

Entry

Passivhaus

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Definition: Passivhaus or Passive House buildings are low-energy buildings in which the design is driven by quality and comfort, hence achieving acceptable levels of comfort through post-heating or post-cooling of fresh air. Additionally, Passivhaus building design follows the Passivhaus design criteria, as described in the Passive House Planning Package (PHPP). This article aims to introduce the Passivhaus background, development, and basic design principles. Finally, it also presents a brief description of the performance of Passivhaus buildings.

Keywords: Passivhaus; Passive House; energy-efficient buildings

1. Introduction

A Passive House, or “Passivhaus”, which is the original German term, is: “[. . .] a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions—without the need for additional recirculation of air [1].”

The Passivhaus method evolved from Swedish super-insulated homes and passive solar architecture, which seek to minimise space heating and to improve the thermal transmittance (U-values) of the building envelope (building fabrics, windows, and doors). These developments led advances in insulation, thermal bridging, airtightness and controlled ventilation, and the commercialisation of triple glazing windows [2].

The term “Passivhaus” was created from a research project in 1988 by Professor Wolfgang Feist from the Institute for Housing and Environment (Germany), Professor Bo Adamson from Lund University (Sweden), and [3]. The first Passivhaus dwellings were built in Darmstadt (Germany) in 1990 as an outcome of their experiments and were followed by the establishment of the Passive House Institute (PHI) in 1996.

The Passivhaus construction design method is founded on five essential principles: (i) super-insulation, (ii) thermal bridge-free construction, (iii) airtight building envelopes, (iv) mechanical ventilation systems with heat recovery (MVHR), and (v) high-performance doors and windows [4]. The correct application of these principles should guarantee high levels of indoor environment comfort, especially indoor air quality. Finally, to reduce further the energy consumption, the use of energy-efficient electric appliances and lighting is critical to achieving the low-primary energy demand required. Table 1 presents the main criteria for Passivhaus certification. The complete design criteria are available in the Passive House Planning Package (PHPP) [5]—current version: version 9. During the certification process, a Passivhaus certification body verifies the PHPP analysis, construction record, and post-completion tests (blower door and ventilation rates). The different certification levels for Passivhaus buildings are EnerPHit for refurbishment projects, Passivhaus Plus for near-zero-energy buildings, Passivhaus Premium for positive energy buildings, and Passivhaus Classic for low-energy buildings.

In cold climates, heating load and heating demand are the most critical aspects to avoid the use of conventional heating systems, ensuring comfortable indoor environment levels [6]. The Passivhaus design and calculations are set to provide the highest level of thermal comfort only by air heating. Comfortable indoor temperatures (indoor operative temperature ≤ 25 °C) are achieved and maintained without conventional heating through



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the supply-air heating load that should not exceed 10 W/m^2 . To achieve such levels of thermal comfort, the volumetric capacity of the system, supplied flow rates ($30 \text{ m}^3/\text{h}$ per person), indoor temperatures, and treated floor area in the project are considered to calculate the peak supply-air heating load [5]. Thus, high levels of indoor environment comfort are linked directly to energy-efficient design as an incentive. Hence, the Passivhaus standard began as an ultra-low-energy concept rather than to reduce CO_2 emissions. The Passivhaus standard addresses energy demand reduction and thermal comfort, unlike other low-carbon standards prioritising energy-efficient design.

Table 1. Overview of the main Passivhaus certification criteria for Central European climates. Adapted from [7].

Passivhaus Certification Criteria (Residential)		Cool-Moderate Climate (Central European)
Specific heating demand	≤ 15	$\text{kWh}/(\text{m}^2\text{a})$
OR specific heating load	≤ 10	W/m^2
Specific cooling demand	≤ 15	$\text{kWh}/(\text{m}^2\text{a}) + 0.3 \text{ W}/(\text{m}^2\text{aK})$. DDH
OR specific cooling load	≤ 10	W/m^2
AND specific cooling demand	≤ 4	$\text{kWh}/(\text{m}^2\text{a}) \cdot \sigma_e + 2 \cdot 0.3 \text{ W}/(\text{m}^2\text{aK})$. DDH-75 $\text{kWh}/(\text{m}^2\text{a})$
Specific total primary energy demand	≤ 120	$\text{kWh}/\text{m}^2/\text{a}$
Airtightness n50	≤ 0.6	h^{-1} (@50 Pa)
Overheating frequency	10%	Percentage of time with operative temperature above $25 \text{ }^\circ\text{C}$

σ_e Annual mean external air temperature ($^\circ\text{C}$); DDH refers to Dry Degree Hours.

In Passivhaus buildings, moisture is removed through ventilation as the infiltration air volume flow is minimal due to high levels of airtightness and is hence insufficient to remove it [8]. In order to do this, outdoor airflow of $5\text{--}10 \text{ L/s}$ per person ($\sim 0.3\text{--}0.6$ air changes per hour or equivalent to $18\text{--}36 \text{ m}^3/\text{h}$ per person) is recommended [9]. Such levels of ventilation should guarantee that CO_2 peak levels are not higher than 1500 ppm , as stated in the German standard (DIN1946). The Passivhaus ventilation design is based on the German standard (DIN1946).

Passivhaus was developed for buildings in Central European countries. Nonetheless, it has expanded beyond Europe as it has gained popularity across the globe. As of March 2018, the Passivhaus database [10] had recorded 212 buildings outside of Europe, built predominantly in the USA (92), Canada (42), New Zealand (22), Japan (21), and China (16). The Passivhaus standard is starting to gain popularity in warmer climates such as those found in Latin America. This article aims to define the Passivhaus background, design concept, and principles, as well as present an overview of the studies that have shaped the Passivhaus. Finally, it briefly presents the performance of Passivhaus buildings, although it is not intended as an exhaustive literature review.

2. Passivhaus Design Concept

2.1. Building Form

Although Passivhaus buildings have freedom in design, their size, orientation, and shape must be planned cautiously. The area/volume (A/V) ratio is the relation between the surface area of the exterior of the building—also known as the building envelope—and the volume of the building. Hence, the A/V ratio will change as the building does. Hence smaller buildings (approximate size: $8 \times 8 \times 8 \text{ m}$; external area: 384 m^2 ; internal volume: 343 m^3) usually have higher A/V ratios ($1.1\text{--}1.3 \text{ m}^2/\text{m}^3$) while bigger buildings (approximate size: $16 \times 16 \times 16 \text{ m}$; external area: 1536 m^2 ; internal volume: 3375 m^3) have lower A/V ratios ($0.46 \text{ m}^2/\text{m}^3$). The A/V ratio places a significant load on cooling and heating demands, regardless of the thermal transmittance value (U-value) of the building envelope [6]. By avoiding energy losses by way of heating or cooling through the building envelope, Passivhaus buildings reduce energy consumption. Therefore, the more compact a Passivhaus building, the less energy it requires. Similarly, the higher a Passivhaus building's A/V ratio, the greater potential for heat transfer. In plain words, smaller

buildings have more significant disadvantages, while larger buildings have a lower penalty for complex forms.

2.2. Insulation

In order to decrease heat transfer, Passivhaus buildings use super-insulation in external ceiling, walls, and flooring. This becomes critical when the difference between indoor and outdoor temperature is high. However, as there is no need to maintain an indoor temperature different from outdoors, it becomes slightly less vital [11]. The typical U-values (0.10–0.15 W/m²K) required for Passivhaus walls [12] can be achieved through an extensive range of thermal insulation. However, some materials, such as foam insulations, might compromise safety in terms of indoor air quality (IAQ) and fire and should be avoided where possible [13]. External insulation in Passivhaus buildings is usually between 200 and 400 mm thick mineral wool, polystyrene, polyurethane foam, or cellulose [1]. Other materials, such as 500 mm thick straw-bale walls or vacuum insulation, tend to be thinner but expensive. In addition, pipework and ductwork must also be insulated to prevent condensation and heat losses.

2.3. Thermal Bridge-Free Construction

A thermal bridge is a component of the building envelope that conducts heat between indoors and outdoors and could cause internal condensation and dampness. Depending on the indoor air temperature, the surface temperature of walls or windows, and air moisture content, thermal bridges in Passivhaus buildings could cause condensation and become a source of unquantified thermal losses, which could be as high as 50% of the heat transmission [14]. Thermal bridges need to be designed, modelled, and assessed carefully through virtual simulation with software such as THERM, developed by the Lawrence Berkeley National Laboratory [15]. However, replicating any of the reference detail sources for the Passivhaus, such as those in the IBO Book [16,17], can save considerable amounts of time.

The most common types of thermal bridges are “constructional”, whereby a construction material penetrates the insulation. Other options include geometric thermal bridges, caused by the shape of the building (i.e., corners); point thermal bridges, caused by structural connections or insulation fixing; and linear thermal bridges, caused by a gap between the edges of two pieces of insulation or where one building material meets another [18].

2.4. High-Performance Doors and Windows

Passivhaus high-performance doors and windows contribute to achieve acceptable thermal comfort as they decrease, or even eradicate, the risk of mould growth, condensation, and drafts. Passivhaus windows, including frames, are designed to make the most of solar gains warming up the building. The windows incorporate two or three layers of glass, usually clear, and are usually filled with inert gas, such as argon or krypton. The G-value represents their solar gains efficiency as it measures the solar heat transfer that penetrates through a proportion of the window contrasted to the energy that reaches the window. Therefore, the higher the solar transmission is, the higher the G-value. Passivhaus windows have higher U-values (<0.8 W/m²K) compared to the walls (0.10–0.15 W/m²K); hence they should be used cautiously. Window sizing is a critical concern for design, as Passivhaus dwellings tend to have small windows to reduce heat loss and solar gains reducing the contact with the exterior. Additionally, window size also has an impact on the opening size and ventilation that may lead to overheating [19,20]. Usually, Passivhaus windows are limited to 0.8 W/m²K [5]; however, this varies in warmer climates [21,22]. It is important to note that windows are critical to balance overheating in summer and heat gains in winter. Although their size varies with the design of each project, a “standard size” for the component certification is 123 × 148 mm. Similar to windows, doors must have a U-value of 0.8 W/m²K and be airtight.

Installation is as important as the characteristics of the windows and doors. A correctly fitted window avoids thermal bridge losses and improves the overall U-value by up to 50%. If the windows are positioned “within the insulation plane of the thermal envelope and that insulation overlaps the frame as far as possible, the thermal bridge loss coefficient of installation can be 0 [7].” Passivhaus has certified components, windows, and doors included, to guarantee the optimisation of solar gains.

2.5. Airtightness

In order to avoid thermal losses through air infiltration, Passivhaus buildings are required to achieve high levels of airtightness. Of particular interest are poorly installed suspended floors, ventilation systems, doors, windows, services (pipes and ducts), and internal partitions, as well as poorly designed construction systems and small cracks and holes in the building envelope, as they are the most common uncontrolled air leakages [23]. Air barriers that seal construction joints and penetration across the envelope are essential to reach the required airtightness levels [24].

The airtight barrier, usually located in the warm side of the building, also works as a vapour control layer protecting the insulation and building structure from moisture and interstitial warm air. The wind barrier layer, usually located in the outside of the building fabric, protects the building envelope from cold air. Both layers are required and must be appropriately marked in the design. The on-site airtightness test or blower door test measures total leakage through the building envelope. The Passivhaus certification process requires that an under-pressure and over-pressure blower door test achieve an $n_{50} \leq 0.6 \text{ h}^{-1} @50 \text{ Pascals (Pa)}$ [7]. The airtightness target is defined by the number of air changes per hour at a reference of $\pm 50 \text{ Pa}$, known as the n50 test (see [25] for more details), and measures air leakage through the building. The n50 test creates a differential pressure of 50 Pa between the outside of the building and the inside through a blower door test. The blower door test involves placing a compressor into a building opening (i.e., a door or a window) and sealing the ventilation inlets and exhaust to create an under-pressure inside the building to identify leakages [1]. Passivhaus buildings can achieve an air exchange reduction of around 27% due to the high airtightness [26] making ventilation systems critical to provide ventilation and acceptable indoor air quality.

2.6. Mechanical Ventilation with Heat Recovery (MVHR) Systems

The main rationale for using Mechanical Ventilation with Heat Recovery (MVHR) systems is to provide an uninterrupted supply of fresh air whilst optimising occupant comfort and reducing energy losses for heating (or cooling) by recovering heat from extracted air [7]. Nonetheless, MVHR systems also protect against outdoor air pollution [6]. Passivhaus air flows should not exceed $30 \text{ m}^3/\text{h}/\text{person}$ [1]. Lower airflow levels may compromise the health and well-being of the occupants, while higher levels may cause dry air. The air is extracted from wet rooms (rooms where moisture or odours may increase due to occupant activities) and supplied to the living areas (rooms where the occupants spend extended periods). The recommended extract airflow rates from wet rooms are $40 \text{ m}^3/\text{h}$ for bathrooms, $60 \text{ m}^3/\text{h}$ for kitchens, and $20 \text{ m}^3/\text{h}$ for other rooms. Passivhaus dwellings should also meet a 0.3 air change rate per hour (ach/h) as a whole house minimum, ensuring:

- Fresh air demand: $30 \text{ m}^3/\text{h}$ per occupant.
- Minimum air change rate: 0.3 ach/h per treated floor area per floor to ceiling height (maximum of 2.5 m height).
- Recommended minimum extract rate from wet rooms (kitchen + bathroom): $60 \text{ m}^3/\text{h} + 40 \text{ m}^3/\text{h}$.

2.7. Energy-Efficient Appliances and Lighting

After meeting the heat and cooling demands and incorporating efficient technologies for domestic hot water, electrical appliances are the most critical component to assess

the final energy demand in dwellings. “It is a part of the Passive House philosophy that efficient technologies are also used to minimise the other sources of energy consumption in the building, notably electricity for household appliances [7].” Hot water connections for washing machines and dishwashers, LED bulbs, fluorescent lamps, and airing cabinets are examples of practices that help to decrease energy consumption without compromising indoor environmental comfort [7,12].

3. Shaping the Passivhaus

The first Passivhaus was built in 1990 and, since then, many Passivhaus studies have been published. Between 1990 and 2020 and particularly in the last decade, the indoor environment and energy performance of new and refurbished Passivhaus buildings have been the subjects of studies—predominantly in cold climates—allowing the building design approach to adapt for different climates. There are many studies on Passivhaus building; however, those that have been critical in shaping the Passivhaus as we know it today are discussed below.

Perhaps the most significant study is the Cost-Efficient Passive Houses as European Standards (CEPHEUS) project (2000–2002). The CEPHEUS is the most extensive Passivhaus study as it tested the performance of two hundred and twenty-one dwelling units (fourteen sites) in five European countries (Figure 1). Its primary goal was to understand the relationship between Passivhaus dwellings and environmental, sustainability, economic, and social contexts, as well as the technical feasibility and cost-effectiveness of reducing energy consumption [12]. Although there were two hundred and twenty-one dwelling units in the CEPHEUS project, the energy performance and thermal comfort of only one hundred were measured.



Figure 1. Location of the Cost-Efficient Passive Houses as European Standards (CEPHEUS) dwellings in France, Switzerland, Germany, Austria, and Sweden. Source: [6].

The airtightness test revealed that only nine of the fourteen sites had $>0.6 \text{ h}^{-1}$ and that those that did not pass could achieve the target with further work between the junctions [6]. The energy monitoring analysis demonstrated that energy consumption for heating was about 80% below that of conventional new buildings (reference). The results also showed that the inconsistencies between the heating loads simulated with the PHPP

and measured heating loads were minimal. A reduction of 50% of the final and primary energy consumption was observed compared to new buildings [6,12].

Although the main objective was to evaluate whether or not energy savings could repay the additional investment for Passivhaus building, building user surveys were taken alongside indoor temperature measurements. Temperature measurement analyses suggest that the Passivhaus maintains a comfortable range during summer, although shading elements and occupancy density play a critical role for thermal comfort [12]. Another study [6] discusses recommendations to improve user satisfaction; of particular attention were user behaviour and the ventilation system's use and maintenance. Users reported satisfaction with their homes, but the absence of radiators to regulate heating produced some anxiety. When comparing the thermal comfort from their previous home and the Passivhaus, about 50% stated that they feel better as their comfort increased; this was attributed to thermal improvements, easy ventilation controls, and good air quality [6].

The Passive House Institute published the Passive House for Different Climate Zones [22] study in November 2011. Through dynamic building simulations, this project demonstrated the success of the Passivhaus standard in achieving ultra-low-energy consumption and high indoor comfort, regardless of the location. It also evaluated the influence of individual on-site parameters to achieve the certification levels. The locations were selected according to two main factors: representative climates and expected new and renovation construction over the following decades. The assumption was that by demonstrating the Passivhaus suitability in extreme weather locations, they could also be built in less demanding climates [22].

Table 2 shows the characteristics of the models. The report concluded that the application of the Passivhaus was viable in the six locations:

- Yekaterinburg (cold climate), where they reduced the heating demand to 22.4 kWh/m²a. While this is greater than 15 kWh/m²a, they considered it acceptable as it was already less than 4% of a standard building in the same climate. The most critical factors in the design are the building's compactness, extremely good airtightness, a great MVHR efficiency, and overnight ventilation via windows.
- Tokyo (subtropical warm climate), where they reduced the heating demand to 14.5 kWh/m²a (~7% of a standard building) and the cooling demand to 7.1 kWh/m²a (~68% of a standard building) using climatisation by air supply. They found that compactness had a positive aspect, as well as separating the cooling and dehumidification functions.
- Shanghai (subtropical warm climate), where the Passivhaus achieved a heating demand of 11 kWh/m²K (~7% of a standard building) and cooling demand of 11.4 kWh/m²K (~30% of a standard building) using climatisation by air supply. Special care is required regarding the glazing ratio as this may tend to reduce the energy demand during summer, especially south-facing windows. However, larger surfaces will increase the cooling load. Therefore, movable outdoor shading is highly recommended.
- Las Vegas (hot and dry climate), where the model reduced the heating demand to 14.5 kWh/m²a (~14% of a standard building) and cooling demand to 15.2 kWh/m²a (~21% of a standard building) using climatisation by air supply. Overnight ventilation in building with higher thermal mass can reduce further the cooling demands; however, the cooling load might not be affected due to critical periods of heat because of the high outdoor temperatures. Compactness and insulated walls and ceilings affect the heating and cooling loads positively.
- Dubai (hot and humid climate), where no heating was needed, but the cooling demands were high (37.7 kWh/m²a). Using climatisation by air supply, this was ~18% less than a standard building. They noted that the airtightness and an MVHR system are key factors to reduce the energy consumption and that the use of humidity recovery in the MVHR system is highly desirable due to dry outdoor conditions. Reducing

- the windows to the minimum required for lighting and outdoor views will result in even lower cooling demands. Compactness is not as crucial as in colder climates.
- Singapore (tropical climate) was incorporated by a different study [21]. Similar to Dubai, no heating was needed, but cooling demand was reduced to 38.5 kWh/m²a using climatisation by air supply. Airtightness and an MVHR system were key factors in achieving less energy consumption. Further savings can be achieved by separating the cooling and dehumidification systems.

Table 2. Characteristics of the models in different climates. Adapted from [21,22].

	Yekaterinburg	Tokyo	Shanghai	Las Vegas	Dubai	Singapore
Wall: U-value (kWh/m ² a); thickness (cm)	0.064; 50	0.202; 15	0.202; 15	0.125; 25	0.125; 25	0.20; 8
Roof: U-value (kWh/m ² a); thickness (cm)	0.042; 80	0.155; 20	0.155; 20	0.200; 15	0.155; 20	0.28; 15
Window frame: U-value (kWh/m ² a)	0.67	0.72	0.72	1.6	1.6	1.6
U-/g-value glazing	0.51; 0.52	1.19; 0.6	1.19; 0.6	1.19; 0.31	0.70; 0.25	1.10; 0.23
Shading	None	Movable	Movable	None	Immovable	Immovable
Airtightness (n ₅₀ , h ⁻¹ @50 Pa)	0.3	0.5	0.5	0.5	0.5	0.5
MVHR efficiency (%)	92	85	85	85	85	85
Humidity ratio of ventilation	0.6	0	0.6	0.8	0.8	0.8
Hear recovery bypass	None	Controlled	None	Controlled	None	None
Overnight ventilation via windows	Yes	No	No	Yes	Yes	No
Climatisation via air supply	Yes *	Yes	Yes	Yes	Yes	Yes
Operation of cooling	No	Cont.	Cont.	Cycling	Cont.	Cont.
Humidity control for cooling	No	Yes	Yes	No	Yes	Yes

Cont. Continuous; * Plus bathroom radiators.

The findings suggest that in extremely cold climates, the additional cost of reducing heating demand down to the Passivhaus standard would not pay for the energy savings. Contrastingly, in tropical regions with slight seasonal variations, and where no heating is needed, the annual cooling demand can be significant. The economic analysis showed that, in fact, solutions that go beyond the functional Passivhaus level (e.g., external shading) are the best economic option for tropical regions, as low heating and/or cooling loads can be achieved with almost no insulation [22].

Passive House Regions with Renewable Energies (PassREg) was an EU project to implement near-zero energy buildings (nZEB) in Europe. It tested the use of renewable energy produced on-site in Passivhaus buildings with the vision to make the building operationally zero-energy on an annual basis. The secondary objectives were to make Passivhaus components more accessible, improve training materials, and boost the market with sustainable products and technologies [7]. Ten European countries participated in this project, which led to the new Passivhaus certifications (Passivhaus Premium, Plus, and Classic) [27].

The project centred its attention on incorporating renewable energies into the buildings, and so a guide was developed summarising the experiences of each country, which would, in turn, help local decision-makers implement PassREg solutions, set the best practice and solutions for each country, and incorporate renewable energies into the PHPP. To achieve the desired target for nZEB in Europe, political actors, architects, and tradespersons need to know about Passivhaus plus renewable energy, while suitable financial incentives for investors are needed [27].

Finally, the EuroPHit project aimed to demonstrate step-by-step refurbishment using Passivhaus principles so that existing buildings could also meet the European target for nZEB buildings by 2020. This resulted in the PHit certifications (Premium, Plus, and Classic), which offer solutions for thermal protection for existing buildings. The minimum standards for all energy-relevant building components and energy demands are slightly higher than those for new Passivhaus buildings, as existing structures have residual ther-

mal bridges and other prevailing problems. The process for retrofitting is explained in detail in [28].

4. Passivhaus Performance

In its origins, the Passivhaus standard was optimised as a design strategy for heating-dominated central- and northern-European climates. The main objective was to reduce the energy consumption needed to heat the building comfortably without using conventional heating systems. Nowadays, the Passivhaus standard has been extended to other countries, such as Mexico [29], Chile [30], China [31], the USA [32], and other warm climates [33], with different climates than those in Europe. Several studies have studied the performance of the building fabric in Passivhaus dwellings, showing a minimum performance gap between “as designed” and “as constructed” measurements [34–37].

The strict guidelines of the Passivhaus standard deliver low-energy homes and, although there is still evidence of deviation from the design intent, the magnitude and extent of the gaps were small [38] when compared to non-Passivhaus dwellings. The most common performance gaps between “as designed” and “as constructed” were observed in airtightness (Passivhaus (+0.05 m³/h/m²@50 Pa of “as designed”) vs. non-Passivhaus (+1.3 m³/h/m²@50 Pa)), walls (Passivhaus (+0.03 W/m²K) vs. non-Passivhaus (+0.14 W/m²K)), the roof (Passivhaus (+0.04 W/m²K) vs. non-Passivhaus (+0.10 W/m²K)), and hole heat losses (Passivhaus (+2.5 W/K) vs. non-Passivhaus (+20.6 W/K)). Another study that evaluated 97 UK Passivhaus dwellings suggests that the mean heating demand is 10.8 kWh/(m²a)—“as constructed” measurements—with no statistical difference compared to the predicted 11.7 kWh/(m²a) [34], which is considerably lower than the UK average dwelling heating demand (145 kWh/(m²a)) and the predicted demand in build homes (50 kWh/(m²a)).

Although the Passivhaus standard proved to be a reliable design method for low-energy homes with a minimum of performance gaps, the construction of Passivhaus dwellings is widely perceived to have a cost premium in homes built to this standard [7,39]. However, the Passivhaus “cost premium” may not always be significant and has the potential to achieve adequate levels of indoor environment quality [19]. Nonetheless, one of the biggest concerns about the Passivhaus is a greater perceived risk of overheating compared to less insulated homes [19,20]. However, there is not a significant difference between overheating frequency measured in Passivhaus and non-Passivhaus dwellings [40]. Moreover, recent works provide evidence against overheating of the Passivhaus through modelling [41] and physical measurements [42].

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