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Systematic Review

Cost-Related Drivers and Barriers of Passivhaus: A Systematic Literature Review

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Abstract: Passivhaus (PH) has gained global recognition for its energy-efficient features despite a 5% to 10% higher construction cost than traditional houses, especially within European countries. However, its adoption and popularity have not met the same fate in other countries like New Zealand. The higher upfront cost has been critical to the slow adoption of the PH movement in New Zealand. This study aimed to demystify the mist around the cost of PHs with a focus on the effects of drivers and barriers on their life cycle costs (LCCs). As such, a systematic literature review was conducted to provide a comprehensive understanding of the cost implications associated with PH. Using the preferred reporting items for systematic reviews and meta-analyses (PRISMA) review method, we examined 71 past studies on PHs from 2005 to 2023. We found that the drivers of PHs include reduced heating demand, increased thermal comfort, and indoor air quality (IAQ). Research showed that the rising market for PHs is fueled by climate change, environmental awareness, innovative materials and technologies, individual commitment, improved regulations, pilot studies, research efforts, and governmental funding and initiatives. However, PHs face significant challenges such as increased complexity, advanced technology, higher initial investments compared to conventional and low-energy houses, national requirements, overheating, difficulties in affording the technologies, and a lack of options in the market. Despite the wealth of research on the economic aspects of PH, there is a lack of in-depth studies exploring the LCC of PHs focusing on cost commitments and benefits. Such studies are essential for assessing and optimising the cost-effectiveness of PH, considering different climates and regions, and comparing them with other low energy standards. The findings of our review provide a crucial focus for PH stakeholders in assessing the long-term financial viability of PH projects, thereby improving decision-making and facilitating effective planning for sustainable and cost-effective housing.

Keywords: energy performance; life cycle cost; passive design technologies; Passivhaus; Passivhaus certification

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1. Introduction

The construction sector is in a pivotal position to address major global concerns, including housing affordability, embodied and operational carbon reductions, increased indoor air quality (IAQ) regulations, and immediate action against climate change [1]. Notably, the building sector is receiving increased attention in global sustainable development policies, as buildings consume 40% of all energy and account for one-third of all global greenhouse gas emissions [2]. Moreover, they also possess the potential to reduce consumption with effective measures and solutions [3]. In particular, residential buildings hold significant potential for reducing energy consumption, particularly through enhanced space heating efficiency [4]. Recognising this potential, many developed countries have responded by establishing environmental assessment frameworks and sustainable construction codes and regulations that consider the local climatic conditions [5].

The Passivhaus (PH) standard was initially created for the cold climates of Central Europe and rapidly disseminated to other climate zones due to its excellent results in lowering the energy demand of buildings while maintaining high thermal comfort and energy efficiency [6,7]. As noted by Jayasena et al. [8], PH building elements are vital in achieving building energy performance. Unsurprisingly, PHs have shown a steady increase since 1990, with growing anticipation of rapid expansion in demand [9].

In New Zealand, the PH standard is implemented as a voluntary certification method [10] for low-carbon and energy-efficient buildings. Since its establishment in 2012, the PHI database [11] lists 84 projects in New Zealand, while Passive House Institute New Zealand (PHINZ) lists only 52 projects [12]. Of 52 projects, 43 are single-family residences, 40 belong to the PH classic category, and 18 are in Otago, New Zealand [12]. Studies have shown that the PH standard provides well-established remedies to the fundamental concerns confronting New Zealand's housing stock: poor IAQ, thermal discomfort, fuel poverty, and insufficient insulation levels [13]. As the New Zealand government has enacted new policies to strive for net-zero emissions by 2050 by improving thermal performance standards for both new and existing buildings towards energy-efficient dwellings with lower petrol emissions [14], one would think that a proven energy-efficient building standard such as PH will have become mainstream in the New Zealand construction industry. However, the PH standard faces resistance throughout New Zealand as it is perceived to challenge prevailing local preconceptions about building construction and performance [10].

A key challenge is the perceived high life cycle cost (LCC) of PHs. PHs are known to cost 16% more than conventional houses [15]. Other studies note an additional initial cost of 5% to 10% higher than conventional houses, and the payback period is predicted to be greater than 20 years [16–18]. In addition, concerns related to summer overheating, draught, and high noise from mechanical ventilation and heat recovery (MVHR) systems during the operational phase of PHs are also rising, thus limiting the cost-effectiveness of PHs [19,20]. As such, there is a lack of demand to invest in an energy-efficient house in terms of cost over time [16]. Understanding the various factors that influence the cost of PHs throughout their life cycle is essential to ascertaining their survival in the New Zealand construction industry.

2. Background

2.1. Passivhaus Development and Requirements

The 1970s oil crisis catalysed a significant increase in interest and innovation in developing houses prioritising energy efficiency, and presently, over 70 low-energy and carbon standards are implemented worldwide [21]. PH construction gained popularity as a proven means of reducing buildings' reliance on fossil fuels [8,22]. The PH standard, also known as Passivhaus in German, is one of the most aggressive, tried-and-true voluntary approaches available today for drastically reducing energy use while ensuring IAQ, durability, and thermal comfort [23]. These houses are designed and constructed to adapt to the climate and take advantage of natural conditions to provide a more comfortable indoor environment while consuming less energy [24].

The PH concept was pioneered by W. Feist and Bo Adamson, leading to the construction of the first PH named "Kranichstein" in Darmstadt, Germany, in 1990 [25]. As a first step, the energy demand of a PH is reduced by increasing the efficiency of its energy systems [8]. Even countries with no certification replicated the most successful initiatives. PH design principles in central Europe revolve around minimising heat losses, harnessing passive solar energy, and implementing solar control and night ventilation during the summer [26]. PH certification typically includes an airtightness test, but it may also take into account the operation of technical systems and their impact on indoor climate [27]. However, there are no explicit restrictions on the building layout or component properties imposed by the PH standard, which is performance-based [26].

Each climate zone adopts different components and techniques considering the culture, available materials, and building regulations to achieve the PH requirements cost-effectively [22]. The elements, including wall and roof (insulation, density, and specific heat), exterior windows (insulation and solar heat gain coefficient), building shape (shape coefficient and window–wall ratio), airtightness, ventilation system, and building layout (orientation), determine the building performance of PHs [8,22]. Table 1 summarises the requirements of PHs concerning energy demand, building envelopes, and systems. However, the requirements may vary depending on the country or region.

Table 1. The summary of Passivhaus requirements across all climatic regions. Adapted from [6,11,28–30].

Energy Demand	
Primary energy demand	≤120 kWh/m^2/year
Space heating energy demand	≤15 kWh/m^2/year
Space cooling energy demand	Roughly matches the heat demand + allowance for dehumidification.
Airtightness	≤0.6 ACH at 50 Pa
Overheating frequency	~10% for temperature > 25 °C without active cooling
Building Envelope	
Wall U-value	≤0.15 W/(m^2 K)
Roof U-value	≤0.15 W/(m^2 K)
Floor U-value	≤0.25 W/(m^2 K)
Window U-value	Triple glazing with U-value of ~0.85 W/(m^2 K)
Window transmittance (g)	Solar energy transmittance ~50%
Window frames	Insulated frames
Window glass layers	Insulated gas in between layers and low-conducting spacers
Door U-value	~0.8 W/(m^2 K)
Thermal bridge	Thermal bridge-free design or ~0.01 W/(m^2 K)
Airtightness envelope	Tested by blower-door test (DIN EN ISO 9972:2018 [31]), ~0.6 ach/h at 50 Pa.
Systems	
Mechanical ventilation efficiency	$n \geq 75\%$
Air infiltration rate	≥0.3 ACH
Minimum ventilation rate per occupant	20–30 m^3/person/h
Mechanical ventilation maintenance	Within 6 months
Temperature air supply	≤52 °C
Specific fan power	≤0.45 W/(m^3/h)
Air exhaust values	Shower and toilet: 20 m^3/h; bathroom 40 m^3/h; kitchen 60 m^3/h
CFL and appliance label	Class A or higher
Domestic hot water demand	10–60 °C—maximum 25 L/person/day
Allowable heat systems	Biomass combustion for biomass fuel (g ≥ 90%; 3–5 kW output), compact burner, on-site renewable energy systems, district heating, and earth-to-air heat exchanger.

Numerous studies have assessed the PH initiatives and their post-occupant analysis, including energy efficiency, IAQ, and economic analysis [18]. These studies highlight the superiority of PHs over their conventional counterparts, which is attributed to their reduced energy demand and consumption, better indoor environmental quality, monitored certification process, and effective energy calculation methods. According to Jayasena et al. [8], the construction of a PH entails addressing more features than a typical house. As such, PHs are technically and socially feasible, providing comfort and potential cost savings over their lifecycle despite requiring a slightly higher initial investment than conventional buildings [18].

2.2. Cost of Passivhaus

Economic analysis of building projects considers initial investment costs, long-term energy savings, and incentives (Shim et al., 2018) [32]. The financial analysis of PHs is perceived to be significantly higher than that of conventional houses. For instance, Audenaert et al. [33] noted that the cost of low-energy houses is 4% more than standard houses. Thus, low-energy certifications such as the PH standard are not always the preferred option regarding houses' environmental or financial sustainability. Other low-energy dwellings or those with a yearly net heating demand over 30 kWh/m^2 floor are often preferred options in some European countries, such as Belgium [34].

In addition, studies conducted in Central Europe (Germany and Austria) reveal that a house's energy efficiency is considered an essential aspect but is not deemed vital to users when deciding on a new house [35]. As such, concerns often arise among investor households regarding the economic viability of building a PH and whether the additional cost will be recouped in the long run through fuel savings [4]. The estimated values of the building cost, operational cost, expected cost savings, and payback period predicted ahead of time are affected by the uncertainties associated with future household energy consumption, energy price fluctuations, inflation, and discount rate [4]. That said, while it is essential to optimise passive performance by considering energy demand, cost, and thermal comfort [22], Persson and Grönkvist [36] cautioned that investments with short payback periods may exacerbate the energy efficiency gap if cost-effective investments with more extended payback periods are overlooked.

Life-cycle cost (LCC) analysis is useful for evaluating building design alternatives that meet a required level of performance, and it can be applied to any capital investment decision in which lower future operating costs offset higher initial costs [25,37]. In this study, we analysed the effects of PH drivers and barriers of PHs on its LCC as published by past studies, shedding light on the economic considerations of this sustainable construction approach.

3. Research Methodology

To achieve the aim of this study, we utilised a systematic literature review using the preferred reporting items for systematic reviews and meta-analyses (PRISMA) review process [38,39]. The detailed PRISMA 2020 checklist, including criteria for introduction, methods, results and discussion sections [38], is attached in the Supplementary Materials. Using the search terms "passive hous*" OR "Passivhaus*" OR "passive building*" (n = 1511), the selection of documents was obtained from the Scopus database (www.scopus.com) accessed on 21 October 2023. Scopus was selected as the preferred database as it has more global content than other providers [40] while maintaining a selective approach [41]. Duplicate records were removed, and this study was limited to journal papers and conference papers to retain robust peer-reviewed references. The dataset was further restricted to articles written in English (n = 1511). Figure 1 lists the selection criteria for the literature review using the PRISMA review process.

After careful consideration, seventy-one (71) papers were selected for further analysis. The selected papers were used to establish the context and analyse the content. The research context is initially analysed by identifying trends, the most influential authors, prominent journals, leading countries, and themes covered. Further, this study focused on the content of the selected papers, focusing on the following research question:

Research Question (RQ): *How do cost-related drivers and barriers affect the LCC of PHs?*

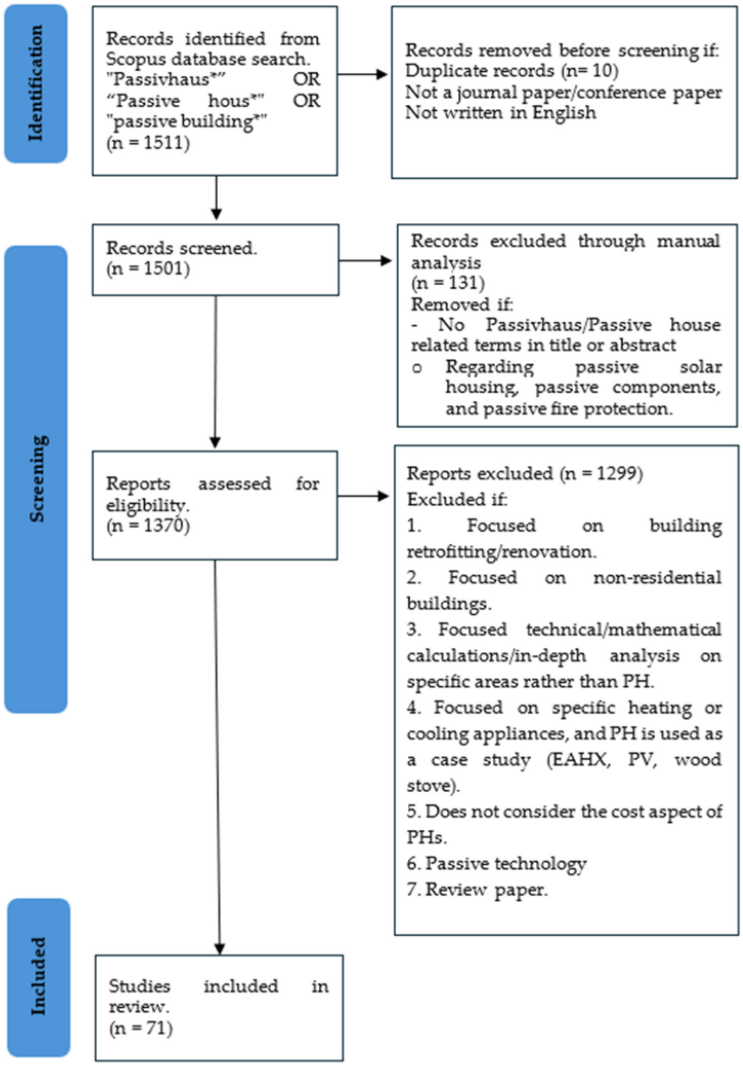

Figure 1. Selection criteria for the literature review using the PRISMA review process (adapted from [39]).

4. Analysis/Results

Context of the Selected Papers

Contextualisation of this study assisted in comprehending the background and the achieved findings. As such, we employed bibliometric analysis to establish the contextualisation. The bibliometric analysis summarised sources of literature and authorship of cost-related research on PHs. Table 2 below illustrates the outcomes of such a bibliometric study.

Table 2. Bibliometric analysis of the selected papers (n = 71).

Timespan	2005:2023
Authors	202
Author's Keywords	227
Sources	43
Documents	71
Document Average Age	8.32
Authors of single-authored docs	9
Average citation per doc	28.4
Annual Growth Rate	3.93%

As shown in the table above, 71 papers spanning 2005 to 2023 were obtained from 43 sources involving 202 authors. Research in this field exhibits an annual growth rate of 3.93%. Further, the analysis uncovered key themes within the studies. Hopefe, Kim, Mlecnik, and Schnieders were identified as prominent authors, and Schnieders has consistently contributed to PH research since 2005. In addition, Feist and Schnieders stand out as the most cited authors. It is apparent from their research that Dr. Feist's contributions have been instrumental in emphasising the crucial role research plays in the development, monitoring, and comprehensive documentation of PHs globally. It is also noted that the interconnectedness of theoretical insights and practical research has significantly impacted the evolution and understanding of PHs worldwide.

Out of the 71 selected papers, most of the papers represent Europe (53), demonstrating its dominance in academic research, followed by significant contributions from Asia (10) and North America (5), with South America (2) and Oceania (2) making smaller but significant contributions. Based on the countries, the UK emerges as the most prolific country in Europe with 13 papers, followed by Germany (6), Belgium, Poland, and Sweden (5) each, Italy and Romania (4), and Turkey (2). South Korea stands out in Asia, with five papers reflecting a strong research presence along with China (3) and the UAE (2). The USA presents four papers in North America, while Canada contributes one. South America and Oceania each have modest contributions, with Brazil and Chile each contributing one paper and New Zealand contributing two papers. Followed by countries, Figure 2 visually represents the keyword cloud, highlighting significant trends and themes within this study.

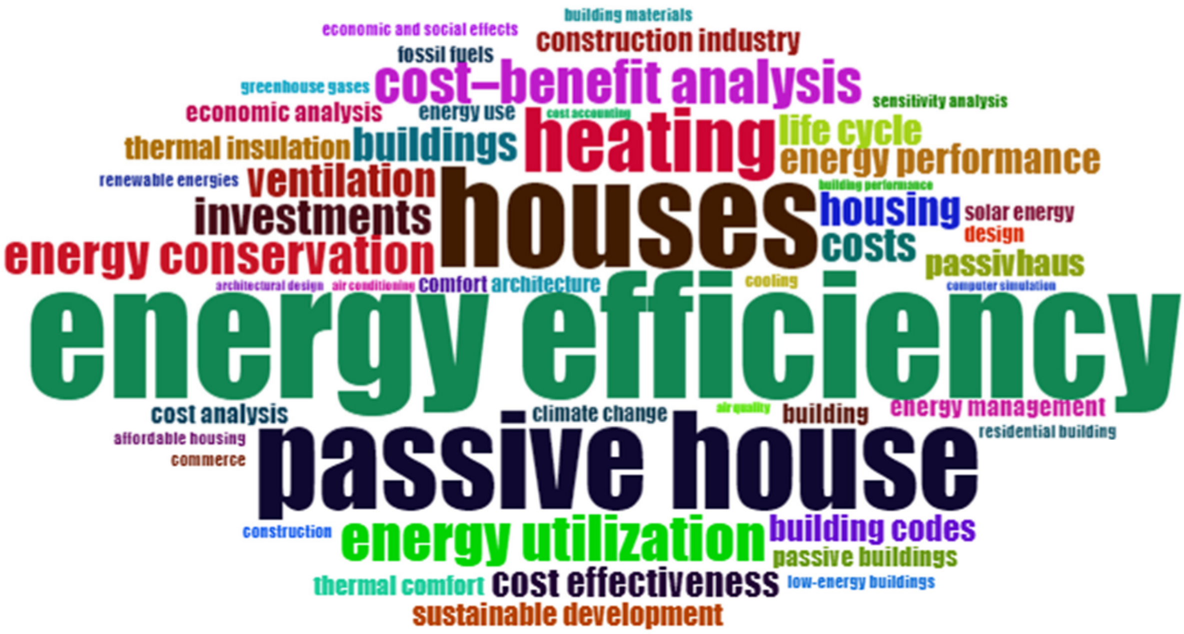

Figure 2. Keyword cloud illustrating major themes in past studies on PHs.

According to Figure 2, the prominent keywords include energy efficiency, houses, PH, energy utilisation, heating, cost–benefit analysis, and energy conservation. These keywords can be categorised into terms associated with energy, types of buildings and their components, costs, and cost analysis. Figure 3 presents the network between the keywords of the selected papers.

Figure 3 illustrates research collaborations based on keywords such as energy efficiency, heating, houses, and energy utilisation. Cost-related keywords, including economic analysis, costs, cost accounting, investments, and cost–benefit analysis, are less concentrated and less connected. Based on the bibliometric findings, the economic aspect of PHs appears, indicating a gap that warrants further research to unveil the economic dimensions of PHs related to different themes. The following diagram, Figure 4, further illustrates the basic themes under the PHs from the selected papers.

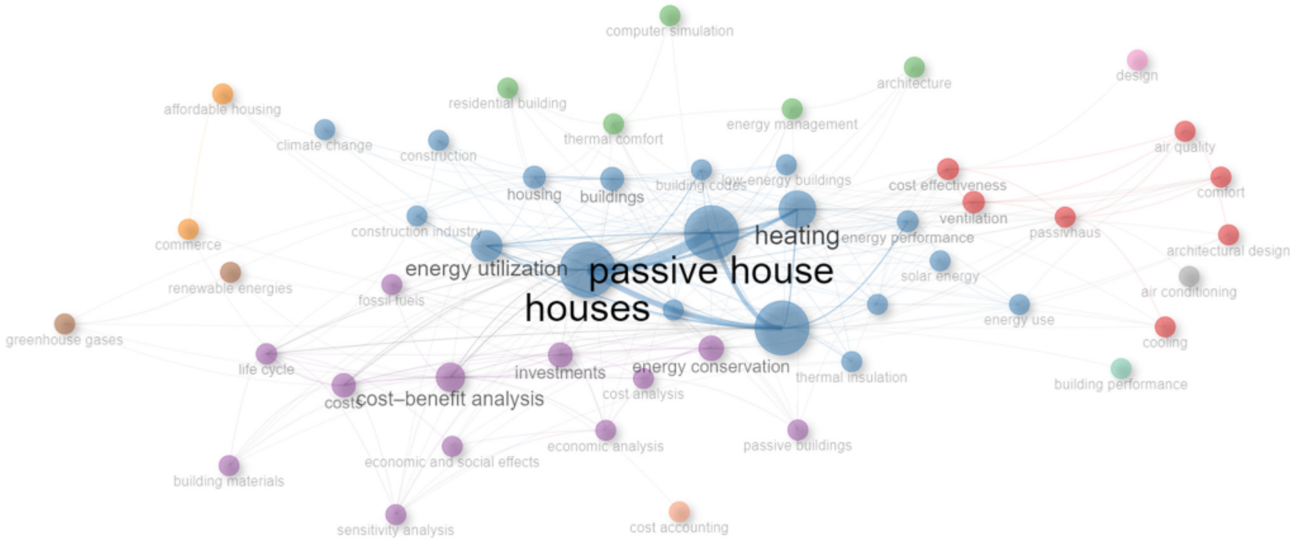

Figure 3. The network between keywords of the selected papers.

Figure 4. Thematic diagram showing the basic themes under global PH research.

The thematic diagram shows the connection between thematic clusters, their relevancy, and maturity. The centrality reflects the strength of the relationship compared to other clusters, while the density shows the strength of a relationship within a thematic group [42]. The higher centrality shows more relevance, while the higher density shows more maturity. Table 3 presents the authors, country, research method used, and the cost-related key findings of the selected papers.

Table 3. Cost-related research findings—drivers and barriers of PHs.

Country	Reference	Research Method			Cost-Related Key Research Findings—Drivers of PHs
		Case Study	Simulation Model	Other	
Europe					
UK	[43]		X		In the typical UK context, the construction costs of PHs can be reduced by up to 366 GBP/m^2 or 22% of the total build cost.
	[44]	X			According to the Tianjin energy efficiency standard, the target for heating energy consumption is 30.9% higher than the German building energy efficiency standard EnEv'2009 and 49.7% higher than the PH standard.
	[45]				The most effective low-energy designs allow occupants to live in better environments with more consistent and regulated levels of thermal comfort and lower energy costs.
	[46]		X		Comparatively, inorganic PCM is less costly than organic PCM.
	[20]		X		MVHR could be removed without sacrificing comfort levels in regions with mild winters and cool summers, resulting in lower capital costs and at least comparable energy savings from PHs.
	[47]		X		Designers can significantly enhance PH site and space performance by using views and orientation, providing enough space for functions, good air quality, temperature controls for different occupants, passive lighting, visual comfort, and horizontal utility systems for multi-user needs.
	[48]		X		The "WHY house" upends the strict requirements of the PH standard by emphasising adaptability and focusing on sustainable architectural design that considers local climate conditions and the environment, as well as adapting and post-disaster contexts.
	[49]			Document analysis	PHs reduce annual energy costs by approximately a factor of 5 in the UK.
	[15]	X			Affordable budgets of PHs can be met without sacrificing architectural design or construction quality. However, the need to import low-energy components highlights the importance of developing local alternatives and quality assurance procedures throughout the design and construction stages.
	[50]	X			In the UK context, PH design measures such as insulation and controlled natural ventilation can meet the PH heating energy standard, eliminating the need for measures including MVHR.
Germany	[51]	X			The PH standard can be implemented in high-quality, aesthetically pleasing architecture and small, economical buildings.
	[52]		X		The PH framework shows a clear trend of decreasing technological complexity and costs from scientific research to construction and final use while emphasising the importance of participation and training at every stage of the process.
	[18]	X			PHs are technically and socially feasible, providing comfort and potential cost savings over their lifecycle despite requiring a slightly higher initial investment than other building types.
	[6]	X			In PH, the useful energy required for space heating has decreased by approximately 80% compared to conventional new buildings, and total primary energy consumption, including all services and electric appliances, has reduced by more than 50%.

Table 3. *Cont.*

Country	Reference	Research Method			Cost-Related Key Research Findings—Drivers of PHs
		Case Study	Simulation Model	Other	
Belgium	[53]	X			PH certification should be enhanced with mandatory passive cooling demand, integrated quality control, mandatory airflow reports, regular CO_2 inspections, noise limits, comprehensive end-user education, satisfaction research for quality assurance, and marketing leveraging comfort appreciation.
	[54]	X			The passive option is the most cost-effective when climate change evidence is detected before 2040. After that date, a standard house with the option of adding efficient energy performance endowment attributes and items will have lower costs.
Poland	[55]	X			Nearly zero-energy buildings with photovoltaic installations are profitable, with a return on investment within the mortgage period.
	[56]	X			Using heat pumps, solar collectors, rainwater, and greywater can reduce energy and water consumption in PHs, reducing reliance on fossil fuels and improving the environment.
Sweden	[57]	X			A Swedish code-compliant building's lifecycle cost can be lowered by roughly 7–12% by switching from heat pumps to district heating.
	[58]		X		The large heat network option generally has the lowest system cost, whereas the individual option typically has the highest system cost.
	[36]	X		Interview	Construction companies view the market for PHs as promising, which has become a driving force.
	[59]	X			Focusing on key areas such as system design, building documents, construction planning, working methods, quality control, leadership, and attitudes distinguished projects that successfully achieved economic and productivity benefits over traditional housing.
	[60]	X			PHs can improve energy efficiency while minimising negative impacts on health, the environment, and the climate, aligning with current political decisions in Sweden.
Italy	[61]	X			The PH is priced at 1800.00 EUR/sqm, corresponding to the market rate for new constructions in Italy. The additional envelope costs have been reduced, making them affordable while remaining 18.8% less expensive than traditional envelope constructions.
	[62]	X			Despite changes, a PH with an extensive and integrated design, PHPP calculations, and on-site worker training achieved a construction cost of approximately 3% higher than that of conventional buildings.
	[63]			Questionnaire	PH classifications allow prospective tenants and buyers to compare the heating costs with other buildings.
Romania	[28]	X			A nearly zero energy building standard can be achieved with less insulation than a PH if combined with an efficient technical system and/or renewable energy generation.
	[25]	X			An additional investment in a house with an energy-efficient HVAC system can be repaid in 16–26 years with a traditional gas-powered system, 9–16 years with an electric system, and 16–28 years with a district distribution system.
	[37]	X			The PH's initial investments were 27% higher due to superior thermal insulation and special mechanical equipment. Over 50 years, the traditional house's higher energy consumption for heating, cooling, and hot water resulted in 53% higher costs than the PH, giving the PH a 46% advantage.

Table 3. *Cont.*

Country	Reference	Research Method			Cost-Related Key Research Findings—Drivers of PHs
		Case Study	Simulation Model	Other	
Turkey	[64]	X			The passive steel house in Istanbul uses 22 monocrystalline panels to meet its energy needs, generating an estimated 18,893.5 kWh per year.
	[65]	X			PHs with zero carbon emissions, which maximise sunlight use while minimising energy storage, are gaining popularity due to cost and energy savings, thermal comfort, and healthier indoors.
Austria	[66]	X			It is advisable to build new buildings per PH guidelines to prevent the need for costly life-cycle refurbishments in the future.
Croatia	[16]	X			Athens has lax building codes regarding energy performance. Hence, improvements in basic and advanced energy efficiency are profitable across a broad spectrum of capital costs and rates of energy price inflation.
Macedonia	[67]		X		In Macedonia, sustainable adaptation results in a 27% reduction in energy consumption while increasing GDP and the share of renewable energy sources in total final energy consumption from 18% to 45% by 2040.
Norway	[68]			Interview + document analysis	Government regulations or commercial powerhouses did not fuel the success of the PH concept and standard. Instead, it thrived due to unwavering faith in scientific principles, a stringent certification process, successful examples, establishing a protected market niche, extensive training initiatives, and effective marketing strategies.
Portugal	[69]	X			Implementing the PH concept in lightweight construction systems is feasible for Portugal, but some changes to construction solutions are required to reduce overheating risks.
Serbia	[70]	X			The cost of PHs can be improved by optimising building features, using affordable, well-known materials with an acceptable environmental footprint, taking advantage of cheaper labour, and avoiding expensive or high-end solutions.
Asia					
South Korea	[9]			Online survey	As material prices have decreased and contractors have gained more familiarity with passive-building techniques, costs have decreased.
	[32]	X			In Korea, building PHs with energy-saving measures adds 1.85–4.20% to the cost of building a conventional house.
	[71]			Focused group	PHs have not been widely adopted in Korean domestic construction due to low energy cost savings compared to construction costs, unlike in other countries.
	[72]	X			PH adaptations to typical contemporary residential buildings in China and Korea are possible with locally available materials and a reasonable effort.
China	[73]		X		The buildings in China's Hot Summer and Cold Winter zones show that reducing insulation from 0.4 to 1.0 $W/(m^2{\cdot}K)$ can reduce energy consumption by 4.65 $kW{\cdot}h/(m^2{\cdot}a)$ when heat gain increases to 20 W/m^2.

Table 3. *Cont.*

Country	Reference	Research Method			Cost-Related Key Research Findings—Drivers of PHs
		Case Study	Simulation Model	Other	
UAE	[74]	X			The cost of construction materials drops while the cost of electricity increases, increasing the economic viability of PHs.
	[5]		X		Based on the findings, a proposal for Saudi Arabia's low-carbon energy consumption targets, ranging from 77 to 98 kWh/m^2, has been made.
North America					
USA	[75]			Document analysis	According to the energy modelling conducted by the Pacific Northwest National Lab (PNNL) in 2020 for residential buildings across all eight North American climate zones, fenestration performance must improve by an average of about 32%, and ceiling and wall insulation must improve by about 40% above International Energy Conservation Code (IECC) 2018 levels.
	[76]	X			The installation of the PCM improved thermal comfort by reducing estimated annual overheating hours from 400 to 200.
	[77]	X			Tailoring architectural and mechanical design strategies to the specific climate of each location along the rocky mountain front range improves the energy efficiency of PHs. It emphasises the importance of localised approaches to sustainable building design.
	[78]	X			It is easily possible to achieve very low energy use buildings in North America with an annual energy consumption half or less than standard housing through efficiency investments at an equivalent cost of 0.10 USD/kWh.
South America					
Brazil	[79]	X			PH requirements in warmer climates can be met economically by improving building fabric.
Oceania					
New Zealand	[80]			Action research	Modern technologies initiate a high-performance housing solution by upgrading an existing prefabrication system to PH standards.
	[81]		X		Compared to EU and PH standards, the minimum NZBC for thermal performance needs to be significantly improved.
Country	**Paper**	**Research Method**			**Cost-Related Key Research Findings—Barriers to PHs**
		Case Study	**Simulation Model**	**Other**	
UK	[82]	X			A PH is priced 12% higher than a Part L 2010 house when both are calculated using a 3.9% annual percentage rate mortgage over 25 years.
	[83]	X			The cost of failure of PHs is more significant due to the media attention.
	[84]		X		Using proxy regional data for PHPP would significantly underestimate the specific annual heat demand in PHs.

Table 3. *Cont.*

Country	Paper	Research Method			Cost-Related Key Research Findings—Barriers to PHs
		Case Study	Simulation Model	Other	
Germany	[26]	X			Implementing the PH standard in countries such as Mexico requires making the necessary technologies available in the market while ensuring affordability for end users despite initial cost considerations.
	[4]	X			The PH may not be economically optimal without financial incentives or favourable conditions, such as a low discount rate and high future fuel prices.
Belgium	[34]	X			The passive standard is not always the best environmental or financial sustainability option. Low-energy dwellings or those with a yearly net heating demand over 30 kWh/m^2 floor are often preferred in Belgium.
	[19]			Interview + document analysis	SMEs face a barrier in aligning their products and services with the PH level, but this can be overcome by specialised agents who clarify the connections with intermediate steps in architectural and modular innovation.
	[33]	X			Low-energy houses cost 4% more than standard houses, while PHs cost 16% more. Isolation and ventilation are the primary contributors to this additional cost.
Poland	[85]	X			Underestimating or overestimating expenses and ignoring significant costs like material, execution, certification, and required testing costs are common problems in cost calculations for PHs.
	[2]	X		Experimental research	PH construction costs should not exceed 120% of a low-energy house with similar usage and geometry.
	[86]			Document analysis	In a PH, the vibro-insulating mat, at 323 EUR/m^2, is ideal for expensive buildings. On the other hand, the wooden wool-enhanced version, which costs about 81 EUR/m^2, strikes a balance between cost and effectiveness, making it ideal for most buildings at a total cost of about 54 EUR/m^2.
Italy	[87]			Document analysis	In a PH, if cost increases beyond a certain point when embodied energy surpasses a certain level.
Romania	[88]		X		Owners must decide between building a more efficient PH to reduce long-term heating costs or a less expensive PH to save money upfront.
Lithuania	[89]	X			In PHs, the share of the embodied input and output flows in the entire life cycle typically exceeds one-third of the life cycle primary energy.
Netherlands	[27]			Document analysis	The additional cost of certification and the legal energy performance certificate are bottlenecks.
Asia					
South Korea	[90]	X			Passive cost increase in the 50-year NPV analysis needs to be reduced from 15.52% to 22.38% to be economically feasible given the discount rate.
China	[17]		X		The complicated supply chain of PHs creates a complex network of factors influencing the cost and challenging the implementation of cost control.
	[22]	X			PHs typically cost 5–15% more to build than conventional houses of the same size and design.
North America					
Chile	[91]	X			Implementing the PH standard in Chilean climates may be more expensive than in other countries, yet feasible.

5. Discussion

This section discusses the cost-related drivers and barriers of a PH, comprehensively focusing on the different aspects of PH. Initially, it examines cost-related drivers and barriers associated with fulfilling PH requirements, including heating and cooling systems, MVHR, insulation, thermal bridges, airtightness, and highly efficient windows. Further, it focuses on the energy-efficient systems, materials, and techniques available in the market and the cost implications. Finally, it discusses the roles of occupants, professionals, government, financial institutions, and research institutions in economic contributions and barriers of PHs. Figure 5 visually represents the cost-related drivers and barriers to PH adoption using the SankeyMATIC diagram. It maps the drivers and barriers, showing the flow of different factors, and provides a clear view of the financial considerations.

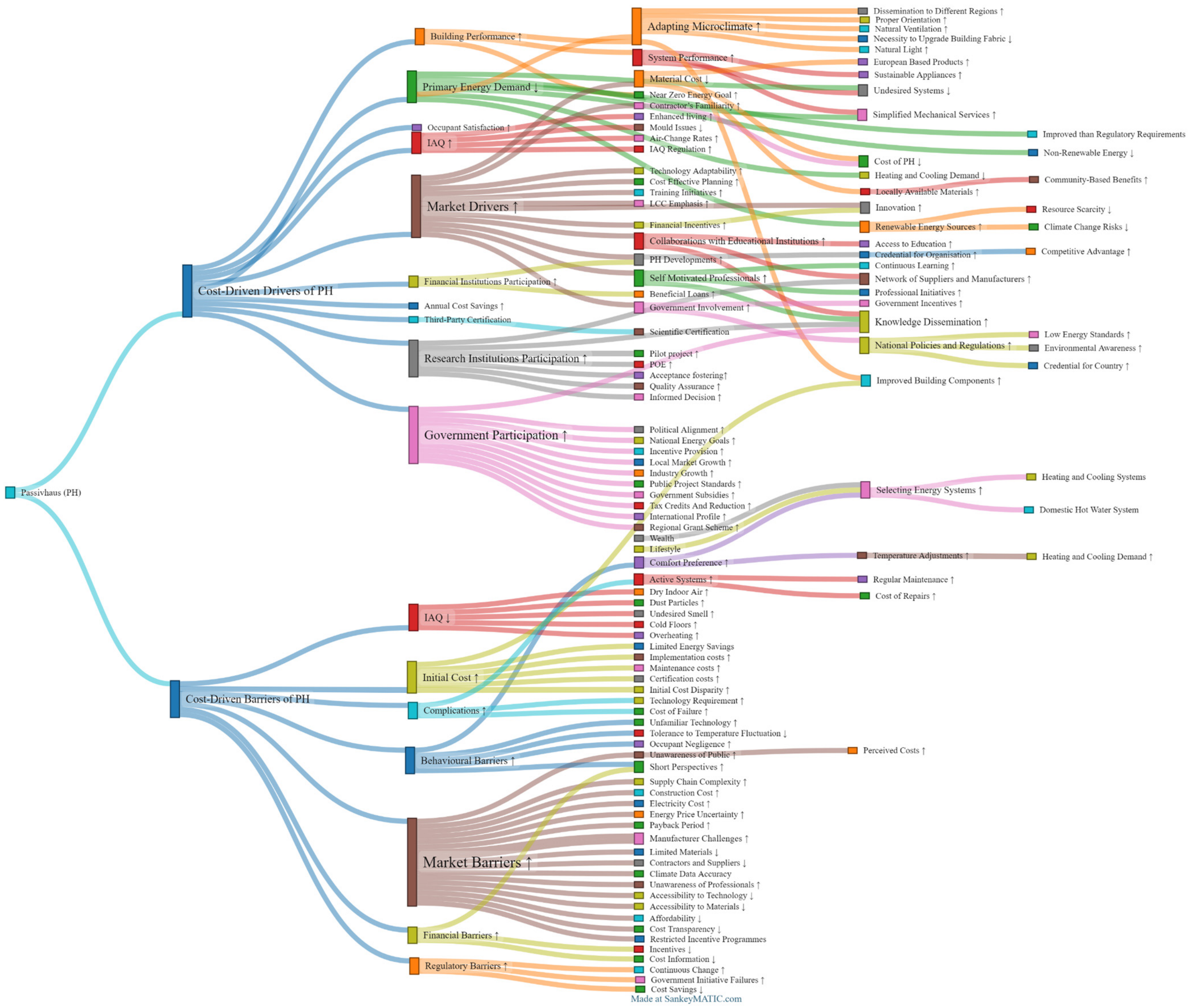

Figure 5. SankeyMATIC diagram of cost-related drivers and barriers to PH adoption. ↑—Increase; ↓—Decrease.

5.1. Drivers of Passivhaus

The continued adoption of the PH movement can be attributed to various drivers within the construction industry. These drivers are discussed in the section below.

5.1.1. Improved Building Elements

PHs were reported to be able to afford better building elements in houses where they are implemented. For instance, PHs adopt appropriate orientation, ventilation, and shading to obtain the required heat and natural light to minimise the artificial heating, cooling, and lighting costs without additional costs [65]. The heat from the sun, occupants, and interior equipment is adequate to maintain a suitable interior temperature for significant portions of the year [36]. Similarly, opening windows alone for ventilation in PHs reduces energy consumption by approximately 560 kWh [74] and minimises the reliance on mechanical ventilation and associated costs [50].

In addition, a PH adopts PHPP software to predict the energy demand at the early design stage. It analyses the energy loads properly, determines the systems, and avoids oversizing [24]. As such, the energy demand of a PH is lower than the national requirements of the countries [60]. The annual space heating energy of a PH is 75% to 95% lower than the conventional buildings with similar geometry [18,22,82], while the annual cooling demand in the UAE was reduced by 48% [74]. The reduced energy demand of a PH is achieved by improving the building components and adopting efficient technologies with a 5–10% cost increase [6,18].

Similarly, the specific climatic conditions of the regions can be effectively utilised to achieve the PH requirement at a lower cost. The climatic conditions of Brazil require less effort to improve building fabric with lower insulation levels than in colder climates [79]. Similarly, Schiano-Phan et al. [50] noted that mechanical ventilation with heat recovery (MVHR) may not be required in the UK context; instead, the PH requirements can be achieved by adapting passive design strategies such as thermal buffering, insulation, and controlled natural ventilation. A PH does not necessarily require the triple-glazed window to achieve the PH requirements [73]. Schnieders et al. [26] noted that the project in Taiwan adopted a double glass window with a U-value between 1.2 and 1.5 $W/(m^2\ K)$ to achieve the PH requirements cost-effectively.

The insulation thickness of the walls, slab and roof, ventilation systems, heat recovery systems, and triple-glazed windows significantly influence the economic disparities due to varying values and serve as primary parameters in the initial investment cost [22,82]. Likewise, PHs consider penetrations on the building façade that permit heat losses through geometrical analysis to identify and prevent excessive losses at the thermal bridges cost-effectively at the early design stages. As a result, the subsequent improved building performance would facilitate the opportunity to either simplify or eliminate building systems [6] that are not required to achieve the expected energy efficiency and indoor environmental quality.

Energy recovery ventilation systems are usually more expensive to install than other ventilation systems, require more maintenance, and consume more electricity [48]. However, the capital cost of MVHR was 3% of the total building cost, which can be redeployed to increase insulation by 23%, improve ventilation control, or use non-polluting materials [20]. With the improved building elements, the reduced energy demand of PHs can be easily supplied through renewable energy sources, which are more cost-effective options [6]. Renewable energy sources are becoming more affordable due to increased performance and decreased prices, making them a crucial focus for the industrialised world to combat climate change risks and resource scarcity [6]. The solar thermal systems fulfil 40 and 60% of the total low-temperature heat demand of PHs and are cost-effective [18].

5.1.2. Improved Indoor Air Quality

The owners and potential tenants seek additional benefits beyond the low energy consumption to move into PHs [18]. The expected benefits primarily include the reputation for living in an energy-efficient house, comfort, wellness, and environmental friendliness. The PH has extended beyond its initial niche market perspective of being ultra-green, thereby gaining an added advantage. The thermal comfort of the PH is approximately 40% higher than the conventional house [22], while CO_2 emissions are reduced by 39% [91].

PHs, by definition, prioritise IAQ to minimise energy consumption without compromising thermal comfort and IAQ [6]. A careful balance of temperature, relative humidity, ventilation, and indoor air pollutants is necessary to maintain a good IAQ [20,92]. Prior studies on post-occupancy evaluation ensured that most PH occupants expressed higher satisfaction with IAQ [49], energy consumption [93,94], ease of ventilation control, and excellent thermal comfort level [18]. Further, PHs exhibit greater air-change rates than those mandated by minimum building codes, leading to positive effects on the health and comfort of occupants [95,96].

5.1.3. Improved Market Conditions

Attaining PH certification is seen as a market recognition in many countries, with the primary goal being the promotion of better energy efficiency requirements than those that are subject to regulation [27]. Third-party certification and testing have been acknowledged by several architects, clients, insurers, manufacturers, regulators, and specifiers as a valid means of proving compliance with standards and other requirements [27]. Further, internal and client initiatives, as well as financial incentives, promote market expansion and encourage building businesses to develop PHs [27,36]. Most companies consider PHs to gain a competitive advantage and be recognised as a market leader [27].

Encouraging the energy efficiency of buildings in the private sector requires addressing affordability [9]. Costs of PHs have decreased due to dropped material prices and contractors' familiarity with passive building technologies [9]. Professionals are expected to continuously explore and utilise more reasonably priced building materials to foster broader adoption of PHs in the market [9]. Schnieders and Hermelink [18] noted that triple-glazed PH windows may cost about 10% more than double-glazed windows, even when mass-produced. Advanced building elements, including highly efficient windows, can be imported initially and subsequently manufactured locally, ensuring viability and cost-effectiveness [52]. Brew [23] noted that local manufacturers still have a market for highly efficient components despite the increasing availability of European products through distributors. Further, the locally available materials and resources allow for cost reduction and community-based benefits [8].

5.1.4. Improved National Regulations

Controlling energy usage for the household sector is crucial for decision-makers. The recent shift in design culture and legislative concern for reduced energy usage has led to many existing and emerging low-energy and zero-carbon standards like the PH standard [50]. Currently, most countries have national policies and regulations to reduce building energy consumption [36]. Governments design complex support systems to promote energy efficiency in new and existing structures [33]. Schmitt et al. [63] acknowledged that the strong dedication of the government and non-government organisations, along with environmental awareness, had contributed to the successful early implementation of building energy efficiency certifications.

Countries have initiated state- and national-level initiatives to improve energy-efficient houses. Germany, Austria, Switzerland, Belgium, France, and Luxembourg started energy efficiency initiatives two decades ago and have provided a framework for related grants and tax reductions [27]. France has adapted industry-initiated objective-setting to set goals for environmentally friendly building practices [27]. On the other hand, a state in Austria has mandated using PH standards for new construction by public housing associations. Another state is committed to constructing municipal buildings according to the PH standard [27]. In addition, Persson and Grönkvist [36] noted that European Union building regulations are showing consistent improvement as a promising regulatory driver.

The national legislation on income tax relief in Belgium has officially recognised the definition of PHs [27]. The consistent use of this definition in legal documents prompted an increase in the number of people pursuing PH certificates [53]. Further, general action plans for implementing PHs in the building market have been developed to reduce building energy at the national level [9].

5.1.5. Available Financial Incentives

In most countries, incentive policies encourage investor participation in implementing PHs [32]. Through incentives, technology sharing, and local market expansion, the government's centralised power and its top–down approach to sustainable development are dispersed with the private sector across a range of fields and industries [9]. Government incentives encourage the development of energy-efficient buildings on a wide scale, making PHs more appealing [33]. The private sector benefits immensely from these endeavours as they lower capital costs and make PHs more affordable in development and construction [9].

Special grants for PHs have been noted in Belgium and Austria; the value of the grants varies based on the regions and cities [27]. China has a fixed tariff structure covering a significant portion of occupants' heating costs by the government or employers [44]. Further, subsidies for energy-saving houses are contemplated depending on integrating high-efficiency elements [27,33]. The Korean government offers tax credits and other structural and financial incentives, such as bonuses for height and density, to buildings that meet specific certification levels (Platinum or Gold) [9]. Financial incentives, such as a 15% reduction in acquisition tax and a 3% reduction in property tax, are offered when Grade 1 of the building energy efficiency criteria is met in Korea [32]. In addition, banks play a crucial role in the market development for PHs. In Germany, the state bank played a significant role by providing a beneficial loan for low-energy and PH construction [53].

5.1.6. Continuous Research Outputs

Detailed research on PHs is one of the key drivers of disseminating PHs in different climate regions. Information is the foundation of a knowledge society, and the adoption of energy-efficient technology depends on the availability of unbiased, independent information regarding its advantages [53]. Pilot projects and survey-based studies were conducted to ensure PHs function as claimed and provide a healthy interior environment [20]. The effectiveness of PH building performance is usually scientifically assessed using energy demand and usage, IAQ, thermal comfort, and occupant satisfaction. Hence, end-user feedback and experiences are collected to inform improved design and support desired building operations [9]. For example, comprehensive studies of the PH standard were conducted as part of the Passive-On program conducted in Central and Southern Europe and Cost Efficient Passive Houses As European Standards (CEPHEUS) conducted in countries including Germany, Sweden, France, Austria, and Switzerland to extend the applicability of the standard to a broader range of regions, particularly those with warmer climates [20]. The dissemination of research findings assisted policymakers, decision-makers, and civil society in developing suitable strategies for creating resilient and sustainable cities.

5.1.7. Educational Awareness

Early education enabled opportunities to avoid costly mistakes during any project's development stage [33]. Persson and Grönkvist [36] noted that companies often collaborate with institutes of technology to educate their employees on PH principles and applications. The participants of these courses gain the capacity to set themselves apart from the competition and achieve a competitive edge in building energy efficiency. These include architects, building designers, construction firms, and subcontractors of specific building technologies. Another point is the importance of education for all parties engaged in the project, including purchasers, managers, estate agents, and others. The benefit of such education is the networking opportunities it creates for suppliers and manufacturers [57] and the facilitation of an efficient demand and supply of PH building materials and technologies.

5.2. Barriers to Passivhaus

The PH movement has also experienced setbacks due to various barriers within the industry. These barriers are discussed in the section below as reported in past works.

5.2.1. Increased Costs and Complications

Increased costs and complications are considered the most significant barrier to adopting PHs. Maximising the building performance of PHs using key design parameters of building elements requires exceptional focus and increased initial capital costs compared to a conventional house [57,82]. The primary energy consumption and climatic impact of buildings are significantly influenced by their energy efficiency level, the temperature setback practices, the choice of heat supply system, and the LCC of heating solutions [57]. Apart from the explicit expenses associated with the heating solution choices, heating solutions for a new building may also impact the construction costs through other mechanisms, such as building envelope design and ventilation solutions [57].

Feist et al. [6] noted that, even with optimisation, the PH will incur additional costs. Most CEPHEUS sub-projects could not reduce overall building service costs; in several projects, planners and builders were unwilling to discontinue the heat distribution system [18]. The ventilation systems in PHs used for heating require significant technological interfaces, extra ducts, and auxiliary fans [65]. Furthermore, the MVHR requires annual filter replacements and is subject to significant repair costs if it malfunctions. In a case study building, an MVHR microchip failed outside the warranty period, costing 14% of the installation cost [20].

The extended living comfort offered by a PH is achieved using only 15 to 20% of the space heating demand of conventional new buildings and 10% additional cost of the overall construction costs [18]. Prices vary significantly across manufacturers and installations [97]. The upfront expenses are often counterbalanced by lower lifetime costs and contribute to improved physical and mental well-being for occupants [98,99]. Maintenance and repair costs are frequently more difficult to estimate than other building expenses [100]. The cost of renewable energy is expected to be affordable [6]. However, integrating designs incorporating wind power generation concepts may escalate costs due to the initial investment and increased maintenance and operational expenses associated with higher technology [8]. Similarly, due to the high cost, several projects avoid renewable energy sources, including photovoltaics or solar collectors [2,26]. On the other hand, maintaining the PH standard is difficult when using a power source with a high index of non-renewable primary energy expenditure and erratic annual sunshine levels [56].

5.2.2. Poor Indoor Air Quality

The IAQ is considered one of the major drivers in PH. However, Persson and Grönkvist [36] identified concerns about attainable indoor comfort in a PH. Schnieders and Hermelink [18] noted that higher air change rates would lead to excessively dry indoor air. Sassi [20] observed that humidity in the environment enables the growth of fungi, moulds, and dust mites and increases the risk of poor IAQ in the PHs. Also, higher temperatures in the heat recovery unit might lead to dust carbonisation in the supply air and ducts, resulting in smouldered dust particles and an undesired smell [18]. Furthermore, PH occupants are more likely to experience cold floors in winter and overheating in the summer [43,101]. These deter potential customers from adopting the PH standards.

5.2.3. Behavioural Barriers

Behavioural barriers reflect the behaviour of end users and their relationship with energy consumption [36]. The PH and its maintenance are vulnerable to occupant behaviour [2]. Most occupants are unfamiliar with the technologies and controls commonly used in PHs [27]. As a result, the desire to work with unknown technology and readiness to modify habits may be reduced [18]. Further, Onyeizu [102] noted that the occupants in mechanically ventilated buildings expressed a lower tolerance for temperature fluctuations and an increased need for air conditioning, leading to higher costs.

The critical nature of building systems and lack of awareness of occupants lead to increased complexity. Mlecnik [19] identified ventilation and heating systems as critical points of attention due to their limited user friendliness and perceived comfort issues, such as dry air in winter and excessive noise. On the other hand, poorly chosen heat pump/ventilation units cause lowered IAQ, increased noise and heat production, and excessive energy consumption [19]. In an attempt to resolve the issue, occupants have frequently disabled the system, negatively impacting energy efficiency and discomfort.

Mlecnik [53] noted that first-time occupants do not always express the need for specific beneficial information related to the maintenance of systems and PHs. Also, occupants consider regular maintenance an issue [71]. Thus, educating the occupants about the required systems, equipment, and maintenance information is vital. Pitts [45] pointed out that with this awareness, occupants are more environmentally conscious, aware of their energy consumption, and motivated to practice more sustainable behaviour.

5.2.4. Market Barriers

Market barriers act as significant barriers to accessing the PHs. For instance, Schnieders et al. [26] cautioned that rather than the question of PH application, the issue is whether these technologies will be widely available in the market and whether end users can afford the additional upfront costs associated with such products. Also, the lack of transparency is considered one of the major market barriers to adopting PHs, as both professionals and users are unaware of the costs associated with low-energy buildings, or PHs [32].

It can be said that the generally perceived high construction costs of PHs are based on consumers' prior knowledge [9]. Lee et al. [9] found that 86% of the public estimated the PH cost to be 20–50% higher than that of a conventional house, with the majority predicting a cost greater than 50%, while professionals estimated a 20–50% higher cost. For construction companies, the adoption costs are preceded by a knowledge buildup through information gathering, learning, and establishing contacts with suppliers [36]. As such, there is a need to demonstrate to building businesses and prospective clients that a PH is feasible and does exist [36]. Therefore, education is critical for changing people's attitudes towards PHs [9].

5.2.5. Regulatory Barriers

The construction sector faces significant challenges in meeting stringent house energy performance regulations [32]. Minor details in legislation in most countries can impede development efforts. For example, Schnieders and Hermelink [18] noted that the overall cost of PHs rises if district heat is required in some regions. Exceptions to such rules for highly efficient buildings should be permitted to have an effective PH.

5.2.6. Financial Barriers

People make less rational investments when faced with high up-front costs and behavioural biases, such as using excessively high discount rates in their personal capital budgeting plans [36]. As a result, short-term investments can expand the energy efficiency gap if cost-effective investments with extended payback periods are overlooked. Construction companies in Sweden expressed concerns about banks having short perspectives and insufficient knowledge of their lending activities. Although life cycle thinking and environmental policies are gaining popularity among contractors, banks do not consider this information in capital budgeting plans [36].

Despite the energy-saving benefits of developing a PH, high investment prices, confusing investment cost information, and restricted incentive programmes discourage investor involvement in PH projects [32]. For instance, investors rely on reduced heating energy costs to obtain financial benefits as there are no efficient emissions trading programs to reward energy-conscious households [4]. Cost estimates and the architectural ambitions of clients and designers significantly impact how a project team supports low-carbon goals [15].

6. Conclusions

The PH standard is one of the most aggressive and tried-and-true voluntary measures for significantly decreasing energy usage while assuring IAQ, durability, and thermal comfort. This study employed a systematic literature review, and 71 papers were chosen for the final study. The bibliometric analysis revealed that the existing body of research focused on the economic aspects of PHs, particularly their energy performance. However, a noticeable gap is perceived considering the broader spectrum of LCC analysis.

The PH standard remains stringent and demonstrates a reduced energy demand compared to alternative standards and national policies. It is attributed to the meticulous consideration of microclimatic elements, resulting in an enhanced ability to address the requirements for space heating, cooling, and hot water generation. Studies have consistently indicated higher occupant satisfaction with indoor environmental quality and energy consumption. However, in recent years, the complaints against summer overheating have also raised concerns.

Anticipated advancements in the PH market point towards a further decrease in prices. This trend is expected to be fueled by several factors, including the improved availability of innovative solutions, increased awareness and preference among the public, a rising number of PH institutes, and a growing community of professionals dedicated to learning and working in PHs. Further, enhanced national regulations on energy contribute to narrowing the gap between the requirements of conventional houses and PHs. The increasing prevalence of PHs, coupled with a growing body of research and improvements in national energy policies, strongly suggests that PHs will become inevitable and preferred in the future.

On the other hand, there is a need to advocate for the refinement of government regulations on energy efficiency and promote the integration of PHs, or energy-efficient systems, in public projects. Strengthening the market involves fostering collaborations with manufacturers and implementing targeted incentives, tax reductions, and subsidies tailored specifically for PHs. This study highlights that addressing challenges associated with PHs can be achieved through effective measures, ultimately reducing LCC and enhancing PH dissemination.

In summary, this study emphasises the imperative of a holistic approach, encompassing regulatory refinement, market interventions, and collaborative endeavours with local entities. This paper is limited to the data obtained through Scopus databases and focused on journal articles and conference papers in the English language that were available online till October 2023. Further, even though the selected papers were frequently mentioned and emphasised LCC, the detailed information was unavailable due to the limitations of the papers. Therefore, it is recommended that a comprehensive and detailed analysis of the LCC of PHs be included in future research to address this gap. In addition, integrating knowledge and lessons from this study provides a foundational framework for advancing the discourse and implementation of PH solutions, specifically focusing on addressing the distinctive considerations pertinent to New Zealand. In the next phase of this study, a close examination will be undertaken to identify specific strategies for enhancing the performance of PHs in New Zealand. The findings from this research can be valuable for individuals and organisations involved in decisions about sustainable and cost-effective housing.

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