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Review article

Powering the future: A comprehensive analysis of solar photovoltaic systems adoption in passive houses

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ABSTRACT

The pressing global issues of climate change and energy sustainability underscore the need to integrate renewable technologies into building designs. Solar Photovoltaic Systems (SPVS) and Passive Houses (PHs) stand out, offering substantial potential to reduce carbon emissions and improve energy efficiency. This study investigates the integration of SPVS into PHs, focusing on global adoption trends, influencing factors, and key design considerations. Data was gathered using the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocol, which led to the final inclusion of 32 articles for this study published between 2012 and 2024. The analysis identified three key adoption trends: project type, geographic distribution, and growth rate. It also identified 18 drivers, nine barriers, and two design considerations pivotal to SPVS-PH adoption. The findings led to the development of a conceptual framework to guide stakeholders, including policymakers, homeowners, and building professionals, in facilitating SPVS-PH adoption. This framework supports global carbon reduction efforts and promotes sustainable practices by addressing barriers and leveraging identified drivers. The study provides actionable insights into enhancing energy efficiency and sustainability in the built environment.

Introduction

The urgent need to address global climate change and sustainable energy issues has heightened the significance of integrating renewable energy technologies into building design. While the building sector contributes significantly to greenhouse gas (GHG) emissions and ozone layer depletion due to its high energy consumption [1], buildings account for 40 % of global energy consumption and 30 % of carbon dioxide (CO_2) emissions [2,3]. This underscores the built environment's vital importance in mitigating and adapting to climate change. Hence, it is crucial to reduce the environmental impact of buildings to achieve global climate goals and promote environmental sustainability [4]. The Passive house (PH) concept is a sustainable building standard focusing on energy conservation to minimise heating and cooling requirements [5]. As a way of addressing high energy demand in buildings, PHs have become a cornerstone of sustainable building practices due to their minimal energy requirements [5], especially for heating and cooling [1].

To obtain PH certification, a building must satisfy five specific criteria [6]. Firstly, the energy required for space heating should not exceed 15 kWh per square meter of net living space annually or have a peak demand of 10 W per square meter [6]. Secondly, the space cooling demand has similar criteria to the space heating demand, with adjustments for dehumidification needs in specific climates [6]. Thirdly, the primary energy requirement should not surpass 60 kWh per square meter of treated floor area annually for the PH classic category, 45 kWh for the PH plus category, and 30 kWh for the PH premium category, which includes energy consumption from all domestic appliances, heating and cooling, domestic hot water, and lighting [6]. Fourthly, the building must achieve airtightness with no more than 0.6 air changes per hour (ACH) at 50 Pascals pressure, confirmed through pressurisation and depressurisation testing [6]. Finally, the building must maintain thermal comfort throughout all living spaces throughout the year, with thermal transmittance (U-values) for opaque elements below 0.15 W/m^2/K and a Solar Heat Gain Coefficient (G-value) for windows less than 0.8 W/m^2/K [6]. Accordingly, these criteria can be met by following the five highlighted PH design principles – i.e., high levels of envelope insulation, efficient windows, airtightness, mechanical ventilation with heat recovery (MVHR), and minimisation of thermal bridges [7].

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To further enhance the energy efficiency of PHs, the integration of solar photovoltaic systems (SPVS) has been recommended [8] to promote energy conservation [9], renewable energy use [10], and overall sustainability in buildings [5]. By incorporating SPVS, PHs can achieve greater energy independence [8] and create a strong synergy that supports both energy efficiency [9], and sustainability [5].

Energy efficiency remains the foundational principle for achieving sustainability in the built environment [11]. By prioritising investments in energy-efficient designs, the overall energy demand for PHs can be significantly minimised [12]. This reduction optimally aligns with the integration of SPVS, ensuring that the system's size and costs are tailored to the reduced energy load [5]. PV technologies now include innovative options like Organic Photovoltaics (OPVs) [13], perovskites [14], and thin-film CdTe [15] offering flexibility, lightweight designs, and architectural adaptability for building-integrated applications, including semi-transparent surfaces and cost-effective large-scale integration [13,16]. The integration of SPVS into Passive Houses occurs through Building-Applied Photovoltaics (BAPV) and Building-Integrated Photovoltaics (BIPV) [9,17]. While BAPV dominates due to retrofitting adaptability and in new construction, BIPV offers dual benefits—functioning as architectural elements and energy generators [18], —when incorporated during construction. Early adoption of BIPV reduces costs and enhances energy efficiency [17], aligning Passive Houses with long-term sustainability and decarbonisation goals. Emerging technologies, such as BIPV, have gained prominence as they offer seamless integration with Passive House designs while enhancing energy performance. For instance, PV/T systems are increasingly utilised to address electrical and thermal energy needs, aligning with sustainability goals [19]. These advancements highlight the evolving landscape of SPVS technologies and their potential to optimise Passive House energy efficiency. Furthermore, Innovations in thermal energy storage systems, particularly the use of phase change materials, have been identified as effective solutions for managing the intermittent nature of renewable energy sources, thereby supporting the integration of SPVS in energy-efficient buildings [20].

While many typical buildings heavily rely on fossil fuel-based energy sources, resulting in substantial CO_2 emissions [21], the adoption of SPVS in PH (SPVS-PH) has been found to significantly contribute to climate change mitigation by decarbonising the building sector [22]. For example, the SPVS-PH technique utilises solar energy to meet a significant portion of a building's energy demands, diminishing dependence on fossil fuels, reducing CO_2 emissions associated with electricity generation, and promoting energy independence and resilience from on-site solar energy generation [23]. However, Research on solar-powered net-zero energy housing highlights challenges like seasonal supply–demand mismatches, which are particularly relevant in temperate climates. SPVS integration in Passive Houses can address these challenges by mitigating winter heating peaks and ensuring consistent energy availability throughout the year [24]. Consequently, PHs become less reliant on centralised energy grids powered by fossil fuels [8,9], thereby enhancing energy security and decreasing vulnerability to energy supply disruptions caused by extreme weather events or environmental-related grid failures [25].

Since the construction of PHs involves the use of materials with high embodied energy, leading to significant GHG emissions throughout their lifecycle [26], the SPVS-PH approach can effectively reduce overall GHG emissions associated with the building's lifecycle [22]. Also, the comprehensive effects of SPVS-PH adoption on climate change mitigation and its potential to drive transformative change in the built environment have been demonstrated by Franchini et al. [9], including its ability to enhance the environmental quality of buildings, as emphasised by [27]. Additionally, the adoption of SPVS-PH systems aligns with the United Nations' Sustainable Development Goals (SDGs) and their targets for a more sustainable future [28]. These systems directly contribute to achieving SDG Target 7.2 by facilitating the transition to renewable energy sources in buildings, a significant step toward a cleaner global energy mix [28]. Furthermore, SPVS-PH promotes responsible production and consumption patterns (SDG Target 12.2) in the building sector, reducing reliance on fossil fuels and potentially minimising construction waste [28]. The integration of solar technology also aligns with SDG Target 9.4, emphasising innovation for sustainable infrastructure development [28]. By enhancing building efficiency and resilience, SPVS-PH technology demonstrates a commitment to progressive infrastructure solutions as envisioned by Target 9.4 [28].

Some researchers have highlighted the usefulness of integrating SPVS with energy-efficient building design, positioning SPVS-PH systems as a model for sustainable development in the built environment. For example, by harnessing solar energy to meet electricity needs, SPVS integration with PHs would reduce reliance on grid-supplied power [5], hence, mitigating associated environmental impacts [29]. Also, Abrahamsen et al. [30] found a strong link between the adoption of SPVS-PH and improved energy efficiency in buildings, therefore, emphasising the capability of SPVS to reduce the overall energy demand of PHs. This integration boosts the energy efficiency of PHs and promotes a shift towards sustainable building practices prioritising resource conservation and environmental protection [31]. While reducing energy demand is crucial for achieving net-zero energy goals, where buildings generate as much energy as they consume over a specified period [22], the optimal performance of the SPVS-PV integration would rely on precise system design optimisation [32]. As a result, factors like PH orientation, panel tilt angle, and shading analysis must be carefully assessed to ensure effective solar energy capture and the optimal performance of SPVS-PH systems [17]. Additionally, using advanced software simulations, designers can accurately evaluate these factors and make data-driven decisions to optimise the placement and configuration of PV panels, ultimately maximising energy production and enhancing the sustainability of passive building designs [32].

Previous studies have made valuable contributions by examining the energy efficiency of PHs [5], assessing the benefits of integrating SPVS with energy-efficient building design [29], and focusing on the potential of SPVS-PH systems in mitigating climate change [22]. However, there is a lack of comprehensive understanding regarding their combined adoption. Specifically, the existing literature lacks insights into global adoption trends, drivers, barriers, and design considerations for integrating SPVS into PHs. Addressing this gap is essential for advancing sustainable building practices and informing effective strategies to accelerate adoption. This study aims to examine the global adoption of SPVS-PH systems, with a focus on (i) exploring the global trend for adopting solar photovoltaic systems in PHs, (ii) identifying the drivers and barriers to adopting solar photovoltaic systems in PHs, and (iii) investigating the design considerations that could enhance the synergy between PHs and SPVS.

The study investigates these aspects to contribute actionable insights to support SPVS integration into PHs and inform the development of a performance-based framework. This framework equips stakeholders—including policymakers, building professionals, and homeowners—with tools to overcome adoption challenges, aligning with global efforts to reduce energy consumption and carbon emissions. Finally, the study highlights the potential of SPVS-PH systems to decarbonise the building sector, enhance energy independence, and promote sustainable practices.

Material and methods

A systematic literature review (SLR) was conducted to gather relevant data from existing literature, fulfilling the objectives of this study. This method ensures a transparent and unbiased [33] exploration of SPVS-PH adoption trends, key drivers, barriers, and design considerations. By adhering to the Preferred Reporting Items for Systematic Reviews (PRISMA) protocol [34], the study aims to provide a detailed and reliable foundation for understanding SPVS-PH integration globally.

Systematic literature review (SLR)

A SLR identifies, assesses, and synthesises existing research to summarise literature and identify research gaps, using a structured approach to avoid biases of traditional reviews [35–37].

The rationale for employing the SLR method in this study lies in its effectiveness in identifying significant current trends within the relevant literature on the research topic. The literature search followed the guidelines of the PRISMA protocol [34]. The PRISMA protocol provides a structured approach to improve the reporting of the identified literature [38]. Its transparency, established reputation, and quality validate its selection for this study [33,36]. Table 1 outlines the criteria and guidelines used for data search according to the PRISMA protocol.

Procedure for data collection

The data retrieval procedure comprised four stages (refer to Fig. 1): (a) identifying relevant papers, (b) evaluation and exclusion of the papers, (c) Eligibility and quality evaluation of the selected papers, and (d) summarising of the selected papers.

(a) Identifying relevant papers

Following the PRISMA protocol, this study utilised Scopus and Google Scholar in April 2024 to conduct a comprehensive search for SPVS-PH adoption research. Scopus offers extensive indexing of peer-reviewed journals across various disciplines, ensuring a thorough search for relevant academic publications on SPVS-PH adoption [39]. Google Scholar complements this by including additional sources like conference proceedings and grey literature, potentially capturing valuable insights beyond traditional academic journals [40].

Keywords related to the research topic, such as "passive house", "solar", and "photovoltaic", were selected to encompass all pertinent literature from the Scopus database. A Boolean logic operator was employed in the Scopus database search, using the following search rule: TITLE-ABS-KEY (("Passive House*" OR Passivhaus) AND (Solar OR photovoltaic*)). The initial search resulted in 303 academic papers, which were subsequently reduced to 286 after the inclusion and exclusion criteria were administered. Moreover, a further search was carried out in the Google Scholar search engine using specific keywords: "Passive House OR Passivhaus AND Solar OR photovoltaic." This search from Google Scholar produced a total of 2,850 scholarly papers.

Table 1
Criteria and guideline for data search.

Stages	Criteria and guidelines for data search
Inclusion criteria	Only academic studies published in English regarding adopting SPVS in PH buildings were included in the study. This approach helps mitigate potential language barriers, and focusing specifically on adopting SPVS for PH buildings ensures that the study remains aligned with its research objectives and scope. Only studies published from 2012 to 2024 were included to align with establishing the SDGs in 2012, ensuring that the study captures relevant data and trends for SDG implementation.
Exclusion criteria	Non-English language studies were excluded from consideration due to the authors' proficiency in English. Additionally, studies that focused on PHs without incorporating SPVS were excluded to maintain the study's focus on adopting SPVS in PHs.
Data search approach in Scopus database	Keywords employed for searching: TITLE-ABS-KEY (("Passive House*" OR Passivhaus) AND (Solar OR photovoltaic*)). Results were limited to the period between 2012 and 2024. Subject areas covered in this study include Energy, Engineering, Computer Science, and Environmental Science. These selected subject areas encompass all disciplines where studies on adopting SPVS in PHs may appear. Only articles published in English were considered, including those in the press and their final stages.
Data search strategy in Google Scholar database	Search keywords used: "Passive House OR Passivhaus AND Solar OR photovoltaic". Results were limited within the timeframe ranging from 2012 to 2024.

(b) Paper evaluation and exclusion

Additional screening was conducted on the identified papers to eliminate those that were not aligned with the study's aim and objectives. This involved evaluating the titles and abstracts of each paper. The Scopus and Google Scholar databases resulted in 260 academic papers selected for eligibility evaluation.

(c) Eligibility and quality evaluation

The eligibility assessment and quality evaluation included applying criteria to the papers selected after screening. Inclusion criteria were restricted to peer-reviewed papers of high quality, with 228 of the 260 full-text academic papers reviewed being excluded during this stage.

(d) Selected papers' summary

Altogether, 32 high-quality, peer-reviewed academic papers were selected for this study. These papers examined the adoption of SPVS in PHs, aiming to enhance the resilience and sustainability of the built environment. They were then exported to Microsoft Excel for more evaluation and assessment.

Results and discussion

The detailed SLR findings on the study's objectives are discussed in the following section.

Articles distribution by year

The SLR process screened relevant articles from 2012 to 2024. The distribution of these publications is shown in (Fig. 2), illustrating varying interest levels in adopting SPVS for PHs, with peaks observed in 2013, 2017, 2021, and 2023. SPVS-PH adoption trends (Fig. 2) indicate a notable increase in publications starting from 2012, with a peak in 2021. This rise aligns with global momentum toward achieving the SDGs and key milestones in renewable energy policies and technological advancements. For instance, adopting the Paris Agreement in 2015 likely catalysed subsequent research activity driven by a heightened global emphasis on climate change mitigation [41].

The upward trend in publications reflects an increasing academic and industry interest in sustainable building practices and integrating renewable energy systems, particularly SPVS, within PHs. This surge underscores the global recognition of SPVS-PH as a critical strategy for achieving energy efficiency and decarbonising the built environment [22,32,42].

Country-wise distribution of articles

The geographical distribution of papers examining SPVS-PH adoption is shown in Fig. 3; the most substantial focus is on Europe, with Romania leading the way with five out of 32 studies, accounting for about 15 % of the total. This prominence likely reflects the EU's commitment to carbon neutrality by 2050 and robust financial incentives for sustainable buildings [30]. In contrast, regions such as Africa and Latin America are under-represented, highlighting a significant research gap. This gap is particularly concerning given developing economies' growing energy needs and renewable energy potential, where SPVS-PH systems could offer transformative solutions.

Romania's leadership within Europe underscores the impact of targeted policy and financial mechanisms on research and adoption trends [43]. Expanding research efforts beyond Europe, particularly in under-represented regions like Africa, could provide valuable insights into the unique challenges and opportunities for SPVS-PH adoption, contributing to global sustainability goals [28].

Beyond Romania, other European countries have also made substantial contributions. Norway, the United Kingdom (UK), and Austria

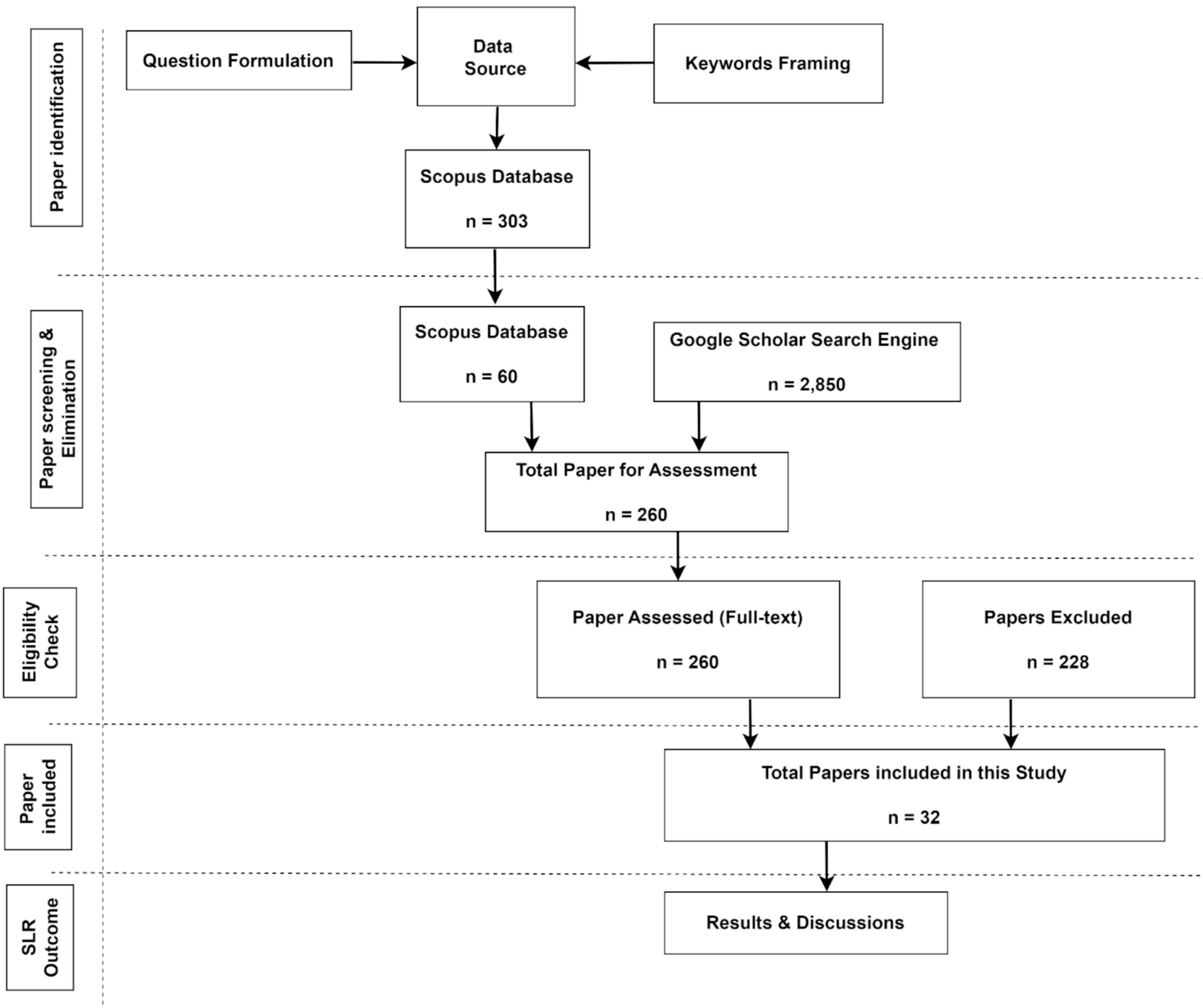

Fig. 1. The PRISMA Protocol for Conducting Systematic Literature Reviews.

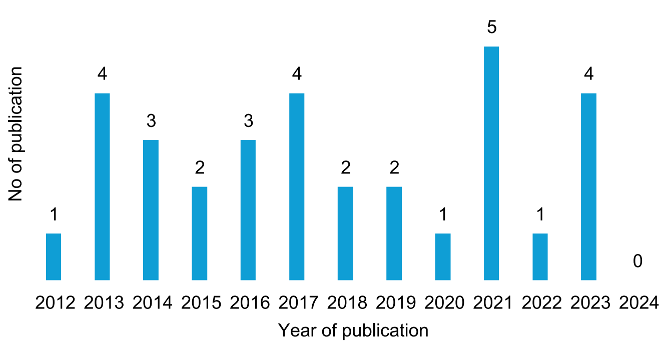

Fig. 2. Journal article distribution by year.

each account for three studies, or approximately 9 % of the total, while Poland, Denmark, Italy, Germany, Belgium, and Portugal contribute one study each (around 3 % each). Overall, Europe dominates with over 60 % of the research, reflecting the region's growing emphasis on sustainability and renewable energy integration. North America and Asia also show significant representation, with the United States of America (USA) contributing four studies (12 %), Canada two studies (6 %), and Asia collectively contributing approximately 15 % of the total, with studies from Dubai (three), Malaysia, China, and Qatar (one each).

Understanding the geographical trends in SPVS-PH adoption can inform policymakers and international organisations on where to focus support and resources. Initiatives to promote research and adoption in under-represented regions could accelerate global progress toward sustainable development goals.

Number of research methods per article

As seen in Fig. 4, most studies on SPVS-PH adoption employed quantitative methods, with 28 out of 32 papers relying on this technique [5,9,43,44], representing 88 % of the total studies. This focus emphasises empirical data and measurable outcomes when exploring SPVS-PH integration. Only one paper uses qualitative methods [45], indicating less interest in utilising non-quantifiable data when exploring SPVS-PH integration. The mixed methods approach is used in three out of the 32 papers [10,31,46], representing 9 %. This imbalance indicates a need for more qualitative and mixed-method research to understand SPVS-PH adoption, such as stakeholder perceptions, regional influences, and policy impacts.

By identifying this methodological gap, our study highlights the need

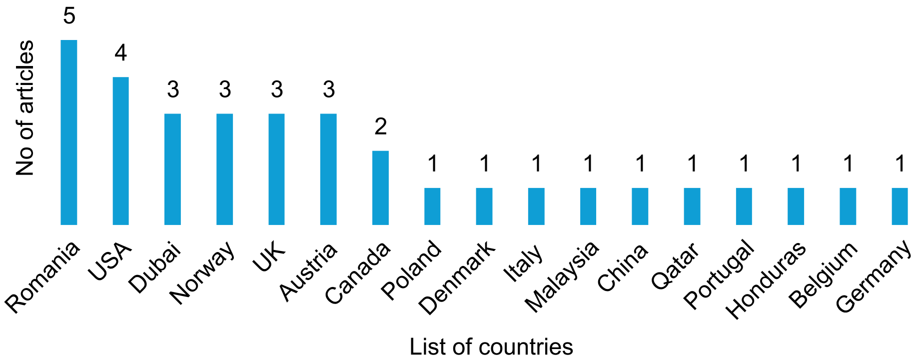

Fig. 3. Country-wise distribution of journal articles.

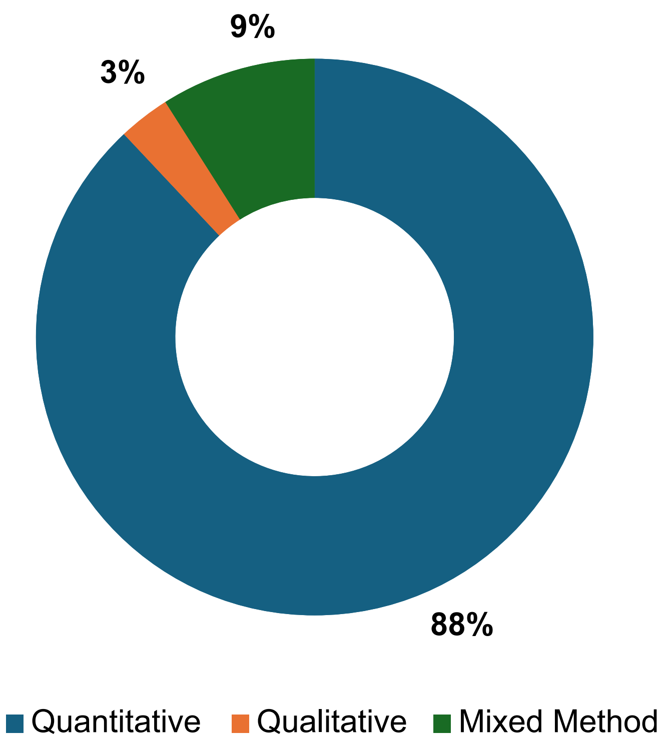

Fig. 4. The research methodology adopted by the journal article.

for more qualitative and mixed-methods research to capture a holistic view of SPVS-PH adoption. Future studies incorporating qualitative insights could provide a deeper understanding of barriers and drivers from the perspectives of various stakeholders.

Identified global trends in SPVS adoption for PHs

A clear trend is the dominance of residential projects across the data set, as shown in Fig. 5. Countries like the USA, Romania, Canada, Norway, Denmark, Italy, UK, Austria, Malaysia, China, Qatar, Portugal, Honduras, Belgium, and Germany focus on residential applications for adopting SPVS in PH (see Fig. 5 and Appendix A for sources). However, there is a limited representation of commercial projects in the data, with Norway [22,30], Romania [47], and Dubai [9] showcasing commercial projects (see Fig. 5). This could indicate that SPVS-PH adoption in commercial buildings might lag behind the residential sector, and there is a potential preference for adopting SPVS-PH in single-family homes or smaller residential buildings.

The dominance of residential projects reflects the accessibility and appeal of Passive House designs and SPVS integration for homeowners seeking energy efficiency and cost savings. This trend is likely due to the relative simplicity and accessibility of integrating SPVS-PH systems into smaller-scale projects, where individual homeowners are motivated by economic benefits and sustainability goals.

In contrast, the limited representation of commercial buildings may indicate potential barriers such as greater complexity, higher costs, and a lack of tailored design frameworks for larger-scale structures. Addressing these challenges could unlock significant opportunities for SPVS-PH adoption across diverse building types, contributing to broader sustainability goals.

Romania has the highest number of studies, with 5 out of the total (see Appendix A for sources). Most of these studies from Romania

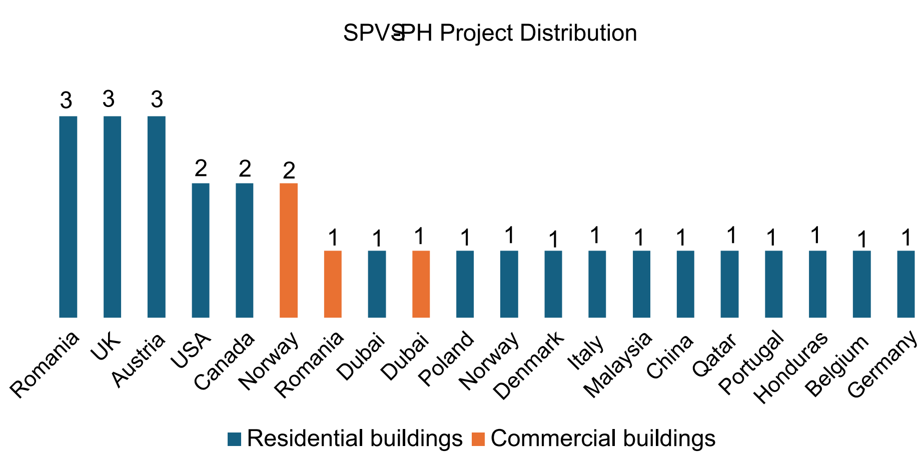

Fig. 5. The SPVS-PH Project Distribution by Country (Residential vs. Commercial).

mention the EU's commitment to carbon neutrality by 2050, which could explain the predominance of the European country's literature in this analysis. Furthermore, the reviewed literature provided valuable SPVS-PH adoption trends from the USA and Norway. In the USA, a 12.9 % adoption rate of SPVS in sustainable residential buildings (including PHs) is reported by Schwartz and Krarti [5]. Similarly, Abrahamsen et al. [30] revealed a 15 % utilisation of SPVS in Norway's nearly zero energy buildings (nZEBs) that adhere to the PH standard. These findings underscore the significant potential of SPVS-PH systems in advancing energy efficiency and sustainability in the built environment.

Identified drivers for adopting SPVS for PHs

The SLR on SPVS-PH adoption revealed 18 key factors that underpin the successful adoption and integration of SPVS in PHs (Refer to Appendix A for sources). These factors were grouped into five main categories: (a) economic, (b) environmental, (c) technical, (d) policy, and (e) education/awareness. Fig. 6 presents a comprehensive overview of the advantages driving SPVS-PH adoption in the built environment. The study highlights the most significant drivers, such as 'cost-effectiveness (21 %)', 'energy savings (12.28 %)', and 'renewable energy generation (10.53 %)'. Economic factors, including cost savings and energy independence, emerged as the most influential drivers for SPVS-PH adoption (Fig. 6). These drivers highlight the strong financial appeal of SPVS-PH systems, particularly in regions where rising energy costs make energy efficiency a pressing priority [17]. This finding aligns with global trends emphasising the importance of financial incentives and long-term energy cost reductions as critical motivators for adopting renewable technologies [5,48]. For instance, financial mechanisms such as subsidies, low-interest loans, and tax credits have significantly accelerated SPVS adoption in Europe [30]. These strategies offer valuable lessons for underrepresented regions like Africa and Latin America, where limited financial support currently constrains adoption [28,30].

From an environmental perspective, drivers, such as carbon emission reduction and renewable energy generation, rank second in importance, reflecting the alignment of SPVS-PH systems with global sustainability goals [28], including commitments under the Paris Agreement [41]. These systems directly address the building sector's significant contributions to global energy consumption and emissions, offering a viable pathway to achieving net-zero carbon targets. Their integration into national and regional strategies could amplify their impact, especially in urbanising regions with growing energy demands [9,31]. On the technical side, factors, including energy independence and system reliability, further underscore the practical benefits of SPVS-PH adoption. However, these advantages hinge on optimal system design and implementation [8]. Building orientation, shading analysis, and PV panel placement are critical in maximising energy production and operational efficiency [8]. Energy simulation software like IES-VE, PHPP, and EnergyPlus can support precise system simulations, helping to overcome technical barriers and optimise system performance [8,9,44].

Regarding policy considerations, policy measures complement economic and technical drivers by establishing a supportive regulatory framework for adoption. Regions with robust financial incentives and mandatory renewable energy targets, such as Europe [30], demonstrate significantly higher adoption rates. Extending such frameworks to underrepresented regions could address disparities and unlock opportunities for broader SPVS-PH integration [41]. Finally, education and awareness initiatives bridge the theoretical potential and practical adoption gap. Targeted campaigns, demonstration projects, and stakeholder education effectively dispel misconceptions about SPVS-PH feasibility and affordability, fostering broader acceptance. By empowering stakeholders with knowledge, these initiatives drive informed decision-making and build momentum for adoption across diverse contexts [8,47]. Subsequent sections explain these factors: economic, environmental, technical, policy, and educational. These drivers create a compelling case for SPVS-PH adoption, offering actionable insights to policymakers, industry professionals, and researchers seeking to advance sustainable building practices globally.

Economic factors

The SLR results, illustrated in Fig. 6, reveal the economic drivers behind SPVS adoption in PHs, including cost-effectiveness (21.05 %), revenue generation (3.51 %), and energy bill elimination (3.51 %). Although the initial investment for integrating SPVS into PH design features can be substantial [49], this cost is offset by significant long-term savings and enhanced energy security for homeowners [5]. Moreover, Schwartz and Krarti [5] note that the capital cost of SPVS is lower than that of other renewable energy technologies, such as geothermal systems.

A key advantage of SPVS is its potential to generate additional revenue. For instance, excess electricity produced during peak sunlight hours can be exported back to the grid, depending on regional net

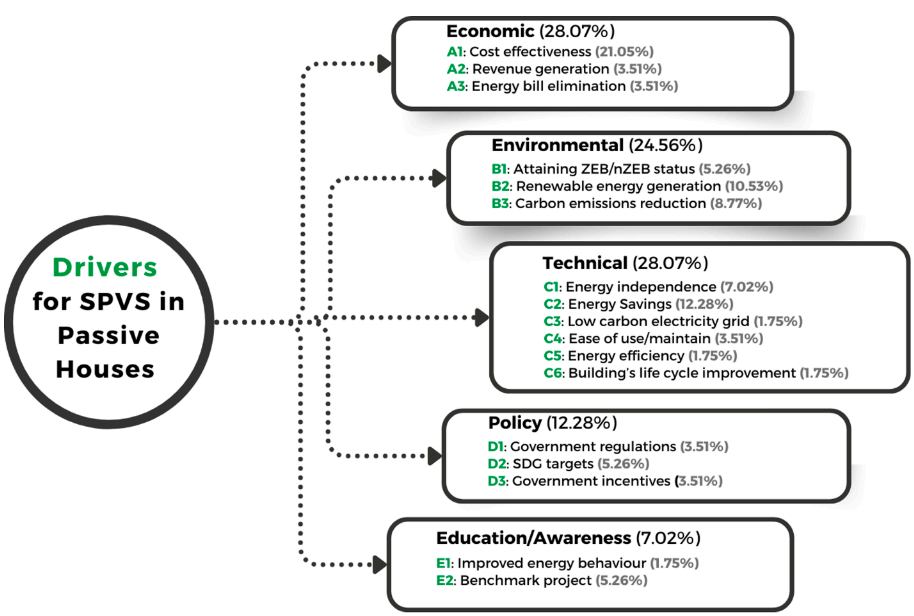

Fig. 6. Identified drivers for adopting SPVS in PHs.

metering regulations, potentially providing homeowners with extra income [43,48]. As the initial investment is recouped, the long-term economic benefits of SPVS-PH systems become increasingly evident. Once the payback period is reached, the ongoing energy cost savings translate into significant financial gains over the system's lifespan [44].

Furthermore, the market appeal of buildings with SPVS-PH features is noteworthy. These energy-efficient and sustainable homes may command higher prices, attracting clients who prioritise these attributes [31]. Supporting this, Alajmi et al. [8] and Manzoor and Iqbal [10] underscore the economic advantages of SPVS over other renewable energy options for PH integration. Alajmi et al. [8] found that SPVS was the most effective renewable energy solution for PH buildings when compared to After evaluating various options, Alajmi et al. [8] found that SPVS was the most cost-effective renewable energy solution for a PH building compared to a combination of SPVS with other technologies like solar water heaters. This finding is consistent with that of Manzoor and Iqbal [10], who emphasised the affordability of SPVS adoption in PHs compared to other renewable energy sources. Therefore, these findings imply that SPVS-PH minimises buildings' energy costs and financial burdens while promoting environmental sustainability.

Environmental factors

Fig. 6 illustrates the environmental drivers for adopting SPVS in PHs, identified through the SLR, including attaining ZEB/nZEB status (5.26 %), renewable energy generation (10.53 %), and carbon emission reduction (8.77 %). Adopting SPVS-PH goes beyond energy savings; it represents a commitment to a more sustainable future [10]. For example, Manzoor and Iqbal [10] pointed out that using SPVS in Newfoundland PHs promotes sustainable living practices and supports the transition towards environmentally friendly housing solutions. This aligns perfectly with the growing focus on sustainability, even in regions like the UAE, where electricity is relatively inexpensive [9]. In such regions, the government prioritises sustainability initiatives, recognising the long-term environmental benefits of SPVS-PH, even when immediate cost savings might be less pronounced [9].

The environmental impact of SPVS-PH systems is further demonstrated by their ability to balance a building's energy demand and achieve nearly Zero Energy Building (nZEB) status. Göttsche et al. [50] demonstrated that installing PV panels on a PH can balance the building's energy demand, effectively reaching nZEB status. This significantly reduces reliance on traditional energy sources and minimises the environmental impact of building operations. Similarly, Parkin et al. [31] highlighted that the desire for zero-energy buildings is a significant driver for adopting SPVS-PH systems, emphasising that these systems are crucial for meeting the zero-energy criteria of nZEBs—a finding supported by [22,32,42].

Furthermore, the installed SPVS's CO_2 emissions over its lifespan are significantly lower than those associated with traditional electricity generation [23]. Moreover, Alajmi et al. [8]'s detailed energy analysis demonstrated that integrating a 26 m2 PV system into PH buildings saved approximately 0.492 tons of CO_2 emissions annually. These findings are further supported by Proietti et al. [48], Franchini et al. [29], who viewed SPVS-PH buildings as a viable solution for reducing a region's overall carbon footprint and global warming potential (GWP). Furthermore, Moran et al. [42] showed a significant reduction in building emissions when a historic building is upgraded to a PH with an integrated SPVS. Therefore, these findings indicate that the SPVS-PH technology brings substantial environmental benefits, including achieving zero or nearly zero energy building status, fostering sustainable practices, generating renewable energy, and reducing carbon emissions.

Technical factors

The identified seven technical drivers of SPVS-PH adoption are shown in Fig. 6, including energy independence (7.02 %), energy savings (12.28 %), low carbon electricity grid (1.75 %), ease of use/maintenance (3.51 %), energy efficiency (1.75 %), and building's life cycle improvement (1.75 %). Schwartz and Krarti [5] study emphasised that utilising SPVS in PH fosters energy autonomy by generating renewable electricity, thereby reducing dependence on the grid and advancing energy independence in PHs. In optimised systems with sufficient SPVS capacity, excess electricity can be exported to the grid under net-metering regulations [5,43]. However, while exporting excess electricity to the grid may not directly reduce a building's carbon footprint, it can be inferred that this clean energy displaces electricity generated from fossil fuels, contributing to a lower-carbon grid overall [42]. Moreover, several studies [5,43,46,48,51,52] have demonstrated that the SPVS-PH system yields substantial energy savings, consistently showcasing the considerable reduction in energy consumption achievable through SPVS in PHs.

Although solar energy production is intermittent and seasonal, the PHs may rely on the grid at night and in winter, the overall energy savings are substantial [43]. However, for a fully continuous and grid-independent power supply, optimally sized SPVS can be coupled with energy storage systems [9]. Furthermore, Manzoor and Iqbal [10] noted that the SPVS-PH systems offer a practical and user-friendly approach to achieving energy efficiency when compared to other renewable energy options, such as the micro-hydro turbine and geothermal, SPVS are generally considered easier to maintain and operate. This ease of use makes them a viable solution for homeowners seeking a low-maintenance approach to sustainable living. Similarly, Schwartz and Krarti [5] observed that other renewable energy technologies, such as geothermal, are less popular than SPVS due to their limited site availability, making SPVS a good option for PH buildings.

Also, beyond just design principles, SPVS-PH systems prioritise achieving practical, in-use energy efficiency [31]; this ensures the building performs as intended, delivering real-world energy savings rather than solely focusing on theoretical design goals. Moreover, although manufacturing solar panels consumes energy [53], Schwartz and Krarti [5], Tanasa et al. [43], Kołodziejczyk-Kęsoń and Grebski [51] showed that SPVS-PH adoption contributes positively to a building's life cycle efficiency. The clean electricity they generate over their lifespan offsets most (74 % for polysilicon panels) of the embodied energy used in their production [53].

Policy factors

Fig. 6 shows the identified policy drivers of SPVS adoption in PHs, highlighting key factors such as government regulations (3.51 %), SDG targets (5.21 %), and government incentives (3.51 %). The UN's SDGs provide a global roadmap for a sustainable future, with SDG 7 focusing on ensuring universal access to affordable, reliable, sustainable, and modern energy [28,54]. Integrating renewable energy sources like SPVS into PHs aligns with this goal, creating energy-efficient buildings that directly contribute to the achievement of SDG 7 [54].

The urgency of addressing climate change has prompted many governments to establish ambitious energy efficiency goals and carbon neutrality targets. A notable example is the EU's commitment to achieving carbon neutrality by 2050 [30]. In line with this, the European Performance of Buildings Directive (EPBD) mandates that all new buildings must attain nearly zero-energy building (nZEB) status by 2021 [22]. These policies have significantly driven the uptake of SPVS in the EU, as these systems are a vital technology for achieving nZEB standards [22,30].

In addition to regulatory measures, many governments offer financial incentives, such as subsidies or feed-in tariffs, to encourage investment in renewable energy technologies like SPVS. These incentives provide monetary rewards for electricity generated and fed back into the grid, thereby offsetting the initial investment costs of SPVS systems [55]. As a result, SPVS becomes a more attractive option for homeowners and developers, further driving its adoption in the pursuit of sustainable and energy-efficient buildings.

Education/awareness factors

The education/awareness drivers of SPVS adoption in PHs, including improved energy behaviour (1.75 %) and benchmark projects (5.26 %), are shown in Fig. 6. Educating the public about energy conservation and protecting the environment are essential in promoting energy-saving behaviours and fostering environmental sustainability [47]. Additionally, changing the energy behaviour of the final consumer is a vital step toward preserving resources for future generations. This shift in behaviour is essential to creating a sustainable society that values energy efficiency and resource conservation [47]. Alajmi et al. [8] emphasised this by showing that successful Energy Conservation Measures (ECM), which include changes in occupant behaviour and natural ventilation, contribute to an annual energy savings of 814 kWh for the PH building and save 0.1 tons of CO_2 emissions at no cost.

Pilot projects, such as the study conducted by Franchini et al. [9] on a UAE government initiative, can significantly impact the success of sustainable building projects by demonstrating that new sustainable construction standards using only SPVS are feasible for reducing the carbon footprint in the entire UAE Gulf region. The SPVS-PH project was designed to prove that sustainable building is possible in the UAE, encouraging further adoption of these technologies [9]. This initiative demonstrated that solar energy could be a viable solution for sustainable construction. In addition to pilot projects, documenting successful PH-SPVS buildings, as practised in New Zealand [56] could be an effective strategy to enhance the public perception of clean energy investments. By formally recognising these sustainable building efforts, such documentations provide a tangible way for developers, businesses, and homeowners to exhibit their commitment to reducing carbon emissions.

Therefore, by promoting education and awareness about energy conservation and shaping a positive public perception of sustainable construction practices, SPVS-PH contributes to a more environmentally conscious society and paves the way for a more sustainable future [9,47].

Identified barriers to adopting SPVS for PHs

Apart from the identified drivers, the SLR process also identified nine barriers to optimising SPVS usage in PHs (sources listed in Appendix B). These barriers were grouped into three categories: (i) economic, (ii) technical, and (iii) awareness and political factors. Fig. 7 summarises all identified challenges to adopting SPVS in PHs under the different categories, highlighting the most significant barriers, including "high initial installation cost (16 %)," "design vs. as-built performance uncertainty (20 %)," and "climate-specific adaptability (20 %)".

Addressing these identified challenges requires supportive financial mechanisms, as this encourages stakeholders to invest in these systems. Targeted measures like subsidies, low-interest loans, and performance-based incentives are essential to address this challenge. Successful examples from Romania [43] and Norway [22] demonstrate that incentivised financial models can significantly alleviate upfront cost burdens, enabling broader adoption.

From a technical perspective, technical barriers hinder scalability and operational efficiency, including suboptimal system design, inadequate grid integration, and maintenance complexities. These challenges are worsened by the scarcity of trained professionals, particularly in regions with emerging renewable energy markets [31]. Bridging this gap requires advancements in user-friendly, low-maintenance technologies and capacity-building initiatives. Integrating smart energy storage systems enhances grid resilience and ensures a consistent energy supply, addressing a critical technical barrier [44].

Regarding awareness consideration, awareness barriers reflect an educational gap among stakeholders, including policymakers, developers, and end-users. Misconceptions about SPVS-PH feasibility and affordability often arise from limited exposure to successful case studies or demonstration projects Franchini et al. [9]. Targeted awareness campaigns, workshops, and accessible educational resources can play a pivotal role in fostering acceptance and promoting understanding of SPVS-PH benefits.

Overcoming these interconnected barriers demands a multi-pronged approach integrating economic incentives, technical advancements, and awareness programs. This study addresses these challenges comprehensively and provides actionable insights to create an inclusive pathway for SPVS-PH adoption, advancing global sustainability goals and carbon reduction targets.

Subsequent sections explain these factors: economic, technical and awareness factors. These barriers create a compelling case for SPVS-PH adoption, underscoring the multifaceted nature of the obstacles faced in adopting SPVS-PH.

Economic factors

The primary barriers facing SPVS adoption in PHs from this study's review include high initial installation costs (16 %), cost-benefit uncertainty (8 %), price variability (4 %) and inadequate government incentives (4 %). Fig. 7 summarises all the identified challenges to adopting SPVS in PHs under the different categories. Schwartz and Krarti [5] and Badea et al. [55] argued that the upfront cost of constructing a PH is generally higher than that of conventional buildings, and adding SPVS further increases the initial investment price, creating a significant barrier, particularly for cost-conscious developers and homeowners.

Furthermore, Parkin et al. [31] noted that clients might hesitate to invest substantially without guaranteed long-term returns, as the perceived risk associated with the upfront cost and uncertainty about

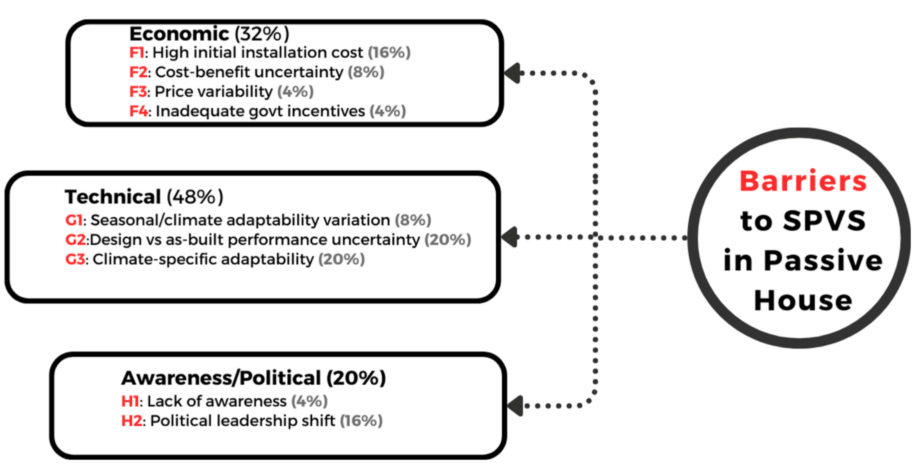

Fig. 7. Identified barriers to adopting SPVS in PHs.

the actual energy savings and financial benefits can deter potential adopters. The cost of installing SPVS-PH systems can vary considerably depending on the country, often linked to the country's specific policies on renewable energy [55]. This disparity, often linked to a nation's specific policies on renewable energy, can discourage the widespread adoption of SPVS in PHs by creating additional financial risks for developers due to the lack of standardisation in costs [55]. Moreover, SPVS-PH adoption may not be financially viable without substantial government support, as a lack of incentives can significantly dampen interest in renewable energy systems, particularly in regions with high initial costs [23].

Badea et al. [55] emphasised that investors face uncertainty when deciding on investment strategies for renewable energy projects in particular countries, prompted by the unpredictability of economic conditions, leading them to weigh the sustainability of immediate investment against awaiting potential economic improvements. However, Badea et al. [55] suggested that government financial incentives, such as partial or total grants, could help offset the high initial investment costs and make renewable energy more attractive to investors. Furthermore, Badea et al. [55] advocated for a comparative study employing published statistical data to determine the most favourable investment avenues before making investment commitments.

Technical factors

Findings from the SLR revealed SPVS seasonal/climate adaptability variation (8 %), design vs as-built performance uncertainty (20 %), and climate-specific adaptability (20 %) as the financial barriers to SPVS adoption in PHs. Fig. 7 summarises all identified challenges to adopting SPVS in PHs under the different categories.

Manzoor and Iqbal [10] underscored the technical challenges posed by the inherent variability of solar energy production, particularly emphasising the constraints imposed by seasonal fluctuations and the absence of adequate technology, such as snow-clearing technology for PV panels in specific regions in Canada. Aghaei et al. [57] further illustrated the variability of solar energy production, observing that cloud cover can significantly reduce daily solar energy absorption, even in regions seemingly characterised by abundant sunshine hours. For instance, despite its geographical positioning, Pulau Perhentian Island, Malaysia, registers an average of 5.5 sunshine hours per day. These factors necessitate careful consideration of local climatic conditions during the design phase, as a "one-size-fits-all" approach might not be effective in achieving net-zero energy goals (NZEB) due to variations in location and microclimates [58].

Moreover, unfamiliar construction methods and materials required for PHs can deter potential adopters [31]. Clients might perceive zero-energy or zero-carbon standards as performance measures rather than design goals, leading to challenges if the PH fails to meet these standards post-construction [31]. This uncertainty towards embracing new technologies creates hesitancy in investing in SPVS-PH. Furthermore, there can be a significant gap between the designed energy efficiency of a building and its actual performance in real-world conditions, termed "design vs. as-built performance uncertainty," which can undermine the perceived benefits of SPVS-PH, emphasising the necessity for optimal system design [31].

Abrahamsen et al. [30] discussed SPVS's environmental footprint, highlighting the influence of a country's energy mix on the embodied emissions linked with PV cell manufacturing. This underscores the necessity for a comprehensive approach that accounts for the environmental impact across the system's entire life cycle beyond solely focusing on its operational energy efficiency [30]. Moreover, Rabani et al. [22] emphasised this point by highlighting the increased embodied emissions from installing PV panels to achieve NZEB in PHs, while Schwartz and Krarti [5] believed that the high energy efficiency of PHs might make integrating SPVS less necessary in some cases. However, other studies suggest that the optimal sizing of the PV system, orientation, and tilt angle play a crucial role in optimising the energy produced by the SPVS [23,49].

Awareness and political factors

Fig. 8 summarises all the identified challenges to adopting SPVS in PHs under the different categories. It shows the awareness and political barriers to SPVS adoption in PHs, including a lack of awareness (4 %) and a political leadership shift (16 %). Schwartz and Krarti [5] observed that a general lack of awareness about the operation of SPVS and its benefits contributes to potential adopters' hesitancy. This uncertainty can make clients reluctant to invest in SPVS-PH, emphasising the need for education and awareness campaigns to address these gaps and increase confidence in the technology. For example, clients may define zero-energy or zero-carbon standards as a performance measure rather than a design goal [31]. Parkin et al. [31] highlighted that this shift in focus can lead to challenges, especially if the PH does not meet these standards after construction. Additionally, Badea et al. [55] pointed out that changes in government leadership can result in inconsistent policies affecting renewable energy adoption. This uncertainty can discourage long-term investments in SPVS-PH, as developers and clients may fear that policy reversals could undermine their financial returns.

Consequently, a clear difference between this study and the 2012 study by da Graça et al. [49] is the number of drivers and barriers identified for SPVS-PH adoption. While the earlier study identified only a few key factors, this study and the more recent research by Schwartz and Krarti [5] uncovered significantly larger drivers and barriers. This difference may suggest that over the past decade, there have been substantial changes in the factors influencing SPVS-PH adoption, with new drivers and barriers emerging. One possible explanation for this change is the growing awareness among stakeholders of the extensive benefits of SPVS-PH systems, providing numerous rational reasons for their implementation. This increased awareness likely reflects technological advancements, shifts in regulatory landscapes, and a broader understanding of sustainability's importance in the building industry.

Design considerations for enhancing SPVS adoption in PHs

Integrating SPVS in PHs presents a compelling strategy for achieving nearly zero/positive-energy buildings [59]. However, maximising the effectiveness of SPVS in PHs requires careful consideration of various design aspects [8].

Fig. 8 summarises the identified design consideration factors for SPVS-PH adoption, grouped under "design orientation" and "smart energy storage systems." Factors for the design orientation include "building design and orientation (27.27 %)," and "SPVS design and integration (36.36 %)," while the factors for smart energy storage system are "battery storage system (22.73 %)," and "building management system (BMS) (13.64 %)."

Building orientation is pivotal for maximising energy efficiency in SPVS-PH systems. For instance, ensuring optimal orientation based on geographical location—southern orientation in the Northern Hemisphere and northern orientation in the Southern Hemisphere—significantly enhances solar energy capture [57]. These considerations are crucial in regions with variable solar irradiation, where even slight deviations in orientation can result in substantial energy losses. Monocrystalline silicon PV panels outperform polycrystalline due to higher efficiency and reduced space requirements [8,44]. This efficiency advantage likely explains their growing market dominance, as declining costs and the need for optimised energy performance make them the preferred choice [60].

Additionally, smart energy storage systems, such as lithium-ion batteries, enhance the reliability of SPVS by addressing solar power's intermittency [61]. These systems enable buildings to store excess energy generated during peak sunlight hours and use it during non-peak periods, ensuring a consistent power supply [8].

Implementing these design considerations has far-reaching implications for advancing SPVS-PH adoption. For instance, precise building

Fig. 8. Key Elements of SPVS-PH Design Considerations.

orientation improves energy efficiency and reduces homeowners' operational costs, making SPVS-PH systems more economically viable. Similarly, integrating advanced energy storage systems reduces dependency on centralised energy grids, enhancing energy resilience in regions prone to power outages or extreme weather events. These considerations underscore the potential for SPVS-PH systems to serve as scalable models for achieving net-zero energy buildings globally, contributing to both environmental and economic sustainability goals.

Subsequent sections explain these factors: design orientation and smart energy storage system. These considerations emphasise the strategic approaches to optimising SPVS-PH integration, ensuring enhanced performance, energy efficiency, and sustainability.

Design orientation

Fig. 8 shows that the primary design considerations identified in the SLR for SPVS in PHs are building design and orientation (27.27 %) and SPVS design and integration (36.36 %). Building design and orientation are crucial for optimising energy efficiency in PH construction [46], and maximising solar exposure for the SPVS system is necessary [17]. The ideal orientation for capturing sunlight throughout the year is south-facing facades in the northern or northern-facing facades in the southern hemisphere [57]. However, PH building energy modelling software (such as PHPP, EnergyPlus, IES-VE and DesignBuilder) can be valuable in this process, aiding in system design and predicting energy production [8,9,44].

Furthermore, while shading is crucial for occupant comfort during hot summers, excessive shading can significantly reduce solar energy generation; therefore, finding the right balance is vital [43]. Depending on the building's orientation, strategically designed overhangs or vertical fins can balance these needs [17,43]. Achieving true zero-carbon performance might necessitate additional strategies beyond the core principles of pH design and SPVS systems, such as improving occupant behaviour and employing highly energy-efficient appliances [46].

Furthermore, optimal SPVS sizing is among the key strategies for achieving net-zero energy in PHs [23]. Alajmi et al. [8] and Mihai et al. [44] demonstrated that selecting high-efficiency PV panels, like monocrystalline silicon, is paramount for maximising energy generation, and the choice of PV technology also influences the integration strategy. Alkhateeb and Abu-Hijleh [17] pointed out that while polycrystalline silicon PVs might require more surface area for rooftops or BIPV applications to meet energy goals, monocrystalline PVs, due to their higher efficiency, might not necessitate BIPV integration.

However, design considerations extend beyond panel choice, as factors such as panel orientation, tilt angle, and potential shading all play a crucial role in optimising the SPVS system [8,49]. While rooftop solar panels are a foundation of SPVS in PHs, Dermentzis et al. [62] and [59] highlighted the potential of integrating PVs into building facades. This is particularly beneficial in urban areas with limited rooftop space, significantly increasing energy generation capacity. Dermentzis et al. [62] further emphasised the challenge of shading from neighbouring buildings in these environments, potentially hindering rooftop PV effectiveness. Interestingly, as noted by Göttsche et al. [50], in cases where rooftop PVs are extensive, they can provide a dual benefit by acting as shading elements for the building itself, contributing to passive cooling. However, determining whether a building necessitates PV-façade integration can be optimally achieved by utilising specialised building energy modelling software such as Polysun, TRNSYS and DesignBuilder [32,42].

Smart energy storage system

Fig. 8 highlights that the identified factors in the smart energy storage system category for SPVS-PH design considerations are battery storage systems (22.73 %) and BMS (13.64 %). While achieving energy autonomy in PHs by storing energy generated by SPVS in the BSS remains a primary goal, maintaining a connection to the grid serves as a valuable step for storing excess energy when the battery is fully charged [9,43,59]. This allows excess energy produced by SPVS to be exported to the grid. Moran et al. [42] noted that unused PV-generated electricity exported to the grid (low-carbon electricity) could be considered offsetting carbon emissions.

However, a BSS is vital in PHs because it is required to achieve energy autonomy [61]. By storing the excess energy generated by SPVS, buildings can ensure a continuous power supply for essential functions such as appliances, lighting, and air conditioning [8]. A study by Luis Ordoez-Avila and Hermida [45] indicated that a BSS with a storage capacity sufficient for at least three days can strike a practical balance between achieving autonomy and maintaining economic viability, ensuring that buildings can sustain their energy needs during periods of low sunlight or high demand while effectively managing costs and system efficiency.

BMS are necessary for maximising the effectiveness of BSS in PHs, as they implement intelligent control systems [32]. The BMS is crucial in leveraging sensors and data monitoring to optimise energy management and efficiency [32,63]. By integrating data from sensors across the PH, along with weather forecasts and occupancy patterns, the BMS adjusts real-time heating, cooling, and energy consumption strategies to optimise the utilisation of stored and generated energy, thereby enhancing the efficiency and sustainability of the building's energy systems [44].

Advanced BMS incorporate self-learning capabilities, enabling continuous improvement in energy management strategies by analysing historical data and user inputs, which leads to enhanced efficiency over time [32]. A BMS equipped with a Smart Building Controller (SBC) is the central hub for managing the entire PH ecosystem [44,61]. It monitors and controls various aspects of the building, including the SPVS, BSS, and grid, enabling accurate adjustment and optimisation of energy usage to ensure efficient system operation [32]. The smart control system manages energy generation and consumption, ensuring that PHs maintain consistent energy availability, promoting energy efficiency and resource conservation [32,61].

Ultimately, the design considerations analysis discovered that the fixed shading elements provide a valuable solution for managing solar gain; however, exploring innovative technologies such as adjustable shading solutions like blinds, shutters, and windows could offer a more flexible and precise method for controlling solar exposure, either through occupant interaction or automated systems, ensuring more accurate management of sunlight entering the building.

Conceptual framework

The SLR findings informed the identification of parameters for this study's proposed conceptual framework, which aims to guide stakeholders in adopting SPVS in PHs for a more resilient and sustainable built environment. This framework illustrated in Fig. 9 shows the interaction between the study's findings and the proposed strategies that could help improve the adoption of SPVS in PHs.

A successful adoption strategy must account for the interplay between various challenges, from economic barriers to education/awareness and design-related considerations, ensuring that each factor supports and reinforces the others. To achieve a holistic impact on SPVS-PH adoption, a comprehensive approach that addresses the interconnectedness of factors is essential. Rather than focusing on individual elements in isolation, a multifaceted strategy is required. For example, while financial incentives can stimulate uptake, their effectiveness depends on the alignment of technical feasibility and policy support. Financial incentives may be less effective if technical challenges, such as grid integration or system performance, are not adequately addressed. Additionally, as technology advances and economies of scale reduce costs, initial economic barriers may diminish, making other factors, such as public acceptance or policy support, more influential. Therefore, a holistic approach is essential to enhance SPVS-PH adoption strategies, with recommendations grouped under "public awareness and education", "regulatory and policy measures", and "technical advancements".

Raising public awareness and providing comprehensive training programs are essential for encouraging SPVS-PH adoption by showcasing these systems' environmental, economic, and social benefits. To further support this, continuous research and development must focus on advancing efficient and cost-effective PV technologies, energy storage solutions, and intelligent building management systems.

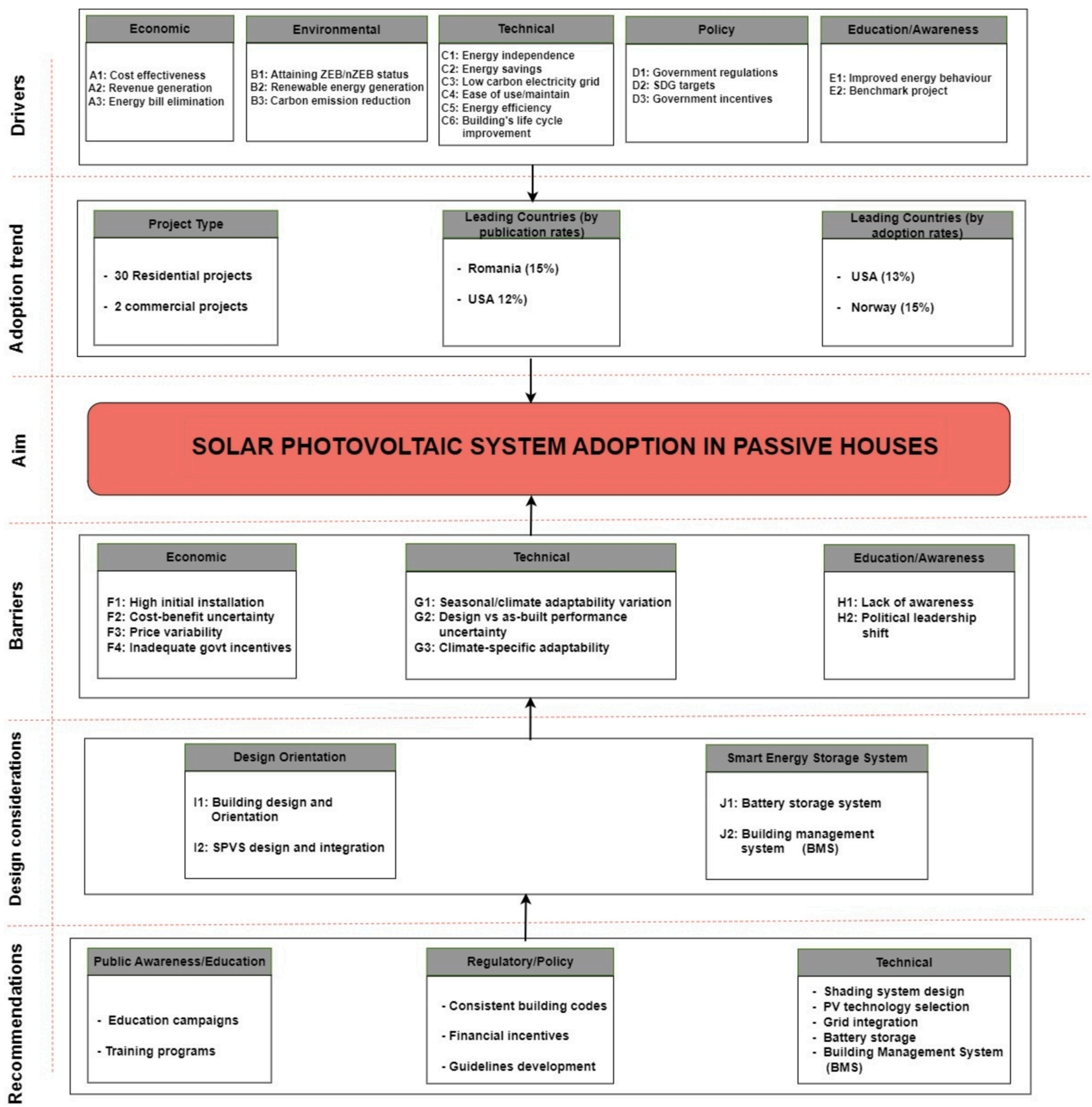

Fig. 9. The proposed conceptual framework for adopting SPVS in PHs.

Collaboration between industry and academia is also crucial in accelerating innovation and facilitating knowledge transfer. Additionally, targeted training programs for installers and maintenance personnel are vital to ensure high-quality installations and long-term system reliability.

Simultaneously with these educational efforts, establishing a supportive policy environment is crucial for accelerating SPVS-PH adoption. Governments may enact clear and consistent building codes that mandate or incentivise the integration of SPVS in both new and retrofitted PHs. Additionally, implementing robust financial incentives, such as feed-in tariffs, tax rebates, and low-interest loans, may significantly reduce the initial costs of these systems, making them more accessible to broader stakeholders. Policymakers are also encouraged to develop best practice guidelines and standards to enhance system performance and boost consumer confidence.

Moreover, incorporating shading systems into SPVS-PH building designs is a key technical recommendation that enhances PV panel efficiency by preventing overheating, benefiting both the solar panels and the building. By leveraging advanced PV technology, energy generation is significantly increased and further optimised through effective grid integration, ensuring a stable energy supply. Implementing a BSS adds another layer of efficiency by ensuring energy availability during peak demand, complementing grid integration by balancing supply and demand. Moreover, integrating a BMS allows for the seamless coordination of all these components, monitoring and optimising shading, PV output, BSS, and grid interactions. This comprehensive approach could ensure that each component supports and enhances the others, creating an integrated system that maximises efficiency, reliability, and the overall adoption of SPVS-PH in buildings. Effective implementation of these recommendations will involve a collaborative effort among key stakeholders, including government agencies, industry associations, and research institutions, to create a supportive environment for SPVS-PH adoption. Such a collective approach will significantly contribute to the widespread adoption of these systems, ultimately benefiting both the environment and society.

Conclusion

Reducing buildings' environmental impact is a critical step toward achieving global climate goals and fostering environmental sustainability. This study examined the integration of SPVS into Passive Houses globally, identifying adoption trends, influencing factors, and design considerations. Guided by the PRISMA protocol, 32 articles published between 2012 and 2024 were systematically reviewed. The analysis revealed three key adoption trends: project type, geographic distribution, and growth rate. It also identified 18 drivers, nine barriers, and two design considerations pivotal to SPVS-PH adoption.

Key findings highlighted cost-effectiveness (21 %), energy savings (12.28 %), and renewable energy generation (10.53 %) as primary drivers. In contrast, high initial installation costs (16 %), performance uncertainty between design and as-built phases (20 %), and climate-specific adaptability challenges (20 %) emerged as significant barriers. Design considerations such as optimal building orientation, shading system design, and selecting appropriate PV technologies (e.g., monocrystalline, polycrystalline, BIPV) were identified as essential for successful SPVS-PH integration. Additional factors included seamless grid integration, battery storage systems for energy autonomy, and BMS to optimise energy production and occupant comfort. These insights informed the development of a conceptual framework (Fig. 9) offering recommendations under three categories: "public awareness and education," "regulatory and policy measures," and "technical advancements."

This research significantly advances knowledge, practice, and policy by holistically synthesising global SPVS-PH trends, drivers, and barriers. It addresses critical challenges such as high initial costs and regional disparities in adoption rates while offering actionable strategies through a performance-based framework. Policymakers, building professionals, and homeowners are equipped with tools to facilitate SPVS-PH integration, aligning with global climate goals and the SDGs. The findings underscore the potential of SPVS-PH systems to decarbonise the building sector, enhance energy independence, and promote sustainable practices.

Despite its comprehensive scope, the study identifies areas for further exploration. Future research should investigate the perspectives of diverse stakeholders, including governments, industry leaders, and end-users, to develop inclusive adoption strategies. Regional-specific approaches tailored to diverse climatic and socio-economic contexts could enhance the global applicability of the proposed framework. Furthermore, advancements in SPVS technologies such as organic photovoltaics (OPVs), perovskites, and thin-film CdTe merit exploration to address performance and adaptability challenges, particularly in regions with unique architectural and climatic needs. Additionally, energy storage systems like flow and sodium-ion batteries should be explored as they offer a more environmentally friendly alternative to lithium-ion batteries. These technologies have lower environmental impacts and promise greater scalability and durability, making them ideal for enhancing the sustainability of SPVS in Passive Houses. Finally, the transition from BAPV to BIPV represents a promising area for future research. By embedding SPVS into passive house designs during construction, BIPV systems could enhance cost-efficiency, energy performance, architectural integration, and sustainability.

CRediT authorship contribution statement

Franklin Chukwuebuka Nkado: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Itohan Esther Aigwi:** Writing – review & editing, Supervision, Funding acquisition. **Dat Tien Doan:** Writing – review & editing, Supervision, Funding acquisition. **Ali GhaffarianHoseini:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Franklin Chukwuebuka Nkado reports financial support was provided by Auckland University of Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. . Drivers

No	Reference	Country	A1	A2	A3	B1	B2	B3	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	E1	E2
1	[5]	USA	x						x	x		x	x							
2	[43]	Romania	x										x							
3	[9]	Dubai					x	x	x				x							x
4	[10]	Canada	x				x		x			x								
5	[51]	USA & Poland	x							x			x							
6	[44]	Romania	x																	
7	[23]	Norway						x										x		
8	[8]	USA	x			x	x	x	x				x						x	
9	[29]	Dubai						x												x
10	[55]	Romania		x													x			
11	[52]	Denmark	x						x	x										
12	[48]	Italy	x					x	x	x			x							
13	[46]	UK						x		x										
14	[59]	Austria	x										x							
15	[57]	Malaysia						x												
16	[63]	Romania											x							
17	[61]	Canada					x													
18	[62]	Austria	X										x							
19	[64]	China										x								
20	[50]	Qatar										x								
21	[49]	Portugal	x									x								
22	[45]	Honduras		x																
23	[17]	Dubai			x		x	x	x											
24	[22]	Norway				x		x							x					
25	[47]	Romania									x				x			x		
26	[31]	UK	x		x		x	x						x						
27	[30]	Norway				x										x				
28	[53]	Belgium												x						
29	[58]	USA					x													
30	[32]	Germany																		
31	[42]	UK						x			x									
32	[54]	Austria			x											x				

Appendix B. . Barriers and design considerations

No	Reference	Country	F1	F2	F3	F4	G1	G2	G3	H1	H2	I1	12	I3	J1	J2
1	[5]	USA	x					x		x						
2	[43]	Romania										x			x	
3	[9]	Dubai										x			x	
4	[10]	Canada					x								x	
5	[51]	USA & Poland														
6	[44]	Romania														x
7	[23]	Norway											x			
8	[8]	USA											x	x		
9	[29]	Dubai												x		
10	[55]	Romania	x	x	x											
11	[52]	Denmark														
12	[48]	Italy														
13	[46]	UK								x		x	x			
14	[59]	Austria											x	x		
15	[57]	Malaysia					x									
16	[63]	Romania	x													x
17	[61]	Canada													x	
18	[62]	Austria												x		
19	[64]	China														
20	[50]	Qatar										x				
21	[49]	Portugal	x						x			x	x			
22	[45]	Honduras														
23	[17]	Dubai										x	x			
24	[22]	Norway						x					x			
25	[47]	Romania													x	
26	[31]	UK		x				x								
27	[30]	Norway						x								
28	[53]	Belgium														
29	[58]	USA							x							
30	[32]	Germany														x
31	[42]	UK									x					
32	[54]	Austria														

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2024.104166.

Data availability

No data was used for the research described in the article.

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