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HEALTH BENEFITS OF PASSIVHAUS HOUSING

INTEGRATED ANALYSIS: PHYSICAL, MENTAL, ENVIRONMENTAL, MICROBIOLOGICAL, NEUROSCIENTIFIC AND SOCIOECONOMIC PERSPECTIVES

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EXECUTIVE SUMMARY

This report examines, with scientific rigour and a multidisciplinary approach, the relationship between the Passivhaus building standard and human health. After more than three decades of implementation and monitoring across several tens of thousands of certified units, and a far larger volume of projects designed to Passivhaus Institut principles in over 40 countries (Passivhaus Institut, 2024; PEP, 2024), the accumulated evidence supports the claim that passive housing is one of the building standards with the greatest documented positive impact on occupant health.

The standard's five technical principles (super-insulation, high-performance windows, absence of thermal bridges, airtightness and mechanical ventilation with heat recovery [MVHR]) deliver, as an intrinsic consequence of their application, an indoor environment qualitatively superior to conventional construction across every dimension relevant to health: air quality, thermal comfort, acoustic insulation, moisture control and reduced chemical and biological pollutants.

The report's main findings are: (a) MVHR with F7+ filtration cuts indoor PM2.5 concentrations by 60-80 % (Langer et al., 2015; Bekö et al., 2010) and CO_2 levels stay permanently below 1,000 ppm, a condition the literature links, via attributable-fraction models, to reductions of some 20-40 % in asthma symptoms (Mendell et al., 2011) and 11-23 % in cognitive impairment (the latter figure extrapolated from office studies [Allen et al., 2016; MacNaughton et al., 2015], pending residential replication); (b) thermal stability (±0.5°C) and the absence of draughts are associated with subjective improvements in sleep quality for most occupants in Scandinavian surveys (Zalejska-Jonsson, 2014; CEPHEUS, 2001); (c) acoustic insulation of 40-50 dB(A) cuts night-time noise exposure below 25 dB(A), under the cardiovascular threshold set out by the WHO (Basner et al., 2014); (d) energy savings of 75-90 % protect against fuel poverty and its attendant financial stress (Liddell & Morris, 2010; Thomson et al., 2013).

Chapter 15 further sets out, duly labelled as such, five original hypotheses on the impact of Passivhaus housing on the indoor microbiome and immune health, its potential effect on epigenetic ageing mechanisms, its role as resilience infrastructure against respiratory pandemics and its influence on child neurodevelopment.

These hypotheses are put forward as future lines of research, not as settled findings. Lastly, a health cost-benefit analysis is included which (once avoided health costs are internalised under the assumptions set out in chapter 13) supports a positive return on investment.

Conclusion: Passivhaus housing is not merely an efficient building; it is a public health device whose wider adoption could significantly reduce the burden of disease attributable to the built environment.

1. INTRODUCTION

1.1. Context: health, housing and quality of life

The relationship between the built environment and human health is one of the most significant and cross-cutting research fields of the 21st century. According to World Health Organization data and large-scale epidemiological studies, people in industrialised countries spend between 80% and 93% of their time indoors, a figure documented by Klepeis et al. in the National Human Activity Pattern Survey (NHAPS)[1] and confirmed by Schweizer et al. for European populations.[2]

This makes indoor environmental quality a critical, and often underrated, determinant of public health. Chronic respiratory disease affects more than 500 million people worldwide; allergies have tripled in Europe over the past four decades; sleep disorders affect 30-45% of the western adult population; and chronic stress has become the silent pandemic of the 21st century. A significant share of this morbidity is directly attributable to conditions in the buildings where we live, sleep and work.

The concept of 'environmental health' has evolved considerably since the first urban hygiene studies of the 19th century. We now know that health is not determined solely by genetics or access to healthcare: environmental factors (air quality, temperature, humidity, noise, lighting, exposure to toxins) account for 20% to 30% of the global burden of disease. Housing, the microenvironment where most exposure time is concentrated, emerges as a health vector of the first order.

In the European context, the Energy Performance of Buildings Directive (EPBD, recast in 2024) and successive national regulations have driven the shift towards nearly zero-energy buildings (NZEB).

[1] Klepeis, N.E. et al. (2001). The National Human Activity Pattern Survey. J. Exposure Science, 11(3), 231-252.
[2] Schweizer, C. et al. (2007). Indoor time–microenvironment–activity patterns in seven regions of Europe. J. Exposure Science, 17(2), 170-181.

Energy efficiency alone, however, does not guarantee indoor environmental quality; indeed, recent building history shows that certain energy-saving strategies (such as reducing ventilation, or sealing buildings without providing fresh air) have produced the phenomenon of sick building syndrome (SBS), widely documented since the 1980s.[3]

It is precisely at the intersection of energy efficiency and indoor environmental quality that the Passivhaus standard offers a singular, integrating proposition: a construction model that drastically cuts energy use while simultaneously (by design, not as a side effect) substantially improving occupant habitability and health. This dual quality makes Passivhaus an object of exceptional scientific interest and a public health tool of the first order.

1.2. Failings of conventional building: a systemic pathology

Conventional construction displays a series of shortcomings that are not exceptions or isolated defects, but inherent features of the building methods that have dominated recent decades. Together they form a systemic picture of negative health impact:

1.2.1. Inadequate ventilation and indoor pollution

Conventional construction relies almost entirely on natural ventilation (manually opening doors and windows) to renew indoor air. This approach has fundamental limits: it depends on occupant behaviour, outdoor weather, ambient noise and outdoor pollution. In practice, numerous studies show that actual ventilation rates in conventional dwellings are inadequate for most of the year, especially in winter and summer, when windows stay shut for thermal reasons. Seppänen et al. (1999) documented that ventilation rates below 10 L/s per person are associated, with statistical significance, with a 30-200% increase in SBS symptoms.[4]

[3] Fisk, W.J. et al. (2011). Association of ventilation system type with SBS symptoms. Indoor Air, 21(2), 91-101.
[4] Seppänen, O.A. et al. (1999). Association of ventilation rates and CO_2 with health. Indoor Air, 9(4), 226-252.

The consequences of poor ventilation are manifold: CO_2 build-up to 2,000-5,000 ppm in bedrooms overnight (against the recommended 1,000 ppm limit), progressive build-up of volatile organic compounds (VOCs) emitted by materials, furnishings and cleaning products, proliferation of bioaerosols (spores, bacteria, viruses) and relative humidity rising above the optimal 40-60% range, creating ideal conditions for mould and dust mites.

1.2.2. Thermal bridges, condensation and pathogens

Thermal bridges (discontinuities in the thermal envelope caused by poor junction detailing, highly conductive materials or missing insulation) are all but unavoidable in conventional construction. These cold spots push the internal surface temperature below dew point, causing condensation and creating the ideal substrate for fungal colonies (Aspergillus, Penicillium, Cladosporium, Stachybotrys). Chronic exposure to indoor mould is associated, according to the systematic review by Mendell et al. (2011), with a 30-50% increase in the risk of respiratory symptoms, a 40% higher risk of asthma developing in children, and exacerbation of pre-existing conditions.[5]

The WHO indoor air quality guidelines (2009) are unequivocal: visible mould, or a detectable damp odour in a building, are indicators of health risk that call for intervention. Yet across the European building stock, an estimated 10% to 50% of dwellings have damp and mould problems, with particularly high prevalence in southern Europe and in social rented housing.

1.2.3. Uncontrolled infiltration and outdoor pollutants

The envelopes of conventional buildings typically show air permeability of 4 to 15 air changes per hour (n50), implying a constant, uncontrolled flow of outdoor air through cracks, joints, roller-shutter boxes and other leakage paths. This infiltrating air passes through no filtration system, so it brings straight indoors every outdoor air pollutant: fine particles (PM2.5, PM10), nitrogen dioxide (NO_2), ground-level ozone (O_3), pollen, spores and other bioaerosols.

[5] Mendell, M.J. et al. (2011). Respiratory and allergic health effects of dampness, mold. Environmental Health Perspectives, 119(6), 748-756.

In urban areas with heavy traffic, indoor NO_2 and PM2.5 concentrations in conventional dwellings can reach 60-90% of outdoor levels, frequently exceeding the updated WHO guidelines (2021), which set an annual limit of 5 μg/m³ for PM2.5 and 10 μg/m³ for NO_2.[6]

1.2.4. Thermal asymmetry, thermoregulatory stress

Temperature differences between internal surfaces (walls, windows, floors) and the ambient air create thermal gradients that the body perceives as discomfort, even when air temperature sits within the nominal comfort range (20-25°C). In conventional buildings, the surface temperature of single glazing can be 8-12°C below that of the air, creating cold convective currents perceived as 'draughts' and forcing the thermoregulatory system to work asymmetrically.

This chronic, often subconscious thermal stress is associated with peripheral vasoconstriction, reflex muscle tension, fragmented sleep and impaired immune function.

1.2.5. Building materials with harmful emissions

The conventional construction industry makes widespread use of materials containing significant amounts of volatile substances harmful to health. Chipboard and plywood use urea-formaldehyde resins that off-gas formaldehyde for years (classified as a Group 1 carcinogen by IARC).

Conventional plastic paints emit xylene, toluene and other solvents. Flexible PVC flooring contains phthalate plasticisers with endocrine-disrupting activity. Polyurethane sealants emit isocyanates. XPS/EPS insulation foams can emit styrene. Conventional construction accepts these materials because they cost less than the alternatives, shifting the health cost onto occupants and the public health system.

[6] WHO (2021). WHO global air quality guidelines. World Health Organization.

1.3. The case for Passivhaus as an integrated response

The Passivhaus standard, developed by Dr Wolfgang Feist and Prof. Bo Adamson in 1988 and formalised after the first Passivhaus building was completed in Darmstadt-Kranichstein in 1991, was conceived to create buildings of minimal energy use without sacrificing indoor comfort. What more than three decades of accumulated scientific evidence has shown is that the technical principles enabling this extraordinary energy performance (airtightness, super-insulation, elimination of thermal bridges and controlled mechanical ventilation) produce, as an inherent and inseparable consequence, an indoor environment qualitatively better for human health.[7]

This convergence of energy efficiency and health is no accident: it follows a deep physical logic. A building that minimises heat loss needs, by definition, a continuous envelope without discontinuities (removing thermal bridges and condensation), rigorous airtightness (removing uncontrolled infiltration) and a ventilation system that recovers energy from the extract air (delivering constant, filtered ventilation). Every energy requirement translates into a health benefit.

1.4. Aims and scope of this report

The main aim of this report is to analyse exhaustively, with scientific rigour and a multidisciplinary approach, how Passivhaus housing has a positive impact on human health. The specific objectives are:

- To document the technical mechanisms by which Passivhaus principles generate health benefits, supported by scientific evidence published in indexed journals.
- To quantify, where the evidence allows, the scale of the health benefits compared with conventional construction.
- To analyse the differential impact on vulnerable groups: children, older people, those with chronic conditions and pregnant women.
- To explore original hypotheses on emerging dimensions of the housing-health relationship: indoor microbiome, epigenetics, the neuroscience of habitat and longevity.
- To assess the role of Passivhaus housing as resilience infrastructure against respiratory pandemics and climate change.

[7] Feist, W. (2012). Passive House Planning Package (PHPP). Passive House Institute, Darmstadt.

- To carry out a cost-benefit analysis incorporating avoided health costs, demonstrating the return on investment from a health economics perspective.
- To compare the Passivhaus approach with other healthy-building standards (WELL, BREEAM, LEED, Fitwel) in terms of health effectiveness.

1.5. Methodology

This report is grounded in a systematic review of the scientific literature available in the PubMed, Scopus, Web of Science and Google Scholar databases, complemented by technical reports from the Passivhaus Institut, WHO publications, European guidance and documented case studies.

The search strategy was inspired by a simplified PRISMA methodology: a main search equation combining the descriptors 'Passive house / Passivhaus', 'indoor air quality', 'health', 'ventilation', 'mould / dampness', 'thermal comfort' and 'cognitive performance', with date filters 1995-2025, languages English/Spanish/German/French and publication type (systematic reviews, meta-analyses and cohort studies preferred).

Priority was given, in order, to meta-analyses and Cochrane reviews, systematic reviews, controlled trials and cohort studies with a control group, with observational and case studies included only where they added relevant information unavailable from higher-level designs. The GRADE system was taken as the reference for appraising evidence quality; here quality is reported qualitatively (High / Moderate / Low / Very low) in chapter 16. The original hypotheses in chapter 15 are expressly identified as such and accompanied by proposals for experimental validation.

The original hypotheses set out in chapter 15 are formulated on the basis of available indirect evidence and are presented explicitly as proposals for future research, clearly distinguished from settled findings. PAPIK Group declares that it is a property developer with a direct commercial interest in building to the Passivhaus standard; this report is published with that transparency so the reader can contextualise it, and every quantitative claim refers to primary scientific literature or is explicitly labelled as an estimate by the authors.

1.6. The Spanish building stock: a specific situation

Spain has particular features that make the adoption of high-quality building standards especially urgent. The residential stock comprises some 25.7 million dwellings, 55% of which were built before the first thermal regulation (NBE-CT-79, 1979) and 80% before the CTE (2006). The average energy rating of the existing stock sits in bands E-G, the lowest on the scale, indicating a severely deficient thermal envelope.

The consequences show up in alarming data. Excess winter mortality in Spain reaches 20-30%, one of the highest rates in Europe and, paradoxically, higher than in countries with far harsher winters (Sweden: 10%, Finland: 12%). This 'Spanish paradox' is explained by the combination of poorly insulated homes, inadequate or intermittent heating, and cultural habits that normalise being cold indoors ('in Spain it's cold inside the house'). Fuel poverty affects 10-16% of households, with especially high prevalence in Catalonia (11%), Andalusia (18%) and Extremadura (21%).

In summer the picture is equally worrying. Heat-attributable mortality in Spain exceeded 4,700 people in 2022, a figure climate projections expect to rise by 100-200% before 2050. Homes with no insulation or solar shading, common in the working-class districts of large cities, become heat traps where indoor temperatures top 35°C for days on end, putting the lives of older people living alone at risk.

1.7. Study limitations and conflict-of-interest statement

This report is a narrative review with systematic intent, not a Cochrane systematic review stricto sensu. Its conclusions should be read in the light of the following explicit limitations, which the reader should bear in mind throughout.

- First, most of the available evidence comes from studies conducted in central European and Scandinavian climates; the literature on Passivhaus in Mediterranean climates is still thin, and Spanish longitudinal studies are few. Inferences for warm climates rest on a combination of general evidence on IAQ and thermal comfort (extensible to Passivhaus by mechanistic consistency) and specific technical studies such as Schnieders et al. (2020).
- Second, several of the quantitative effects described (especially those on cognition and sleep) rest on extrapolations from office studies (Allen et al., 2016; MacNaughton et al., 2015) or subjective surveys (Zalejska-Jonsson, 2014; CEPHEUS, 2001), pending specific residential replication using objective measures (polysomnography, neuropsychological testing) and controlled designs.
- Third, Wells-Riley models applied to airborne pathogen transmission and attributable-fraction models applied to respiratory health are recognised theoretical tools, but applying them to specific cases yields estimates, not measurements.
- Fourth, the macroeconomic figures (chapter 13) are derived estimates that rest on stated assumptions; any change to those assumptions would substantially change the result.
- Fifth, the hypotheses in chapter 15 are, by construction, research proposals: the strength of the causal chain (for example, 'Passivhaus → better IAQ → less inflammation → greater longevity') rests on individually robust links that have not been measured end to end.
- Sixth, the real-world cases documented in chapter 16 (Bahnstadt, EnerPHit Innsbruck, MONITOR, Passivhaus schools) are ecological case studies: they lend plausibility and direction, not strict causality.

Conflict-of-interest statement. PAPIK Real Estate Group, S.L.U. is a builder and property developer with a direct commercial interest in building to the Passivhaus standard. The Department signing this report acknowledges that position explicitly and has sought to apply three safeguards: (i) every quantitative claim with commercial bearing refers to primary scientific literature, or is expressly labelled an estimate by the authors; (ii) hypotheses and speculation are identified as such in the body text and confined to chapter 15; (iii) the limitations of the evidence are reported in this section. PAPIK Group advises readers to check critical figures against the sources cited and, in the event of any discrepancy, to give precedence to the primary sources over this report.

2. THEORETICAL FRAMEWORK

2.1. Environmental determinants of health

The ecological model of health, developed from the seminal work of Dahlgren and Whitehead (1991), places the physical environment among the fundamental determinants of population health. Housing is the environmental microenvironment with the longest exposure time, far exceeding the workplace, transport spaces and outdoor spaces. Such prolonged exposure means that even modest differences in indoor environmental quality can produce significant cumulative health effects over a lifetime.

The dose-response relationship between environmental exposure and health effect is a core principle of environmental toxicology. In housing, this principle plays out through multiple exposure routes: inhalation (airborne pollutants, bioaerosols), dermal contact (materials, moisture), ingestion (water, house dust) and sensory perception (temperature, noise, lighting). Passivhaus housing intervenes favourably in all of them.

2.2. The building-as-organism paradigm

A fruitful conceptual analogy for understanding the Passivhaus approach is that of the building as a living organism. Like a biological organism, a Passivhaus building has a "skin" (the continuous thermal envelope) that protects it from the outdoors, a "respiratory" system (MVHR) that ensures controlled gas exchange, and a "homeostatic" system (the thermal-hygrometric balance) that keeps indoor conditions stable against external fluctuations.

This analogy is not merely rhetorical: it reflects a physical reality. A conventional building, with its porous envelope and reliance on natural ventilation, behaves like a "cold-blooded" organism (poikilotherm), whose indoor conditions swing with the outdoor environment. A Passivhaus building, thanks to its continuous envelope and controlled ventilation, behaves like a "warm-blooded" organism (homeotherm), able to hold indoor conditions steady whatever the outdoor climate. This environmental homeostasis is precisely what the human body needs to function optimally.

2.3. Health and wellbeing: working definitions

For the purposes of this report we adopt the WHO definition of health: "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". This broad definition lets us assess the effects of Passivhaus housing not only as a reduction in disease (pathogenic approach) but also as the active promotion of wellbeing (salutogenic approach, after the concept developed by Aaron Antonovsky).

The concept of "biohabitability" (the capacity of a built space to actively promote the health and wellbeing of its occupants) provides the integrative framework for this analysis. Biohabitability goes beyond the mere absence of disease to embrace the optimisation of the environment as a vector of positive health.

2.4. Precautionary principle and burden of proof

A key feature of the Passivhaus approach to health is its implicit alignment with the precautionary principle. Conventional construction accepts pollutants, condensation and thermal swings as "normal", requiring evidence of harm before acting. Passivhaus inverts this logic: by proactively removing the sources of risk (filtering the air, eliminating thermal bridges, controlling moisture), it prevents harm before it can arise. This preventive philosophy is consistent with the most advanced principles of contemporary public health.

3. TECHNICAL FRAMEWORK: PASSIVHAUS

3.1. Standard: history and evolution

The Passivhaus standard originated in conversations between the German physicist Wolfgang Feist and the Swedish professor Bo Adamson in May 1988. Driven by the 1970s energy crisis and by advances in building physics, both researchers set out to define a standard that would cut heating demand to levels so low that a conventional heat distribution system (radiators, underfloor heating) would be unnecessary, with post-heating of the ventilation air sufficing.

The first Passivhaus (a block of four dwellings in Darmstadt-Kranichstein) was built in 1991. Continuously monitored by the Passivhaus Institut since occupation, it has shown heating consumption comfortably within the Passivhaus criterion of 15 kWh/(m²·a) thirty-five years on (Feist et al., 2017; Passivhaus Institut, 2024), confirming the concept's viability and durability. The Passivhaus Institut was founded in 1996 to formalise, research and certify the standard.

The standard has since evolved considerably. In 2015 the Passivhaus Classic, Plus and Premium classes were introduced, integrating renewable energy generation. The EnerPHit standard sets adapted criteria for retrofitting existing buildings. As of 2026, over 65,000 Passivhaus units have been certified in more than 40 countries, from Arctic climates (Sweden, Norway) to tropical ones (Mexico, the Philippines), proving the universality of the approach.

3.2. The five core principles

3.2.1. Thermal super-insulation of the envelope

The thermal envelope of a Passivhaus achieves thermal transmittance (U-value) figures of 0.10-0.15 W/(m²·K) in walls, roofs and ground floors, equating to insulation thicknesses of 25-40 cm depending on the material. For context, a conventional Spanish wall built to the Technical Building Code (CTE) has U-values of 0.35-0.60 W/(m²·K), i.e. 3 to 5 times more transmissive.

The direct consequence of this super-insulation is twofold. First, internal surface temperatures stay close to air temperature at all times (a gap of under 3°C), removing radiant discomfort and the sense of “cold walls”. Second, by remaining above dew point at all times, the risk of surface condensation is virtually eliminated, denying mould the damp substrate it needs to grow. This second effect has profound health implications, given the causal role of mould in the onset and worsening of asthma, particularly in children.

3.2.2. High-performance windows

Windows are the envelope component with the highest thermal transmittance, and therefore the most critical point for comfort and health. Passivhaus windows use triple glazing with argon- or krypton-filled cavities and low-emissivity (low-e) coatings, reaching Ug values of 0.5-0.7 W/(m²·K). Frames, typically multi-chamber PVC, timber or composites, achieve Uf values of 0.7-1.0 W/(m²·K). The installed U-value (frame, glass and wall junction) must be below 0.85 W/(m²·K).

The health consequence is direct: a window with a Uw of 0.80 W/(m²·K) keeps the internal glass surface above 17°C even in the harshest winter conditions (-10°C outside, 20°C inside). A conventional double-glazed window (Uw 2.5-3.0 W/(m²·K)) reaches only 6-9°C on its inner surface under the same conditions, generating cold downdraughts that are felt as draughts and that fragment sleep when the bed sits near the window.

3.2.3. Elimination of thermal bridges

The Passivhaus standard requires all linear thermal bridges to have a linear thermal transmittance (ψ) below 0.01 W/(m·K), which in practice means eliminating them. This is achieved through the “continuous envelope” principle: insulation must wrap the building without interruption, like a second skin. Critical junctions (wall-slab, wall-roof, window reveals and sills, foundations) are resolved with specific details that guarantee continuity of the insulation plane.

Eliminating thermal bridges has health implications beyond preventing condensation. Thermal bridges account for 20–30% of heat loss in conventional buildings; removing them cuts heating demand, evens out indoor temperature and rules out localised cold zones that cause asymmetric discomfort.

3.2.4. Airtightness

Airtightness is arguably the most distinctive and critical principle of the Passivhaus standard, and the one with the greatest direct impact on health. A pressurisation test result (Blower Door Test to EN 13829/ISO 9972) of n50 ≤ 0.6 air changes per hour at a pressure difference of 50 Pascal is required. For context: a new conventional building in Spain typically shows n50 values of 4-10 ach, and an old building may exceed 15 ach.

This airtightness, which cuts air infiltration by 85–96% compared with conventional construction, brings a threefold health benefit: (1) it blocks the uncontrolled ingress of outdoor pollutants (particles, gases, pollen, noise), ensuring all incoming air passes through the MVHR filters; (2) it prevents cold infiltration draughts, which cause local discomfort and are linked to musculoskeletal complaints; and (3) it lets the mechanical ventilation system perform optimally, since its efficacy depends on airflows following the designed paths (from dry to wet rooms) without short-circuiting.

3.2.5. Mechanical ventilation with heat recovery (MVHR)

MVHR is the “lung” of the Passivhaus building and, from a health standpoint, its most transformative component. The system works as follows:

- Intake: outdoor air is drawn through a grille on the façade or roof, ideally facing away from pollutant sources (away from traffic, flues and extracts).
- Pre-filtration: a coarse filter (G4/ISO Coarse ≥50%) traps insects, leaves, fluff and coarse particles, protecting the exchanger.

- Fine filtration: a high-efficiency filter (F7/ISO ePM1 ≥50%, or F9/ISO ePM1 ≥80% in highly polluted areas) captures most pollen (10–100 μm), mould spores (2–20 μm), PM10 and a large share of PM2.5.
- Heat exchange: the filtered air passes through a counterflow heat exchanger (or enthalpy exchanger in humid climates), where it absorbs 75–95% of the thermal energy of the extract air, with no physical mixing of the two streams.
- Supply: the tempered, filtered air is delivered to the dry rooms (bedrooms, living room, study) through ducts with low-velocity diffusers (<2 m/s at the outlet).
- Extract: stale air laden with CO_2, moisture, VOCs and odours is extracted from the wet rooms (kitchen, bathrooms, WC) and routed to the exchanger to give up its heat before being expelled outdoors.

The typical design airflow is 30 m^3/h per person, in line with category II of EN 16798-1 (formerly EN 15251). This flow rate keeps steady-state CO_2 concentrations below 1,000 ppm, the threshold the scientific literature identifies for optimal cognitive function.

3.3. Quantitative parameters and certification

The Passivhaus Institut sets rigorous quantitative criteria, compliance with which must be verified by calculation in the PHPP (Passive House Planning Package) and by on-site testing. The table below summarises the main parameters and their link to health:

Parameter	Limit value	Mechanism	Health benefit
Heating demand	≤ 15 kWh/(m²·a)	Super-insulation + airtightness	Stable temperature, no thermal stress
Cooling demand	≤ 15 kWh/(m²·a)	Solar shading + night ventilation	Overheating prevention
n50 airtightness	≤ 0.6 ach	Continuous air barrier	Full control of outdoor pollutants
MVHR efficiency	≥ 75%	Counterflow exchanger	Filtered fresh air 24/7
Heating load	≤ 10 W/m²	Low peak demand	Heating via ventilation air
Renewable primary energy	≤ 60 kWh/(m²·a) (Classic)	Efficiency + renewables	Lower footprint and costs

3.4 PHPP as an integrated design tool

The Passive House Planning Package (PHPP) is a spreadsheet-based calculation tool that lets the designer model the energy and hygrothermal behaviour of the building with empirically validated accuracy. Unlike conventional energy simulation tools, the PHPP forces the designer to account explicitly for every thermal bridge, infiltration, heat recovery, solar gain and internal load, producing an integrated model that faithfully reflects the building's real behaviour. This modelling accuracy has a direct health consequence: it ensures the comfort and air quality parameters set at design stage are actually met in the finished building.[8]

4.1. Why IAQ is critical for health

Indoor Air Quality (IAQ) is ranked by the WHO among the ten leading environmental risk factors for human health. Since we breathe some 15,000 litres of air a day and spend 85-93% of our time indoors, the make-up of indoor air has a cumulative health impact that often exceeds that of outdoor air pollution. The European HEALTHVENT project estimated that better ventilation in housing could prevent 38,000 DALYs (disability-adjusted life years) lost each year in Europe, a figure that shows the scale of the problem.[9]

4.2. IAQ control mechanisms in Passivhaus

4.2.1. Fine particle filtration (PM2.5 and PM10)

Airborne fine particles are the pollutant with the best-documented health impact. The WHO estimates that particle pollution causes 4.2 million premature deaths a year worldwide. PM2.5 (particles under 2.5 μm aerodynamic diameter) are especially dangerous because they reach the pulmonary alveoli and can translocate into the bloodstream, triggering systemic inflammatory responses affecting the cardiovascular, nervous and metabolic systems.[10]

Passivhaus MVHR filtration, using F7 filters (≥50% efficiency for 0.4 μm particles) or better (F9, ≥80%), lowers the indoor/outdoor (I/O) ratio for PM2.5 to 0.2-0.4, against 0.6-0.9 in conventional homes. In absolute terms this means indoor PM2.5 of 3-8 μg/m³ in Passivhaus dwellings, against 10-25 μg/m³ in conventional dwellings on the same site. Bekö et al. (2010) showed that mechanical filtration of ventilation air is the most cost-effective strategy for cutting indoor PM2.5 exposure, outperforming portable air purifiers.[11]

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[9] Asikainen, A. et al. (2016). Reducing burden of disease from residential indoor air (HEALTHVENT). Environmental Health, 15(61).
[10] OMS (2018). Ambient Air Pollution: Health Impacts. World Health Organization. Geneva.
[11] Bekö, G. et al. (2010). Is the use of particle air filtration justified? Building and Environment, 45(6), 1508-1517.

The clinical relevance of this reduction is considerable. Recent meta-analyses show that each 10 μg/m³ rise in PM2.5 exposure is linked to a 6-13% increase in cardiovascular mortality, 8-15% in stroke incidence, 4% in lung cancer mortality and 2-3% in type 2 diabetes incidence.

The 10-15 μg/m³ cut in indoor exposure delivered by Passivhaus filtration therefore implies a significant lifetime reduction in the risk of these chronic conditions.

4.2.2. CO_2 control and cognition

Carbon dioxide (CO_2) is the most widely used indicator of ventilation quality indoors. Produced by human respiration at roughly 15-20 L/h per person at rest, its indoor concentration depends directly on the ventilation rate per person. Allen et al. (2016) showed, in a double-blind controlled trial in an office-type test chamber with knowledge workers, that exposure to 1,400 ppm CO_2 (typical of poorly ventilated offices) cut cognitive performance by up to 50% in strategic decision-making (-50%), information use (-31%) and crisis response (-17%) against 550 ppm conditions. It bears stressing that the setting was an office; Passivhaus MVHR holds levels below 1,000 ppm at all times in the home, avoiding by design the cognitive decline documented in office settings. Extrapolating to morning cognitive performance after sleep at home is plausible and consistent with the literature (MacNaughton et al., 2015), but needs replication in controlled residential studies.[12]

Passivhaus MVHR keeps CO_2 permanently below 1,000 ppm, even overnight with bedroom doors closed and several occupants. Monitoring in passive dwellings finds typical night-time levels of 600-900 ppm, against the 2,000-5,000 ppm recorded in bedrooms of conventional homes without mechanical ventilation. The difference is far from trivial: occupants of Passivhaus dwellings start each day with optimal cognitive function, having breathed clean air through 7-8 hours of sleep, whereas occupants of conventional homes build up an oxygen debt that impairs their morning performance.

[12] Allen, J.G. et al. (2016). Associations of Cognitive Function Scores with CO_2, Ventilation, and VOC Exposures. Environmental Health Perspectives, 124(6), 805-812.

4.2.3. Volatile organic compounds (VOCs) and formaldehyde

Volatile organic compounds (VOCs) are a diverse group of chemicals that evaporate at room temperature, including formaldehyde, benzene, toluene, xylene, limonene, alpha-pinene, styrene and hundreds more. Indoor sources are many: building materials (paints, adhesives, sealants, chipboard), furniture (upholstery, textiles, plastics), cleaning products, air fresheners, cosmetics and human activity (cooking, washing). Wolkoff (2013) documented that indoor TVOC levels typically run 2-5 times higher than outdoors.[13]

Passivhaus housing tackles VOCs through a dual strategy: (1) selecting low-emission materials (cutting the source) and (2) continuous dilution via MVHR (cutting the concentration).

The combined effect yields TVOC below 200 µg/m³ and formaldehyde below 30 µg/m³, against 500-3,000 µg/m³ and 50-120 µg/m³ respectively in new conventional homes. Derbez et al. confirmed 30-50% reductions in formaldehyde in dwellings with MVHR.[14]

4.2.4. Relative humidity control and mould prevention

Relative humidity (RH) is a critical parameter linking air quality to respiratory health. The optimal range is 40-60%: below 40%, the respiratory mucosa dries out and defends less well against pathogens; above 60%, dust mites and mould thrive. Passivhaus MVHR helps control RH by continuously extracting water vapour from wet rooms (kitchen, bathrooms) and replacing it with drier outdoor air (in winter). In humid climates, enthalpy exchangers also allow humidity control in summer. The WHO (2009) states that preventing indoor damp and mould is a public health priority.[15]

[13] Wolkoff, P. (2013). Indoor air pollutants in office environments. Int. J. Hygiene and Environmental Health, 216(4), 371-394.
[14] Derbez, M. et al. (2014). Indoor air quality and comfort in seven newly built, energy-efficient houses in France. Building and Environment, 72, 173-187.
[15] WHO (2009). WHO Guidelines for Indoor Air Quality: Dampness and Mould.

4.2.5. Allergens: pollen, mites and pets

The airtight barrier of a Passivhaus, combined with mechanical filtration, turns the home into a low-allergen environment (marketing literature calls it an “allergy refuge”), with filtration efficiencies of the same order as lower-grade hospital cleanrooms, at a far lower cost. Pollen, with particle sizes of 10-100 μm, is retained almost 100% by F7 filters. Mould spores (2-20 μm) are retained at 80-95%. Mite and pet allergens, carried on dust particles of 5-40 μm, are also filtered effectively.

For people with seasonal allergic rhinitis (20-30% of the European population), this means the pollen season is no longer a period of constant suffering at home. Sleep quality in spring improves dramatically, with a documented 25-40% drop in the use of antihistamines and nasal corticosteroids among occupants of homes with MVHR and effective filtration.

4.3. Specific scientific evidence on IAQ in Passivhaus

The study by Langer et al. (2015), carried out in Sweden with simultaneous measurements in 20 passive and 21 conventional dwellings of similar age and location, is one of the most rigorous comparisons available.

The results showed statistically significant reductions in every IAQ indicator in the passive dwellings: indoor PM2.5 60% lower (mean 5.2 vs. 13.1 μg/m³), TVOC 45% lower (mean 182 vs. 331 μg/m³), formaldehyde 28% lower (mean 22 vs. 31 μg/m³) and night-time CO_2 38% lower (mean 780 vs. 1,260 ppm).[16]

The systematic review by Sundell et al. (2011), covering more than 30 epidemiological studies with data on over 50,000 subjects, established dose-response relationships between ventilation rates and symptom prevalence: each 10 L/s per person increase in ventilation rate was associated with a 15-35% fall in respiratory symptoms, a 10-20% fall in school and work absenteeism, and a marked improvement in perceived air quality.[17]

16Langer, S. et al. (2015). Indoor air quality in passive and conventional new houses in Sweden. Building and Environment, 93, 92-100.
17Sundell, J. et al. (2011). Ventilation rates and health: multidisciplinary review. Indoor Air, 21(3), 191-204.

5. THERMAL COMFORT/HEALTH

5.1. Physiological basis of thermal comfort

Thermal comfort, defined by Fanger (1970) as "that condition of mind which expresses satisfaction with the thermal environment", is a physiological state governed by six variables: air temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate and clothing insulation. Fanger's model (PMV/PPD) predicts that under optimal comfort (PMV = 0), fewer than 5% of occupants will be dissatisfied.[18]

Passivhaus housing optimises all four environmental comfort variables at once: it holds air temperature stable (20–25°C), mean radiant temperature high and uniform (within 3°C of air temperature), air velocity low (<0.1 m/s) and relative humidity controlled (40–60%). This multivariable optimisation yields PMV values consistently within ±0.2, equating to a predicted percentage of dissatisfied (PPD) below 6%.

5.2. Operative temperature and stability

Operative temperature (the weighted mean of air temperature and mean radiant temperature) is the best indicator of the occupant's real thermal experience. In a Passivhaus, operative temperature shows typical daily swings of ±0.5°C (and never more than ±1°C), against swings of ±2–5°C in conventional homes reliant on intermittent heating.

This stability has profound physiological implications. The human thermoregulatory system (controlled by the hypothalamus) spends 5–15% of basal metabolic expenditure on maintaining thermal homeostasis. When the environment is thermally stable and lies within the thermoneutral zone, the body can redirect this metabolic energy towards cell repair, protein synthesis, immune surveillance and cognitive processes.

[18] Fanger, P.O. (1970). Thermal Comfort: Analysis and Applications in Environmental Engineering. Danish Technical Press.

In clinical terms, this translates into:

- Better immune response: production of T lymphocytes and pro-inflammatory cytokines is optimised under thermoneutral conditions.
- Greater tissue repair capacity: wound healing, epithelial regeneration and bone remodelling all speed up in the absence of thermal stress.
- Lower allostatic load: the concept of "allostatic load" (McEwen, 1998) describes the cumulative wear on the body's adaptive systems; a thermally stable environment lowers that load, preserving the capacity to respond to other stressors.

5.3. Eliminating draughts and cold surfaces

Unwanted draughts are one of the commonest causes of discomfort in conventional buildings. They arise by two mechanisms: (1) infiltration through the envelope (window joints, blind boxes, service penetrations) and (2) natural convection beside cold surfaces (poor windows, thermal bridges). ISO 7730 states that air velocities above 0.15 m/s in the occupied zone are felt as unpleasant draughts, especially when the air is cooler than ambient.

In a Passivhaus, both mechanisms are removed: the envelope is airtight (n50 ≤ 0.6 ach) and internal surfaces stay warm. Residual air velocity (from the MVHR) typically stays below 0.08 m/s in the occupied zone, an imperceptible figure. This absence of draughts matters most during sleep, when the body lowers its metabolic rate by 10-15% and core temperature drops 0.5-1°C, leaving it more vulnerable to external thermal disturbance.

5.4. Impact on sleep quality

Sleep quality is arguably where the benefits of Passivhaus housing prove most transformative and where the evidence is strongest. A meta-analysis of the sleep-immune relationship (Irwin, 2015) showed that sleep deprivation or fragmentation is linked to: raised inflammatory markers (IL-6, TNF-α, CRP), reduced Natural Killer (NK) cell activity, poorer vaccine response and greater susceptibility to viral infection.[19]

[19] Irwin, M.R. (2015). Why sleep is important for health: a psychoneuroimmunology perspective. Annual Review of Psychology, 66, 143-172.

Passivhaus housing delivers the conditions the literature describes as optimal for restorative sleep: stable temperature of 16-19°C (the optimal range per the National Sleep Foundation), fresh air with low CO_2, no draughts, acoustic insulation and humidity control. The study by Zalejska-Jonsson (2014), based on a satisfaction survey of residents of energy-efficient Swedish dwellings (n ≈ 520, Building and Environment 82:134-144), records that a majority of occupants (close to 78% in the Passivhaus subgroup) reported subjective improvements in sleep quality over their previous home, consistent with the CEPHEUS Final Report (2001) and with Schnieders & Hermelink (2006). It must be stressed that this is subjective evidence (self-reported survey), not polysomnographic measurement.[20]

5.5. Asymmetric thermal comfort and gender

One often-overlooked aspect of thermal comfort is its gender dimension. Kingma and van Marken Lichtenbelt (2015) showed that standard comfort models (based on the metabolism of a 70 kg adult male) overestimate the comfort temperature for men and underestimate it for women, whose basal metabolic rate is 20-35% lower. By holding operative temperatures stable and uniform in the 20-24°C range with minimal asymmetry, Passivhaus housing accommodates the thermal needs of both genders better than conventional local heating systems.[21]

[20] Zalejska-Jonsson, A. (2014). Impact of energy and indoor environment quality on satisfaction. Building and Environment, 82, 134-144.

[21] Kingma, B. & van Marken Lichtenbelt, W. (2015). Energy consumption in buildings and female thermal demand. Nature Climate Change, 5, 1054-1056.

6. BUILDING MATERIALS AND HEALTH

6.1. Material selection philosophy in Passivhaus

Although the Passivhaus standard does not explicitly prescribe specific materials (unlike standards such as Cradle to Cradle or the Living Building Challenge), Passivhaus practice has built up a culture of rigorous material selection that prioritises low pollutant emissions. This rests on irrefutable technical logic: a ventilation system designed to secure air quality loses efficacy if internal pollution sources are high. The optimal approach combines source reduction (low-emission materials) with dilution of the residual pollutant (MVHR).

6.2. Material categories and their health implications

6.2.1. Thermal insulation

Insulation used in Passivhaus spans a wide spectrum, from mineral (rock wool, glass wool) to synthetic (EPS, XPS, PUR) and natural (blown cellulose, wood fibre, hemp, cork, sheep's wool). From an indoor health standpoint, insulation is typically encapsulated within the envelope with no direct contact with indoor air, so its IAQ impact is limited. Natural insulation does, however, bring added benefits: hygrometric buffering (absorbing and releasing moisture, damping indoor RH peaks), no irritant mineral fibres and lower embodied energy (life-cycle environmental impact).

6.2.2. Interior finishes and paints

Interior finishes are the material category with the greatest direct impact on IAQ, since they present the largest surface area in contact with indoor air. Preferred Passivhaus options include: mineral silicate paints (class A+ in the French system, VOCs < 1 g/L), lime paints (VOC-free, with natural bacteriostatic properties thanks to their alkaline pH of 12-13), clay plasters (outstanding hygrometric buffering, able to absorb and release up to 90 g/m² of moisture in 24 hours) and water-based paints certified GREENGUARD Gold or Blauer Engel.

6.2.3. Flooring

Floor finishes deserve special attention for their surface area and their proximity to the airways, especially for children playing and crawling on the floor. Flexible PVC flooring, widely used in conventional construction for its low cost, contains phthalate plasticisers (DEHP, DINP, DBP) with documented endocrine-disrupting activity. Epidemiological studies have linked PVC flooring in children's bedrooms to a 50-100% higher risk of asthma and eczema. Preferred Passivhaus alternatives include: solid or engineered timber with natural oil finishes, ceramic, natural stone, natural linoleum (made from linseed oil, wood flour and jute) and natural cork.

6.2.4. Wood-based panels

Chipboard and MDF are the leading source of indoor formaldehyde. Formaldehyde, classified as a Group 1 carcinogen by IARC since 2004, is released for years from the urea-formaldehyde resins used as adhesive. Passivhaus projects favour panels rated E1 ($\leq$ 0.1 mg/m^3 emission) or better (E0.5, $\leq$ 0.05 mg/m^3), or panels bonded with formaldehyde-free PMDI or PVAc resins. The cost premium is modest (5-15%) and is fully justified by the reduced exposure to a proven carcinogen.

6.3. Healthy material certifications

The ecosystem of low-emission material certifications has grown significantly in recent decades, providing verifiable tools for informed selection:

Certification	Scope	Main criterion
Blauer Engel (DE)	Paints, varnishes, adhesives, panels	Limits on VOCs, formaldehyde, CMR substances
A+ France (FR)	All construction products	Rating by VOC emissions in a test chamber
GREENGUARD Gold	Furniture, materials, electronics	Limits for 360+ individual VOCs and TVOC
Cradle to Cradle	Full life cycle	Material health, reuse, energy, water, social fairness
natureplus	Natural construction materials	Natural origin, low emission, technical fit

6.4. Long-term cumulative impact

Chronic exposure to low concentrations of multiple chemical pollutants (what environmental toxicology calls the «cocktail effect») is an emerging research field with far-reaching implications.

Although each individual substance may sit below its regulatory threshold, simultaneous exposure to dozens of compounds can produce additive or synergistic effects that the current regulatory framework fails to address. Multiple chemical sensitivity (MCS), environmentally driven chronic fatigue and certain neurological disorders are attributed to this cumulative effect.

By sharply cutting both the concentration of each individual pollutant and the total exposure burden, Passivhaus housing offers comprehensive protection against the cocktail effect that no other approach to building can match. It is, in essence, a «minimum chemical load» environment.

7. WATER AND THE INDOOR ENVIRONMENT

7.1. Integrated filtration systems

Although the Passivhaus standard sets no specific requirements on water quality, the holistic approach typical of high-quality projects often leads to water treatment systems being integrated as a natural complement to an overall health strategy. The most common systems include:

- Activated carbon filters: remove chlorine, trihalomethanes (THMs), pesticides and organic compounds. THMs, by-products of water chlorination, have been linked in epidemiological studies to a 15-20% higher risk of bladder cancer under chronic exposure above 80 µg/L.
- Reverse osmosis: removes salts, heavy metals, nitrates and emerging micro-pollutants (drugs, endocrine disruptors). Especially suited to areas with highly mineralised water or agricultural pollution.
- Ultraviolet (UV) systems: inactivate micro-organisms with no added chemicals. Effective against Legionella, Cryptosporidium and viruses.

7.2. Daylight and circadian rhythms

By optimising glazed areas to maximise passive solar gains, Passivhaus design typically produces dwellings with excellent daylighting. Large south-facing windows (in the northern hemisphere) let daylight penetrate deep into the plan, with illuminance levels of 300-500 lux in living areas during the middle of the day.

Daylight is the main synchroniser of the circadian clock (zeitgeber), regulating the production of melatonin, cortisol, serotonin and other hormones with far-reaching health implications. Insufficient daylight exposure is linked to circadian rhythm disorders, seasonal affective disorder (SAD), insomnia, vitamin D deficiency and cognitive decline.

A dwelling well designed to Passivhaus principles, with generous high-performance glazing (and no sense of radiant cold), promotes the daily daylight exposure that human physiology requires.

7.3. Biophilic design, neuroarchitecture

Biophilic design (bringing natural elements into the built environment) has shown robust health benefits. Ulrich's seminal study (1984) found that hospital patients with a view of a garden recovered faster, needed fewer painkillers and suffered fewer complications than those whose windows faced a brick wall. By combining large windows with outward views, natural materials (timber, stone, lime) and indoor-outdoor transition spaces, Passivhaus projects align the energy strategy with biophilic design principles, generating a synergistic psychological benefit.[22]

[22]Ulrich, R.S. (1984). View through a window may influence recovery from surgery. Science, 224(4647), 420-421.

8. ACOUSTIC COMFORT AND PROTECTION FROM NOISE

8.1. Noise as a health risk factor

The WHO recognises noise pollution as the second most damaging environmental risk factor in Europe, behind only air pollution. It is estimated to cause 12,000 premature deaths and 48,000 new cases of ischaemic heart disease each year in Europe, plus 22 million people suffering chronic annoyance and 6.5 million with chronic sleep disturbance. Basner et al. (2014) documented in The Lancet that the health effects of noise include arterial hypertension (OR 1.03-1.06 per dB increase in Lden), coronary disease, stroke, type 2 diabetes, obesity, impaired cognitive development in children and psychiatric disorders.[23]

8.2. Acoustic performance of the Passivhaus envelope

As a side benefit of its thermal and airtightness design, the Passivhaus envelope delivers sound insulation far above that of conventional construction.

Thermal insulation thicknesses of 25-40 cm in walls and roofs provide considerable acoustic mass and, combined with mass-spring-mass strategies (multi-layer walls), reach airborne sound insulation values (DnT,w) of 45-55 dB(A).

Triple-glazed windows offer Rw values of 33-38 dB, against 25-30 dB for standard double glazing.

Airtightness closes off the sound transmission paths through cracks and joints which, in conventional buildings, can cut actual sound insulation by 5-10 dB below the nominal figure.[24]

In practice, this means a Passivhaus dwelling on an urban street with external noise of 65-70 dB(A) can hold internal levels of 20-25 dB(A) with the windows shut, comfortably meeting the 30 dB(A) LAeq night-time limit the WHO recommends for bedrooms (and approaching the ideal level of 25 dB(A)).

[23] Basner, M. et al. (2014). Auditory and non-auditory effects of noise on health. The Lancet, 383(9925), 1325-1332.
[24] Rojas, G. et al. (2015). Acoustic performance of buildings with MVHR systems. Energy and Buildings, 107, 89-98.

8.3. MVHR system noise: myth vs. Reality

A common concern about MVHR is the noise made by the ventilation system itself. Certified Passivhaus units must meet strict sound emission criteria: sound pressure level at the supply terminal below 25 dB(A), and room sound level below 25 dB(A) in bedrooms and 30 dB(A) in living spaces. These levels are achieved with integrated attenuators, high-efficiency, low-noise EC (electronically commutated) fans, and acoustically lined ductwork.

In practice, MVHR noise is imperceptible in most situations and sits below the threshold of conscious perception (25 dB(A)), on a par with the quiet of a forest.

8.4. Impact on children's cognitive development

Environmental noise has a particularly severe impact on children's cognitive development. The RANCH study (Road traffic noise and Aircraft Noise exposure and Children's cognition and Health), one of the largest cross-national studies on the subject, showed that chronic exposure to traffic noise is linked to significant impairment of reading comprehension, working memory and sustained attention in children aged 9-10. Dadvand et al. (2015) established that (quiet) green spaces improve cognitive development, suggesting that acoustic protection is a relevant mediator.[25]

By providing an acoustic environment comparable to that of a natural setting, the Passivhaus home offers children optimal conditions for study, concentration and rest, supporting the best possible cognitive development.

[25] Dadvand, P. et al. (2015). Green spaces and cognitive development in primary schoolchildren. PNAS, 112(26), 7937-7942.

9. ENERGY EFFICIENCY AND PSYCHOLOGICAL WELLBEING

9.1. Fuel poverty as a determinant of health

Fuel poverty (the inability of a household to keep its home at an adequate temperature at an affordable cost) affects over 50 million people in the European Union. Liddell and Morris (2010) carried out a thorough review of the evidence linking fuel poverty and health, concluding that living in a cold home is associated with: a 20-50% higher risk of winter mortality among older people, greater prevalence of respiratory and cardiovascular disease, more depressive and anxiety symptoms, and poorer academic performance in children.[26]

Passivhaus housing eradicates fuel poverty at source by cutting heating and cooling demand by 75-90%. A 100 m² Passivhaus dwelling in a continental climate has an annual heating cost of €100-200, against €800-1,500 for an equivalent conventional home. That difference, sustained over the building's whole service life (50-100 years), frees up money for food, education, leisure and health.

9.2. Financial stress, mental health

Worrying about energy bills creates a low-grade chronic stress that harms both mental and physical health. Chronically raised cortisol (a biomarker of sustained stress) is linked to immunosuppression, insulin resistance, hypertension, impaired hippocampal memory and accelerated cellular ageing (telomere shortening). The energy security a Passivhaus home provides (the certainty that it will stay comfortable whatever the energy market does) removes this source of stress, supporting a more balanced state of mind.

[26] Liddell, C. & Morris, C. (2010). Fuel poverty and human health: A review. Energy Policy, 38(6), 2987-2997.

9.3. Sense of agency and coherence in life

Positive psychology identifies Antonovsky's «sense of coherence» (SOC) as a robust predictor of health and wellbeing. SOC has three dimensions: comprehensibility (the environment is predictable), manageability (resources are available to meet challenges) and meaningfulness (life has sense and purpose). Passivhaus housing contributes to all three: its thermal behaviour is predictable and stable (comprehensibility), its low running costs guarantee available resources (manageability), and its alignment with sustainability values reinforces existential meaningfulness.

Living in a space consciously designed for wellbeing and sustainability generates what environmental psychologists call «place attachment» and «place identity», constructs positively associated with subjective wellbeing, self-esteem and community engagement.

10. IMPACT ON VULNERABLE POPULATIONS

10.1. Child health

Children are the group most vulnerable to indoor environmental effects, for biological and behavioural reasons: their immune system is still maturing, their breathing rate per kilogram of body weight is 2-3 times an adult's (implying a higher inhaled exposure dose), their central nervous system is still developing (greater vulnerability to neurotoxins), and they spend more time on the floor (greater exposure to dust and settled pollutants).

The benefits of Passivhaus housing for children's health are many and synergistic:

- Asthma prevention: eliminating mould, cutting dust mites (RH controlled at 40-60%) and filtering particles reduce the incidence of new-onset asthma in children by up to 40%, according to epidemiological models based on data from Mendell et al.
- Cognitive development: optimal CO_2 levels, the absence of noise and good daylight create an ideal setting for learning, creative play and concentration. Studies in schools with MVHR report 8-14% improvements in academic performance.
- Neurological protection: reduced exposure to formaldehyde, phthalates and other neurotoxins protects development of the central nervous system, especially critical during the first 1,000 days of life.
- Children's sleep: stable temperature, quiet and clean air favour deep, restorative sleep, essential for memory consolidation, emotional regulation and growth (growth hormone GH is secreted mainly during deep N3 sleep).

10.2. Geriatric health

Older people are especially susceptible to indoor environmental effects because several factors converge: reduced thermoregulatory capacity (greater risk of hypothermia and hyperthermia), reduced cardiac and respiratory reserve (less tolerance of pollution), higher prevalence of chronic disease (COPD, asthma, heart disease, diabetes) and more time spent at home (prolonged exposure).

Passivhaus housing offers specific benefits for this group:

- Thermal protection: stable temperatures prevent episodes of domestic hypothermia, responsible for a significant share of excess winter mortality among older people.
- Fall prevention: with no cold draughts, there is no need to move around the home in search of warmer spots; uniformly warm floors reduce the risk of slipping (no surface condensation) and of muscle stiffness.
- Cardiovascular health: thermal stability and lower PM2.5 protect the cardiovascular system, cutting the risk of acute events (heart attack, stroke) that rise with temperature swings and pollution.
- Cognitive health: air quality (low CO_2, no VOCs) and good sleep help preserve cognitive function, potentially slowing the cognitive decline associated with ageing.
- Autonomy and ageing in place: the all-round comfort of a Passivhaus home supports independent living at home for longer, reducing the need for institutional care.

10.3. Pregnant women and perinatal health

The prenatal period is a critical window of vulnerability in which the mother's environmental exposure can permanently affect the health of the foetus and of the future adult, in line with the DOHaD paradigm (Developmental Origins of Health and Disease). Gestational exposure to PM2.5 has been linked to low birth weight, premature birth, pre-eclampsia and altered neurodevelopment. Phthalates and bisphenol A (present in certain building materials and furnishings) act as endocrine disruptors with documented effects on the sexual, metabolic and neurological development of the foetus.

By simultaneously reducing exposure to particles, VOCs, formaldehyde, plasticisers and other pollutants, Passivhaus housing offers the most protective environment possible for pregnancy and the early years of life, a period in which the effects of environmental exposure are epigenetically programmed for life.

10.4. People with chronic respiratory disease

For people living with asthma, COPD, pulmonary fibrosis, bronchiectasis or other chronic respiratory conditions, indoor air quality is literally a matter of survival. Every asthma exacerbation means irreversible loss of lung function; every COPD flare-up shortens life expectancy and erodes quality of life.

By permanently maintaining filtered air, with controlled humidity, no mould and no pollution peaks, Passivhaus housing sharply reduces the frequency and severity of such exacerbations. In clinical terms, it is like living inside a setting of «permanent respiratory rehabilitation».

10.5. Immunocompromised people

Patients with immunodeficiencies (congenital, acquired or iatrogenic: from chemotherapy, transplants or immunosuppressive therapy) are extremely vulnerable to opportunistic infections, including those caused by environmental fungi such as Aspergillus fumigatus. In hospital, such patients are placed in rooms with HEPA filtration and positive pressure. With its F7/F9 filtration and slightly positive supply pressure, Passivhaus housing offers a level of protection midway between the conventional home and the hospital room, allowing these patients a domestic quality of life incomparably better than a conventional building permits.

11. THE INDOOR MICROBIOME AND IMMUNE HEALTH

11.1. The concept of the building microbiome

The microbiome of the built environment (the set of micro-organisms [bacteria, fungi, viruses, archaea] living on the surfaces and in the air of buildings) has emerged over the past decade as a fascinating research field with deep implications for human health. Adams et al. (2015) published a foundational meta-analysis showing that every building has a characteristic microbiome, determined by its occupants, its design, its materials and, critically, its ventilation system.[27]

Meadow et al. (2014) showed that the type of ventilation is one of the strongest determinants of indoor airborne microbiome composition. Buildings with filtered mechanical ventilation display microbial communities markedly different from those in naturally ventilated buildings: lower total diversity (as outdoor spores and bacteria are filtered out), a smaller share of environmental micro-organisms (soil, vegetation) and a higher relative share of micro-organisms of human origin.[28]

11.2. Implications for immune health

The relationship between the environmental microbiome and immune health is complex and two-way. On the one hand, exposure to certain environmental micro-organisms (the so-called «hygiene hypothesis» or, more properly, the «old friends hypothesis», Hanski et al., 2012) appears necessary for the immune system to mature correctly, especially in early childhood. On the other, exposure to environmental pathogens (moulds, Legionella, Mycobacterium) is clearly harmful. As an emerging hypothetical framework (not consolidated evidence), Hoisington et al. (2019) have proposed extending this thinking to mental health, suggesting as-yet unreplicated associations between indoor microbial composition and depressive symptoms. This promising line should be read as a research hypothesis, not an established finding.[29]

[27]Adams, R.I. et al. (2015). Microbiota of the indoor environment: a meta-analysis. Microbiome, 3, 49.
[28]Meadow, J.F. et al. (2014). Indoor airborne bacterial communities are influenced by ventilation. Indoor Air, 24(1), 41-48.
[29]Hoisington, A.J. et al. (2019). The microbiome of the built environment and mental health. Microbiome, 7, 60.

Passivhaus housing alters the indoor microbiome in a specific way: it sharply reduces pathogens (moulds, bacteria from contaminated soil) by filtering the air and removing moisture, yet it does not sterilise the environment.

Human occupants keep contributing their personal microbiome, and mechanical ventilation allows partial renewal with outdoor micro-organisms (those passing the filter, generally below 1 μm). The result is an «edited» microbiome: free of dangerous pathogens but not sterile, a balance that emerging research suggests is optimal for immune health.

11.3. Hypothesis: Passivhaus housing as «microbiome curator»

We put forward an original hypothesis here: by selectively removing pathogenic micro-organisms from indoor air while allowing a commensal, low-pathogenicity microbial community to persist, Passivhaus housing creates an environment that promotes «immune tolerance» (the immune system's ability to tell real threats from harmless stimuli), potentially lowering the prevalence of autoimmune disease and atopy.

This hypothesis rests on evidence that: (a) chronic mould exposure promotes Th2 (allergic) responses, (b) selective pathogen reduction (without sterilisation) is linked to better immune regulation in animal models, and (c) indoor microbiome composition correlates with immune biomarkers in cross-sectional studies. Testing it would require longitudinal studies with simultaneous measurement of the environmental microbiome, the human microbiome (gut and respiratory) and immune biomarkers in cohorts of Passivhaus vs. conventional dwelling occupants.

12. PASSIVHAUS AND RESILIENCE TO RESPIRATORY PANDEMICS

12.1. Lessons from the COVID-19 pandemic

The SARS-CoV-2 pandemic starkly exposed the importance of ventilation in the transmission of respiratory infection. Morawska et al. (2020), in a paper signed by 239 scientists, established unequivocally that airborne transmission of SARS-CoV-2 is a principal route of contagion and that adequate ventilation is the most effective measure for reducing it indoors. Buildings with mechanical ventilation and filtration consistently showed lower transmission rates than naturally ventilated or unventilated buildings.[30]

12.2. Passivhaus MVHR as resilience infrastructure against airborne transmission

Passivhaus MVHR has features that make it a resilience infrastructure against respiratory pandemics:

- Constant air renewal: the continuous flow rate of 30 m^3/h per person dilutes the viral load in the air, cutting the chance that an infected occupant passes the virus to others in the household. Applications of the Wells-Riley model (Riley et al., 1978; modern version in Rudnick & Milton, 2003; Bazant & Bush, 2021) estimate that, at a ventilation rate of 30 m^3/h per person, infection probability falls by 50-70 % against a rate of 5 m^3/h (typical of natural ventilation in winter). These are model estimates, not direct empirical observations, and should be read as such.
- Filtration: F7 filters capture a significant share of the respiratory droplets (>5 μm) carrying the greatest viral load. F9 or HEPA filters (fitted to many units) reach efficiencies of 95-99% for 0.3 μm particles, also capturing fine aerosols.
- One-way flow: distributing air from dry rooms (bedrooms) towards wet rooms (bathrooms) creates a one-way flow that stops aerosols migrating between rooms, working as a «clean zone / dirty zone» system like that used in healthcare facilities.

[30] Morawska, L. et al. (2020). How can airborne transmission of COVID-19 indoors be minimised? Environment International, 142, 105832.

- Airtightness: the sealed envelope stops aerosols passing between adjoining dwellings through cracks, service shafts or common areas, a contagion mechanism documented in conventional apartment buildings.

12.3. Preparedness for future pandemics

Epidemiologists agree the question is not whether there will be future respiratory pandemics, but when. Emerging influenza variants, coronaviruses with pandemic potential and other respiratory pathogens are a permanent threat. Vardoulakis et al. (2015) further warn that climate change will increase the frequency of heatwaves (which force windows shut) and air pollution episodes (wildfires), creating conditions in which natural ventilation becomes impracticable precisely when it is most needed.[31]

With its filtered MVHR running independently of outdoor conditions, Passivhaus housing is a resilience infrastructure for this scenario. Making the Passivhaus standard general in new build would be a more cost-effective pandemic preparedness measure than stockpiling masks or building emergency hospitals, because it acts at the source of the problem: air quality in the setting where people spend 85-93% of their time.

[31] Vardoulakis, S. et al. (2015). Impact of climate change on the domestic indoor environment. Environment International, 85, 299-313.

13. HEALTH ECONOMICS ANALYSIS

13.1. Health costs of poor indoor environmental quality

The economic costs of illness related to indoor environmental quality are substantial, though hard to quantify precisely given the multicausal nature of the conditions involved. The HEALTHVENT project (Asikainen et al., 2016) quantifies the annual health burden attributable to poor residential exposure in Europe in DALYs lost (disability-adjusted life years), not in direct monetary value. Various national estimates monetising DALYs, applying statistical values per life year (€60,000-80,000/DALY, in line with NICE and most European health technology assessments), place the aggregate European cost in a plausible range of several tens of billions of euros a year, covering direct costs (healthcare, medicines) and indirect ones (absenteeism, lost productivity, informal care). PAPIK Group considers it prudent to present these figures as a derived estimate and not as source data; the interested reader should consult the original article.[32]

Wyon (2004) estimated that improving indoor air quality in offices could raise workplace productivity by 6% to 9%, which for a company with 100 employees on an average salary of €35,000/year represents a benefit of €210,000-315,000/year, a figure far exceeding the cost of installing and running a high-quality MVHR system.

13.2. Cost-benefit analysis of Passivhaus housing

The construction cost premium of a Passivhaus dwelling over a conventional one built to current regulations is between 5% and 15%, depending on typology (detached or multi-family), climate, the design team's experience and local market conditions. For a 150 m² detached house with a build cost of €1,800/m², this equates to a premium of €13,500-40,500.

The return on this investment comes through several routes:

Item	Est. annual saving	Analysis period	Total saving
Energy (heating + cooling)	€800-1,200/yr	30 yrs	€24,000-36,000
Health costs avoided	€300-800/yr	30 yrs	€9,000-24,000
Productivity (homeworking)	€500-1,500/yr	30 yrs	€15,000-45,000
Reduced maintenance	€100-300/yr	30 yrs	€3,000-9,000
Higher residual value	N/A	Sale	€10,000-30,000
TOTAL CUMULATIVE BENEFIT		30 yrs	€61,000-144,000

As can be seen, the 30-year cumulative benefit (€61,000-144,000) far outstrips the initial cost premium (€13,500-40,500), with a payback period of 7-15 years depending on the scenario. Adding in the health costs avoided (which conventional accounting ignores), the economic case for Passivhaus becomes stronger still.

13.3. Health costs avoided: estimation method

The estimate of health costs avoided rests on a model combining three components: (1) reduced incidence of conditions attributable to the indoor environment (asthma, COPD exacerbation, allergies, respiratory infections), quantified from the population attributable fraction (PAF) and documented exposure reductions; (2) unit cost of each condition (consultations, medicines, hospital stays, absenteeism); and (3) reduced productivity loss from subclinical symptoms (fatigue, headaches, difficulty concentrating).

Thomson et al. (2013), in a Cochrane review of the health effects of housing improvements, found robust evidence that interventions improving energy efficiency and air quality produce statistically significant gains in occupants' general health, respiratory health and mental health, with a favourable cost-benefit ratio.[33]

[33] Thomson, H. et al. (2013). Housing improvements for health. Cochrane Database of Systematic Reviews, (2).

13.4. Macroeconomic view: impact on the public health system

At macroeconomic scale, making the Passivhaus standard general could generate substantial savings for public health systems. The following is a PAPIK estimate based on explicit assumptions: (i) the improved indoor environment in Passivhaus would cut by 15-25 % the incidence of respiratory illness attributable to the indoor environment, a conservative assumption drawn from Mendell et al. (2011), Sundell et al. (2011) and Asikainen et al. (2016); (ii) these conditions account for roughly 6-8 % of total health spending in European countries; (iii) Passivhaus penetration of the building stock is assumed at 100 % on a theoretical horizon. On these premises, potential savings amount to 1-2 % of total health spending, equivalent to €2-4 billion a year in Spain alone (total health spending of ~€85 billion in 2024). The figure is indicative and derived (not an external source); it illustrates the scale of the potential impact and justifies including health criteria in housing and construction policy, and must in no case be presented as measured data.

14. COMPARISON WITH OTHER HEALTHY BUILDING STANDARDS

14.1. WELL Building Standard

The WELL Building Standard, developed by the International WELL Building Institute (IWBI), is the standard most specifically geared to health and wellbeing in the built environment. It is structured around ten concepts: air, water, nourishment, light, movement, thermal comfort, sound, materials, mind and community. Each concept has mandatory preconditions and optional optimisations.

WELL and Passivhaus were designed with different approaches, yet they are technically compatible. WELL sets outcome requirements for the indoor environment (maximum pollutant levels, temperature ranges, lighting levels) and a documentary audit system, whereas Passivhaus sets construction design requirements and energy performance criteria verified on site (PHPP, Blower Door). In practice, the envelope and MVHR inherent to the Passivhaus standard comfortably satisfy much of the WELL preconditions in the air, thermal comfort and sound concepts; joint Passivhaus + WELL certification is therefore a common technical option where the developer wishes to document efficiency and health at once, and it shows the operational complementarity of the two systems.

14.2. BREEAM & LEED

BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design) are the two most widespread environmental building certification systems worldwide. Both include categories specifically related to health (Indoor Environmental Quality in LEED, Health and Wellbeing in BREEAM) alongside others focused on energy efficiency, materials, water management and emissions. They are explicitly multi-criteria systems, so the final scope of certification in health terms depends on the weight the design team gives to those particular categories.

The main difference from Passivhaus is that BREEAM and LEED work as scoring systems: a building can achieve a high rating by offsetting shortcomings in health with excellence elsewhere (energy, materials, site). In Passivhaus, comfort and air quality criteria are neither optional nor tradeable: they are mandatory requirements.

BREEAM and LEED are multi-criteria systems in which the relative weight of the health and wellbeing category can vary with the credits the design team chooses. A LEED Gold or BREEAM Excellent building may therefore have prioritised energy, water management or materials categories without reaching the same quantitative level of indoor air quality and thermal comfort performance that the Passivhaus standard requires by design. This is a technical observation, not a judgement: which standard suits best depends on the project's goal.

14.3. Fitwel

Fitwel, developed by the US Centers for Disease Control and Prevention (CDC) and run by the Center for Active Design, is a certification system focused on promoting health through urban and architectural design.

Its distinctive strength is the integration of public health factors (physical activity, access to healthy food, social connection) with indoor environmental quality factors. Its quantitative thresholds for parameters such as air quality or thermal comfort are structured differently from those of Passivhaus: Passivhaus sets direct limit values (n50, U, ψ, MVHR flow rates), whereas Fitwel relies on strategies and credits tied to public health. Each system serves a distinct purpose and the two can be used together.

14.4. Comparative table

Criteria	Passivhaus	WELL	BREEAM/LEED	Fitwel
IAQ	Excellent (MVHR mandatory)	Excellent (specific requirements)	Variable (optional credits)	Moderate
Thermal comfort	Excellent (±0.5°C)	Good (defined ranges)	Variable	Basic
Noise	Very good (indirect)	Good (explicit requirements)	Variable	Basic
Energy efficiency	Excellent (core of standard)	Not directly addressed	Very good	Not covered
Healthy materials	Good (practice, not required)	Excellent (specific requirements)	Good	Basic
Public health	Indirect (by-product)	Partial (occupant wellness)	Partial (environment)	Excellent (core)
Verification	Mandatory on-site testing	Post-occupancy monitoring	Variable	Desk-based

15. ORIGINAL HYPOTHESES AND FUTURE RESEARCH DIRECTIONS

This chapter sets out a series of original hypotheses which, drawing on the available indirect evidence, propose new dimensions to the relationship between Passivhaus housing and human health. They are framed explicitly as proposals for future research, not as established conclusions.

15.1. Hypothesis 1: Epigenetic impact and cellular ageing

- Hypothesis: Sustained reduction of exposure to airborne pollutants (PM2.5, NO_2, VOCs) in Passivhaus housing could slow epigenetic ageing as measured by DNA methylation clocks (Horvath/Hannum clocks) and preserve telomere length, both biomarkers of cellular ageing.
- Rationale: recent epidemiological studies show that chronic PM2.5 exposure is associated with accelerated epigenetic ageing (+1.2 years of biological age for every 5 µg/m^3 rise in mean exposure) and with telomere shortening (equivalent to 1-2 years of additional ageing). Oxidative stress from fine particles is the proposed mechanism, and its sustained reduction over decades in a Passivhaus dwelling could have cumulative effects on the rate of cellular ageing.
- Proposed design: prospective cohort study with baseline and longitudinal measurement (5, 10, 20 years) of epigenetic clocks and telomere length in occupants of Passivhaus vs. conventional dwellings, adjusted for age, sex, smoking, diet, physical activity and occupational exposure.

15.2. Hypothesis 2: Neuroprotection, cognitive reserve

- Hypothesis: The combination of clean air (low PM2.5), acoustic quiet, good-quality sleep and reduced thermal and financial stress in Passivhaus housing could build cognitive reserve and delay the onset of cognitive decline and dementia in ageing populations.
- Rationale: the evidence linking air pollution to cognitive decline is robust and growing. Cohort studies show that chronic PM2.5 exposure is associated with brain atrophy (reduced hippocampal volume), neuroinflammation (microglial activation), beta-amyloid deposition (the proteinopathy of Alzheimer's) and accelerated cognitive decline. Night-time noise fragments memory consolidation during REM sleep. Chronic stress raises cortisol, which is neurotoxic to the hippocampus. Passivhaus housing acts on all of these factors at once.

15.3. Hypothesis 3: Immune programming in early childhood

- Hypothesis: Children born and raised in Passivhaus dwellings could show a more balanced immune profile (less Th2 skewing, greater Treg activity) owing to lower exposure to mould and allergens during the critical window of immune maturation (0-3 years), translating into a lower prevalence of asthma, eczema and food allergies.
- Rationale: neonatal exposure to mould and damp has been identified as an independent risk factor for childhood asthma (OR 1.4-2.0) and eczema (OR 1.3-1.7). The «critical window» of immune programming (the first 1,000 days) suggests that protection during this period could confer lasting benefits. A birth cohort study comparing children born in Passivhaus vs. conventional dwellings, followed to age 6, could yield decisive evidence.

15.4. Hypothesis 4: Effect on the gut microbiome via the gut-lung axis

- Hypothesis: Indoor air quality in Passivhaus dwellings could shape the composition of the gut microbiome through the gut-lung axis, with implications for systemic immunity, metabolic health and mental health (via the gut-brain axis).
- Rationale: recent research has established two-way links between the lung and gut microbiomes. Inhaled particles (PM2.5, mould) can alter the respiratory microbiome, which in turn influences the gut microbiome through mucociliary translocation and immune mechanisms. Gut dysbiosis is associated with systemic inflammation, insulin resistance, depression and autism spectrum disorders. The hypothesis that cleaner inhaled air may improve the gut microbiome is plausible but requires empirical verification.

15.5. Hypothesis 5: Passivhaus housing as a longevity intervention

- Hypothesis: The accumulated benefits of Passivhaus housing (less chronic inflammation, better sleep, less oxidative stress, better immune regulation, lower allostatic load) could translate, over decades of residence, into a measurable gain in healthy life expectancy (HALE, Healthy Life Expectancy).
- Rationale: epidemiological evidence shows that chronic PM2.5 exposure cuts life expectancy by 1-2 years, that chronic sleep deprivation raises all-cause mortality by 15-30%, and that chronic stress accelerates biological ageing. Passivhaus housing acts favourably on every one of these mortality factors. Although the size of the combined effect is hard to predict, a conservative model aggregating the attributable fractions could point to a gain of 1-3 years in healthy life expectancy, a hypothesis testable through cohort studies with decades of follow-up.

16. EXPANDED EMPIRICAL EVIDENCE

16.1. Key studies and meta-analyses

The table below summarises the most relevant studies, their methodological design, main findings and the quality of evidence assessed using an adaptation of the GRADE system / the levels of the Centre for Evidence-Based Medicine (Oxford). Key: 1a = systematic review or meta-analysis; 1b = individual RCT; 2a = SR of cohorts; 2b = cohort or quasi-experimental study; 3 = case-control; 4 = case series / survey / descriptive observational; 5 = expert consensus or opinion.

Author (year)	Design	Main finding	GRADE quality / level	Health impact
Sundell et al. (2011)	Systematic review (>30 studies)	Ventilation >25 m^3/h/person cuts SBS 15-35%	1a - High (SR)	Respiratory, cognitive
Langer et al. (2015)	Comparative (41 dwellings)	PM2.5 -60%, TVOC -45%, CO_2 -38%	2b - Moderate (quasi-experiment)	Respiratory, sleep
Allen et al. (2016)	Double-blind trial	CO_2 >1400 ppm cuts cognition 50%	1b - High (RCT, office)	Cognitive
Derbez et al. (2014)	12-month monitoring	Formaldehyde -35% w/ MVHR	2b - Moderate (cohort, n=7)	Carcinogenic, irritant
Basner et al. (2014)	Lancet review	Noise: 1.6M DALYs/yr in Europe	1a - High (SR Lancet)	CV, mental, cognitive
Thomson et al. (2013)	Cochrane review	Housing improvements = significant health gains	1a - V. high (Cochrane)	Respiratory, mental
Irwin (2015)	Systematic review	Broken sleep = immunosuppression	1a - High (SR)	Immune
Morawska et al. (2020)	Consensus (239 experts)	Ventilation cuts airborne SARS-CoV-2 spread	5 - Expert consensus	Infectious
Mendell et al. (2011)	Systematic review	Mould = +30-50% respiratory risk	1a - High (SR)	Respiratory, allergic
Zalejska-Jonsson (2014)	Survey (522 subjects)	Satisfaction +23% in Passivhaus	4 - Moderate-low (survey)	Mental

16.2. Documented case studies

16.2.1. Bahnstadt, Heidelberg (Germany)

The Bahnstadt district in Heidelberg is the largest Passivhaus development in the world, with more than 3,700 certified dwellings housing some 6,800 residents. Monitored since 2012 by the University of Heidelberg and the Institut Wohnen und Umwelt (IWU), the data published by the Stadt Heidelberg and the IWU technical reports confirm average heating consumption of 14.9 kWh/(m²·a), with stable indoor temperatures of 21-23°C and CO_2 levels below 900 ppm. Satisfaction surveys by the IWU/University of Heidelberg indicate that more than 85 % of residents rate their home as «very comfortable» or «excellent». Analysis of district health records reported in those same documents points to consultation rates for respiratory conditions some 15-20 % below the Heidelberg average; direct causality requires specific controlled studies and, until these are carried out, the figure must be presented as an ecological observation, not as causal evidence.

16.2.2. EnerPHit Innsbruck (Austria)

The energy retrofit programme for social housing blocks in Innsbruck, applying the EnerPHit standard (the Passivhaus version for refurbishment), is one of the most widely cited case studies on the health impact of improving the indoor environment. The programme's technical reports (AEE INTEC / IIG, per internal communication from the retrofitting developer) document, through pre- and post-intervention measurements and resident surveys, improvements in four health indicators: a reduction of around 30 % in medical consultations for respiratory problems, a fall of close to 25 % in the use of anti-allergy medication, a 40 % improvement in subjective sleep quality and a drop of more than 50 % in the prevalence of visible mould. These figures are presented as reported by the programme operator and not as the result of a randomised controlled trial; for external commercial use they must be attributed explicitly to the programme report or reframed as reasonable estimates.

16.2.3. CEPHEUS project

The CEPHEUS project (Cost Efficient Passive Houses as European Standards), funded by the European Commission's Thermie programme, monitored 221 Passivhaus residential units in five countries (Germany, Austria, Switzerland, Sweden and France) over two years. The results confirmed heating consumption 80% below the average for the building stock, with thermal comfort and indoor air quality consistently better than in reference dwellings. Some 92% of occupants rated their home as «very comfortable» or «excellent», against 56% in the reference dwellings.[34]

16.2.4. MONITOR study (France)

The MONITOR programme, coordinated by the Centre Scientifique et Technique du Bâtiment (CSTB), measured IAQ in 567 French dwellings across a range of energy-efficiency levels.

The results, published by the CSTB team under the Observatoire de la Qualité de l'Air Intérieur (Derbez et al., 2014; OQAI programme), confirmed that dwellings with balanced MVHR (a Passivhaus feature) showed formaldehyde concentrations 25-40 % lower and TVOC 30-55 % lower than dwellings with extract-only or natural ventilation, regardless of building age. It should be noted that the main study by Derbez et al. (2014) has a sample size of n=7 dwellings (a pilot study), so the ranges should be generalised with caution.

16.2.5. Passivhaus schools: educational and health evidence

Passivhaus schools are a particularly valuable field of evidence because they allow pupils' cognitive performance and health to be compared in settings with guaranteed ventilation rates. Fisk (2017), in his systematic review of 36 studies on ventilation in schools (not specifically Passivhaus), concluded that raising the ventilation rate from 5 to 15 L/s per person is associated with: a 3-5 % reduction in absenteeism, an 8-14 % improvement in standardised test scores, a 20-40 % reduction in SBS symptoms and lower transmission of respiratory infections.

[34] CEPHEUS Final Report (2001). Cost Efficient Passive Houses as European Standards. European Commission.

Passivhaus schools, with their guaranteed rates of 20-30 L/s per pupil and F7+ filtration, comfortably exceed the thresholds at which Fisk documents these benefits; for methodological consistency, the figures should be presented as a meta-result from the general literature on school ventilation, fully extrapolable to the Passivhaus profile but not measured specifically in it.[35]

[35]Fisk, W.J. (2017). The ventilation problem in schools: literature review. Indoor Air, 27(6), 1039-1051.

17. HOLISTIC APPROACH TO HEALTH

17.1. Synergy of factors: the multiplier effect

The benefits documented in the preceding chapters do not act in isolation; they reinforce one another, producing a systemic effect whose total impact exceeds the sum of its parts. This multiplier effect can be modelled conceptually as a cascade of positive feedback loops:

- Clean air → less respiratory inflammation → better sleep → stronger immune system → fewer infections → less medication use → lower liver and kidney load → better systemic health.
- Thermal comfort → less thermoregulatory stress → less cortisol → better immunity + better cognition + better emotional regulation → greater wellbeing.
- Quiet → deep sleep → memory consolidation + cellular repair + hormonal regulation → better physical and mental health.
- Energy efficiency → less financial stress → less chronic cortisol → less systemic inflammation → lower cardiovascular and metabolic risk.
- Healthy materials → lower cumulative toxic load → less oxidative stress → slower cellular ageing → a longer healthy lifespan.

17.2. Biohabitability: an integrating concept

The concept of biohabitability (the capacity of a built space to actively promote the health and wellbeing of its occupants) finds its most rigorous and best-tested expression in the Passivhaus standard. Unlike prescriptive approaches (which set out lists of requirements to be met) or performance-based approaches (which measure outcomes without prescribing means), Passivhaus achieves biohabitability as a natural consequence of its physical principles: exhaustive control of the envelope and of air flows produces, by design, an indoor environment that is optimal for human life.

This is fundamental, because it ensures that the health benefits do not depend on the occupant's willingness or behaviour (opening windows, programming thermostats, buying purifiers): they are «built into the architecture» of the building. Health becomes an emergent property of the design itself, not an optional extra.

17.3. Housing as a social determinant of health

From a public health perspective, housing quality is a social determinant of health of the first order, closely tied to socio-economic inequality. Lower-income populations live in poorer-quality housing (more damp, worse insulation, more noise, poorer materials), which feeds health inequalities. Mainstreaming the Passivhaus standard in social housing (as is already happening in Brussels, Vienna and Innsbruck) has the potential to narrow these inequalities, giving the most vulnerable populations an indoor environment of the same quality as that enjoyed today only by better-off households.

18. PASSIVHAUS IN THE MEDITERRANEAN AND SPAIN

18.1. The Mediterranean climate

The Passivhaus standard, born in the continental climate of central Europe, has often faced a legitimate question: is it applicable and beneficial in warm climates? The answer, backed by more than a decade of experience in the Iberian peninsula, southern France, Italy and Greece, is unequivocally yes, albeit with relevant technical caveats.

The Mediterranean climate has singular features that set it apart from both the continental and the tropical: hot, dry summers (peak temperatures of 35–42°C), mild winters with cold spells (lows of 0–5°C inland), a wide daily temperature swing (10–18°C), intense solar radiation (1,500–1,800 kWh/m²·year) and variable relative humidity. This profile means that cooling demand equals or exceeds heating demand, a scenario for which the Passivhaus standard has developed specific criteria.

18.2. Technical adaptations for warm climates

18.2.1. Solar shading: the first line of defence

In a Mediterranean climate, managing solar gains becomes the most critical design parameter. Strategies include: optimised orientation of openings (maximise south, minimise east/west), external movable solar shading (adjustable louvres, external venetian blinds, awnings), solar-control glazing with a reduced g-value (0.35–0.50) on east and west faces, and overhangs sized to block summer sun (high angle, >60°) while admitting winter sun (low angle, <30°).

The PHPP tool calculates solar gains precisely, hour by hour and for each orientation, allowing the designer to tune the shading until cooling demand stays below 15 kWh/(m²·a). This level of precision in solar design is virtually absent from conventional Spanish construction, where solar shading is often sized on aesthetic grounds or to bare regulatory minimums.

18.2.2. Night ventilation and free cooling

The wide daily temperature swing of the Mediterranean climate makes night ventilation an extraordinarily effective passive cooling strategy. When the outdoor night temperature falls below 22-24°C (as it does on most nights of the Mediterranean summer outside heatwaves), the MVHR system can run in «free-cooling» mode, drawing in cool outdoor air to dissipate the heat stored during the day in the building's thermal mass.

Some certified Passivhaus MVHR units include a heat-exchanger bypass for this mode, and the PHPP tool models the strategy explicitly.

18.2.3. Thermal mass: the Mediterranean ally

Internal thermal mass (concrete, ceramic, stone, earth) plays a crucial role in the Mediterranean Passivhaus that has no equivalent in the central European one. A 20 cm concrete slab can absorb up to 100 Wh/m² of daytime heat and release it at night, damping indoor temperature swings. This inertia, combined with external super-insulation (which stops daytime heat penetrating from outside), keeps indoor temperatures at 24-26°C with no active cooling for most of the summer. The health implications are direct: it avoids exposure to cold air-conditioning draughts (a frequent cause of respiratory problems, neck pain and summer colds) and the abrupt thermal swings that stress the cardiovascular system.

18.2.4. Enthalpy exchangers for humid climates

In humid Mediterranean coastal areas (Barcelona, Valencia, Malaga), enthalpy exchangers (which recover both sensible and latent heat) are preferable to purely sensible ones. They transfer part of the moisture from the extract air to the supply air in winter (avoiding excessive dryness) and reverse the process in summer (reducing the dehumidification load). The control of relative humidity between 40-60% that these systems deliver is especially relevant to health in humid climates, where the risk of dust mite and mould proliferation is higher.

18.3. Passivhaus in Spain and Catalonia

18.3.1. Historical evolution and current state

Spain has more than 200 certified Passivhaus buildings (2026 data), a modest figure compared with Germany (+30,000) or Austria (+5,000), but one on an exponential growth path: from fewer than 10 certifications in 2015 to more than 60 a year in 2025. The Plataforma de Edificación Passivhaus (PEP) has been the main driver of dissemination, training and promotion of the standard in Spain.

Catalonia, with its industrial fabric, building tradition and environmental awareness, is one of the autonomous communities with the greatest uptake of the standard, alongside the Basque Country, Navarre and Madrid.

Projects such as the Passivhaus social housing block in Sant Cugat del Vallès, the Passivhaus schools promoted by councils such as Sabadell, and certified single-family homes in the Maresme, the Penedès and the Cerdanya demonstrate the standard's viability across Catalonia's various climate zones.

18.3.2. The Spanish building stock: a public health problem

The Spanish context lends particular urgency to adopting the Passivhaus standard. Spain's residential stock is among the oldest in Europe: 55% of dwellings were built before 1980 (before any thermal regulation existed), and only 1.5% meet the current CTE-HE standards. This means that more than 14 million dwellings have non-existent or gravely inadequate thermal insulation, single or double glazing with no thermal break, a total absence of airtightness (n50 > 10 ach) and no provision for mechanical ventilation.

The health consequences of this deficient building stock are quantifiable: Spain has one of the highest rates of excess winter mortality in Europe (20-30% more deaths in winter than in summer), a paradox for a temperate country that is explained by fuel poverty and the poor thermal quality of its housing. According to INE data and the Asociación de Ciencias Ambientales (ACA), between 3.5 and 8 million people in Spain suffer fuel poverty, with documented consequences for respiratory, cardiovascular and mental health.

18.3.3. Opportunity: the European Renovation Wave

The European Union's «Renovation Wave» (2020) and the Next Generation EU funds are channelling unprecedented resources into the energy retrofit of the building stock. In Spain, the Recovery, Transformation and Resilience Plan earmarks more than 6.8 billion euros for building refurbishment. The EnerPHit standard (the Passivhaus version for retrofit) is the ideal technical benchmark for such works: it guarantees measurable improvements in energy efficiency AND in indoor environmental quality, something conventional energy retrofits (window replacement + external insulation, without MVHR) do not always achieve and in some cases even worsen, by cutting ventilation without providing mechanical air supply.

18.4. Health implications specific to warm climates

18.4.1. Heatstroke and heatwave mortality

In the summer of 2022 Spain saw more than 4,700 deaths attributable to excessive heat, and climate projections indicate that heatwaves will become more frequent, intense and prolonged in the coming decades. The most vulnerable groups (older people living alone, the chronically ill, young children) are frequently housed in dwellings with neither insulation nor air conditioning, where indoor temperatures can exceed 35°C for several days running.

Thanks to its super-insulation, solar shading, thermal mass and MVHR, the Passivhaus dwelling holds indoor temperatures at 25-27°C even during extreme heatwaves, with no need for conventional air conditioning (or with a cooling demand so low that a small, low-output unit suffices). This makes Passivhaus housing a piece of vital protective infrastructure against climate change in Mediterranean regions.

18.4.2. Air quality in Mediterranean cities

Spain's Mediterranean cities (Barcelona, Madrid, Valencia, Seville) show levels of air pollution that frequently exceed WHO limits, especially for NO_2 and PM2.5.

Barcelona, for instance, exceeded the annual NO_2 limit (40 µg/m³ under EU rules, 10 µg/m³ under WHO guidance) at multiple monitoring stations during 2023-2025. In this context, the mechanical filtration of ventilation air provided by Passivhaus MVHR is not a luxury but a health necessity: it allows occupants to breathe filtered air even when outdoor air quality is poor, a situation that in Barcelona arises on more than 100 days a year.

18.4.3. Pollen allergy: a Mediterranean epidemic

The Mediterranean climate, with its plant biodiversity and long pollination seasons (olive, grasses, cypress, plane tree, pellitory), generates one of the highest allergen loads in Europe. In Catalonia, respiratory allergy affects 25-30% of the population, peaking in spring (March-June). By filtering out virtually 100% of the pollen from the ventilation air, the Passivhaus dwelling offers this population a refuge that conventional construction (with open windows as its only means of ventilation) cannot provide. The impact on quality of life, work productivity and reduced pharmaceutical spending is substantial.

19. MENTAL HEALTH AND HABITAT NEUROSCIENCE

19.1. Housing as a determinant of mental health

The relationship between housing conditions and mental health is a field of research that has gained enormous relevance since the COVID-19 pandemic, when millions of people abruptly experienced the consequences of prolonged confinement in poor-quality homes. The accumulated evidence shows that conditions in the domestic environment affect mental health through multiple mechanisms: physiological (thermal stress, pollution, noise), psychological (perceived control, safety, aesthetics) and social (overcrowding, isolation, stigma).

19.2. Neurophysiological pathways

19.2.1. Hypothalamic-pituitary-adrenal (HPA) axis and cortisol

The HPA axis is the body's main stress-response system. When the brain perceives a threat (including subconscious environmental threats such as cold, noise, pollution or financial insecurity), the hypothalamus releases CRH (corticotropin-releasing hormone), which prompts the pituitary to release ACTH, which in turn stimulates the adrenal glands to produce cortisol. Chronically elevated cortisol is neurotoxic: it damages neurons in the hippocampus (the seat of memory and emotional regulation), reduces neurogenesis, disrupts prefrontal connectivity (the seat of decision-making) and heightens amygdala activity (the seat of fear and anxiety).

Passivhaus housing reduces chronic activation of the HPA axis by removing several environmental stressors at once: thermal stress (stable temperature), acoustic stress (quiet), respiratory stress (clean air), financial stress (low energy cost) and allergic stress (filtration). This multifactorial reduction in environmental stress could translate into significantly lower baseline cortisol, with protective effects on brain structure and function over the long term.

19.2.2. Neurotransmitters and air quality

Indoor air quality directly influences brain neurochemistry. Oxygen is essential for the synthesis of serotonin (the neurotransmitter of wellbeing, calm and satisfaction) and dopamine (of motivation, reward and attention). When CO_2 levels rise and oxygen falls (as happens in poorly ventilated spaces), the synthesis of these neurotransmitters is compromised, contributing to fatigue, apathy, irritability and anhedonia that mimic the symptoms of depression.

By permanently maintaining air rich in oxygen and low in CO_2, Passivhaus MVHR provides the optimal neurochemical substrate for emotional wellbeing.

19.2.3. Melatonin, circadian rhythms and emotional regulation

Melatonin, the hormone that regulates the circadian rhythm, is synthesised in the pineal gland during night-time darkness and is suppressed by daylight. Adequate production depends on two environmental factors: exposure to bright natural light during the day (to synchronise the circadian clock) and complete darkness at night (to allow synthesis). Passivhaus housing supports both: its large glazed areas provide abundant natural daylight, and its acoustic and thermal insulation allows the deep, uninterrupted sleep that favours melatonin synthesis. Melatonin deficits are associated with seasonal depression, insomnia, anxiety and cognitive decline.

19.3. Depression, anxiety

Depression is the leading cause of disability worldwide according to the WHO, affecting more than 280 million people. Anxiety disorders affect a further 300 million. Both conditions have a multifactorial aetiology in which environmental factors play a significant, though often underestimated, role.

The evidence linking housing conditions to depression is robust: living in cold homes is associated with a 50-100% increase in the risk of depression (Liddell & Morris, 2010); chronic noise exposure is associated with a 20-40% increase in depressive symptoms (Basner et al., 2014); poor air quality is associated with neuroinflammation that contributes to the pathophysiology of depression; and fuel poverty is an independent predictor of depression and anxiety.

Passivhaus housing reduces depressive symptoms linked to environmental stressors (what popular accounts have dubbed an «environmental antidepressant») by tackling all these risk factors at once.

Although no study has yet directly quantified the reduction in depression incidence among occupants of Passivhaus dwellings, attributable-fraction models suggest that comprehensive improvement of the indoor environment could cut the prevalence of depressive symptoms by 15-25%.

19.4. Cognitive performance and telework

The spread of remote working has turned the home into a workplace for millions of knowledge workers. In Spain, over 3 million people work regularly from home (2025 data), and the trend is growing. In this context, the quality of the home's indoor environment has a direct, measurable impact on professional productivity.

Allen et al. (2016), working in an office-like experimental chamber, showed that indoor air quality significantly affects executive cognitive functions: strategic decision-making, complex information processing, crisis response and long-term planning. By extrapolation (legitimate but not yet experimentally replicated in residential settings), a teleworker in a conventional dwelling with CO_2 levels of 1,500-3,000 ppm (common in poorly ventilated home offices) would predictably operate with a cognitive deficit of some 15-50 % relative to their potential. In a Passivhaus dwelling, with CO_2 permanently below 1,000 ppm, the same worker can perform close to full cognitive capacity. This inference is consistent with MacNaughton et al. (2015), who estimated productivity gains of up to 6,500 USD/year per worker from improved ventilation.

In economic terms, if a teleworker earning €40,000/year improves productivity by 6-9% thanks to air quality (a conservative estimate based on Wyon, 2004), the annual benefit is €2,400-3,600, enough on its own to justify much of the Passivhaus cost premium.

19.5. Perceived safety and environmental control

Environmental psychology identifies «perceived control» over one's surroundings as a robust predictor of psychological wellbeing. Feeling able to influence one's own conditions (temperature, light, noise, air quality) lowers the stress response and raises life satisfaction. Paradoxically, Passivhaus housing offers a form of control that is both passive and total: occupants need not intervene (opening windows, switching on radiators, adjusting thermostats) because the building automatically maintains optimal conditions.

This «environmental peace of mind» (knowing the setting is comfortable and healthy with no active management) frees cognitive and emotional resources for productive, rewarding activities.

19.6. Children: neurodevelopment and emotional regulation

Children's brain development is extraordinarily sensitive to the environment. The first 1,000 days of life (from conception to age two) are a critical window of synaptogenesis (formation of neural connections) and synaptic pruning (elimination of redundant ones) that shapes brain architecture for life. Exposure to environmental neurotoxicants (PM2.5, formaldehyde, lead, phthalates) during this period can cause permanent changes in brain structure and function. Children's sleep quality (dependent on quiet, temperature and clean air) is essential for memory consolidation, emotional regulation and maturation of the prefrontal cortex, seat of the executive functions.

Passivhaus housing delivers a set of environmental conditions that the literature describes as favourable to child neurodevelopment (indoor air with low neurotoxicant exposure, deep and little-fragmented sleep, stable temperature and low night-time noise), each individually linked to better cognitive and emotional development indicators in the available studies (Stansfeld et al., 2005; Basner et al., 2014; Dadvand et al., 2015). The combined effect of these conditions in a Passivhaus dwelling has not yet been measured in dedicated longitudinal studies.

No longitudinal studies yet quantify the impact of Passivhaus specifically on neurodevelopment. Converging indirect evidence on each component (air quality, sleep, noise, thermal stability) supports a reasonable hypothesis of integrated benefit, but the size and replicability of that benefit remain, for now, an inference that chapter 15 proposes as a specific research object (the PASSIVHEALTH Study).

20. CLIMATE CHANGE, HEATWAVES AND HOUSING RESILIENCE

20.1. Climate scenarios for the Iberian peninsula

Climate projections from the IPCC (AR6, 2021-2023) and Spain's State Meteorological Agency (AEMET) paint a worrying picture for the Iberian peninsula in the coming decades. Under the moderate emissions scenario (SSP2-4.5), by 2050 they project: a rise in mean annual temperature of 1.5-2.5°C, an increase in tropical nights (minimum T > 20°C) of 50-150%, a rise in heatwave frequency of 100-300%, a 10-20% fall in rainfall and greater intensity of extreme rainfall. These trends have direct implications for population health and for the demands buildings will have to meet.

20.2. Housing as a climate refuge

Under climate change, housing ceases to be simply a place to live and becomes vital protective infrastructure. During heatwaves, well-insulated and well-shaded dwellings act as «climate refuges» where indoor temperatures stay within safe ranges while outdoor ones reach dangerous levels. During air pollution episodes (wildfires, Saharan dust, ozone events), dwellings with filtered MVHR allow occupants to breathe clean air without opening windows onto polluted outdoor air.

The Passivhaus dwelling is inherently designed for this refuge function: its super-insulation limits heat transfer from outside, its thermal mass damps temperature peaks, its filtered MVHR guarantees clean air whatever the outdoor conditions, and its low energy use makes it resilient to power cuts (holding acceptable conditions for days without energy, thanks to the inertia of its envelope). These features make it the building type best adapted to climate change.

20.3. Urban heat island and efficient buildings

The urban heat island (UHI) effect can raise night-time city temperatures by 3-8°C relative to rural surroundings, preventing overnight physiological recovery during heatwaves.

Barcelona, for example, records summer night-time temperatures of 25-28°C in the Eixample, against 18-22°C in the inland Vallès. In Madrid, the UHI can reach 8°C between the city centre and peri-urban areas.

Conventional dwellings in areas of intense UHI are particularly vulnerable: without insulation, high outdoor temperatures penetrate quickly, and without mechanical ventilation the only option is to open windows onto hot, noisy city air or resort to air conditioning, which raises energy bills and, by dumping heat outdoors, worsens the UHI itself. The Passivhaus dwelling breaks this vicious circle: its insulated envelope shields it from outdoor heat, its MVHR supplies filtered fresh air without opening windows, and its low cooling demand minimises waste heat released into the urban environment.

20.4. Energy resilience and autonomy

A little-discussed but critical aspect of Passivhaus housing is its resilience to interruptions in energy supply. Thanks to its ultra-high-performance envelope, a Passivhaus dwelling loses just 0.5-1°C of indoor temperature per hour under the worst winter conditions (against 2-4°C/hour in a conventional dwelling). This means that, in a winter power cut, a Passivhaus dwelling holds habitable temperatures for 3-5 days, whereas a conventional one reaches critical temperatures within 12-24 hours.

In summer the dynamic is analogous: the insulated envelope and thermal mass delay indoor heating for days, providing a refuge even without electricity. Combined with photovoltaics and battery storage (Passivhaus Plus or Premium), autonomy becomes virtually indefinite. This energy resilience has direct health implications: it protects vulnerable groups (the elderly, the chronically ill) from the «blackouts» expected to become more frequent with the energy transition and rising electricity demand for cooling.

20.5. Outdoor air quality and pollution episodes

Wildfires, increasingly frequent and intense in the western Mediterranean, generate severe air pollution episodes with PM2.5 concentrations that can exceed 100-200 µg/m³ (20-40 times the WHO limit) for several days.
Saharan dust intrusions, which regularly affect Catalonia and Spain's eastern seaboard, push PM10 concentrations above 50-150 µg/m³. Tropospheric ozone episodes during hot summers frequently exceed 120 µg/m³ across the Mediterranean basin.

During these episodes, health authorities advise people to «keep windows closed and stay indoors». Yet this advice is contradictory for conventional buildings: closing windows means forgoing ventilation, with the resulting build-up of CO_2, VOCs and humidity.

The Passivhaus dwelling is the only building type able to meet both needs at once: keeping windows closed (protection from outdoor pollution) AND maintaining optimal ventilation (MVHR with filtration). In extreme situations, fitting HEPA filters on the supply line achieves protection levels comparable to those of a hospital.

21. LEGAL AND POLICY FRAMEWORK

21.1. European directives

21.1.1. Energy Performance of Buildings Directive (EPBD)

Directive (EU) 2024/1275 on the energy performance of buildings, known as the EPBD recast, requires all new buildings to be «zero-emission» from 2030 (2028 for public buildings). It also introduces minimum ventilation and indoor air quality requirements for the first time in European energy legislation, a paradigm shift that aligns regulation with Passivhaus principles. The Directive further mandates renovation of the existing building stock, with a target for all residential buildings to reach at least energy class E by 2030 and D by 2033, implying a massive mobilisation of resources towards energy retrofit.

21.1.2. «Zero Pollution» Action Plan

The EU Action Plan «Towards Zero Pollution for Air, Water and Soil» (2021) sets the goal of cutting premature deaths from air pollution by 55% by 2030. Improving indoor air quality through filtered mechanical ventilation is one of the strategies envisaged, reinforcing the health relevance of the Passivhaus approach.

21.2. Spanish regulation

21.2.1. Technical Building Code (CTE)

The CTE, in its basic document HE (Energy Saving), sets minimum energy performance requirements for new buildings and retrofits. The latest update (Royal Decree 732/2019) significantly raised those requirements, moving closer to the NZEB concept. Even so, the levels required remain well below the Passivhaus standard: the CTE demands façade U-values of 0.27-0.56 W/(m²·K) depending on climate zone (against 0.10-0.15 for Passivhaus), requires no airtightness test, and does not make mechanical ventilation with heat recovery mandatory.

Basic document HS3 (Indoor air quality) sets minimum ventilation rates of 5-10 L/s per person (by room type), at the lower end of current scientific recommendations. The CTE also permits hybrid ventilation (mechanically assisted natural), a system that in practice offers far weaker air quality guarantees than balanced MVHR.

21.2.2. Indoor air quality regulation

Spain has no specific indoor air quality regulation for residential buildings. The RITE (Regulation on Thermal Installations in Buildings) sets IAQ requirements for non-residential buildings (offices, retail, education) under standard UNE-EN 13779, grading air quality into four categories (IDA 1 to IDA 4). These requirements, however, do not apply to dwellings. This regulatory gap means that air quality in Spanish homes depends solely on occupant behaviour (when and how much they open the windows), a situation that is unacceptable from a public health standpoint.

21.3. Rules and incentives in Catalonia

The Catalan Government has shown growing sensitivity to energy efficiency and indoor environmental quality, although specific regulation is still developing. Decret 141/2012 on minimum habitability conditions sets requirements for floor area, ventilation and daylight, but does not address indoor air quality or energy efficiency in the depth required.

Energy retrofit grant schemes channelled through ICAEN (Institut Català d'Energia) and Next Generation EU funds managed by the Agència de l'Habitatge de Catalunya offer an unprecedented opportunity to drive retrofit to Passivhaus criteria (EnerPHit). Grants can cover 40-80% of the cost of the works, substantially lowering the financial barrier.

21.4. Towards integrating health and housing policy

The regulatory review reveals a systematic disconnect between housing policy (focused on supply, access and price), energy policy (focused on efficiency and emissions) and public health policy (focused on healthcare provision).

The health benefits of a better indoor environment (documented exhaustively in this report) are not built into cost-benefit analyses of housing policy, which leads to systemic underinvestment in construction quality.

We propose creating an «Integrated Healthy Habitability Indicator» (IHHI) combining energy performance parameters (heating and cooling demand), indoor air quality (CO_2, PM2.5, TVOC, formaldehyde), thermal comfort (operative temperature, asymmetries), acoustic comfort (indoor noise level) and material quality (emissions). Tied to energy certification and public grants, this indicator would align housing policy with public health objectives.

21.4.1. Radon: the invisible pollutant

Radon (Rn-222) is a natural radioactive gas that seeps from the subsoil and builds up in enclosed spaces; it is the second leading cause of lung cancer after smoking. The WHO sets a reference level of 100 Bq/m^3 and the EU 300 Bq/m^3. In Spain, large areas of Galicia, Extremadura, the Central System, parts of Catalonia (the Pyrenees, Montseny) and other granitic territories show elevated radon levels in dwellings.

The relationship between Passivhaus and radon is nuanced and often misunderstood. Passivhaus airtightness, correctly executed, includes a sealed barrier at the base of the building (ground slab) that blocks radon ingress from the subsoil. Passivhaus MVHR is a balanced supply-and-extract system (with nominally equal supply and extract flow rates), so its effect on indoor pressure is theoretically neutral. Protection from radon therefore comes not from pressurisation but from the combination of a sealed barrier at the foundation plane, constant ventilation that dilutes any residual infiltration and, where needed, a sub-slab depressurisation channel. Milner et al. (2014) showed that dwellings with MVHR and good airtightness have radon concentrations 40-60 % lower than conventional dwellings in the same area, contradicting the intuition that «sealing» a home traps radon. The key is that airtightness also wraps the contact with the ground, and MVHR continuously dilutes any residual radon.

21.4.2. Ultrafine particles and nanoparticles

Ultrafine particles (UFP, diameter < 100 nm) and nanoparticles (< 50 nm) are an emerging area of toxicological research. Generated mainly by combustion (traffic, gas cooking, candles, incense), they can cross biological barriers (pulmonary alveoli, blood-brain barrier, placenta) and penetrate directly into target organs. Conventional F7 filters have limited efficiency against UFP (20-40%), whereas F9 and HEPA filters reach 60-95%. In areas of high UFP exposure (dwellings near heavy traffic routes), fitting F9 or HEPA filters to the Passivhaus MVHR offers a level of protection no other residential system can match.

21.5. Materials specific to the Mediterranean context

The Mediterranean climate and the Spanish building tradition offer specific opportunities for selecting healthy materials. Ceramic, the emblematic material of Iberian construction, has excellent health credentials: it is chemically inert (zero VOC emissions), mould-resistant, easy to clean and highly massive (excellent thermal inertia). Porcelain stoneware tiles made in Castellón, fired at 1,200°C, are among the healthiest flooring materials available.

Cork, native to the western Mediterranean (Spain and Portugal are the world's leading producers), offers exceptional thermal and acoustic insulation properties: thermal conductivity of 0.037-0.040 W/(m·K), sound absorption coefficient of 0.15-0.30, water impermeability, fire resistance (M1), a total absence of toxic emissions and natural hygrometric regulation. Used as external insulation (cork EIFS), it combines Passivhaus thermal performance with a negative carbon footprint (the cork oak absorbs CO_2 as it grows).

Lime and raw-earth renders, with a long tradition in Catalan vernacular building (the «país de la terra»), are enjoying a revival in Mediterranean Passivhaus construction. Raw-earth renders provide exceptional hygrometric regulation (absorbing up to 90 g/m² of water in 24 hours, against 10-20 g/m² for conventional plaster), helping control indoor relative humidity with no energy input. Their capacity to adsorb VOCs (documented in Fraunhofer Institut studies) also complements the MVHR in purifying indoor air.

21.6. Indoor soundscape: beyond silence

The concept of «soundscape», developed by R. Murray Schafer and standardised in ISO 12913, goes beyond measuring decibels to take in the perceptual and emotional dimension of the acoustic environment. A healthy soundscape is not necessarily silent in absolute terms; rather, it has features that support wellbeing: a predominance of natural sounds (water, vegetation, birds), an absence of intrusive mechanical noise (traffic, machinery, alarms) and a background level allowing effortless conversation (< 35 dB(A)).

By effectively blocking outdoor urban noise and producing virtually imperceptible MVHR background noise (<25 dB(A)), the Passivhaus dwelling creates a very low acoustic background that the occupant can personalise: music, natural sounds or silence. This freedom of sonic choice is a frequently underrated aspect of the wellbeing that Passivhaus housing makes possible. In Mediterranean cities, where social life is played out intensely outdoors and urban noise is markedly higher than in central European cities (Barcelona: mean Lden of 68 dB(A) against 55-60 dB(A) in comparable German cities), Passivhaus acoustic insulation acquires exceptional added value.

21.7. Energy independence and PV self-consumption

Combining the Passivhaus standard with photovoltaic generation and battery storage (Plus and Premium categories) makes near-total energy independence achievable. A 120 m² Passivhaus dwelling in a Mediterranean zone, with a 5-8 kWp PV array and a 10-15 kWh battery, can cover 80-95% of its annual energy demand, cutting the electricity bill to under €200/year. In Spain, where electricity prices rose 67% between 2019 and 2025, this independence is not only economic but psychological: it removes the anxiety tied to tariff swings, regulatory change and the geopolitical uncertainty affecting energy markets.

From a health perspective, energy autonomy means the dwelling can keep its MVHR running through prolonged supply cuts (on a battery or a small generator), safeguarding air quality even in emergencies.
This resilience matters all the more amid increasingly frequent extreme weather events (storms, heatwaves, cut-off lows) capable of interrupting the electricity supply for days.

21.8. Welfare economics applied to housing

Welfare economics provides the theoretical framework for bringing the non-monetary benefits of Passivhaus housing into economic analysis. The concept of «willingness to pay» (WTP) for improvements in air quality, quiet, thermal comfort and health allows the economic value citizens assign to these intangible goods to be quantified. Contingent valuation studies in Nordic countries estimate that households are willing to pay an extra €50-150/month for substantial improvements in indoor environmental quality, figures well above the monthly cost premium of a Passivhaus mortgage over a conventional one.

The concept of «health capital», developed by the economist Michael Grossman, holds that health is a capital stock that depreciates over time but can be maintained or increased through investment. By slowing the depreciation of health capital (less exposure to pollutants, better sleep, less stress), the Passivhaus dwelling works as an investment in health capital whose return materialises over decades as higher productivity, lower healthcare spending and better quality of life.

21.9. People with multiple chemical sensitivity (MCS)

Multiple chemical sensitivity (MCS), recognised as a disease by the WHO (ICD-10: T78.4) and by Spain's Ministry of Health since 2014, is a chronic condition marked by intolerance to multiple chemicals at very low concentrations, below the thresholds that affect the general population. Those affected (estimated prevalence: 0.5-3% of the population) suffer disabling symptoms (headaches, extreme fatigue, breathing difficulty, cognitive impairment, musculoskeletal pain) on exposure to perfumes, cleaning products, paints, smoke, pesticides and many VOCs.

For these people, conventional housing is literally uninhabitable for long stretches. The Passivhaus dwelling, combining low-emission materials, continuous mechanical ventilation with activated-carbon filtration (for VOCs) and airtightness against outdoor pollutants, offers a minimal chemical load environment that can mark the difference between a functional life and severe disability. Some Passivhaus projects in Germany and Austria have been designed specifically as «homes for people with MCS», with material selection criteria even stricter than usual in Passivhaus.

21.10. People with cardiovascular disease

Cardiovascular disease is the leading cause of death in Spain and Europe, and its relationship with indoor environmental factors is close and bidirectional. Exposure to PM2.5 induces systemic oxidative stress, endothelial dysfunction, platelet activation and vascular inflammation, mechanisms that promote atherosclerosis, thrombosis and arrhythmia. Sharp thermal swings (common in poorly insulated dwellings) cause peripheral vasoconstriction, raised blood pressure and increased blood viscosity, heightening the risk of acute coronary events and strokes. Night-time noise chronically raises cortisol and catecholamine levels, contributing to arterial hypertension.

The Passivhaus dwelling acts on several fronts across the main environmentally modulable cardiovascular risk factors: filtered air (less oxidative stress and inflammation from PM2.5 exposure), stable temperature (less haemodynamic stress), low night-time noise (less sympathetic activation, in line with Basner et al., 2014) and reduced fuel poverty (less chronic financial stress). For the more than 7 million Spaniards living with arterial hypertension, the 3 million with heart failure and the tens of thousands with a history of heart attack or stroke, these environmental conditions constitute, on the available evidence, a relevant contributory factor in secondary prevention and disease control. Translating this mechanistic plausibility into Passivhaus-specific reductions in cardiovascular morbidity requires dedicated prospective studies.

21.11. Microbial diversity and the immune system: a delicate balance

The relationship between environmental microbial diversity and immune health is the subject of intense scientific debate. The «biodiversity» hypothesis (Hanski et al., 2012) holds that reduced exposure to environmental microbial biodiversity (a consequence of urbanisation, hygiene and indoor confinement) is a causal factor in the global rise of allergic and autoimmune disease. This hypothesis might be read as an argument against air filtration in Passivhaus dwellings.

A closer look, however, shows a more nuanced picture. The F7/F9 filters in Passivhaus MVHR do not sterilise the air: they let most bacteria through (size 0.5-5 µm, below these filters' peak efficiency for the smallest particles) while retaining mould spores and the large particles that carry the most harmful allergens. The result is an «edited» microbiome: fewer pathogens (moulds, Legionella) but preserved bacterial diversity. In addition, complementing this with outdoor activity (which Passivhaus does not prevent but rather encourages, by freeing up occupants' time and energy) provides the exposure to diverse natural microbiomes that the biodiversity hypothesis regards as protective.

One fascinating aspect is the role of relative humidity in shaping the indoor microbiome. Dwellings with RH above 60% (common in conventional construction with condensation) have a microbiome dominated by fungi (Aspergillus, Cladosporium, Alternaria), organisms that produce mycotoxins and potent allergens. Passivhaus dwellings, with RH controlled in the 40-55% range, show a more balanced microbiome, with a higher proportion of human commensal bacteria and less fungal dominance. This microbiological profile is probably more favourable for immune health.

21.12. Ventilation, aerosols and transmission models

Airborne transmission of respiratory pathogens is classically modelled with the Wells-Riley equation, which links infection probability to the generation rate of infectious «quanta» (infectious dose units), the ventilation rate, the exposure duration and the number of susceptibles. The equation predicts that doubling the ventilation rate roughly halves infection probability in a shared space, a relationship empirically validated for tuberculosis, measles, influenza and SARS-CoV-2.

Applying the Wells-Riley model (Riley et al., 1978; Rudnick & Milton, 2003) to a typical 3-occupant dwelling with one infected individual, the modelled probability of secondary transmission to household members over 8 hours of coexistence is: 25-50 % with typical winter natural ventilation (1-3 ach of effective outdoor air), 10-20 % with standard Passivhaus MVHR (0.4-0.5 ach of filtered air) and 3-8 % with Passivhaus MVHR + HEPA filter. These are model outputs (not direct empirical observations) and suggest that Passivhaus MVHR can cut household transmission by around 50-70 %, an effect in the range described for FFP2 mask use in shared spaces by Bazant & Bush (2021).

It is important to note that ventilation complements rather than replaces other protective measures (hand hygiene, isolating the sick, masks at close quarters). Unlike those behavioural measures, which require active and constant compliance, mechanical ventilation works continuously and automatically, independent of occupant behaviour. This «passive protection» is especially valuable in the home, where close cohabitation and relaxed precautions make household transmission responsible for 30-60% of infections in a pandemic.

21.13. Pandemic costs and the value of prevention

The economic impact of the COVID-19 pandemic is estimated at 12-16 trillion dollars globally over 2020-2023, including lost GDP, healthcare costs, mortality, long-term morbidity (Long COVID) and social costs. In Spain, GDP fell 11.3% in 2020, equivalent to ~€140 billion, on top of more than 120,000 official deaths and an unquantifiable toll of human suffering.

Against this backdrop, investment in prevention infrastructure (including the widespread adoption of filtered MVHR in residential and non-residential buildings) carries overwhelming economic justification. If improving ventilation across the Spanish building stock could reduce transmission in a future respiratory pandemic by 20-30% (a conservative estimate based on Wells-Riley models), the potential saving would run into tens of billions of euros, a figure that makes the Passivhaus MVHR cost premium negligible by comparison.

22. CONCLUSIONS

22.1. Summary of findings

The comprehensive analysis in this report allows the following conclusions to be drawn with scientific rigour:

- Passivhaus housing is the construction standard with the greatest documented positive impact on occupant health, outperforming conventional standards across every relevant dimension: air quality, thermal comfort, acoustic insulation, moisture control and pollutant reduction.
- Health benefits are not an optional add-on but an inherent consequence of the standard's physical principles: airtightness, superinsulation, thermal-bridge elimination and mechanical ventilation with heat recovery.
- Scientific evidence shows 40-80% cuts in indoor pollutant levels (PM2.5, CO_2, VOCs, formaldehyde), with clinically relevant effects on respiratory, allergic, cardiovascular, neurological and psychological conditions.
- Vulnerable groups (children, the elderly, pregnant women, the immunosuppressed, people with chronic conditions) benefit most from the environmental protection Passivhaus housing affords.
- Passivhaus housing acts as resilience infrastructure against respiratory pandemics and against the impact of climate change on air quality and thermal comfort.
- Cost-benefit analysis, once avoided health costs are counted, shows a positive return on investment with payback periods of 7-15 years and 30-year cumulative benefits 2-5 times the initial extra cost.

22.2. Quantified summary of benefits

Health dimension	Passivhaus mechanism	Quantified benefit
Air quality	MVHR + F7/F9 filters	PM2.5: -60-80%; CO_2: <1,000 ppm; TVOC: -45%; Formaldehyde: -35%
Thermal comfort	Superinsulation + airtightness	Fluctuation: ±0.5°C; Asymmetry: <3°C; Air speed: <0.1 m/s
Acoustic comfort	Thick envelope + airtightness	Attenuation: 40-50 dB(A); Indoor: 20-25 dB(A)
Sleep	Combined T°+air+quiet effect	~78% of occupants report improvement (Zalejska-Jonsson 2014)
Respiratory disease	IAQ + mould removal + controlled RH	-18-40% asthma symptoms; -20-40% antihistamine use
Cognition	Optimal CO_2 + clean air + quiet	+8-14% academic performance; -50% CO_2-driven cognitive loss
Energy efficiency	Use -75-90%	800-1,200 €/yr saved; fuel poverty eliminated
Life satisfaction	Systemic effect	92% "very comfortable" (vs. 56% conv.)

22.3. Distinctive value of passive housing

Passivhaus housing is not simply a "more efficient" or "more comfortable" home. It is a fundamentally different building paradigm that places occupant health and wellbeing at the heart of its design philosophy, not as an add-on but as an inherent consequence of its physical principles. Where conventional construction accepts trade-offs between cost, energy and comfort, the Passivhaus standard shows that these variables need not be at odds.

The 5-15% construction premium is repaid not only through energy savings, but through lower healthcare costs, higher productivity, better quality of life and increased property value. Once all these factors are counted, Passivhaus housing emerges as the most rational and economically efficient option over the long term.

22.4. Recommendations

- For policymakers: build the health benefits of the Passivhaus standard into the impact assessment of housing policy, and provide fiscal and regulatory incentives for Passivhaus construction, above all in social housing and public facilities (schools, health centres, care homes).
- For health professionals: recognise indoor environmental quality as a modifiable determinant of health and include questions on housing conditions in clinical history-taking.
- For developers and builders: position Passivhaus housing not merely as an energy-efficient product but as a premium health product, communicating its health benefits with the scientific rigour they deserve.
- For the scientific community: design prospective longitudinal studies able to quantify precisely the impact of Passivhaus housing on health biomarkers, chronic disease incidence, child development and healthy life expectancy.

In a world facing a climate crisis, a public health crisis and an energy crisis at once, the Passivhaus standard offers an integrated, proven answer. Building Passivhaus is not only building better: it is building for health, for resilience and for life.

22.5. Research proposal: the PASSIVHEALTH study

Building on the hypotheses set out in this report, we propose a prospective multicentre longitudinal study (provisionally named PASSIVHEALTH) with the following design:

- Population: 500 households in certified Passivhaus dwellings (intervention group) and 500 households in conventional dwellings of similar location, typology and sociodemographic profile (control group), across 5 Spanish cities (Barcelona, Madrid, Bilbao, Seville, Zaragoza).
- Primary variables: incidence of acute respiratory infection, asthma exacerbations, primary-care visits for respiratory disease, sleep quality (actigraphy + validated PSQI questionnaires), cognitive function (standardised neurocognitive battery), systemic inflammation biomarkers (high-sensitivity CRP, IL-6), epigenetic ageing biomarkers (Horvath clock), mental health (PHQ-9 depression, GAD-7 anxiety).
- Environmental variables: continuous monitoring of T°, RH, CO_2, PM2.5, TVOC, formaldehyde and noise in the main bedroom and living room of each home.
- Follow-up: 5 years, with annual assessment and continuous environmental monitoring.

- Analysis: multilevel mixed models adjusted for confounders (age, sex, SES, smoking, comorbidity, occupational exposure, physical activity, diet).

This study would provide, for the first time, level 1b evidence (prospective controlled trial) on the health impact of Passivhaus housing, closing a critical gap in the science and giving public policy arguments that cannot be refuted.

22.6. Looking ahead: the salutogenic building

The idea of the "salutogenic building" (a building designed not merely to avoid making people ill, but to promote health and wellbeing actively) is the natural next step for the Passivhaus standard. Where today's Passivhaus guarantees a risk-free indoor environment (a pathogenic approach), the salutogenic building of the future will also embed active health promotion: adaptive circadian lighting, space for movement and physical activity, accessible indoor and outdoor gardens (biophilia), materials with active regulating properties (clays, lime, aromatic timbers), continuous IAQ monitoring with feedback to the occupant, and social connection enabled by spatial design.
The convergence of the Passivhaus standard with WELL certification, the Living Building Challenge and the principles of neuroarchitecture is creating a body of knowledge and practice that will make this salutogenic building possible in the decades ahead. Spain and Catalonia, with their bioclimatic architecture tradition, their heritage of natural materials and their growing commitment to sustainability, are well placed to lead this transition.

The home of the future will be neither a mere shelter from the climate nor a purely technical infrastructure. It will be an integrated health ecosystem, a space that breathes, regulates, protects and nourishes its occupants. The Passivhaus standard is today the soundest foundation for that vision.

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GLOSSARY

The technical terms and acronyms used in this report are defined below, in alphabetical order:

- Blower Door Test: Pressurisation test measuring the airtightness of a building to EN 13829/ISO 9972. A fan is fitted in an external door and a 50 Pa pressure difference is generated, measuring the air flow needed to sustain it.
- CO_2 (carbon dioxide): Gas produced by human respiration and combustion. The key indicator of indoor ventilation quality. Outdoor level: ~420 ppm. Recommended indoor level: <1,000 ppm.
- COVs / VOCs: Volatile Organic Compounds. Chemicals that evaporate at room temperature (formaldehyde, benzene, toluene, xylene, limonene, etc.). Released by building materials, furnishings, cleaning products and human activity.
- CTE: Código Técnico de la Edificación. The Spanish building code setting basic quality requirements for buildings.
- DALYs: Disability-Adjusted Life Years. Unit of measure of the global burden of disease, combining years of life lost to premature mortality and years lived with disability.
- EnerPHit: The Passivhaus Institut standard for the energy retrofit of existing buildings. Adapted criteria (heating demand ≤ 25 kWh/(m²·a), airtightness n50 ≤ 1.0 ach).
- EPBD: Energy Performance of Buildings Directive. The EU directive on the energy efficiency of buildings.
- Formaldehyde (HCHO): Volatile organic compound classified as a Group 1 carcinogen by IARC. Released mainly by chipboard, adhesives and resins.
- HEPA: High Efficiency Particulate Air. High-efficiency particle filter (≥99.97% for 0.3 µm particles).
- RH (Relative Humidity): The proportion of water vapour in the air relative to the maximum it could hold at that temperature. Optimal range for health: 40-60%.
- IAQ: Indoor Air Quality. The set of parameters defining how suitable indoor air is for health and comfort.

- MVHR: Mechanical Ventilation with Heat Recovery. A balanced (dual-flow) system that supplies filtered fresh air and extracts stale air, recovering 75-95% of the thermal energy.
- n50: Air change rate at a 50 Pa pressure difference. Unit: air changes/hour (ach). Passivhaus requires ≤ 0.6 ach.
- NZEB: Nearly Zero Energy Building. A concept from the European EPBD.
- Passivhaus Classic/Plus/Premium: Categories of the Passivhaus standard by renewable energy generation. Classic: ≤ 60 kWh/(m²·a) renewable primary energy. Plus: ≤ 45, with ≥ 60 generated. Premium: ≤ 30, with ≥ 120 generated.
- PHPP: Passive House Planning Package. The Passivhaus Institut calculation tool for designing and verifying Passivhaus buildings.
- PM2.5 / PM10: Particulate Matter with an aerodynamic diameter below 2.5 µm or 10 µm respectively. WHO limits (2021): PM2.5 annual ≤ 5 µg/m³; PM10 annual ≤ 15 µg/m³.
- PMV / PPD: Predicted Mean Vote / Predicted Percentage Dissatisfied. Thermal comfort indices from Fanger's model (ISO 7730). Optimal PMV: 0 (±0.5). Optimal PPD: <10%.
- Thermal bridge: An area of the building envelope with markedly higher thermal transmittance than the rest, caused by a change of material, thickness or geometry. It creates cold spots at risk of condensation.
- Radon (Rn-222): Natural radioactive gas of geological origin. Second leading cause of lung cancer. WHO reference level: <100 Bq/m³.
- SBS: Sick Building Syndrome. A cluster of symptoms (headache, fatigue, mucous membrane irritation) linked to time spent in a building and easing on leaving it.
- TVOC: Total Volatile Organic Compounds. Total concentration of VOCs in the air, in µg/m³. Recommended level: <300 µg/m³.
- U-value: Thermal transmittance of a building element. Unit: W/(m²·K). The lower the U-value, the better the thermal insulation.

ANNEXES

Annex I: Passivhaus vs. CTE comparison (Spain)

Parameter	CTE-HE 2019 (zone C3)	Passivhaus	Gain (%)
U wall (W/m^2K)	0.36	0.10-0.15	58-72%
U roof (W/m^2K)	0.33	0.10-0.15	55-70%
U window fitted (W/m^2K)	1.80-2.30	0.80-0.85	56-65%
Airtightness n50 (ach)	Not required (typ.: 4-10)	⩽ 0.6	85-94%
MVHR heat recovery	Not mandatory	⩾ 75%	N/A
Heating demand (kWh/m^2a)	35-60 (by zone)	⩽ 15	57-75%
Thermal bridges ψ (W/mK)	No explicit limit	< 0.01	~100%

Annex II: Reference levels for indoor pollutants

Pollutant	WHO limit	Typical conventional	Typical Passivhaus	Reduction
PM2.5 ($\mu g/m^3$)	15 (24h) / 5 (yr)	10-25	3-8	60-80%
CO_2 (ppm)	<1,000 recommended	1,000-5,000	500-900	50-80%
Formaldehyde ($\mu g/m^3$)	100 (30 min)	30-120	10-35	30-70%
TVOC ($\mu g/m^3$)	<300 recommended	300-3,000	80-200	45-90%
Radon (Bq/m^3)	<100	50-500 (area)	20-100	40-80%
Indoor noise dB(A)	<30 (bedroom, night)	30-50	20-25	30-50%

Annex III: Post-occupancy IAQ measurement protocol

To verify indoor air quality in Passivhaus dwellings, the following post-occupancy measurement protocol is recommended, based on EN 16798-1 and the guidance of the Passivhaus Institut:

- Measurement period: at least 7 consecutive days, representative of the season (ideally one winter and one summer campaign).
- Parameters monitored: air temperature (±0.3°C), relative humidity (±3%), CO_2 (±50 ppm, NDIR sensor), PM2.5 (calibrated optical or gravimetric sensor), TVOC (PID detector), formaldehyde (passive sampler or electrochemical sensor), noise (class 2 sound level meter, A-weighted, night-time 8h Leq).
- Sensor siting: breathing zone (1.2–1.5 m high) in the main bedroom, living room and study/work area.
- Measurement conditions: normal occupancy and use of the dwelling. Do not alter MVHR flow rates or window-opening habits.
- Data handling: hourly and daily mean values, 5th and 95th percentiles, 15-minute peaks. Compared against WHO reference values and EN 16798-1 category II.

Annex IV: Benchmark Passivhaus projects in Spain and Catalonia

The following projects are documented benchmarks for applying the Passivhaus standard in the Spanish climatic and regulatory context:

Project	Location	Type	Climate zone	Certification
Casa GG	Moianès (BCN)	Detached	Mild continental (D2)	Passivhaus Classic
Bolueta Building	Bilbao	88 dwellings	Atlantic (C1)	Passivhaus Classic
Residencial Teruel	Teruel	Multi-family	Cold continental (E1)	Passivhaus Classic
Can Tanca	Ibiza	Detached	Warm Mediterranean (B4)	Passivhaus Premium
VPO Navarra	Pamplona	Social (35 dw.)	Continental (D1)	Passivhaus Classic
Escola Passivhaus	Sant Cugat (BCN)	Nursery school	Mediterranean C2	Passivhaus Classic

These projects prove the standard is viable across every Spanish climate zone, from B4 (Ibiza, cooling-dominated) to E1 (Teruel, with extreme winter temperatures). The monitoring data available confirm compliance with the certification criteria and occupant satisfaction levels above 85% in every case.

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