priming"), which makes deviations more obvious and negatively viewed [35].

With the necessary modifications, a building idea based on the Darmstadt Passivhaus Standard, such as the PH in Bronzolo, was claimed to be usable in warmer European climes [36]. Noticeably, hot period overheating has been reported in a two-story PH in Lidköping, Sweden [37]. In Mühlweg in Vienna, Austria, Wagner et al. [38] tested multifamily buildings, including four houses and 70 apartments, and the duration in hours of defined overheating. Larsen and Jensen [39] conducted research on the interior environments of 10 PHs in Skibet, Denmark, in the same year. Overheating indicators such as CO_2 levels, relative humidity, and dry-bulb temperature were examined. The results revealed that in July 2009, 40% of the limits were exceeded, whereas in 2010, they were exceeded 60% of the time [39].

Rising global temperatures were a concern at 15 international PH conferences in 2011. An international shift toward energy efficiency was also noted [40]. And a report published by the Bundesministerium für Verkehr, Innovation und Technologies in Austria [41] compared the results from measurements carried out in five PH homes in Austria. Some projects have also highlighted the overheating risk that occurs in the hot period. A simulation study showed that the hot period temperature exceeded that in the Swedish PHs in the Lambohov neighborhood of Linköping [42]. Meanwhile, a literature review on PH indoor air quality written by Thomsen and Berge [43] in Norwegian declared (based on findings from the studies) that there was little evidence to suggest that the indoor climate in PHs was worse than in conventional houses. They concluded that measurements and the users' experiences of the indoor climate were mainly positive.

During this period, most studies were conducted and presented in native languages, including theses, regional reports, and PH documents. Comparing the current stage to the previous one, the applied methodology was clearly lacking, and the studies' advice on development was only partially useful. For example, obtaining professional sensors that could measure all environmental components and their fluctuations was difficult. The details of the examined cases were also not described very well, and additionally, the quantity and functionality of the simulation software were restricted. For this reason, unlike in the third stage, the results are not very accurate or comparable.

3.2.3. The Third Stage of Studies in Europe between 2013 and 2024

Indoor thermal environments in nine passive dwellings in Sweden were evaluated by Rohdin et al. [44]. They discovered that the PHs generally had good indoor thermal comfort; however, they also discovered several complaints about the high hot period temperatures. Eleven units of Vienna's PH Utendorfgasse have individual temperature controls, and 90% of those polled expressed satisfaction with the living room temperature. To maintain the ideal room temperature, 14.3% of people with individual room temperature preferences chose to continuously ventilate their bedrooms [45].

POE analysis in PH office buildings was used in studies in the hot period of 2013 in Romania; the results showed good indoor air quality and comfort [46]. In the same year, overheating was reported in several PH studies in subtropical climates in Europe [47]. However, even in regions with temperate climates, overheating was frequently reported [48]. A one-year study on PHs in Cesena, Italy, an area with high precipitation, revealed that overheating occurred in the hot period [49]. Dynamic simulations of tall PHs in northern Spain identified overheating on hot days; this study examined various strategies to cool the indoor environment and concluded that the best course of action depended on the building's location, use, orientation, activity, climate, and form [50].

To predict the overheating risk in hot periods, Goncalves et al. [20] investigated by comparative analysis several airflow modeling methodologies with PHs relying on natural ventilation and concluded that PH overheating in a temperate or colder climate is of lower risk, but in a warmer climate, it is underestimated and needs more attention. Even Horner et al. [51] stated that to maintain comparable hot period comfort in Germany with a cold climate over the longer term, more efforts to deal with hot period overheating and more comprehensive cooling measures would also be required [51].

Studies have been conducted to support the application of the standards in warmer regions, even though the PH standard was originally established for cold weather situations, representative of Central and Northern Europe [52]. Overheating during the warm season is found when using PH concept implementation in southern Europe [53,54]. A recent study on the indoor air quality of PHs conducted on 15 PHs in Hungary concluded that relative humidity, overheating, and improper particle filters in the mechanical ventilation system were found to be common issues pertaining to the building features [55]. The research that has been conducted in Europe on the risk of overheating in PHs is collated in Table 1.

Table 1. Studies on overheating risk in passive houses in Europe.

Author	Year	Region/ Climate Class	Building Type	Methodology	Specified Risk Area	Type of Construction	Results
Mlakar and Štrancar	2011	Slovenia, Cfb	Single-family house	Simulation		N	Without measures like night-purge ventilation and outdoor shade, the building would experience inside temperatures much above 26 °C [56].
Hidalgo et al.	2015	Spain, Cfb	Single-family house	Monitoring	Kitchen, living room, and dining room	R	Overheating was observed because the period over 25 °C exceeded 11.8%. The home does not adhere to Passivhaus standards [57].
Figueiredo et al.	2016	Portugal, Csa/Csb	Detached house	Dynamic simulation		N	Long durations of overheating throughout the summer (from 13 to 43%) and long times of thermal discomfort during the heating season (from 60 to 92%) were both recorded [58]
Fokaides et al.	2016	Cyprus, Csa, and BSh	Detached residential building	Dynamic simulation		N	Adaptive thermal comfort levels are met during the hot period, with relatively few instances when the temperature deviates from the ±3 °C threshold specified by the standard [47].
Heracleous and Michael	2018	Cyprus, Csa, and BSh	Educational building	Dynamic simulation	Classrooms	N	During 4% of the occupied hours, classrooms facing east and west experience temperatures that surpass the CIBSE standards [59].
Abrahams et al.	2019	Belgium, Cfb	Dwelling	Monitoring, simulation, and quantitative method	Living room		Different areas of the building were at risk of overheating, particularly the living room where 8% of the time is thought to be overheated annually [60].
Finegan et al.	2020	Ireland, Cfb	Dwelling	Monitoring and simulation	Bedroom	N	The output average housing temperature shows a significant difference between overheating that is simulated and reality [24].
Tian and Hrynyszyn	2020	Norway, Dfb	Dwelling	Simulation	Bedrooms	R	Under the current condition, the 2050s, and the 2080s, it was discovered how many hours in the studied rooms were unacceptable [61].
Figueroa-Lopez et al.	2021	Spain, Cfb	Residential tower	Dynamic simulation		N	Overheating on warm days was reported and a mix of strategies was suggested to minimize the risk [50].

N: new construction; R: retrofitted.

3.3. UK-Based Studies

Although the first official PH in the UK was constructed only in 2010 [21], 200 PHs had been completed by 2014 [62]. This energy-efficient concept has been widely accepted in the UK in recent times, and the number of buildings is growing. Dengel and Swainson conducted a detailed review of the data regarding overheating in UK houses and found that the evidence supporting the claims that homeowners overheat is growing [63]. According to McLeod et al. [64], despite confirmed claims of overheating, the UK and neighboring Ireland did not give the issue of overheating any consideration in the scientific literature on PH dwellings until 2012.

Monitoring of the first certified PH in the UK by Ridley et al. [21] demonstrated that for a quarter of a year, the living room in the Camden house exceeded 25 °C in the hot period 22.5% of the time, and the living room was warmer than 25 °C. A comprehensive study across the UK assessed the risk of overheating during the cooling season in social housing flats constructed according to the PH standard. With more than two-thirds of dwellings exceeding the standard, there was a high risk of hot period overheating. Even though overheating levels in different flats vary significantly, a thorough investigation shows that this is more a function of occupant behavior rather than structure [65]. Zhao and Carter [66] used the Passivhaus Trust database to identify 34 residential projects completed and inhabited in the UK between 2011 and 2015.

Through "perceived comfort" assessments considering social elements that affect comfort, the meaningful relationship between assessments and occupants' individual experiences was excluded. Another study in the UK revealed that by analyzing individual rooms, only 60% of bedrooms in houses satisfy the PH standard. It is recommended that to boost trust in the PH application during the design phase and gain a deeper comprehension of the overheating risk, it is essential to compare two different tools and their techniques, referring to collected in-use data [7]. A PhD thesis in the UK focused on indoor air quality in winter, spring, and the hot period in five PHs and four conventional houses, using qualitative (interviews and diaries) and quantitative (monitoring) methods. The results proved that in the hot period, high indoor temperatures can negatively affect the health of occupants [67].

A comparison of five Scottish PHs demonstrated overheating issues at maximum temperatures above 30 °C; systems with unbalanced MVHR and an insufficient IAQ were discovered due to inadequate ventilation in 80% of the houses [68]. In another study [69], various inclined façades were evaluated using dynamic simulation modeling software to understand how well they reduced the risk of overheating. According to the research, installing a tilted façade may reduce the chance of overheating in the UK climate; however, it would have some adverse effects on daylighting and natural ventilation. Nevertheless, by the 2080s, such geometric considerations would not eradicate the risk of thermal discomfort and overheating. Table 2 presents the findings of research conducted in the UK regarding the potential for overheating in PHs.

Table 2. Studies completed on overheating risk in passive houses in the UK.

Author	Year	Region and Climate Class	Building Type	Methodology	Place under Risk	Orientation	Type of Construction	Results
McLeod et al.	2013	London, Cfb	Terrace dwelling	Dynamic simulation	Bedrooms		N	Evidence reveals that Passivhaus buildings and super-insulated homes are already at risk of overheating [64].
Ridley et al.	2013	London, Cfb	Small family dwelling	Monitoring	Living room and bedroom		N	For 123 h (about 10 days), the operating temperature in the living room surpassed the 28 °C threshold set by (CIBSE) Guide A (2006), while for 43 h (about 4 days), the operating temperature in the bedroom exceeded 26 °C [21].
Ridley et al., Ridley and Stamp	2014	Camden, Cfb	Detached house	Monitoring	Bedrooms	West and south	N	15% of the time, the living room's temperature exceeded 25 °C, breaking the PH limit. In the bedroom, the CIBSE TM52 criterion was not fulfilled. Occupant survey results, however, indicated that this is not a concern [21,70].
Ingham	2014	Wimbish, Cfb	Terrace dwelling	Interview and monitoring		South	N	Higher internal gains and the absence of hot period bypass in the MVHR contribute to overheating [71].
Mackintosh	2015	Lockerbie, Cfb	4 semi-detached houses	Monitoring and Simulation	Bedrooms	East–west	N	By having no hot period bypass on the MVHR and little hot period shade, warm interior gains were generated by uninsulated pipes in the hot period [72].
Leeds Beckett University for the Gentoo Group	2015	Houghton-le-Spring, Cfb	Terraced bungalows	Thermographic survey; Fabric testing; and surveys	Bedrooms	South–north	N	29% of people indicated that the heat of hot periods was bothersome. Overheating is said to be made worse by the MVHR's boost function and a lack of overnight cooling [73].

Table 2. *Cont.*

Author	Year	Region and Climate Class	Building Type	Methodology	Place under Risk	Orientation	Type of Construction	Results
Tabatabaei Sameni et al.	2015	West Midlands, Cfb	Social housing	Monitoring	Living room		N	There is a significant chance of hot period overheating because almost two-thirds of apartments are larger than average [65].
Foster et al.	2016	Southwest and west Scotland, Cfb	Four semi-detached homes and one end-of-terrace house	Monitoring, interviews, and behavior profiling	Bedrooms	East–west	N	With maxima over 30 °C, there is overheating. In 80% of the homes, improper mechanical ventilation with heat recovery (MVHR) systems led to unsatisfactory indoor air quality [68].
Fletcher et al.	2017	UK, Cfb	End-of-terrace bungalow dwelling	Monitoring	Kitchen and bedroom	South	N	There is significant night-time overheating and apparent overheating during the cooler months that might put vulnerable people in danger [8].
Botti	2017	Edinburgh, Cfb	51 dwelling flats and terraced houses	Monitoring and survey			N	The investigations revealed frequent overheating, with the number of users and ventilation specified as the main factors [74].
Morgan et al.	2017	Barrhead, Livingston, and Glasgow, Cfb	21 low-energy houses and 5 PH dwelling	Monitoring and survey	Bedrooms and living room		N	The data gathered over a year showed that Scotland's PHs are experiencing worryingly important levels of overheating [23].
Mitchell and Natarajan	2019	Various cities, Cfb	82 homes 82 dwellings, and 62 houses and remaining flats	Monitoring	Bedrooms			Instead of considering overheating throughout the house, Passivhaus buildings should take specific rooms into consideration [7].
Jang et al.	2022	UK, Cfb	A comparative study (typical residential and PHs)	Monitoring	Bedrooms			Although the chance of an entire home overheating is low, bedrooms in highly insulated homes may carry an overheating risk [75].

N: new construction.

3.4. Studies in Asia

The simulation study conducted by Jayasinghe and Priyanvada [76] in multi-storey dwelling PHs in Sri Lanka found that this strategy could not provide thermally comfortable quality in the hot period due to high indoor temperatures. China's first certified PH appeared at the Shanghai World Expo in 2010 with the "Hamburg House" [77]. The simulation study demonstrated that in hot periods and cold winters in China, without active cooling, the PH cannot achieve the ideal indoor thermal environment [77].

The Zaishuiyifang community is the first residential PH dwelling in China, located in the north-east of the country, which is classified as a cold climate zone. The maximum bedroom temperature was 28.9 °C, and the minimum level of temperature was 26.8 °C in the hot period, slightly higher than the standard requirement [78,79]. Shu Zhiyong's team monitored a PH building in Jiangsu Province. The indoor temperature reached above 28 °C for part of the time, and the humidity reached a maximum of over 90%, with an average value of 72.5%, resulting in overheating and humidity discomfort [80]. Zhou Bin's simulation study showed that more active cooling equipment was needed in the hot period to achieve indoor comfort standards for PHs [81].

In a study conducted in northern China on PH overheating, window openings were found to be required. Perceived discomfort was mainly reported in the hot period and in winter in certain rooms for a short period. However, overheating occurrences during the cooling season (July to August) were recorded almost 28% of the time [82]. Zhao et al. [83] compared two PHs in cold areas in Beijing and Shijiazhuang, China, through simulation and on-site measurements, showing that in Beijing, the primary method for enhancing performance in the winter was to use an attached sunspace, but this also introduced the issue of overheating in the hot period. The Beijing test example experiences hot period overheating.

In another study, two PHs during a hot period and cold winter climate were simulated to understand the effects of insulation and airtight buildings. The results show a hot period overheating risk. Although the hot periods in many of China's areas are hot and humid, proper passive cooling and dehumidification technologies that provide indoor thermal comfort were not completely considered [84]. Korean PHs demonstrated a minimized heating demand but with overheating during the cooling season [85]. The research conducted on the potential for overheating in PHs in Asia is summarized in Table 3.

Table 3. Studies completed on overheating risk in passive houses in Asia.

Author	Year	Region	Köppen–Geiger Classification	Building Type	Methodology	Place under Risk	Construction Type	Results
Hu and Zhao	2014	China, Qinghuangdao	Cfa	Residential apartment	Monitoring	Bedroom	N	The bedroom temperature is between 26.8 and 28.9 °C (1 July–31 August 2014), slightly higher than the standard requirements [78].
Zhou and Zhang	2015	China, Hefei	Cfa	Office and school buildings	Simulation	Office room	N	It does not meet the energy-saving standards of German passive buildings. In the hot period, more active cooling equipment is needed to achieve indoor comfort standards for passive buildings [81].
Shu et al.	2019	China, Jiangsu	Cfa	Office building	Monitoring	Office room	N	The measured indoor temperature reaches above 28 °C part of the time, and the humidity comes to a maximum of over 90%, with an average value of 72.5%, and there will be overheating and humidity for part of the time [80].
Fu	2019	China, Hangzhou	Cfa	Office building	Simulation	Office room	N	The simulation results show that when there is no active cooling, the indoor temperature and humidity detected are comfortable for 70% of the time [77].
Zhao et al.	2020	China, Beijing and Shijiazhuang	Dwa and BSk	Dwelling	Simulation	Living rooms and bedrooms	N	This study mentioned the overheating issues in the hot period but did not prove them [83].
Zhang	2020	China, Ürümqi	BSk	High-rise commercial and residential buildings	Monitoring	Bedroom	N	The highest temperature reached 37.88 °C. The average temperature in Apartment No. 1 was about 26 °C. 35–45% dissatisfaction in the hot period was reported [86].
He et al.	2023	China, Qingdao	Cwa	Office building	Monitoring and survey	Office room	N	Overheating occurrences during the cooling season (July to August) were recorded, almost 28% of the time. 60% of end-users felt thermal neutral, while 26% felt slightly warm to hot [82].

N: new construction.

3.5. Studies in the Americas and Australia

The underestimation of the overheating risk by PHPP through dynamic simulation of an Australian PH has been identified [87]. The study investigated the performance of the first student residence in Melbourne, Australia, built according to PH standards, which was evaluated by Kang et al. [88]. The case study building is concerned with overheating and energy utilization, according to a long-term measuring and monitoring effort focusing on thermal comfort conditions. The first USA PH was built in Wisconsin in 2010, and an occupant analysis in 2011 showed users' satisfaction during the hot period [4]. In the first study conducting a thermal comfort analysis on a Latin American PH in Mexico, measurements of humidity and indoor air temperature showed temperatures over 25 °C being recorded in the living room (8.03%), the kitchen (8.20%), and the bedroom (7.53%) for a portion of the year [89]. There was evidence of overheating in the kitchen and bedroom. The building failed all three criteria in both cities, indicating an elevated risk of overheating [90]. In a typical single-family home in Canada that has been modified to meet PH requirements, it was recognized that under free-running conditions, the risk of overheating for a typical Canadian house converted to the PH standard will increase dramatically starting in 2020 [91]. Table 4 presents the findings of the research.

Table 4. Studies completed on overheating risk in passive houses in Australia and the Americas.

Author	Year	Region and Climate Class	Building Type	Methodology	Place under Risk	Construction Type	Results
Moreno-Rangel et al.	2021	Mexico, Cwb	Dwelling	Monitoring	Bedroom and kitchen	N	For 7.53% of the year, the bedroom had temperatures above 25 °C, and this temperature was exceeded for 8.03% and 8.20% of the year, respectively, in the living room and kitchen [89].
Kang et al.	2022	Australia, Melbourne, Cfb	Student accommodation	Simulation		N	The case study building has issues with overheating and energy use [88].
Gnecco et al.	2022	Brazil São Paulo, and Manaus, Cfa and Af	Elementary school	Dynamic simulation	Classroom		There was a risk of overheating reported due to the lack of sun shading [90].

N: new construction.

4. The Main Factors Affecting the Overheating Risk

4.1. Building Characteristics

4.1.1. Materials

One of the most efficient passive measures to improve inside temperature, reduce temperature fluctuations, and decrease overheating is thermal mass, which is using a material's capacity to capture, retain, and release heat [92]. A simulation study on a super-insulated and energy-efficient Nottingham house showed that thermal mass can reduce overheating throughout the year [93]. Another study by Zune et al. [94] in tropical climates revealed that 3.6% hours of over-warming time per year could be avoided by utilizing shade in conjunction with the high thermal mass of the PH building envelope. Ozarisoy and Elsharkawy [95] studied the overheating risks and thermal comfort in UK prototype dwellings. It was concluded that the super-insulated and airtight buildings had insufficient ventilation in the living areas, and the high heat gains through the composite cladding material were the main causes of the unsatisfactory thermal performance. Conversely, the general intensity of urban overheating is determined by the materials used in the outside envelope of buildings [96]. The use of phase change material storage is an extra technique for delivering space cooling. It absorbs energy from its surroundings during the melting phase, and when it solidifies, it releases the same amount of latent heat to its surroundings [42].

Reducing the U-values can cause hot period overheating, a problem observed in Romania, which has higher temperatures compared to central European countries experiencing colder weather, such as Germany [97]. According to a study on PH dwellings in Korea, some societies have tailored their methods to address specific needs arising from unique local contexts. Modifying the prototype's U-values prevents overheating risks brought on by using 'Ondol,' a conventional underfloor heating system that runs on water [85].

4.1.2. Thermal Insulation

Several post-occupancy studies have found that improved insulation and airtightness increase the risk of overheating [98]. Recently, increased airtightness has raised the risk of the building overheating. Higher insulation modestly reduces the amount of time that bedrooms overheat in this investigation [61]. Using computer modeling, the Zero Carbon Hub [99] examined many UK locations in 2010 and discovered that high insulation levels and minimal air leakage, combined with increased solar gain, increased hot period discomfort. Similarly, overheating risk enhancement associated with more insulation and decreased airtightness was identified by Mulville and Stravoravdis [100]. Meanwhile, another study has the opposite view when analyzing poorly and very well-insulated buildings; the results indicated that insulation had a negligible impact on overheating. Insulation is therefore responsible for decreasing and increasing overheating, depending on the impact of additional factors, particularly at night, such as proper ventilation and solar shading. The parameter ranking reveals that insulation accounts for up to 5% of the overall overheating [101]. Further, Blight and Coley [102] stated that insulation is most effective between 0.25 and 0.30 m; thicker insulation may not significantly reduce energy use and may increase the need for cooling.

The first multifamily-certified PH in Bronzolo, Italy, concluded that while the highest level insulation is a crucial component of a PH in Northern and Central Europe, less stringent insulation standards can be developed for warmer regions [36]. Similarly, another study, through a dynamic simulation study on the energy performance of PHs in Italy, showed that unlike in a continental climate, many south-facing windows in this area had an increased need for cooling in the hot period. Bruno et al. [103] confirmed that the correct insulation thickness on the ground floor must be found to balance keeping heat in during the winter and letting heat out during the hot period. The negative effects of super-insulation during hot days were highlighted when a southern Italian flat in a warm Mediterranean climate was retrofitted according to PH principles. The envelope prevents heat from being adequately transferred outdoors during the hot period, especially at night [104]. The results from an analysis of a typical building in the hot and dry climate of Algeria revealed that despite the passive house standard's recommendation to super-insulate the building envelope with a thermal transmittance of 0.10–0.15 W/m^2 K, a cooling-dominated climate may not need this amount of insulation [105]. Another study was conducted in the Singapore region where the need is predominantly cooling; here the insulation of the floor raised the cooling demand and stopped heat leakage from the structure. Therefore, it was beneficial to remove the floor insulation to lower the need for cooling. Additionally, it was observed that although night cooling decreased the need for cooling, the higher humidity created an unfavorable indoor climate [106]. An investigation in regions in China with a hot period and a cold winter demonstrates that improving airtightness and thermal insulation leads to a rise in cooling energy use throughout the hot period and transition season, which is related to overheating [107].

4.1.3. Number of Windows and Glazing Ratio

Lightweight, airtight homes with little opportunity for cross ventilation, such as single-aspect apartments, are highly vulnerable to the risk of overheating [63]. As an example, in the UK, a PH must have optimum glazing on the south façade and fewer windows on the north façade to take advantage of the beneficial solar effects. A study showed that excessive glazing might increase the chance of hot period overheating [108], and another declared that a PH dwelling with a higher glazing ratio and a south orientation experienced more elevated overheating on summer days [70]. In the Wiesbaden–Lummerlund terraced house project (22 passive houses, 8 low-energy houses), satisfaction with living conditions was high despite the noise level and subjectively low efficiency of the ventilation system [35]. A study conducted by Carletti et al. in Italy [109], investigating the problem of passive buildings overheating in the hot period, they suggested minimizing the hot period solar gain through reducing the glazing ratio. Kalamees [110] conducted a recent study on the thermal comfort and hygrothermal performance of the building envelope of Estonia's first certified passive single-family detached house. The results primarily attribute the high room temperatures to the large south-facing windows and the minimal heat loss of the building envelope. An evolutionary algorithm was used to analyze three single-family PHs located in distinct climatic zones in southern Brazil. The study indicated that a well-designed combination of shading features and windows has a considerable positive impact on internal thermal comfort [111].

4.1.4. Form, Configuration, and Orientation

Rodrigues et al. [93], in a simulation study on a super-insulated Nottingham house, showed that the living room, kitchen, and south bedroom experienced the highest level of overheating, while in the north bedroom, it was negligible. Similarly, it was found that the risk of overheating frequency above 25 °C was strongly influenced by the south façade's window-to-wall ratio and the solar transmission reduction offered by an entire external shading mechanism [64]. An end-user study in the Netherlands on PHs showed that south orientation and a lack of shading lead to high temperatures in the hot period. A total of 29 respondents thought the living room overheated during the hot period, and 49% of the 88 respondents thought the bedroom was too hot [112]. The relationship between a building's internal volume and its external surface area has a significant impact on its overall energy demand. The surface area-to-volume (A/V) ratio indicates the compactness of the building. A desirable compactness ratio is one where the A/V ratio is less than 0.7 m^2/m^3 [108].

The building characteristics and urban heat island (UHI) impacts on overheating risks in London dwellings were investigated by Mavrogianni et al. [113]; they found that building form, orientation, and characteristics and surrounding buildings were more significant predictors of variation in high indoor temperatures than a building's position inside London's UHI. Although this study did not focus on PHs, it can provide a vision for overheating variations in the urban context. Controlling the radiative qualities of a building's exterior surface will significantly impact the need for space heating and cooling, according to Ascione et al. [114]. The indoor thermal performance will be impacted by the building's size. For instance, in a tropical climate study comparing a passive house in a cold setting, significant parts of the building envelope functioned slightly better in the free-running mode than others [94].

A study on a replica Victorian end-of-terrace house in Manchester, UK, accurately predicted the overheating risk in bedrooms occurring as early as the 2020s [115], while the impact of thermal mass on the future overheating risk was assessed for semi-detached houses in south-east England. The findings verified that problems would occur after 2050 [116], and incidental gains are another factor that cause overheating [117]. Although these studies did not focus on PHs, the results can be used for environmental analysis. In retrofitted case studies that were awarded PH certification, building typologies and their capacity to overheat must be considered. This suggests that designers should be more cautious about the risk of overheating associated with upcoming climate change.

4.2. Occupants' Behavior

Utilizing the full potential of low-energy dwellings requires post-occupancy engagement with occupants, both from a technical point of view to ensure proper operation of the residence and through training of the residents to ensure they fully take advantage of the design features [118]. However, Hasselaar [119] stated that the complexity of PH design is considered a design with absolute rules, and with increasing occupant awareness of the benefits, they are more likely to adapt their lifestyle. To fully unlock the potential of PHs, occupants can play a crucial role by adjusting their daily routines and behaviors. A higher level of satisfaction requires pre-occupancy training and adjustment time [120]. The frequency of overheating is significantly influenced by occupant behavior, including their vulnerability to high temperatures and how they manage the indoor climate [48]. The occupants' behavior and preferences significantly affect the overheating risk in PHs [70]. Emery and Kippenhan [121] found after a 15-year study on home energy consumption that occupant behavior had a more significant influence on total household energy use than the construction of the buildings and the use of insulation. By investigating a PH in Jiangsu Province, Shu Zhiyong's team concluded that human factors are one of the primary causes of indoor temperature changes [80]. A hot period survey in July 2013 in an office PH in Bragadiru, Romania, without an additional cooling system, concluded that the occupants showed adaptive behavior, and it is recommended that an adaptive thermal comfort assessment be conducted [46]. User experiences should be increasingly considered in PH design. Assumptions about user behavior consistent with existing norms are to be reconsidered [122]. Occupants' behavior in terms of appliance control [70,123] and the way in which occupants use PHs, particularly the selected temperature in the room and the window opening frequency due to indoor thermal comfort, significantly impact energy efficiency [124]. Dianshu et al. [125] demonstrated how internal heat loads are rising in homes due to the increased use of appliances and electronic gadgets in China. To build a successful PH, precise mechanical and architectural planning must be combined with community rules that establish social standards and allow occupants to engage with the PH concept. The PH concept will benefit significantly from habitation as it spreads to more people and reaches its total capacity for sustainable housing [66].

4.2.1. Density of Occupation

By examining the possibility of overheating in a current structure, Vellei et al. [126] discovered proof of overheating in 10 of the 86 rooms in nine residences. Regarding the monitored places, bedrooms and kitchens appeared to have the greatest overheating risk. Notably, the number of inhabitants was highlighted as an influential factor. A post-occupancy survey on affordable PHs in Edinburgh in the hot period of 2015 revealed the essential factors that influence overheating risk. Examples were increased internal heat gains brought on by the rising number of occupants and the use of domestic appliances, as well as, in some situations, a dependence on inadequate natural ventilation to expel excess heat [74]. Due to the high number of users, one PH's three children's bedrooms in the south experienced more overheating [87].

4.2.2. Personal Factors of Users

Individual characteristics such as clothing, the degree of activity, and the state of health affect thermal comfort in buildings were investigated by Chen [127]; further Porritt et al. [128] investigated the occupant characteristics associated with overheating in British homes built in the 19th century by monitoring a family and an old couple. The most effective remedy for older occupants is external shutters for windows rather than external wall insulation, while adding interior wall insulation is proven to extend overheating [129].

4.2.3. Simple Design and Occupant Awareness

Encouraging occupants to utilize advanced technologies in passive housing (PH) is a crucial element in boosting the effectiveness of this concept. The design should be simple, allowing managers and users to adjust to crucial factors that have previously been overlooked. According to a German study, tenants complain about the shading's excessive complexity and potential for overheating [130].

4.3. Climate Conditions

The Köppen–Geiger classification helps comprehend the extensive body of research and is widely accepted and used in many studies [131]. Reviewing the studies based on this classification demonstrated that buildings in each of the following regions experienced overheating in the hot period: temperate oceanic climate or subtropical highland climate (Cfb), hot hot-period Mediterranean climate, warm hot-period Mediterranean climate (Csa-Csb), hot semi-arid climate (Bsh), cold semi-arid climate (Bsk), warm- hot-period humid continental climate (Dfb), humid subtropical climate; (Cfa), monsoon-influenced hot-period humid continental climate (Dwa), subtropical highland climate (Cwa), monsoon-influenced humid subtropical climate (Cwb), and tropical rainforest climate (Af). It should be noted that Cfa and Cfb are the climate zones with a higher risk, according to the reported cases. Also, it can be noted that more studies have been conducted in these regions (Figures 3 and 4).

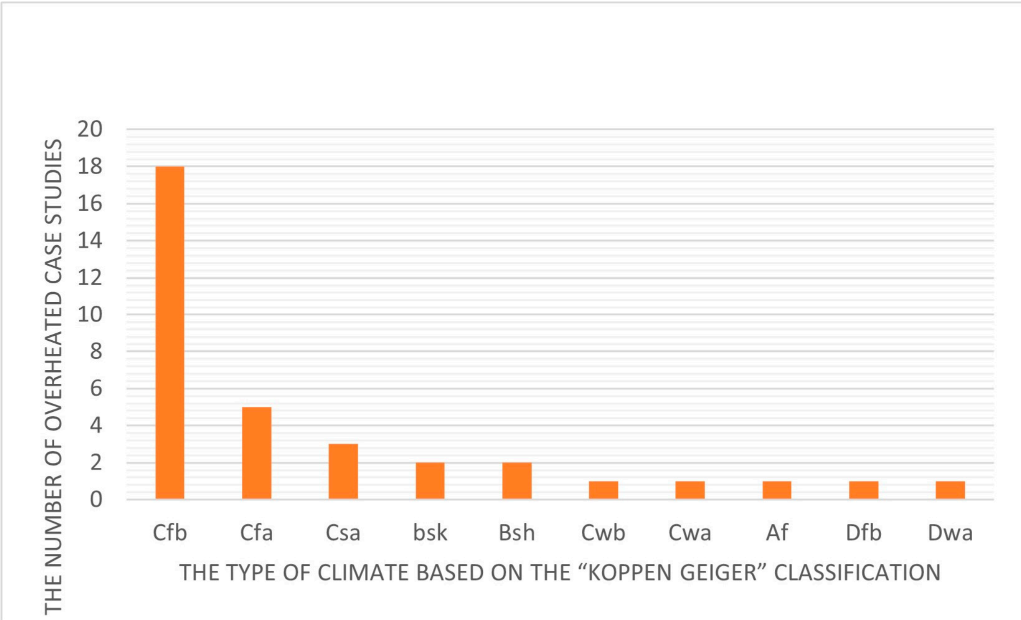

Figure 3. The climatic spread and frequency of overheated PH cases, according to studies.

The legend in Figure 4 illustrates the distribution of case studies concerning the maximum number of overheated instances reported, ranging from one to twelve cases per region. It is important to note that the aim of this mapping is not to show the density of cases, but to highlight the distribution of these instances and underscore the necessity of considering the overheating risk across various regions.

Reviewing the research reveals that the risk of overheating in the hot period has been considered in many studies on super-insulated PHs. These can be found in Central Europe [56], Southwestern Europe [57,132], Southern Europe [47,57,59], Northern Europe [37,39,42,61], Northwestern Europe [123], and the UK [7,8,21,24,64,65,75]. Also, there are several studies focused on the overheating risk in PHs in Australia [88], America [89,90], and Asia, mostly from China [77,79,80,82,107].

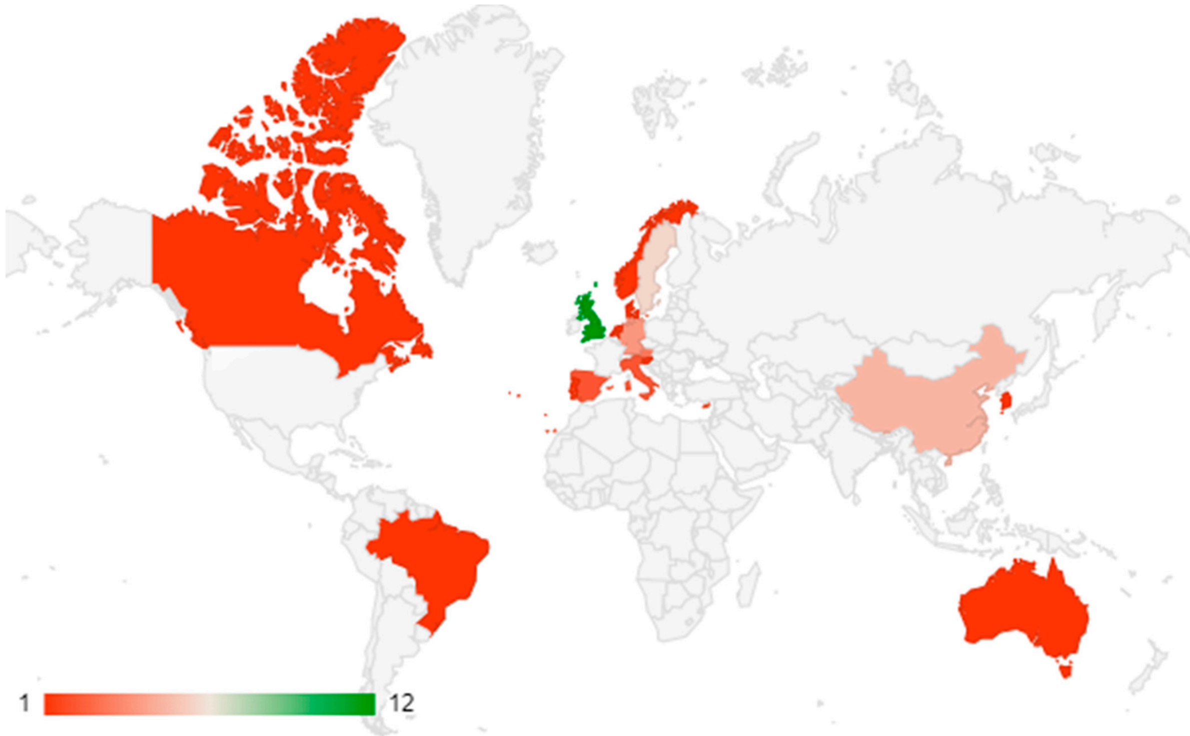

Figure 4. Mapping the geographical spread of overheated PH examples.

4.4. Study Risk of Bias Assessment and Certainty Assessment

4.4.1. Occupant Behavior and Lifestyle

Early-Stage Considerations

In the earlier studies within the review period (from 1988 to the early 2008s), there was a lack of understanding and consideration of occupant behavior and lifestyle. This oversight may have led to inaccurate or incomplete assessments of the overheating risk in PHs.

Impact on Results

As occupant behavior and lifestyle significantly affect the outcomes related to overheating, studies that did not account for these factors may present biased or skewed results.

4.4.2. Technological Advancements

Time Frame Variability

The time frame of this review spans from 1988 to 2024, a period characterized by rapid technological advancements and changes in building practices. Studies conducted in the early part of this period did not have access to the advanced technologies available in later years, potentially leading to differences in the findings and conclusions. Therefore, the timeline depicts the studies separated into three time frames in order to best illustrate this feature. This is also explained in Table 5.

Table 5. Risk of bias assessment and certainty assessment for study.

Occupant Behavior and Lifestyle		
a.	Early-stage considerations	From 1988 to the early 2008s, there was a lack of understanding and consideration of occupant behavior and lifestyle, which can lead to inaccurate or incomplete assessments of overheating risk in PHs.
b.	Occupant behavior and lifestyle impacts on study results	Although some studies find that occupant behavior and lifestyle are less impactful in PH dwellings, the role of occupant behavior is highlighted in many studies [11,46,48,65,70,123] as a factor that can significantly affect the outcomes related to overheating.

Table 5. *Cont.*

Technological Advancements		
a.	Time frame variability	This review spans from 1988 to 2024. Studies conducted in the early part of this period did not have access to the advanced technologies available in later years, potentially leading to differences in the findings and conclusions.
b.	Availability and integration of advanced technologies	The availability and integration of advanced technologies over time likely influenced how occupant roles and behaviors were considered, which leads to different focuses on various factors.
Contextual Differences		
a.	Geographical and cultural context	The consideration of occupant roles in different contexts, such as varying geographical locations and cultural settings, may have led to inconsistent findings.

Differential Impact

The availability and integration of advanced technologies over time likely influenced how occupant roles and behaviors were considered, resulting in varying degrees of emphasis on these factors across different studies, as mentioned earlier, in each stage.

4.4.3. Contextual Differences

Geographical and Cultural Context: The consideration of occupant roles in different contexts, such as varying geographical locations and cultural settings, may have led to inconsistent findings. Different regions and cultures have distinct living habits and building practices, which can impact the generalizability of the results.

5. Solutions

5.1. Optimal Orientation

A correct layout with reduced needless solar gain, enough thermal mass, good ventilation, and minimized internal gains possesses crucial elements that can prevent or reduce overheating [133]. For example, in the United Kingdom, a north–south orientation with daylight-optimized windows on the north façade and between 15 and 25% glazed on the south façade is optimal [108]. Lower south-facing windows enhance resistance to future warming in PHs in the UK [134]. In a south Brazilian PH analysis, considering the acceptable hot period indoor temperature of 26 °C in a humid subtropical climate, a 6.9% overheating frequency was the outcome, which is less than the permitted maximum limit. It is advised to employ passive design techniques, such as ensuring a building orientation to the east/west axis, appropriate building density, and glass on the north facade, to achieve positive results [135]. Buildings should be pointing southward in the Northern Hemisphere or toward the equator and lightly shaded because passive solar energy is a critical component of PH design. Most of the research on PH buildings focuses on the issue of the possibility of indoor overheating in PH buildings without making any recommendations for finding solutions. Additionally, the range of energy consumption and other design parameters has only been regulated by considering PH guidelines, making it challenging to ensure an ideal outcome [136]. A study on orientation and optimal glazing size in European climates classified as CFb, specifically Ljubljana, Budapest, Munich, and Stockholm, revealed the following: After accounting for the U-value and the G-value, the results indicated that the optimal glazing share for the main façade varied between 38% and 42%, depending on the characteristics of the glass. The reduction could range from 0 to 20% for the ESE (121.5°) direction, or from 0 to 24% for the WSW (247.5°) orientation [137].

5.2. Building Envelope Material Optimization

Heat loss and gain are substantially influenced by material qualities such as U-values, solar absorptivity, and thermal mass; therefore, choosing the optimum material properties is essential to enhancing a building's thermal performance [94]. A building's high thermal mass and vertical shades outside the east and west façades provide thermal comfort in hot periods [4]. Another study indicated that the interior temperature varies less throughout the day when there is a high thermal mass and the exterior shades are closed. However, it increases considerably when the night ventilation system is turned on, particularly in lightweight construction in temperate climates [138]. In a social housing PH study in southern Brazil, the results revealed that due to the significant daily temperature change, the heat gained throughout the day is released through the envelope, which results in high thermal transmittance and helps to cool the residence. During the night, when the air conditioning is turned on, this behavior helps to reduce the cooling demand [52]. Moreover, the roles of thermal inertia in conjunction with creative free-cooling technical solutions and dry assembled opaque walls made of natural materials were studied by Bruno et al. [139] in Mediterranean regions.

5.3. Ventilation

The use of higher external shading, thermal insulation, and natural ventilation are frequent passive tactics that replace standard mechanical devices to lessen the likelihood of overheating in the hot period [27]. Other research supporting these options indicates that solar shade and night ventilation can prevent interior warming. In order to keep the internal temperature constant and comfortable, it is required and potentially sufficient to keep the windows open at night during warm hot period days, to shade the southern and western windows, and to use as little internal energy as possible [56]. Through the analysis of 11 PH projects as part of CEPHEUS (Cost Efficient Passive Houses as European Standards), it was discovered that proper ventilation techniques can provide users with comfort in hot periods. Ventilation behavior overshadows the significance of occupancy and shading components [33]. According to Breesch et al. [140], natural night ventilation appears to be significantly more successful than an earth-to-air heat exchanger at enhancing comfort in a PH. Similarly, Ridley et al. [21] indicate that increasing ventilation may prevent overheating better than boosting shading. Another study confirmed that the most efficient options, when both initial and ongoing expenses are considered, are ventilation strategies, such as 'night-purge ventilation', smart ventilation, and cross-ventilation. Notably, the limitation of passive ventilation needs to be considered; for instance, in the comparative study by Ridley et al. [70], occupants preferred not to open windows for bedroom ventilation due the risk of insects entering. An early study conducted on PH schools in Germany in the hot period and winter warned about the poor indoor air quality due to the high level of CO_2. Proper natural ventilation in addition to mechanical ventilation should be considered [141].

According to Grussa et al. [142], to provide the proper design of an efficient management approach, ventilation, shade, and glazing interactions need to be assessed together at the planning stage. Another study by Fokaides et al. used dynamic simulations to test how well the first PH worked in Cyprus's subtropical climate. They identified zones that were too hot and applied an optimized night ventilation strategy, which resulted in a drop in the interior air temperature of 1.4 °C on average, and it was discovered that increasing the HVAC's cooling capacity had a substantial positive impact on the zone's thermal efficiency [47]. It should be noted that in warm regions, active ventilation is inevitable; otherwise, indoor thermal discomfort will occur [4,104]. Moreover, active cooling lowered the incidence of overheating in the first Australian PH from 26% to 6% using 10.8 kWh of cooling energy [25]. To investigate MVHR and natural ventilation, two PH flats in Cardiff, Wales, were compared. Based on the findings, it may be possible to stop using MVHR in regions with warm winters and cool hot periods without compromising comfort. By using the PH model, this can be accomplished with lower capital costs and at least comparable energy savings [143].

5.4. Shading

In early studies in Belgium [144], it was shown that sun blinds could restrict solar heat gain during the hot period. Another study showed that by using natural ventilation, the overheating hours might be reduced by 28–35% in the 2050s and by 9–11% in the 2090s [129]. The best ways to lower overheating were external shutters and night-purge ventilation [129]. Indoor thermal comfort can be provided by opening a window for airflow at night or during unfavorable suitable daytime hours [145]. In the hot period, a high thermal mass structure provides thermal comfort with exterior shading on the east and west façades—also cross-ventilated by opening the bedroom window. The inhabitants were satisfied on the hottest hot-period day when the outdoor temperature was raised to 35 °C [4]. A significant reduction in the risk of future overheating can be achieved by optimizing glazing ratios and exterior shading devices [64]. Accordingly, a study on the first PH constructed in southern France revealed that a PH can maintain comfortable inside temperatures during the hot period, and a functional exterior sunshade is required for this in Marseille. It is stated that insulating the building envelope has benefits in both the winter and the hot period [5]. A total of 40% of the end-users in the Hanover–Kronsberg estate made extra solar shading investments [28]. Not only may night ventilation and window shading increase the sustainability and resilience of domestic cooling, but they can also lower peak cooling demand, which helps Switzerland minimize the consequences of climate change. Shading might cut cooling loads by 71% and night ventilation needs by 38% [146]. The significant drawbacks of Korean PHs are thought to be related to overheating in the hot period and ondol heating during the winter; however, additional architectural approaches such as external shading, an optimal glazing ratio, and mechanical systems have been able to resolve such concerns [85]. According to a simulation study on shading devices, including outside blinds, external shades, and overhangs to reduce temperatures during the hot period in Romania, the former two devices were more effective than the latter [53]. The shading system in classrooms effectively impacts the energy demand relating to orientation. As the south-facing façade reaches the highest solar gain compared to the north-facing, it would be more efficient in the hot period [147].

A new method for avoiding the overheating risk by collecting data from sensors and then simulating various strategies in a typical PH in Belgium that faces an overheating risk in the hot period was proposed by Abrahams et al. in 2019. This study's simulations of three distinct overheating mitigation tactics reveal that although it will cost more than other options, controlling solar blinds in response to solar radiation with a shade factor is the most effective method [60]. The designer created a double-layer heat rejection roof to expel hot air from the sunspace and placed a reed sunshade on the exterior that could be adjusted based on user activity to prevent overheating in China's cold environment [83]. Similarly, Li et al. advise hybrid shading and ventilatory cooling for the same climate conditions [84]. Another long-term study carried out on the early-stage design of two PH buildings in Germany, which included an office building and a school, revealed that the school occasionally overheated during the hot period because of strict shading restrictions [130]. A Romanian single-family PH energy-efficient study aims to enhance the overall hours of comfort spent indoors by implementing the proposed hot period shading system [148].

6. Results and Discussion

Addressing Overheating Risk in Passive Houses and Mitigating Strategies

This study employs data from the PubMed database and utilizes the VOS viewer software (Version 1.6.19) to map the knowledge structure associated with PHs, providing a good understanding of the keywords in previous studies. The space between the clusters shows the degree of correlation between the keywords. Out of the 857 total keywords, 142 meet the threshold; those with large recurrence counts were chosen to map the network and a minimum number of 5 occurrence of keywords was established. A co-occurrence network of terms is depicted in Figure 5.

Table 6 highlights the timeline when the concept of the PH was first proposed in different regions as early as 1988. According to the review of the relevant sources, since 2008, the overheating risk has been acknowledged as a concern in PH design in relation to climate change. The timeline was created using information gathered from scientific research, reports, and documents provided by the official PH institute from 1988, the year the PH idea was first proposed. According to a review of the relevant sources, it seems that after 2001, the overheating risk was acknowledged as a concern in PH design. The fourth IPCC report issues a warning that the major effects of global warming are obvious [149]. However, before that, several documents demonstrated tenant satisfaction with hot period indoor thermal comfort [5,30].

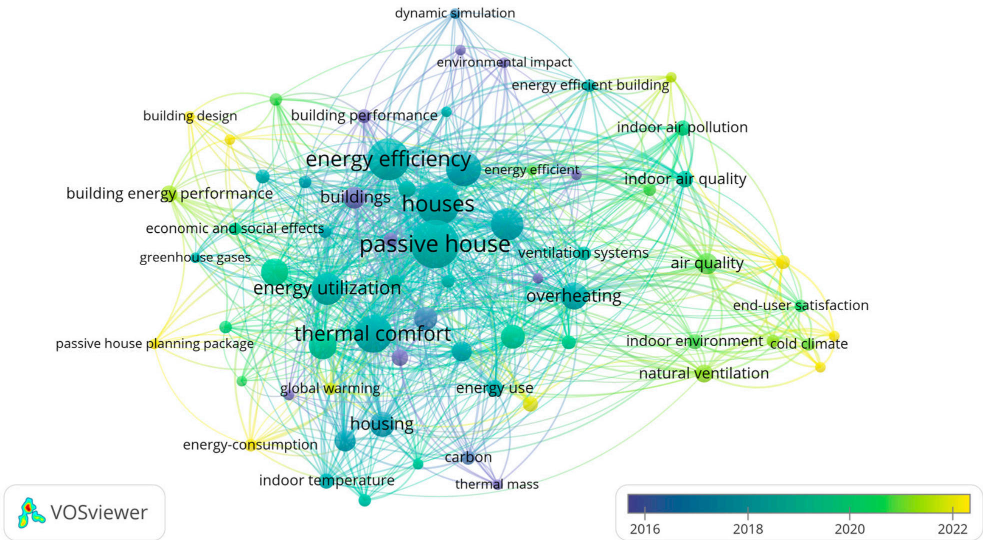

Figure 5. Co-occurrence network of keywords.

Table 6. Dates of the development of first PHs in different countries.

Year	Country/Region
1988	Germany—initiation of PH concept
1991	Germany—first PH created
2000	Germany—first multi-storey PH
2001	Sweden
2003	America
2004	Ireland
2004	Romania
2005	France
2006	Slovenia
2007	Poland
2008	Denmark
2009	Spain
2010	UK
2010	China
2011	Chile
2011	Indonesia
2012	New Zealand
2013	South Korea
2013	Japan
2014	Latin America
2019	Thailand

Table 7 shows the overheated cases reported in studies from 2001 to 2024. It also identifies the locations of PH buildings across the UK (as well as elsewhere) to help visualize which area was most at risk. It can be concluded that after 2009, there was a significant increase in research concentrating on the risk of overheating in relation to climate change and rapid global warming.

In Table 7, the timeline shows that the risk of overheating in the hot period has been part of many studies focused on PHs in a number of regions: Central Europe [56], the southwest of Europe [57,58], Southern Europe [47,57,59], Northern Europe [37,39,42,61], Northwestern Europe [123], and the UK [7,8,21,24,64,65,75]. Also, there are several studies focused on the overheating risk in PHs in Australia [88], America, [89,90], and Asia, mostly from China [77,78,80,82,84]. The timeline was created using information gathered from scientific research, reports, and documents provided by the PH Institute.

Table 7. The progression of studies on the risk of overheating across the world.

Date	Region	Country/Area
2001	Europe	Germany
2005	Europe	Germany
2007	Europe	Germany
2009	Europe	Sweden
2010	Europe	Austria
2010	Asia	South Korea
2011	Europe	Slovenia
2011	Europe	Austria
2011	Europe	Denmark
2012	Europe	Netherlands
2013	Europe	UK (South)
2013	Europe	UK (South)
2013	Europe	Sweden
2014	Europe	UK (South)
2015	Europe	Sweden
2015	Europe	Spain
2015	Europe	UK (North)
2015	Europe	UK (North)
2015	Europe	UK (Central)
2016	Europe	UK (North)
2016	Europe	Portugal
2016	Europe	Cyprus
2017	Europe	UK (North)
2018	Europe	Italy
2018	Europe	Cyprus
2018	N. America	Canada
2019	Asia	China
2019	Europe	Belgium
2019	Europe	UK
2020	Europe	UK

Table 7. *Cont.*

Date	Region	Country/Area
2020	Europe	Ireland
2020	Asia	China
2020	Europe	Norway
2020	Central/South America	Latin America
2021	Europe	Spain
2022	S America	Brazil
2022	Europe	UK
2022	Australasia	Australia
2023	Asia	China

The fourth IPCC report issued a warning that the major effects of global warming were becoming obvious [149], although before that point, several documents produced by the Passive House Institute demonstrated tenant satisfaction with hot period indoor thermal comfort [30,33,150,151]. It may be inferred that after 2008, there was an increasing research interest in the risk of overheating in relation to climate change and rapid global warming.

The number of studies that have confirmed the overheating issue has increased from 2009 to 2024, whereas there was just one report of overheating in Germany in 2001, as illustrated in Figure 6.

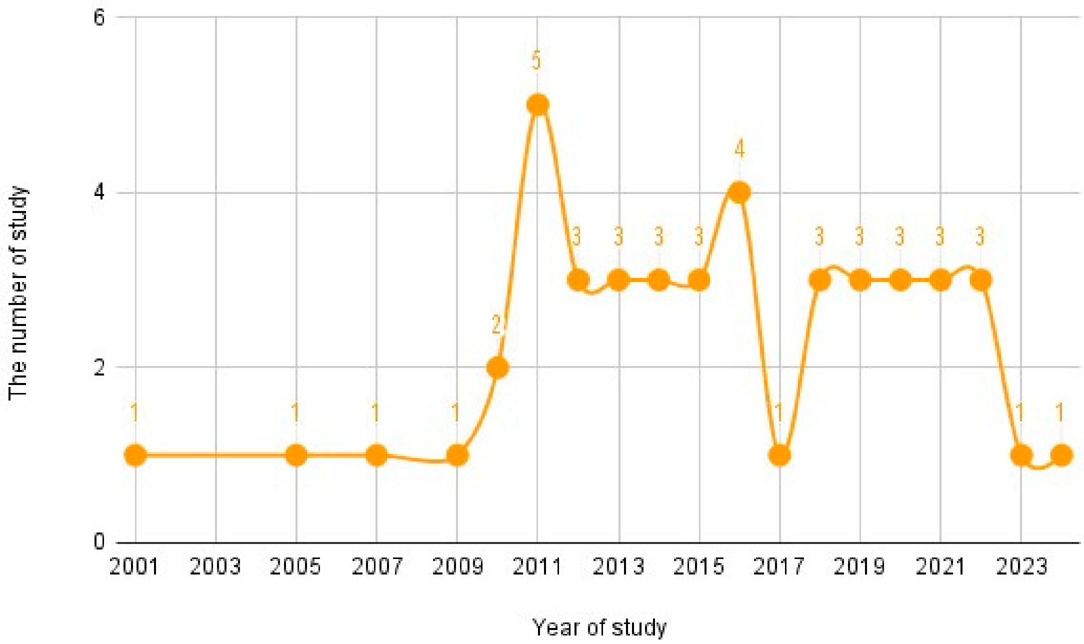

Figure 6. The rise in studies on the overheating risk of passive houses between 2001 and 2024.

The studies employed several approaches, such as simulation, dynamic simulation, monitoring, monitoring and simulation, monitoring and surveying, and simulation and surveying, which are arranged according to their frequency of usage in the Figure 7 pie chart. Prior to 2011, studies utilized monitoring and interviews as their methodologies. The pie chart illustrates the distribution of methodologies used in studies conducted after 2011, reflecting advancements in technology and sensor applications. The most significant amount of research used simulation methods including sensitive and static simulation and sensitive sensors to measure and monitor data. More research, including surveys and behavior profiling and monitoring, appears to be required to obtain more accurate findings about the significance of occupant behavior in the frequency and severity of overheating risks in PHs.

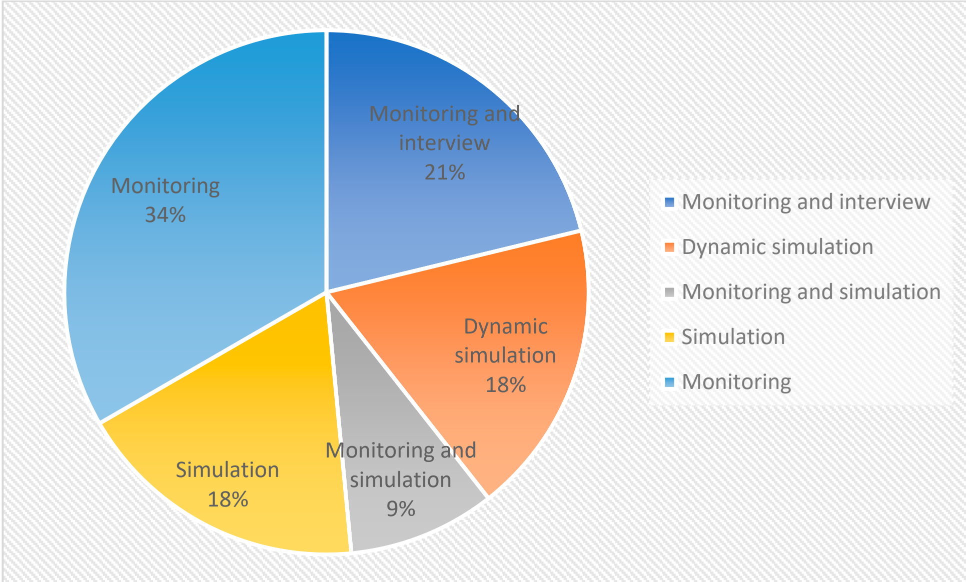

Figure 7. Distribution of methodologies used in studies post-2011.

Conversely, many overheating cases have been reported in European countries like Sweden, the UK, and Norway with latitudes higher than 46°, while Badescu et al. [152] pointed out that cooling should be unnecessary in European locales at latitudes higher than 46° N. This further emphasizes the time dependency of climate change phenomena. When considering regions in the Southern Hemisphere, the cooling demand is highly location-dependent. Conversely, in various countries, the need for more information about hot period overheating is emphasized by Mlecnik [153]. Compared to the rest of the world, Europe has more overheated case studies due to the higher number of PH buildings. Even though this study's primary focus is on European countries, the reviewed studies cover the region of Europe, America, Asia, and Australia, which highlights the number of studies on the overheating risk in PHs and reveals that the majority of studies were carried out in Europe, specifically northern Europe, as shown in Figure 8.

Figure 8. Location-based number of overheated cases based on studies.

Overheating is most frequently reported in bedrooms, and sometimes in living rooms, kitchens, and dining rooms in PH dwellings. It is also experienced in classrooms in educational buildings and office rooms in office buildings, as illustrated in Figure 9.

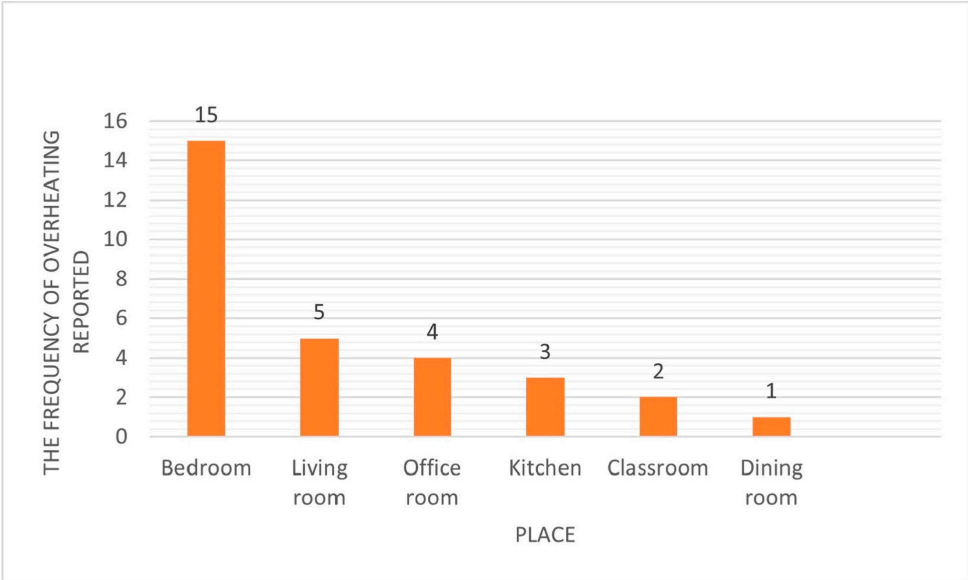

Figure 9. The frequency of overheated spaces in PH buildings according to the reviewed studies.

The majority of PHs have been constructed in Europe, as shown in Table 8 specifically in the north-west and northern regions, as this concept originated in Europe and spread to other continents. Asia follows in second with 593,000 m^2 of Treated Floor Area (TFA), followed by North and South America and the South Pacific [154]. Consequently, the overheating risk in PHs is reported in various countries and regions, from North and Western Europe to South Europe, China, and Australia. Studies focusing on the overheating risk in PHs significantly increased after 2008, while the IPCC warned about global warming.

Table 8. Passive house certification worldwide provided by passive house database, https://passivehouse-database.org/, accessed on 1 July 2024.

Europe	Asia	North and South America	South Pacific
2,659,000 m^2 TFA	593,000 m^2 TFA	203,000 m^2 TFA	53,000 m^2 TFA

Using a PH simulation over 25 global areas, Harkouss et al. [155] showed that the percentage of overheating hours would be as high as 43–81% in hot climates and as low as 27–45% in mixed climates. Although initially, the PH concept was applied in colder climates in Europe, after 2005, buildings with PH standards were constructed in other areas. The PH concept, with its high thermal inertia, good insulation quality, and relatively low glazed surface, may be used, with the proper modifications, in warmer European climates as well [36].

In the early stage of studies, most of the overheating occurred due to a lack of knowledge about technologies and devices, and a lack of understanding of shading and control for inhabitants. The absence of the possibility of room temperature control was reported in German PHs [28]. Also, in the primary studies in the second stage, the main complaint in Swedish PHs was the inability of residents to adjust the indoor temperature [27]. While shading and both mechanical and natural ventilation are recommended as the primary solutions for overheating, questions remained about the insulation properties, climate conditions, and overheating risk. Identifying the most optimal orientation and configuration of PHs is an essential component in each region; nevertheless, the specific solutions that yield the greatest effectiveness will vary depending on the local climate conditions. For instance, many studies have confirmed that a PH's well-insulated, airtight building envelope maintains the building's temperature year-round and helps limit hot period heat gain [156]. However, a review of case studies confirmed that insulation should be used more carefully [98], and specifically in warm areas, super-insulation negatively affects overheating in the hot period [104]. In regions with high temperatures and humidity, such as areas of China, insulation negatively affects overheating and thermal comfort [157]. Li et al. [84] showed that improving airtightness and thermal insulation resulted in a remarkable 62% reduction in winter energy use. However, due to overheating, the energy required for cooling increased during the transition and hot period seasons compared to cold winter climates in China. Figure 10 presents the recommended design alternatives from the investigations. In order to enhance indoor climate quality and energy efficiency, researchers have focused on the impacts of climate change and highlighted the need to adapt architectural design principles to local climatic demands [158]. The optimization of orientation and glazing area to match climate conditions also needs more focus.

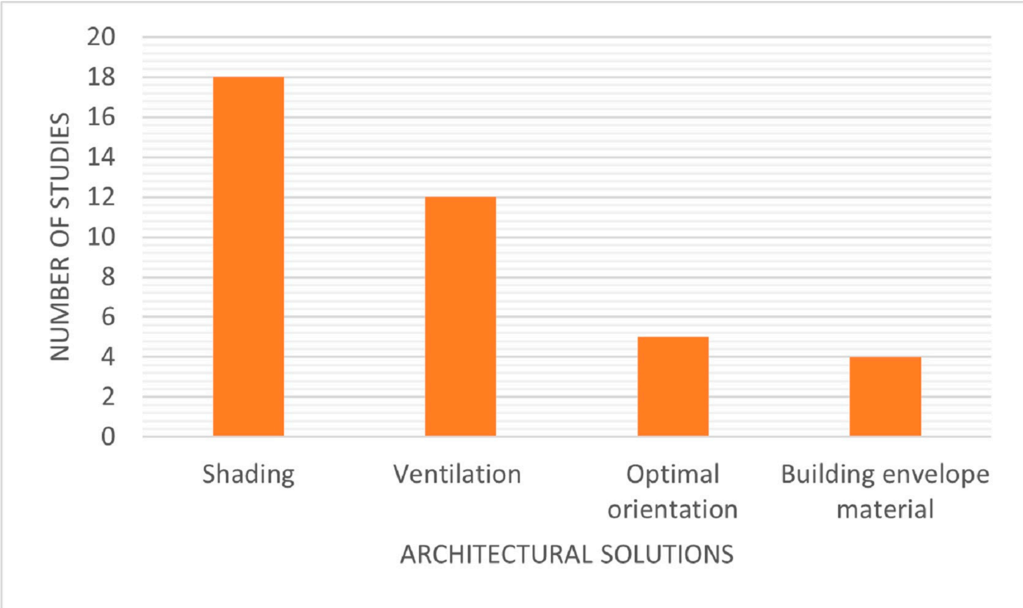

Figure 10. The frequency of various architectural solutions to minimize the overheating risk in PHs recommended in the reviewed studies.

Apart from architectural design and local climate conditions, inhabitants' thermal comfort level and perception significantly affect their satisfaction; Morgan et al. [23] found that occupants' perception of overheating and their subsequent behavior are significant factors. Although Blight and Coley [102] found that PH dwellings are less responsive to occupants' behavior than previously believed, the role of occupant behavior is highlighted in many studies [46,48,65,70,123,124,159]. Conversely, in the Dutch Ministry of Housing database, occupant characteristics and behavior were identified as substantial factors that impact energy use; however, it was revealed that building factors have a ten times larger influence on a home's energy use than use patterns generally [160]. Variations in the upper temperature value have been investigated too. Sigalingging et al. [161] used a typical terraced house in Jakarta, Indonesia, to apply the PH concept, in which Jakarta's upper comfort range was set at 27.6 °C instead of the PH standard's 25 °C. An experimental study in Vietnam by Le in 2021 analyzed the thermal comfort of occupants; indoor temperatures ranging between 23.7 °C and 29.6 °C were found to be acceptable (80% acceptability), with a comfort temperature of 27.9 °C. A significant relationship between participants' assessments regarding their individual PH comfort and the social side of comfort is confirmed by Zhao and Carter [66]. Due to the cultural norms in south

Brazil, the idea of airtight structures with sealed windows feels burdensome to people. Sealed windows present in a PH feel constricting, and they are opened frequently. Since they are designed to operate with closed windows, highly insulated buildings will not perform as effectively in these circumstances [162]. The requirement for BES modelers to establish a consistent standard that will be used to evaluate overheating is highlighted by the notable difference in the overheating results found in simulations, which is dependent on comfort criterion selections [20]. For instance, climate and behavioral patterns in China vary significantly from those in the north of Europe, from where the PH concept originates, leading to differences in the way thermal sensations are measured under identical thermal conditions [159].

In terms of the method used to predict and evaluate the overheating risk, several studies have shown the inability of PHPP to predict the overheating risk with thermal comfort being confirmed [22,74,87]. Due to China's various climates and enormous dimensions, the post-occupancy evaluation showed widely different results from PHPP indicators [163]. Therefore, it is crucial to compare two distinct tools and their methodologies with real-world data [7]. Further, there is a need to provide a more sensitive and accurate method for airflow modeling to help minimize the future overheating risk.

Local building regulations are an important factor that is not covered in this study due to differentiation and diversity. Moreover, through a qualitative study, the main factors evaluated by Krechowicz [164] and three categories of factors are identified, including installation, construction site, and the architectural and construction design. In the construction design section, technological errors need more consideration, including factors that are not examined by current studies. It was also found in the first stage of this study, that there were complaints about the inability to control the indoor air temperature due to a lack of education provided to users.

7. Conclusions

This study examines the time lag between the introduction of PHs in various countries and the publication of research on overheating issues in those locations. These data can be instrumental for future studies exploring potential connections between local climate and overheating risks. The research highlights a ten-year gap between the construction of the first PH in Germany (1991) and the publication of the first European overheating case study. This suggests that overheating may not be immediately recognized as a concern in new building concepts. The present study further identifies several key factors influencing overheating in PHs: architectural design including construction elements, occupant behavior, climatic conditions, perceptions of indoor environmental quality, and the urban context, including green infrastructure around the building like trees that can provide shading, the density of the urban area, and the height and configuration of other buildings in neighborhood

A review of existing research reveals four key categories of factors influencing overheating in PHs:

Building Characteristics: This category encompasses material properties, building envelope performance, building form, configuration, and orientation, glazing ratio, and insulation details. The key aspects impacting overheating include the following:

- Sun shading/protection strategies;
- Solar heat gain;
- Thermal mass and insulation effectiveness;
- Internal heat gains from appliances and occupants;
- Night cooling potential;
- Ventilation rate;
- Glazing properties such as ratio, transmittance, and orientation [58].

Whilst all of these are included in PH design principles and the operation of PHPP, the authors believe that this review can indicate opportunities for further refinement and detail.

Occupant Behavior: Occupancy patterns, user numbers, age and gender demographics, knowledge about PH operation, and equipment usage all influence thermal comfort and can contribute to overheating. These features are likely to have increased importance in the future because of comfort considerations and the means to also consider adaptive comfort options which might influence set points for temperature control in potentially overheating PHs.
Climate Conditions: Regional variations in temperature, humidity, and solar radiation significantly affect the likelihood and severity of overheating in PHs. As global warming progresses, such factors need to be understood in even greater detail for successful PH design and construction.
The Potential Role of Urban Context: While the impact of the urban context on overheating in PHs remains inconclusive, further research is needed to explore the potential influence of surrounding buildings and heat island effects. Additionally, a deeper understanding is required regarding the interaction between PH envelopes and their role in both urban heat islands (UHIs) and indoor overheating risks.

General findings

1. In summary, the following features need a more complete and detailed understanding, shade, ventilation, air conditioning, evaporative cooling, solar chimneys, earth tubes, reflectors, and nighttime radiation, which are standard comfort cooling techniques in hotter climates [42]. In addition to mechanical cooling, design techniques include effective home appliances and technical setups, bypassing ventilation heat recovery units, sun shading windows, building orientation, and window sizes and characteristics. The findings indicate that as the risk of overheating increases under future climate-related situations, space heating needs decrease and cooling needs grow [165].
2. In order to lower the internal temperature and prevent overheating, the beneficial effects of mitigation methods such natural ventilation have been suggested in several studies in Europe [33,50,56,70,140], and active ventilation in warm regions [4,104] has also been proposed in warm and humid areas in Asia [76]. Although natural ventilation can increase air pollution, high indoor air humidity [166], and noise pollutants [35] in PHs, considering the future climate [50], it is concluded that the effectiveness of mixing several passive strategies in reducing overheating is higher in southern Europe. Moreover, shading is suggested as a helpful strategy in various studies, from early studies [5,28,144] to recent studies [4,53,59,60,64,83,85,145–147]. Mixing strategies and increasing occupant engagement can significantly minimize the overheating risk in PH dwellings [82].
3. Combining with other strategies: For a comprehensive strategy to mitigate overheating, this study recommends that green walls be utilized in conjunction with other passive cooling strategies such as natural ventilation, reflecting coatings, and appropriate building orientation. Integrating plants into the façade can help regulate indoor temperature and improve air quality, aligning with PH principles. Although retrofitted PH constructions were more likely to overheat due to orientation restrictions and material modifications, the studies did not expressly state what kind of construction was involved, indicating that most cases were newly constructed. Because there are few studies in the retrofitting case studies, it is not possible to draw any significant conclusions about them.
4. Previous studies concluded that south-facing PHs are at a higher risk of overheating [64] in the UK and in the Netherlands [112]; while reviewing the studies, it becomes clear that north, west, and east-facing PHs in the UK are also at risk. As a result, providing appropriate shading based on heat gain quantity and ventilation is essential in addition to building orientation. Even though researchers are aware of the primary factors influencing the risk of overheating in PHs, this study thoroughly analyzed every component, offered remedies for gaps, and indicated the quantity of studies that failed to uncover the primary elements that should have received more attention. Additionally, as the majority of studies are conducted using simu-

lation software, it is evident from this systematic review that greater focus needs to be paid to combining case study techniques, including monitoring, surveying, and behavior profiling.

5. Addressing the gaps: Upon analyzing the literature on overheated PHs, it is evident that a data gap exists for the themes of analysis in this paper. The glazing ratio and details were not sufficiently covered in the early stages of studies. Some studies did not specify the overheated areas in PH buildings, which would help researchers to study with more focus and provide more practical solutions. Another crucial factor that should have been noted in case study evaluations is the number of occupants. More accurate results would be produced if more extensive data on earlier case studies involving overheating were available.
6. The necessity of strong energy performance requirements for practically zero-energy dwellings, together with design and execution quality assurance, is emphasized by Mlecnik et al. [112]. The review showed that the importance of execution and construction quality is overlooked and needs more attention.
7. Although comprehensive studies in the UK compare numerous examples [7,65,74], they did not highlight the location and features of each case. By sharing this information, the overheated PH buildings could be categorized based on their typology. It would help architects and researchers identify high-risk configurations, orientations, and locations in the UK. More studies in the UK and other regions need to focus on the sustainable strategy for large-scale PH building projects, specifically focused on building typology, configuration, and materials.
8. Overall, the lack of studies that examine overheating in urban contexts with a focus on PHs has been identified. The PH concept is an occupant-dependent strategy, and occupants have a significant role in the success of this idea. Therefore, educating occupants and increasing their interaction will help to achieve sustainable outcomes. As stated by Farrokhirad and Gheitarani, 2024 [167], increasing public awareness is essential for the successful implementation of energy-efficient strategies. Regarding the variation in the impacts of future climate change, it is important to consider more design options to control indoor air temperature. It is recommended that the details of case studies that encountered the overheating risk need to be included in the official documents by the PH Institution for more in-depth investigation and analysis. By providing more details about the projects, researchers and designers can identify specific features and critical reasons more accurately from both theoretical and practical points of view.

In compiling this paper, the authors take the view that since passive house design is now both well established and also being developed to try to take account of new building techniques/technologies and, at the same time, consider impacts of global warming, this review has substantial benefit in showing the history and development of the interest in overheating issues.

8. Suggestions for Future Work

8.1. Overlooked Factors and Potential Solutions

While the existing research explores overheating risks in PHs and proposes solutions, a crucial aspect often remains overlooked: the role of envelope materials and their contribution to UHI intensity, particularly in large cities. Additionally, the focus on architectural design features, while essential, neglects the potential of building façades in mitigating overheating.

8.2. Green Walls: A Multifaceted Approach

Integrating green walls as a nature-based solution addresses this gap by tackling both the overlooked issue of envelope materials and UHIs. Furthermore, GW implementation complements the established factors influencing overheating in PHs. By lowering surface temperatures and promoting cooler indoor spaces, GWs directly combat overheating risks.

Their insulating properties further enhance thermal performance during the winter months. GWs offer an eco-efficient solution to regulate building temperatures. Through evapotranspiration and shading, they reduce surface temperature during the hot period months. Conversely, their insulating properties and ability to act as a wind barrier contribute to warming the building in the winter. This dual functionality allows GWs to be adapted to various climate conditions and regions, ultimately promoting a more comfortable indoor thermal environment. It should be highlighted that while GWs are widely acknowledged by scientists and there have been several studies on the thermal performance of this nature-based solution, there is lack of knowledge on how the green envelope affects passive houses' thermal performance according to particular principles. Further research is needed to demonstrate the effectiveness of these two energy-efficient solutions when combined with super-insulation and airtightness regulation in PHs. Figure 11 illustrates and example of the potential design.

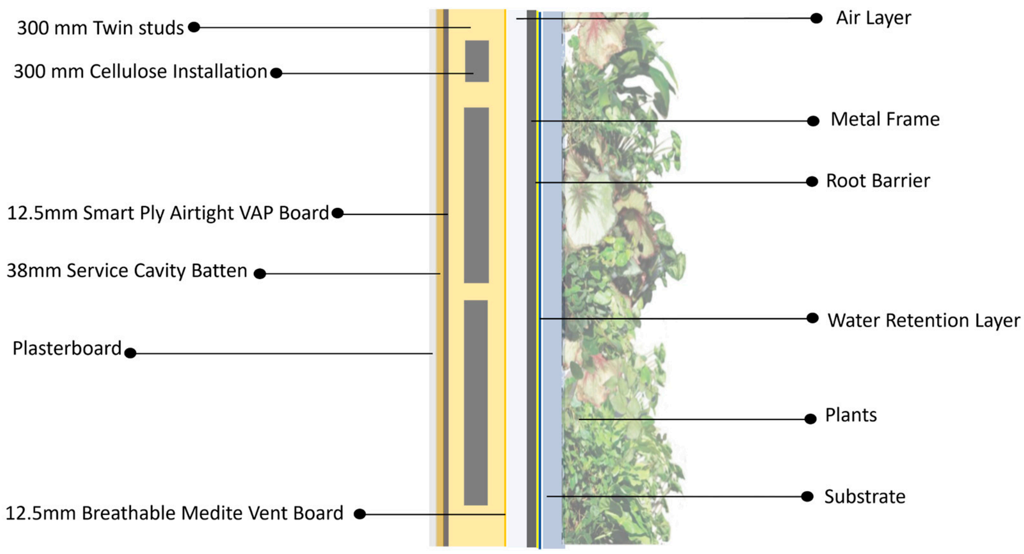

Figure 11. An example of a PH plant-covered façade proposed by the authors.

8.2.1. Beyond Thermal Benefits

The advantages of GWs extend beyond thermal regulation. They actively contribute to broader sustainability goals by promoting biodiversity, improving occupant well-being, and enhancing air quality. This aligns with the vision of creating sustainable and livable urban environments. Green walls can be a promising strategy to reduce the overheating risk in passive houses.

8.2.2. Reduced Surface Temperature

Green walls utilize evapotranspiration, as plants release water vapor through their foliage. This process cools the surrounding air through a similar principle as sweating. Consequently, the building envelope (walls) covered by the green wall experiences a lower surface temperature [168,169]. Wall surface cooling and vegetation solar transmittance were significantly correlated, but not with the evapotranspiration rate [170]. GWs reduce heat transfer into the interior space [171].

8.2.3. Shading Effect

The foliage of green walls acts as a natural shade, blocking direct sunlight from hitting the building façade. This significantly reduces solar heat gain, keeping the indoor environment cooler [172]. Moreover, it decreases heat infiltration and raises the building envelope's thermal resistance [173].

Improved Insulation: during the colder months, the green wall acts as an additional layer of insulation, trapping heat within the building and contributing to improved thermal performance [174].

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