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Research article

Green building energy: Patents analysis and analytical hierarchy process evaluation

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ABSTRACT

In the dynamic sphere of building energy systems, this study explores advancements in energy integration, storage technologies, management practices, and occupant behavior, assessing sustainable energy practices, including emerging technologies like fuel cells and energy storage systems. It underscores the significance of efficient energy management, considering both renewable and conventional energy mechanisms. The study comprises four key strata: (i) a thorough literature review of recent energy trends, (ii) a comparative study of global energy patents using the World Intellectual Property Organization (WIPO) database, (iii) a comprehensive analysis of building-energy patents, and (iv) expert-guided Analytic Hierarchy Process (AHP) evaluation. These realms encompass five primary sources: (i) energy-efficient building design, (ii) intelligent building automation, (iii) optimizing energy systems integration, (iv) energy storage, and (v) energy management and optimization. Findings reveal energy storage's dominance, with water energy storage and emerging hydrogen technology leading the trajectory. Global energy patent scrutiny underscores China, the United States, and Japan as influential players in optimizing energy markets. The research shapes energy futures, identifies gaps, and drives sustainable energy practices within the built environment, serving as a compass for policymakers and researchers.

1. Introduction

Energy consumption in buildings is a paramount global concern that profoundly impacts sustainability and the natural environment. As the demand for energy-efficient buildings and sustainable energy sources continues to escalate [1], there is an increasingly urgent need to accurately predict and effectively optimize energy usage.

Buildings significantly contribute to global greenhouse gas emissions, making them a focal point for addressing climate change. Studies consistently show that the building sector accounts for a substantial portion of energy-related CO_2 emissions, with estimates

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ranging from 20 % to 40 % [2,3]. Inefficient energy utilization in buildings exacerbates environmental challenges and contributes to climate change. Extensive research demonstrates that implementing energy-efficient measures reduces energy consumption and greenhouse gas emissions significantly [4]. For instance, studies have shown that energy-efficient technologies and strategies can save up to 50 % of energy savings compared to conventional buildings [5]. These energy savings translate into substantial carbon emission reductions, helping mitigate climate change's impacts.

Furthermore, energy-efficient design principles have proven highly effective in promoting sustainability in the built environment [6]. Research indicates that passive design strategies, such as optimal insulation, efficient windows, and natural ventilation, can reduce building energy demand by 30 %–60 % [7]. By integrating renewable energy systems, such as solar panels and geothermal heating, buildings can achieve even more significant energy savings [8], with some studies reporting reductions of up to 80 % [9]. These findings underscore the significant potential for energy-efficient design to positively impact both energy consumption and carbon emissions.

Given the substantial energy savings and emission reductions associated with energy-efficient measures, it is evident that promoting energy efficiency in buildings is a crucial step toward achieving global climate goals. Implementing energy-efficient technologies and design strategies reduces the environmental footprint of buildings and contributes to long-term energy security and cost savings for building owners and occupants [10,11].

Integrating renewable energy systems in buildings presents a crucial pathway for achieving sustainable energy transitions. Renewable energy sources, such as solar photovoltaics (PV) and wind power, offer clean and abundant alternatives to traditional energy sources [12]. Numerous studies emphasize the potential of renewable energy integration in buildings. For example, research reveals that rooftop solar PV systems can generate a significant portion of a building's electricity demand [13,14]. Building-integrated wind turbines have also shown promise in on-site renewable energy production [15,16]. These findings underscore the importance of embracing renewable energy systems to reduce reliance on fossil fuels and foster a low-carbon energy future.

Smart building automation technologies have emerged as transformative tools for enhancing energy efficiency [17]. By utilizing sensors, data analytics, and automated control systems, smart buildings can optimize energy consumption based on real-time conditions. Extensive research consistently highlights the energy-saving potential of smart building automation. Implementing such technologies can lead to substantial energy savings compared to conventional buildings [18]. Moreover, smart building systems enable demand response programs, allowing buildings to adjust their energy usage in response to grid signals. This dynamic energy management approach contributes to grid stability and efficiency of energy systems [19].

Effective energy management and optimization strategies are essential for sustainable energy consumption in buildings. Building Energy Management Systems (BEMS) provide tools and algorithms for monitoring, analyzing, and controlling energy usage [20]. Research demonstrates significant energy savings through the implementation of BEMS. For example, effective energy management practices can result in savings ranging from 10 % to 30 % in different building types [21]. Additionally, advanced optimization techniques, such as machine learning and artificial intelligence, hold promise for further enhancing energy efficiency. Studies highlight the potential of machine learning algorithms in optimizing energy consumption patterns and reducing building operational costs [22].

The indoor environment significantly impacts energy consumption in multiple closed environment like urban buses and buildings. Research highlights the importance of efficient Heating [23], Ventilation, and Air Conditioning (HVAC) systems in reducing energy use [24]. Studies have shown that upgrading HVAC systems to high-efficiency models can save up to 30 % [25]. Additionally, minimizing the reliance on artificial lighting and achieving substantial energy savings by optimizing natural lighting and incorporating daylighting strategies. A recent study showed that daylighting strategies can reduce lighting energy consumption by 30 %–80 % [26]. These findings underscore the significance of considering the indoor environment as a crucial factor in energy prediction and optimization.

The energy performance of buildings can be evaluated comprehensively using the Life Cycle Assessment (LCA) approach. The LCA considers all the stages of a building's life cycle, from construction to operation and eventual demolition. Various studies have applied LCA to assess the environmental impact of buildings and identify opportunities for energy optimization. For example, a recent study compared the energy performance of different building materials and construction methods using LCA, highlighting the importance of sustainable material choices [27]. By considering the life cycle perspective, LCA enables a holistic approach to energy prediction and optimization in buildings.

Energy use in buildings can be predicted and optimized using energy modeling and simulation tools. These tools enable detailed analysis of building energy performance under various scenarios, facilitating informed decision-making for energy-efficient design and operation. Multiple studies have demonstrated the effectiveness of energy modeling in identifying energy-saving opportunities. For instance, a recent study used energy modeling to assess the impact of different building envelope designs on energy consumption, revealing the significant potential for energy savings through improved insulation and glazing systems [28]. By leveraging energy modeling and simulation, stakeholders can make evidence-based decisions to enhance building energy efficiency.

Occupant behavior has a significant influence on energy consumption in buildings. Research highlights the importance of engaging occupants and promoting energy-conscious behaviors to achieve energy savings. Studies have shown that providing occupants with real-time feedback on energy usage can lead to energy reductions ranging from 5 % to 20 % [29]. Occupant education programs and awareness campaigns have fostered sustainable behaviors and reduced energy waste. By considering occupant behavior as a dynamic factor in energy prediction and optimization, buildings can achieve more significant energy savings and enhance overall energy performance.

In order to achieve high energy efficiency in buildings, various energy sources and technologies have been developed, including wind energy, solar energy, geothermal energy, and hydropower. Each energy source has its advantages and disadvantages in terms of availability, cost, and suitability for different regions and building types. Additionally, the development of innovative energy-efficient

Table 1
Literature Summary of the recent advancements in building energy systems.

Author(s) & year	Methodology & scope	Finding(s)	Limitation & Gap(s)
Palomba V, Borri E, Charalampidis A et al. (2020) [34]	This article models a solar-biomass system for multi-family houses, providing comprehensive renewable energy coverage. The system includes a PV/T collector, biomass boiler, ORC unit, absorption chiller, and thermal storage tank. Performance is assessed across various climates and building types in Madrid, Berlin, and Helsinki.	The article demonstrates the system's ability to attain high solar fractions and decrease greenhouse gas emissions relative to conventional methods. Key parameters influence system performance, including solar collector area, biomass boiler power, ORC working fluid, and thermal storage capacity.	This article does not consider the system's economic feasibility and environmental impact in detail. It also does not account for the variability and uncertainty of the solar and biomass resources and the demand profiles. Moreover, it does not compare the system with other RES-based systems or different configurations and components.
Liu Z, Liu Y, He B et al. (2019) [35]	reviewing the critical technologies for nearly zero energy buildings (NZEBs) in China, including passive energy-efficient measures (EEMs) and active renewable energy technologies (RETs). evaluates the feasibility and suitability. The paper aims to provide guidance and suggestions for developing NZEBs in China.	NZEBs in China effectively utilize a range of EEMs and RETs like solar thermal, photovoltaic, ground source heat pumps, and biomass. These strategies contribute significantly to reducing carbon emissions and improving energy efficiency.	The article identifies limitations in current NZEB research in China: insufficient data, limited case studies, lacking evaluation methods, user comfort neglect, and future scenario uncertainty. Future work directions include integrated design methods, innovative EEMs/RETs exploration, life-cycle performance assessment, and incentive policy establishment.
Habash R (2022) [36]	This research explores the concept of buildings as control systems, integrating sensing, processing, and action to optimize performance. Introducing sensors, controllers, actuators, feedback loops, and control algorithms. The study surveys various building control systems, including building automation systems (BAS), building management systems (BMS), and smart building systems.	Building control systems provide manifold benefits to stakeholders, enhancing energy efficiency, indoor environmental quality, occupant comfort, operational reliability, maintenance efficiency, safety, and environmental sustainability. The study underscores challenges and opportunities, including system integration, technology utilization, human factors, and stakeholder alignment.	The article recognizes constraints in building control systems, encompassing the lack of comprehensive evaluation methods, scarcity of empirical data, intricate building dynamics, and conflicting objectives. Moreover, it identifies research gaps, advocating for integrated design approaches, innovative control strategies, life-cycle performance assessments, and supportive policy frameworks.
Mariano-Hernández D, Hernández-Callejo L, Zorita-Lamadrid A et al. (2021) [37]	This paper reviews four management strategies for BEMS to improve energy efficiency: model predictive control, demand side management, optimization, and fault detection and diagnosis. The article compares these strategies for different types of buildings and systems.	The article finds that BEMS can reduce energy use and cost, improve indoor comfort and quality, and support grid stability and renewable integration. Highlighting the choice of management strategy depends on the building characteristics, objectives, constraints, and available data.	The article recognizes BEMS research limitations, including the absence of comprehensive evaluation methods, limited empirical data, complex building dynamics, and conflicting objectives. It suggests future work on integrated design, innovative technologies, life-cycle assessment, and supportive policies for addressing these gaps.
Fu Y, O'Neill Z, Wen J et al. (2022) [38]	This research reviews building-level control strategies for using (HVAC) systems to provide grid services, such as energy efficiency, load shifting, load shedding, and load modulating. The article compares these strategies based on numerical and experimental studies.	The article discovers HVAC systems' grid interactions via diverse control algorithms like rule-based and model-based. These interactions yield mutual benefits, decreasing energy usage, enhancing indoor comfort, and aiding grid stability and renewable integration.	The article recognizes limitations in HVAC-grid research, such as lacking evaluation methods, data scarcity, and system complexity. It suggests future directions like integrated design, tech innovation, lifecycle assessments, and policy support.
Casini M (2022) [39]	The article introduces the Construction 4.0 framework, covering digitalization, innovative technologies, materials, and construction techniques. It discusses the industry's significance, challenges, opportunities, and impacts on energy and the environment. It also presents emerging paradigms of zero-energy, green, and smart buildings, detailing their characteristics and design strategies.	The article concludes that Construction 4.0 can revolutionize the design, construction, and operation of built assets, fostering an appealing, energy-efficient, comfortable, affordable, safe, and sustainable built environment. It can also tackle global challenges like resource scarcity, climate change, and population growth.	The article acknowledges Construction 4.0 research and practice limitations, including the absence of standards and regulations, high initial costs, low public awareness, and insufficient technical skills. It suggests research gaps like integrated design methods, innovative technologies, and incentive policies.
Chen Z, Xiao F, Guo F et al.(2023) [40]	This paper reviews previous studies that used interpretable machine-learning techniques for building energy management. these techniques are categorized into ante-hoc and post-hoc approaches and compared based on specific methods. The article aims to help users understand and trust machine learning models for improving building energy efficiency and flexibility.	The article highlights the benefits of interpretable machine learning for building energy management, including explaining model decisions, identifying essential features, detecting anomalies, and optimizing control strategies. Technique choice depends on model complexity, data availability, and user preference.	Interpretable machine learning for building energy management, including lacking comprehensive evaluation methods, limited empirical data, complex system dynamics, and conflicting objectives. Future work includes integrated design, innovative technologies, life-cycle performance assessment, and supportive policies.

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Table 1 (*continued*)

Author(s) & year	Methodology & scope	Finding(s)	Limitation & Gap(s)
Moudgil V, Hewage K, Hussain S et al. (2023) [41]	The article reviews studies integrating the Internet of Things (IoT) into building energy infrastructure (BEI) to enhance energy efficiency and flexibility. It analyzes benefits, challenges, and opportunities, aiming to guide IoT-enabled BEI development.	The article finds that IoT enhances BEI with remote operations, automated management, user-centric facilities, and cognitive intelligence, benefiting buildings and the grid by reducing energy use, improving indoor comfort, and supporting grid stability.	The article acknowledges constraints in IoT and BEI fusion research, like the lack of thorough assessment approaches and limited empirical data. It highlights challenges in system dynamics and conflicting objectives, proposing future research directions for integrated strategies, novel technologies, and supportive policies.
Casini M (2022) [42]	The paper reviews advanced construction materials to enhance building performance and sustainability. It covers composites, nanomaterials, smart materials, and biomimetic materials, discussing their properties, applications, and challenges for building design and construction.	The article suggests that advanced construction materials offer benefits like enhancing structural strength and durability, reducing energy consumption, and improving indoor comfort. However, their integration requires innovative technologies and techniques for fabrication, characterization, and integration into building systems.	The article acknowledges limitations in advanced construction materials, like the lack of standards and high costs. Future research directions include integrating design approaches, exploring new materials, assessing life-cycle performance, and establishing supportive policies.
Casini M (2022) [43]	The article offers a thorough review of the digital transformation in the construction sector, focusing on Construction 4.0. It explores emerging trends, technologies, and strategies in smart building design, construction, and operation. Additionally, it provides guidelines for leveraging the "digital twin-building life cycle" through digital technology integration.	The article identifies Construction 4.0's potential to enhance the built environment through augmented digital design, automated construction, and smart building operations. It aims to create a sustainable, energy-efficient, and affordable environment while addressing global challenges like resource shortage and climate change.	The article acknowledges the challenges of Construction 4.0, including skills, standards, regulations, interoperability, security, and trust. It emphasizes the need for cultural change, strategic vision, and increased research and development. Overcoming these hurdles is crucial for successfully adopting and implementing Construction 4.0.
Bohara B, Pandey B, Pungaliya R et al. (2023) [44]	The article presents an experimental study of the model predictive control (MPC) for a residential split air conditioner (AC). The paper proposes an MPC algorithm that optimizes AC operation based on indoor temperature, humidity, and thermal comfort. The article also implements the MPC algorithm in a hardware-in-loop (HIL) setup and tests it in a real residential house.	The article finds that the MPC algorithm can improve the energy efficiency and thermal comfort of the AC system compared to conventional thermostat control. The paper also finds that the MPC algorithm can adapt to weather conditions and user preferences by adjusting the control parameters.	The article recognizes limitations in the experimental study, including limited test cases, user behavior uncertainty, and algorithm complexity. It suggests future research, such as developing realistic models, exploring diverse control objectives, and assessing economic and environmental benefits.
Cioccolanti L, Tascioni R, Moradi R et al. (2022) [45]	The paper outlines a smart control unit for residential concentrated solar combined heat and power (CHP) systems. It details the hardware and software components, optimizing micro-scale ORC unit operation coupled with linear Fresnel reflectors (LFR) solar field and latent heat thermal energy storage (LHTES) tank. evaluating performance in a hardware-in-loop (HIL) setup.	The smart control unit enhances CHP system efficiency and flexibility by adjusting the oil flow rate and temperature based on weather conditions and user demands. It ensures safe operation by preventing overheating, overpressure, and oil degradation.	The article notes limitations in the study, including a small number of test cases, uncertainty in user behavior, and algorithm complexity. Future research could focus on developing robust models, exploring diverse control objectives, and assessing economic and environmental benefits.
Sayegh M, Danielewicz J, Nannou T et al. (2017) [46]	This article reviews the trends and developments of district heating (DH) technologies in Europe. The paper covers four areas related to DH systems and their interaction with fossil fuels, renewable energy sources, energy efficiency, and environmental and human health impacts. The article aims to provide an overview of DH's current status and future prospects in Europe.	The article emphasizes DH's significance in enhancing energy security, affordability, and sustainability in Europe. It advocates integrating innovative technologies like building automation, smart meters, IoT, and nanotechnology, identifying key drivers and barriers influencing DH adoption.	The article acknowledges limitations in current DH research and practice in Europe, such as the need for comprehensive evaluation methods and data, understanding system dynamics, and addressing conflicting objectives. It proposes integrated design methods and novel technologies for future DH advancements.
Cielo D, Subiantoro A (2021) [47]	This article reviews the challenges and potentials of New Zealand's net zero energy buildings (NZEBs). The paper examines four factors that influence the adoption of NZEBs: legislative, climatic, technological, and economic. The article collects and analyzes secondary data and literature on these factors.	The article identifies New Zealand's favorable climate and resources for NZEBs, offering benefits like carbon emission reduction, enhanced energy security, and cost savings. It highlights barriers such as policy gaps, lack of incentives, awareness, and skills.	The article notes limitations in NZEB research in New Zealand: lack of evaluation methods, data scarcity, complexity, and policy gaps. It suggests integrated design and technology innovation,
Jabłoński I (2017) [48]	The research explores metrology's role in engineering, focusing on an energy-	Metrology aids in managing complex systems like smart buildings.	Limitations in smart building and telemedicine research include inadequate

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Table 1 (*continued*)

Author(s) & year	Methodology & scope	Finding(s)	Limitation & Gap(s)
	efficient smart building with telemedicine features. It reviews the multisensory measurement network's effectiveness for optimizing heating systems in an office building.	Multisensory networks and data fusion enhance energy efficiency. Telemedicine benefits health monitoring in smart buildings.	evaluation methods, limited empirical data, and complex system dynamics. Addressing these gaps requires exploring novel strategies, integrating advanced technologies, and establishing robust regulatory frameworks.
Buonomano A, Barone G, Forzano C (2023) [49]	The paper discusses contributions from a special issue of Energy Reports on the 16th Sustainable Development of Energy, Water, and Environment Systems Conference. Topics include renewable energy, building design, energy management, clean fuels, and conservation measures.	The article highlights advancements and challenges in sustainable energy transition toward a net zero energy economy. It emphasizes novel energy solutions and multidisciplinary approaches for sustainable development, ensuring a just transition and reducing sources of conflict.	The article does not comprehensively review or analysis of the papers included in the virtual special issue. It also does not address the policy implications or recommendations for implementing the technologies and methods discussed in the papers.
Nižetić S, Djilali N, Papadopoulos A et al. (2019) [50]	The article reviews 27 papers from the 3rd International Conference on Smart and Sustainable Technologies in 2018. It covers smart technologies for energy efficiency, sustainable resource utilization, and waste management.	The article examines advancements and challenges in four key areas: Green Buildings, Solar Energy, Efficiency, and Smart Cities. It stresses interdisciplinary cooperation and innovative energy solutions for sustainability and environmental mitigation.	The article does not provide a comprehensive analysis or comparison of the papers included in the review. It also does not address the policy implications or recommendations for implementing smart technologies in different contexts and scenarios.
Ascione F (2017) [51]	The study evaluates passive cooling renewable technologies for buildings to mitigate climate change and reduce cooling needs. It examines methods governing energy interaction and discusses their benefits and challenges for urban energy efficiency, sustainability, and environmental quality.	The article emphasizes passive cooling's benefits in curbing energy use and enhancing comfort and air quality. It demonstrates integration with renewables like solar and geothermal for zero-energy buildings and highlights adaptability to varied climates and structures.	The article acknowledges passive cooling's challenges including technical, economic, social, and regulatory factors. It stresses a holistic, multidisciplinary approach and calls for further research and innovation to address design, construction, and operational uncertainties.
Fawaier M, Bokor B (2022) [52]	The study comprehensively analyzes structural configurations of building thermal insulation, covering conventional and dynamic types. It conducts comparative analysis, including mathematical models, experiments, and numerical simulations, to evaluate dynamic (Active) insulation systems integrating airflow.	The investigation confirms dynamic insulation's promise in modulating heat transfer rates through building envelopes over time. It effectively adapts the envelope's transmissivity to outdoor conditions, yielding substantial heat loss reductions and enhancing energy savings compared to static systems.	The study acknowledges dynamic insulation's multifaceted challenges: technical, economic, social, and regulatory. Addressing them necessitates a holistic, interdisciplinary approach with diverse stakeholders.
Fawaier MBokor BHorváth M (2021) [53]	The study assesses transpired solar collectors' (TSC) potential in recapturing wall heat loss across European climates. It reviews literature, standards, and regulatory frameworks. Simulation-based analysis examines TSC thermal performance and energy-saving capabilities, considering wall orientations and geographical locations.	Empirical evidence confirms TSCs' effectiveness in recapturing wall heat loss, reducing heating demand and overall energy consumption. TSCs excel in colder climates, especially integrated into south-facing walls. They provide fresh and preheated air for ventilation and space heating.	The study recognizes TSCs' challenges: technical complexities, economic viability, social acceptance, and regulatory compliance. Overcoming hurdles requires interdisciplinary approaches involving diverse stakeholders. Further research is vital to address gaps and uncertainties in TSC systems.

building technologies and systems has led to numerous patents covering various applications, including insulation, lighting, HVAC, solar panels, energy storage, and building automation.

Applying Analytic Hierarchy Process (AHP) in optimizing building energy systems is a pivotal engineering approach [30]. AHP's mathematical rigor offers structured analysis, integrating expert insights and data to assess complex energy choices [31,32]. Its adaptable framework captures technical, economic, and environmental dimensions, yielding precise, transparent, and defensible decisions in intricate energy landscapes. In the engineering sector, AHP's role in evaluation development is paramount. AHP quantifies diverse criteria, translating subjective input into objective metrics [33]. Amid sustainability imperatives, AHP aligns feasibility, viability, and impact, guiding energy decisions through uncertainty. AHP's strategic integration fosters future-centric solutions that bridge energy efficiency and environmental responsibility.

In this study, applying AHP will encompass five distinct expert cohorts, namely (i) building engineers, (ii) architects, (iii) construction managers, (iv) environmental specialists, and (v) energy economists. This comprehensive amalgamation of expertise ensures a holistic evaluation process, enriching the analysis with multifaceted insights from diverse domains crucial to optimizing building energy systems.

The present study aims to provide a comprehensive investigation into energy efficiency in buildings and energy patents, with the primary objective of advancing knowledge and understanding in this field. The research endeavors to achieve several key goals and contributions, including (i) conducting an extensive literature review to assess the current state of research on energy-efficient building design, effective energy management practices, occupant behavior, and integration of renewable energy sources, (ii) undertaking a rigorous analysis of energy patents to identify significant advancements and discern prevailing trends in energy-related technologies, with a particular focus on energy storage, fuel cells, managing energy, and emerging technologies, (iii) presenting the findings and engaging in a thorough discussion to shed light on the identified patterns, challenges, and opportunities within the domain of energy efficiency in buildings and energy patents and (iv) evaluating, prioritizing and ranking of the investigated energy types and technologies (criteria and alternatives) in buildings by applying analytical hierarchy process (AHP).

2. Comprehensive literature review on buildings energy systems

The investigation of building energy patents has been the subject of extensive scholarly research. This research conducted a comprehensive literature review to explore the recent advancements in building energy systems. The search focused on "Renewable energy," "Sustainable energy," "New sources, methods, emerging and future technologies," "Fuel cells," "Energy storage(s)", "Managing energy", and "Conventional energy support". This rigorous exploration of the literature aimed to synthesize the existing knowledge and shed light on critical findings, methodologies, limitations, and research gaps related to the impact of the chosen keywords. The outcomes of this review are presented along with the methodologies, scopes, findings, limitations, and gaps in Table 1.

The literature review presented significant findings and scientific facts regarding building energy systems. It highlighted the potential of renewable energy integration in reducing greenhouse gas emissions and reliance on fossil fuels, emphasizing the need to address climate change and achieve sustainability goals. Energy storage technologies were identified as promising solutions for enhancing energy efficiency and reliability in buildings, optimizing management, and reducing costs. Effective energy management practices, including, building automation systems and smart grids, achieved significant energy savings, while occupant behavior and engagement were recognized as crucial factors in promoting sustainable energy practices. The review also emphasized the importance of integrating energy-efficient technologies and strategies to reduce energy consumption and carbon emissions in conventional energy-dependent buildings. The policy frameworks and regulations were identified as essential for facilitating the transition to cleaner and more sustainable energy systems. The comprehensive literature review provided valuable insights, identified research gaps, and laid the foundation for future advancements and innovation in building energy systems, ultimately contributing to sustainability, energy efficiency, and societal well-being.

3. Global patent analysis for energy

The analysis section of this study delves into a comprehensive examination of energy patents, employing a systematic approach to explore the intellectual property landscape in the realm of energy technologies. The patent searching is performed World Intellectual Property Organization (WIPO) patent database to conduct a rigorous investigation encompassing various energy-related keywords, facilitating a thorough exploration of patents worldwide. This analytical endeavor aimed to uncover trends, patterns, and emerging technologies in energy innovation.

In the initial step, a wide-ranging search was conducted to identify energy patents from the year 2000 up to 2023. An extensive

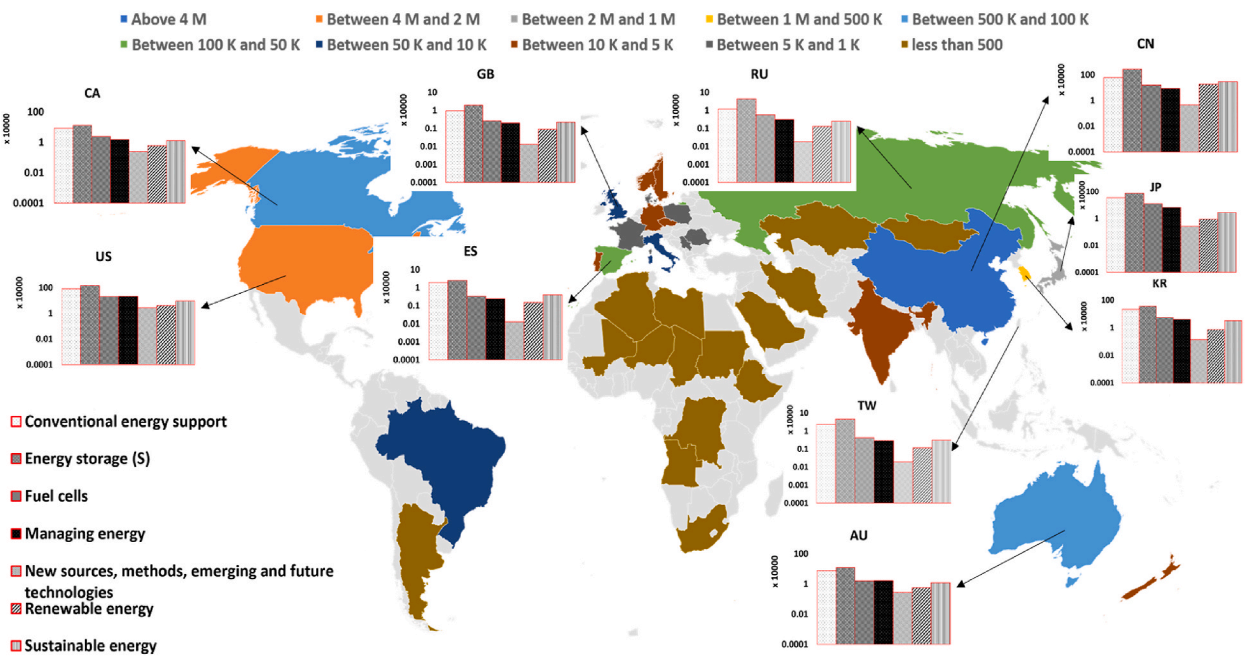

Fig. 1. Energy patent map distribution (2000–2023) (Please check Appendix 1).

corpus of patents was assembled by employing specific keywords that spanned a diverse range of energy types and concepts, such as conventional energy support, energy storage, fuel cells, managing energy, new sources, methods, emerging and future technologies, renewable energy, and sustainable energy. This diligent process enabled the accumulation of a substantial dataset, facilitating a comprehensive analysis of global patent trends and distributions.

Subsequently, the focus shifted towards examining building energy patents, wherein a meticulous investigation was undertaken for the top eight countries worldwide. This examination involved detailed scrutiny of distinct keywords associated with specific energy types and concepts pertinent to building energy systems. An exhaustive array of keywords was employed to explore the patent landscape, from solar collectors and wind energy to biomass gasification and energy management optimization. This rigorous analysis of building energy patents enabled a granular understanding of technological advancements, innovation hotspots, and regional variations across the top patent-holding countries.

Through this meticulous analysis using the WIPO patent database, the research sheds light on the evolving landscape of energy patents, highlighting the ingenuity and progress made in developing sustainable energy solutions. By delving into the intricate details of patent records, this study aims to provide valuable insights into technological advancements, emerging trends, and potential areas for future research in energy innovation.

3.1. Global patent analysis for energy: leading countries and key technologies

In the first section of the patent analysis, a comprehensive evaluation was performed to gain insights into the global landscape of energy patents. Fig. 1 visually represents the energy patent map distribution (Please check Appendix 1), highlighting the top ten leading countries in patent activity. The analysis focused on seven essential keywords encompassing various aspects of energy innovation, including conventional energy support, energy storage, fuel cells, managing energy, new sources, methods, emerging and future technologies, renewable energy, and sustainable energy.

This analysis revealed noteworthy trends and patterns in the patent landscape. The top 10 countries demonstrated a significant presence in energy-related patents, indicating their commitment and advancements in energy technology. The distribution of patents across these countries showcased their efforts in various domains of energy innovation, encompassing conventional energy support, the development of energy storage solutions, advancements in fuel cell technologies, effective energy management strategies, exploration of new and emerging energy sources, and a focus on renewable and sustainable energy practices.

This comprehensive analysis offers valuable insights into the global energy patent landscape, enabling a deeper understanding of the technological advancements and research activities across different countries. It serves as a foundation for further investigations into specific areas of energy innovation. It provides a basis for identifying potential collaborations, knowledge sharing, and future research directions to enhance the development and deployment of sustainable energy solutions worldwide.

The analysis continues with Fig. 2, a logarithmic scale bar diagram representing the patent activity of the top 10 countries in the energy sector. The logarithmic scale allows for a meaningful comparison, highlighting the substantial gap between the top three countries (China, USA, and Japan) and the rest. This approach emphasizes the dominant position of these leading countries and provides a clearer understanding of patent distribution in the energy sector.

The three leading countries in energy patents, namely China, the USA, and Japan, demonstrate remarkable innovation and research activity in the energy sector. China's rapid ascent as a global leader in energy patents can be attributed to its strong policy support and emphasis on renewable and sustainable energy technologies. The country has witnessed a significant increase in patent applications,

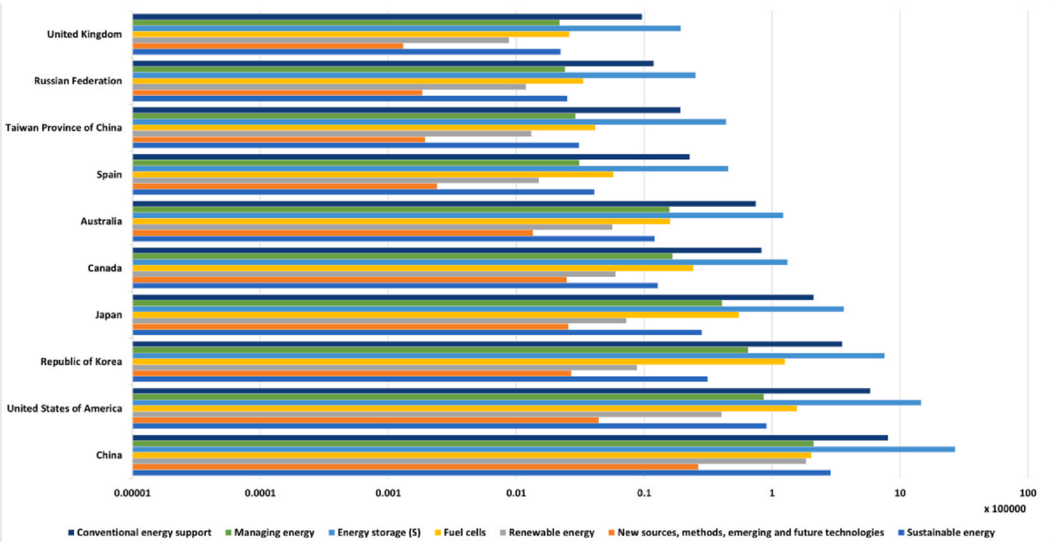

Fig. 2. Top ten patent holder countries in energy (2000–2023).

Table 2
Energy-building patents for the top eight countries (2000–2023).

Energy-building patents (top 8 countries)											
Number	**Energy Type**	**CN**	**US**	**JP**	**KR**	**AU**	**ES**	**CA**	**RU**	**TOTAL**	**RANK**
1	**Solar Collectors**	30260	16378	4870	3602	2042	1650	1393	9629	69824	30
2	**Solar Photovoltaic**	276524	82138	46045	40076	7470	3737	4973	1301	462264	12
3	**Wind Energy**	907887	203225	136185	74463	20388	7349	22423	7787	1379707	7
4	**Wave Energy**	783965	673818	332179	160566	45714	9533	49424	21367	2076566	4
5	**Tidal Energy**	34363	17673	7435	9488	2961	439	2466	479	75304	27
6	**Hydro Energy**	31775	45300	13330	17053	8477	951	11515	3897	132298	20
7	**Geothermal Energy**	41259	21770	9376	7496	2947	449	3728	631	87656	22
8	**Biomass Energy**	147929	68130	23250	14507	13140	2605	14620	3761	287942	15
9	**Biomass Gasification**	24577	12983	4943	2621	2853	473	3171	510	52131	31
10	**Biomass (gasification) to Hydrogen**	10	20	4	0	2	0	8	0	44	51
11	**Biogas to Biofuel**	0	1	1	0	0	0	1	0	3	52
12	**Algae Energy**	22	76	22	12	16	0	11	0	159	49
13	**Waste to Energy**	68	155	29	15	21	24	32	18	362	46
14	**Waste Plasma Gasification**	3981	2634	778	562	443	71	520	197	9186	38
15	**Lignocellulosic Biomass/ Cellulosic Ethanol**	2532	7100	869	586	1518	165	1805	97	14672	36
16	**Concentrated Solar Energy**	65819	39868	18675	15151	4510	1305	3425	766	149519	19
17	**Enhanced Geothermal Energy**	3518	6940	1536	588	895	34	1105	74	14690	35
18	**Artificial Photosynthesis Energy**	10304	13550	2795	1937	1771	172	1756	219	32504	34
19	**Vortex Bladeless Wind Energy Generation**	100	32	14	21	5	1	6	5	184	48
20	**Heat Pump to Energy**	73	130	17	6	26	19	31	10	312	47
21	**Hydrogen Energy**	828072	680776	483311	236828	74668	14930	85990	20476	2425051	2
22	**Hydrogen Fuel Cells**	81383	100176	86845	31938	8653	1642	13795	2058	326490	14
23	**Mixed/Hybrid Fuel Cell**	15939	33166	13966	7853	2844	244	3671	227	77910	26
24	**One-way Grid Connected Fuel Cell**	2090	6070	1034	840	390	22	398	45	10889	37
25	**Two-way Grid Connected Fuel Cell**	1983	4203	563	406	253	12	235	16	7671	39
26	**Grid-connected Fuel Cell with its Own Energy Storage**	486	673	103	56	44	2	46	2	1412	42
27	**Off-grid mixed Fuel Cell System**	192	495	40	41	39	1	47	1	856	43
28	**Simple Mix Fuel Cell**	14612	19565	6496	2784	2537	211	2701	256	49162	33
29	**Multi-source Fuel Cell**	295	334	68	44	34	0	27	0	802	44
30	**Biomass gasification, Hybrid Fuel Cell System**	370	1344	148	129	292	17	312	18	2630	41
31	**Cogeneration**	18469	8405	15664	4413	856	555	1279	498	50139	32
32	**Trigeneration CCHP**	46	18	5	0	2	0	5	0	76	50
33	**Fuel Cells**	155635	201654	125927	55016	15887	3348	24253	5713	587433	11
34	**Mechanical Energy Storage**	716068	595004	234785	110546	53935	10186	59919	15300	1795743	5
35	**Thermal Energy Storage**	628258	468208	288689	129884	40621	8926	45153	13811	1623550	6
36	**Electrical Energy Storage**	1025031	789662	286881	151941	56632	10573	61850	15831	2398401	3
37	**Water Energy Storage**	1220997	613201	393965	187843	78459	15028	83058	23941	2616492	1
38	**Heat Exchange Energy Storage**	278670	165191	109181	48323	21725	3570	21487	6727	654874	9
39	**Natural Ventilation Energy Storage**	34253	23016	11426	5795	2644	583	2678	868	81263	24
40	**Active Ventilation Energy Storage**	23313	26521	8649	4433	2770	533	2812	826	69857	29
41	**Natural Shielding Energy Storage**	19262	21392	24841	7949	2215	163	2283	442	78547	25
42	**Active Shielding Energy Storage**	26416	36979	33844	12233	2894	263	2933	526	116088	21
43	**Simple (Manual) Control Energy Management**	52398	64129	12231	6095	7959	1113	7091	938	151954	18
44	**Passive Control Energy Management**	42173	99134	15248	10528	7968	1052	8149	1437	185689	17
45	**Active Control Energy Management**	152229	277005	57163	40140	27240	4113	25321	5059	588270	10
46	**Predictive Control Energy Management**	15022	45524	10074	4039	4712	356	4731	432	84890	23
47	**Optimization Energy Management**	96294	99686	16538	10265	8154	1215	8054	1588	241794	16
48	**Policy Support Energy Management**	17889	40906	6312	4609	1763	158	1812	262	73711	28
49	**Subsidy Energy Management**	1950	793	355	221	114	3	96	14	3546	40
50	**Electric Energy Conventional Energy Support**	230381	303651	181145	91550	22787	7283	25998	4930	867725	8
51	**Natural Gas Conventional Energy Support**	67937	145614	56328	30204	20420	2742	22122	2383	347750	13
52	**Heating Oil/Gasoline Conventional Energy Support**	168	273	128	62	38	14	40	6	729	45

reflecting its commitment to driving advancements in the energy sector. Similarly, the USA has a long-standing tradition of pioneering energy innovations, with a diverse range of patents spanning conventional energy support, energy storage, fuel cells, and emerging technologies. Japan, known for its technological prowess, excels in energy-related patents, particularly in managing energy, renewable energy, and sustainable energy practices. These three countries are pivotal in shaping the global energy landscape and serve as critical drivers of innovation in pursuing sustainable and efficient energy systems.

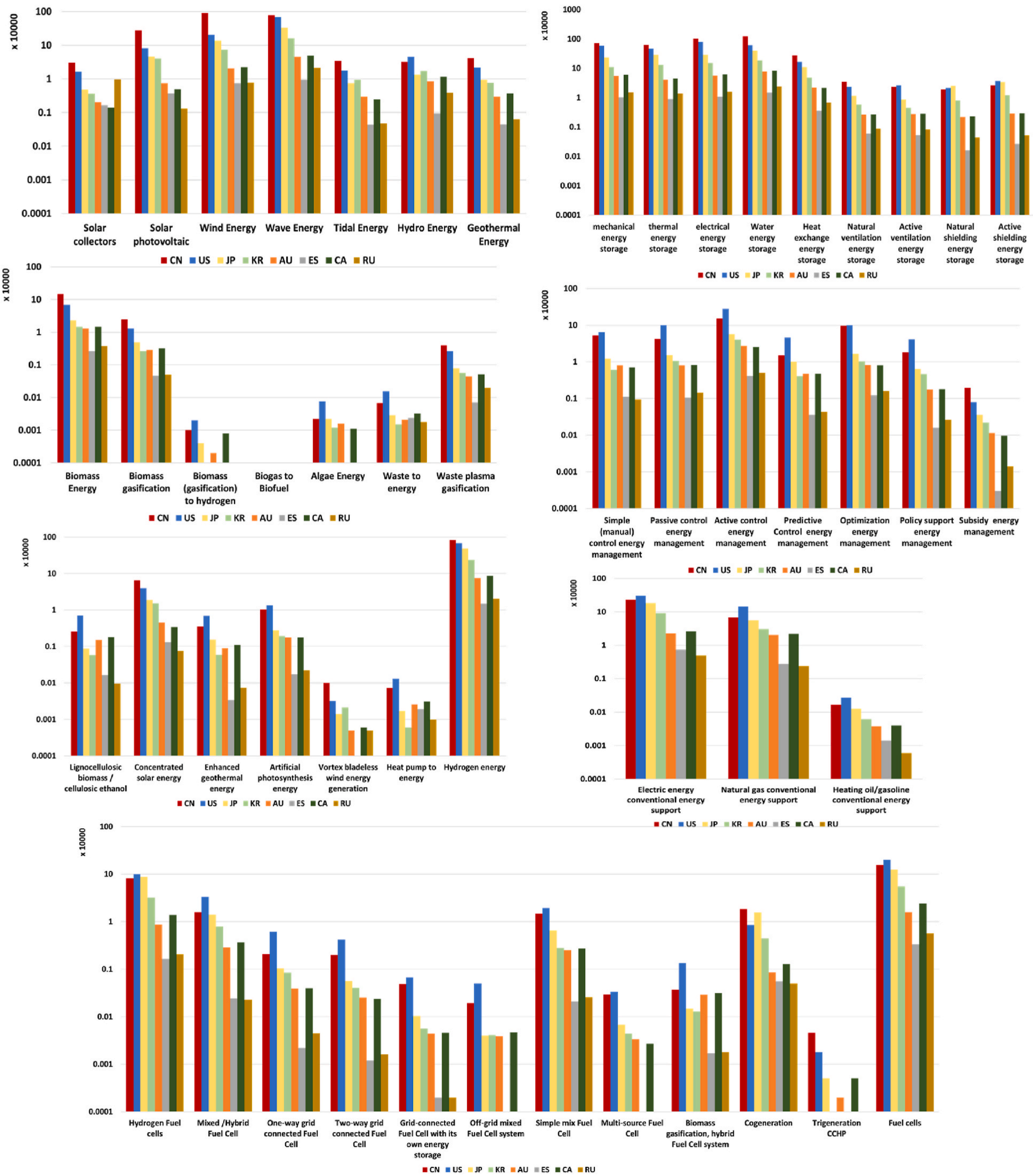

Fig. 3. Energy-building patents for top eight countries (2000–2023).

3.2. Global patent analysis for energy in buildings

In the „Energy Patent Analysis in Building" section, an in-depth examination was conducted to investigate the landscape of building energy patents across the top eight countries worldwide. This analysis delved into specific energy types and concepts relevant to building energy systems, utilizing a comprehensive set of keywords to explore the patent landscape. The main aim was to gain insights into technological advancements, identify innovation hotspots, and uncover regional variations among the leading patent-holding countries.

Table 2 serves as a valuable summary of the 52 building energy types considered in the analysis, providing a comprehensive overview of the various technologies and innovations covered. This ranking and categorization of building energy types offer a systematic and organized perspective on the field's diversity and distribution of patents.

Table 2 summarizes essential outcomes across the top 8 countries in renewable energy sources and energy storage technologies. The table categorizes patent activity into 52 distinct energy types, providing a nuanced understanding of the diverse range of energy technologies under development and the geographical distribution of innovation.

Solar energy is a dominant player globally, with the United States and China leading installations. Its clean and abundant nature has contributed to its widespread adoption. Wind energy follows closely, with China taking the lead in installations, followed by the US. This alternative energy source is gaining popularity due to its viability. Wave and tidal energy, harnessing the power of ocean waves and tides, show promise, with the UK and Spain excelling in wave energy, while China and the US lead in tidal energy. Hydro energy, utilizing flowing water, has succeeded in the US, followed by China. Geothermal energy, tapping into the Earth's heat, sees significant installations in China, the US, and Japan. Biomass energy, utilizing organic materials, is prominent in the US. Hydrogen energy and fuel cells have gained global adoption, with China, the US, and Japan demonstrating substantial installations. Additionally, energy storage technologies, including mechanical, thermal, electrical, and water storage, play crucial roles in integrating renewable energy into the grid. Overall, solar and wind energy dominate the renewable sector, while wave, tidal, and geothermal energy hold promise for the future. Adopting hydrogen energy, fuel cells, and energy storage technologies is vital for efficient and sustainable energy utilization.

The examination of patent data unveils notable trends in emerging energy technologies. Notably, there's a concentrated effort in wave energy patents, particularly in the UK and Spain, indicating a push to tap into oceanic resources. Similarly, advancements in tidal energy, led by China and the US, reflect a growing interest in exploiting predictable tidal currents for electricity generation.

In hydrogen energy and fuel cells, substantial installations in China, the US, and Japan reflect a drive towards cleaner energy solutions. This is significant due to hydrogen's versatility as a fuel source and the potential of fuel cells to power various applications.

Energy storage technologies, including mechanical, thermal, electrical, and water storage solutions, play a crucial role in grid integration. Mechanical systems like flywheels and pumped hydro storage offer scalable options for storing excess energy from intermittent sources like solar and wind.

Thermal storage technologies, enhance the performance of solar thermal power plants. Electrical storage solutions like batteries ensure grid stability, while water storage technologies provide large-scale energy storage capabilities.

In conclusion, the detailed patent analysis across renewable energy and storage underscores global efforts toward a sustainable energy landscape. Leveraging solar, wind, wave, tidal, geothermal, and biomass energy, alongside advances in hydrogen and storage technologies, can pave the way for a cleaner, more efficient future.

Furthermore, Fig. 3 visually compares the different building energy types, clearly understanding the relative patent activity across the categories. The logarithmic scale utilized in the comparison ensures a more effective and meaningful representation of the patent numbers, allowing for better visibility and comparison between the energy types.

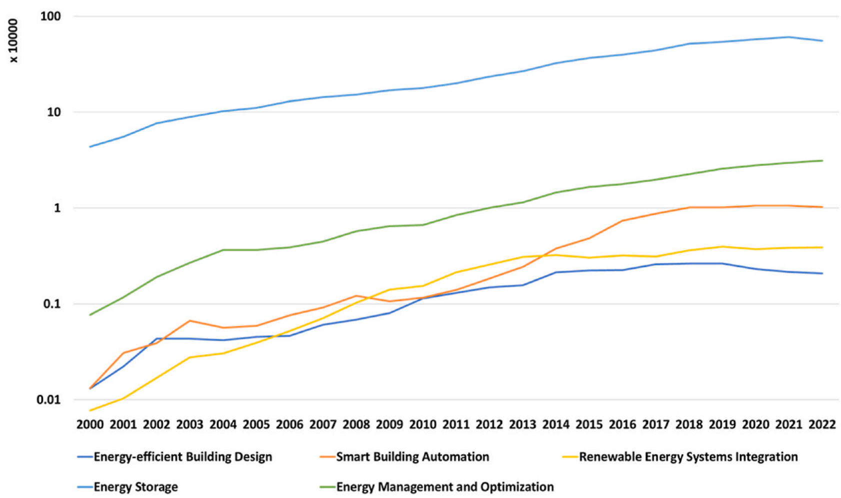

Fig. 4. Trends in building-energy patents between 2000 and 2022.

Through this meticulous examination of building energy patents, this research aims to shed light on the technological advancements and innovation trends in building energy systems. These results offer valuable insights for policymakers, researchers, and industry professionals, guiding future developments and fostering collaborations to drive sustainable and efficient energy solutions in the built environment.

3.3. Mapping the global landscape of building-energy patents: trends and geographical distribution

The field of building energy systems has witnessed significant advancements driven by ongoing efforts to enhance energy efficiency, reduce environmental impact, and promote sustainable development. Patents play a crucial role in fostering innovation and protecting intellectual property rights, serving as valuable indicators of technological progress. Understanding the temporal trends and geographical distribution of building-energy patents is essential for identifying emerging research areas, technological developments, and geographic concentrations of innovation.

In this study, the current researcher has comprehensively analyzed the building-energy patents, focusing on five significant patent groups encompassing key field areas. These patent groups include energy-efficient building design, smart building automation, renewable energy systems integration, energy storage, and energy management and optimization. This analysis aims to provide a holistic view of the trajectory of building-energy patents, shedding light on temporal trends, global distribution patterns, and comparative assessments of leading countries.

In this research, Fig. 4 was drawn in order to examine the temporal trends for each energy group. Fig. 4 illustrates the patent filings over time, which allows for a detailed examination of each patent group's growth, stabilization, and resurgence patterns. By observing the temporal trends, we can discern the evolving research priorities, technological advancements, and innovation cycles within the building energy sector.

Fig. 4 presents the temporal analysis, depicting the trends in building-energy patents from 2000 to 2022. This timeline showcases the advancements, fluctuations, and emerging trends in patent activity over time. Combining the temporal analysis with the worldwide distribution map provides a comprehensive understanding of building-energy patents' evolution and geographical dynamics. Such insights enable decision-makers to track the progress of energy solutions, identify periods of accelerated innovation, and predict future developments. By leveraging this knowledge, stakeholders can align research and development efforts with industry demands, drive targeted investments, and facilitate cross-border collaborations to propel advancements in building energy systems worldwide.

Additionally, Fig. 5 provides a comprehensive worldwide distribution map of building-energy patents, showcasing the concentration of innovative activity across different regions (Please check Appendix 2). The map reveals each energy group's top ten leading countries, highlighting their contributions to the investigated patent areas. By examining this geographic distribution with the corresponding timeline, stakeholders gain insights into global hotspots for specific building-energy patent groups. The visual representation in Fig. 5 facilitates the identification of key regions driving innovation, aiding policymakers, researchers, and industry professionals in fostering international collaboration and facilitating technology transfer. This information is crucial for shaping policies, directing investments, and promoting knowledge sharing in building-energy patents.

A comparative analysis was conducted in this research for the top ten leading countries for each energy group (Fig. 6). This analysis allows us to assess countries' relative influence and expertise within specific building-energy areas. We gain valuable insights into the

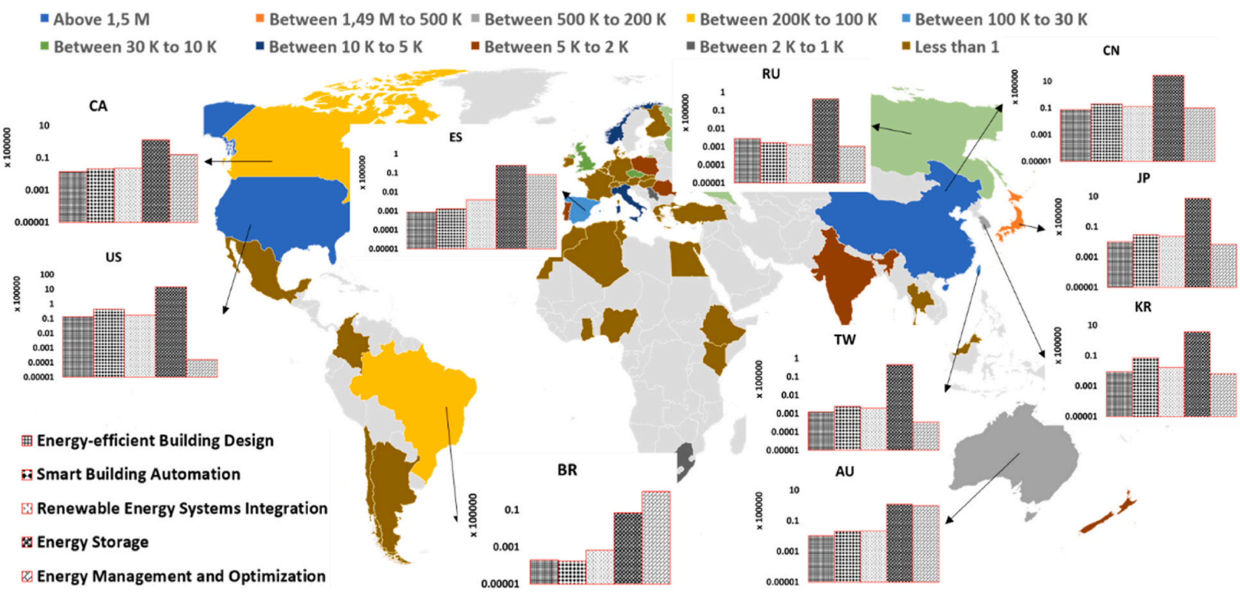

Fig. 5. Global distribution of building-Energy patents (2000–2023) (Please check Appendix 2).

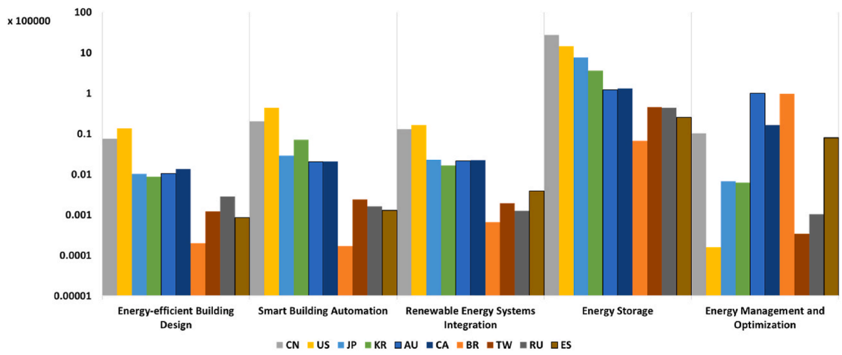

Fig. 6. Comparative analysis of leading countries in building-energy patents (2000–2023).

global landscape of building-energy patents by comparing the dominant countries across energy-efficient building design, smart building automation, renewable energy systems integration, energy storage, and energy management and optimization. The logarithmic scale is used here as well to give a more precise comparison between different countries and to minimize the gap between the top leading country (China) and the significant number of patents in the Energy storage group compared to other groups.

The analysis of building-energy patents is represented in a comprehensive table (Table 3) summarizing the distribution of patents across countries. The table showcases the number of patents for each energy group, highlighting the leading countries in each category. The United States and China emerged as prominent players, exhibiting high patent counts across multiple energy groups. Notably, energy storage patents show substantial numbers globally, indicating their significance in building energy systems research and development. The table offers valuable insights into the distribution of patent activity, providing a basis for understanding the global landscape of building-energy innovation.

The data given in Table 3 analysis provides valuable insights into the global distribution of building-energy patents. The United States emerges as a dominant player across all five patent categories, strongly emphasizing innovation in energy-efficient building design, smart building automation, renewable energy systems integration, energy storage, and energy management and optimization. China also demonstrates a significant presence, particularly in energy-efficient building design, smart building automation, and renewable energy systems integration. Notably, energy storage emerges as a prominent area of focus globally, with high patent numbers in all countries, reflecting its growing importance in enabling efficient energy management and the integration of renewable sources.

The variations in patent numbers across countries suggest disparities in research and development investments, policy frameworks, and technological capabilities. Additionally, the distribution of patents is influenced by local market demands and environmental priorities. For instance, Japan and South Korea strongly emphasize smart building automation, reflecting their advanced infrastructures and focus on energy efficiency. Analyzing the global distribution of building-energy patents presents opportunities for collaboration and knowledge-sharing among countries. Identifying countries with expertise in specific energy groups can foster partnerships and facilitate the exchange of best practices, ultimately accelerating technological advancements.

Overall, the findings highlight the significance of building-energy patents as indicators of technological progress and innovation in the energy sector. Understanding the distribution patterns and cause-effect relationships can inform policymakers, researchers, and industry professionals in shaping strategies, fostering collaborations, and advancing building energy systems on a global scale.

4. Analytic hierarchy process study

The utilization of the Analytic Hierarchy Process (AHP) methodology in this research plays a pivotal role in comprehensively evaluating the various energy sources and types within the domain of building systems. AHP's intrinsic ability to systematically assess, weigh, prioritize, and rank criteria and alternatives enhance the precision of decision-making processes, making it particularly adapt for the intricate evaluation involved in building energy systems [54]. The renowned Saaty scale, as portrayed in Table 4, empowers experts to express their judgments cohesively, yielding quantifiable and dependable outcomes.

At the heart of the AHP methodology lies the hierarchical model, visually portrayed in Fig. 7, which adeptly captures the complex interplay between criteria and alternatives. This hierarchically structured framework assists experts in deconstructing multifaceted

Table 3
Top 10 countries in the trending building-energy patents.

Building energy group	CN	US	JP	KR	AU	CA	BR	TW	RU	ES
Energy-efficient Building Design	7579	13668	1033	879	1053	1352	20	122	281	86
Smart Building Automation	20491	43878	2880	7121	2053	2079	17	243	163	130
Renewable Energy Systems Integration	13033	16539	2296	1682	2143	2263	67	195	126	389
Energy Storage	2705505	1458516	759726	363656	122205	131860	6732	45384	43644	25224
Energy Management and Optimization	10265	16	687	634	99748	16571	96698	34	105	8062

Table 4
Saaty scale [55].

Math. Representation	1	2,4,6,8	3	5	7	9
Meaning	Both are equally important	Values between moderate and strong importance	One is moderately more important than the other	One is strongly more important than the other	One is very strongly more important	One is extremely more important than the other

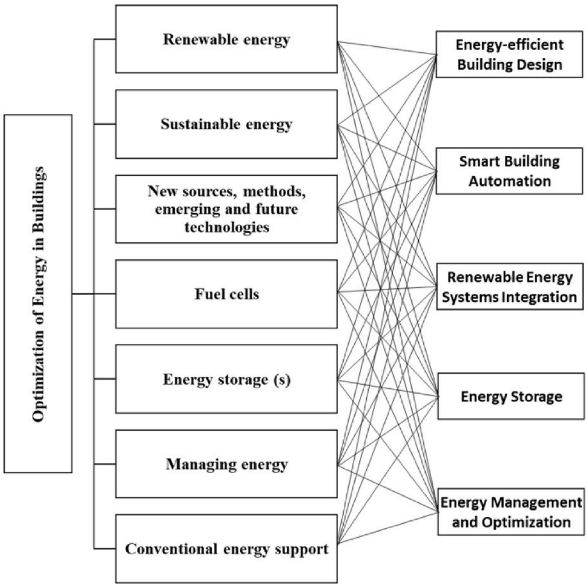

Fig. 7. Energy in buildings hierarchal model.

evaluation processes into discrete elements, ensuring a methodical and transparent approach to decision-making.

Table 5 provides a comprehensive demographic breakdown of the participants; this comprehensive tabulation unveils descriptive metrics, encompassing participant count (N), average age (M), and age variability measured through standard deviation (SD) for every expert segment., presenting a comprehensive overview of the diverse expert groups encompassing building engineers, architects, construction managers, environmental specialists, and energy economists.

Delving further into the expert cohorts, the subsequent two pie charts (Fig. 8) intricately illustrate the distribution of age and gender among the participants, presenting a vivid depiction of demographic diversity within the study. These visual representations serve to underscore the interdisciplinary and inclusive nature of the AHP evaluation process, reflecting a well-rounded and comprehensive perspective.

With these methodological tools at the present disposal, the study embarks on harnessing the collective expertise of these diverse expert groups, driving the investigation into energy sources and types within building systems towards a holistic and rigorously informed assessment. This approach ensures the integration of various perspectives and reinforces the significance of using AHP to facilitate a well-rounded evaluation process, particularly pertinent within the engineering sector.

Furthermore, the culmination of the AHP methodology manifests in Table 6, a comprehensive repository of outcomes that intricately detail the weights and rankings assigned by each expert group to the diverse components of the hierarchical model. This table serves as a vital synthesis of collective expertise, clearly and concisely depicting the consensus achieved among the experts. By amalgamating the perspectives of building engineers, architects, construction managers, environmental specialists, and energy economists, Table 6 provides a comprehensive overview of the relative importance of various criteria and alternatives, unraveling the

Table 5
The participants' demographical characteristics.

Variables		Total	Building Engineers	Architects	Construction Managers	Environmental Specialists	Energy Economists
N		46	14	10	5	6	11
Age	Mean	33	31	30	39	36	29
	SD	7	4	5	6	8	4
Gender %	Male	68 %	72 %	57 %	75 %	69 %	60 %
	Female	32 %	28 %	43 %	25 %	29 %	40 %

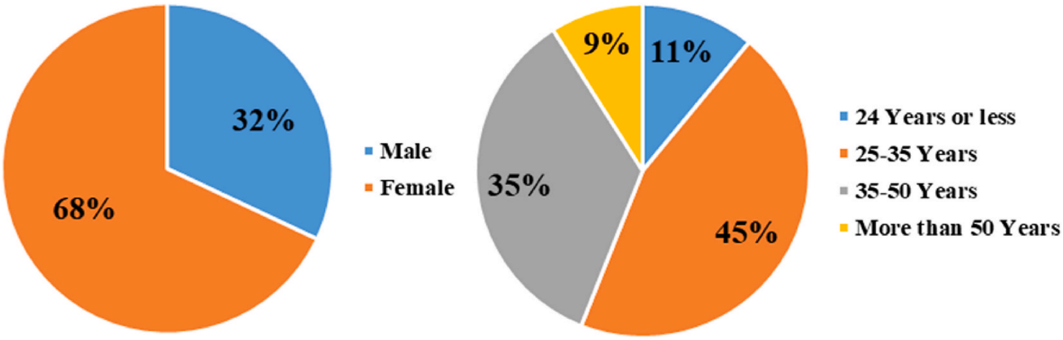

Fig. 8. Gender distribution (left), and age range (right) of the participants.

Table 6
Energy -building criteria comparison.

Criteria	Project Management		Building Engineers		Architects		Construction Managers		Energy Economists		Average	
	Weights	Rank	Weights	Rank	Weights	Rank	Weights	Rank	Weights	Rank	Weights	Rank
Renewable energy	11.34 %	5	9.57 %	6	10.07 %	6	8.73 %	6	10.02 %	5	9.95 %	5
New sources, methods, emerging, and future technologies	8.48 %	7	6.47 %	7	12.38 %	5	5.93 %	7	7.57 %	7	8.17 %	7
Energy storage (s)	26.09 %	1	20.67 %	1	19.27 %	2	23.52 %	1	21.17 %	1	22.14 %	1
Managing energy	13.09 %	3	16.17 %	4	15.97 %	3	15.53 %	3	15.47 %	4	15.25 %	3
Conventional energy support	19.29 %	2	17.97 %	2	20.67 %	1	22.03 %	2	20.82 %	2	20.16 %	2
Sustainable energy	10.13 %	6	11.98 %	5	9.07 %	7	9.63 %	5	8.57 %	6	9.88 %	6
Fuel cells	11.58 %	4	17.17 %	3	12.57 %	4	14.63 %	4	16.38 %	3	14.47 %	4

intricate dynamics governing energy sources and types within building systems. The outcomes encapsulated in Table 6 not only illuminate the decision-making process but also underscore the efficacy of employing the AHP methodology in elucidating the complex interplay of factors underpinning the evaluation of building energy systems.

According to the survey results, the most essential factors are energy storage (s), conventional energy support, and managing energy techniques. These criteria are all concerned with the practical elements of executing green energy initiatives, integrating novel energy sources with existing energy infrastructure, and managing a building's or site's total energy usage. Fig. 9 could give a more

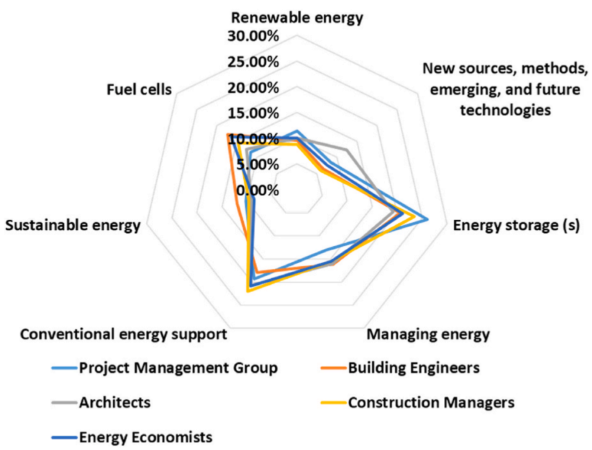

Fig. 9. Energy -building AHP- criteria comparison.

accurate comparison of the outcomes.

A variety of reasons can explain the survey results. First, conventional energy-building technologies are frequently inefficient. This means that a significant amount of energy is wasted, which can result in high prices and environmental issues. By storing energy when it is produced and then utilizing it when it is needed, energy storage (s) can assist in increasing the efficiency of energy-building systems. This can assist in minimizing the amount of energy lost while also improving the dependability of the energy supply.

Second, conventional energy support is still required for many clean energy initiatives. This is due to the fact that sources of clean energy like solar and wind power are not always accessible. When renewable energy sources are unavailable, conventional energy sources can be utilized to complement them. This can assist in ensuring the reliability of green energy projects and their ability to satisfy the energy demands of buildings and locations. Third, managing energy is essential for all buildings and locations, whether they use green power. This is due to the fact that energy is an invaluable asset that must be used efficiently. Managing energy has the potential to save energy expenses while simultaneously improving the environmental performance of buildings and facilities. According to one research, energy efficiency measures can save up to 30 % of the energy utilized in buildings. The survey results suggest a need to improve the efficiency of energy-building systems and develop new ways to manage energy. This is essential for creating a more sustainable energy future. By taking these steps, it is possible to reduce the environmental impact of buildings and sites and to create a more sustainable energy future.

Table 7 presents data analysis of the alternative solutions in energy-building development analysis. The data represents weights and ranks assigned to each alternative based on specific criteria, and an average score is provided for each alternative.

The data presented in the table evaluates the performance of five alternatives. The analysis involves weights and ranks assigned to each alternative by different stakeholders. Upon examining the data, it becomes evident that "Energy-efficient Building Design" received relatively lower support across all groups. The alternative obtained the lowest average rank, signifying its limited appeal among the stakeholders.

Conversely, "Energy Storage" emerged as the preferred alternative with substantial support from most expert groups. It achieved the highest average rank, signifying a unanimous consensus among the stakeholders that it is the most desirable option. Followed by "Renewable Energy Systems Integration" and "Energy Management and Optimization" alternatives which exhibited varying levels of support from the expert groups. These differences can be attributed to each group's specific considerations, expertise, and knowledge focus.

The online survey conducted for this study maintained ethical standards, ensuring participants' anonymity and privacy. Written Informed consent was obtained, outlining the voluntary nature of participation and research purposes. Data security measures were implemented to safeguard participants' information. Ethical guidelines were followed to prevent coercion, deception, or harm, aligning with the principles of online survey research.

Fig. 10 visually illustrates an entire comparison of all the expert groups by comparing all alternative solutions for energy-building development by assessing their feasibility and desirability among five expert groups.

The findings of this research provide a comprehensive perspective for a complete and multifaceted selection and prioritization of building-energy sources and solutions. The AHP analysis emphasizes the need to consider numerous viewpoints and stakeholder input to enable a full evaluation of energy solutions and promote informed decision-making in the quest for energy efficiency and environmental sustainability.

5. Discussion

The urgency to address environmental sustainability and reduce greenhouse gas emissions has driven extensive research and development efforts in energy optimization. This has led to exploring and implementing various strategies and technologies across different sectors, including buildings. These endeavors encompass a wide range of areas, such as building envelope design, lighting systems, HVAC controls, renewable energy integration, smart sensors, IoT devices, machine learning algorithms, and advanced energy storage systems. Through analyzing patents in the energy sector, valuable insights can be gained regarding the advancements, trends, and international comparisons in energy optimization technologies.

Table 7
Energy -building alternatives comparison.

Alternatives	Project Management		Building Engineers		Architects		Construction Managers		Energy Economists		Average	
	Weights	Rank	Weights	Rank	Weights	Rank	Weights	Rank	Weights	Rank	Weights	Rank
Energy-efficient Building Design	**13.16 %**	**5**	**13.07 %**	**5**	**10.77 %**	**5**	**14.72 %**	**5**	**6.02 %**	**5**	**11.55 %**	**5**
Smart Building Automation	**16.11 %**	**4**	**16.47 %**	**4**	**17.38 %**	**4**	**21.93 %**	**3**	**17.52 %**	**4**	**17.88 %**	**4**
Renewable Energy Systems Integration	**17.08 %**	**3**	**23.62 %**	**2**	**19.27 %**	**3**	**23.92 %**	**1**	**21.17 %**	**3**	**21.01 %**	**3**
Energy Storage	**28.91 %**	**1**	**26.17 %**	**1**	**25.97 %**	**2**	**22.30 %**	**2**	**30.47 %**	**1**	**26.76 %**	**1**
Energy Management Optimization	**24.74 %**	**2**	**20.67 %**	**3**	**26.61 %**	**1**	**17.13 %**	**4**	**24.82 %**	**2**	**22.79 %**	**2**

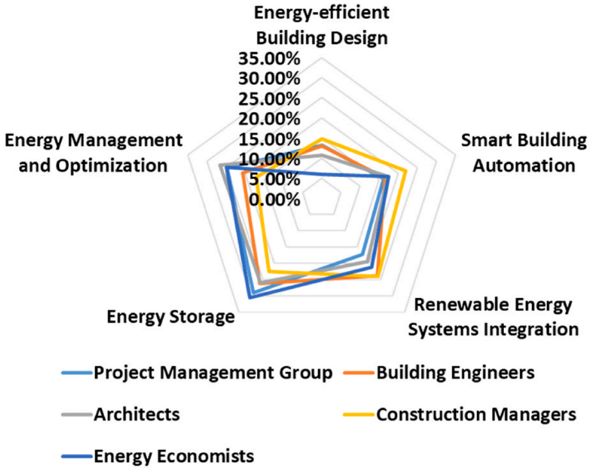

Fig. 10. Energy-building AHP- alternatives comparison.

The first section in the patent analysis illustrated Energy Patent Map Distribution (2000–2023) which provides a comprehensive view of the global distribution of energy patents across different countries. The top-ranking countries in terms of total energy patents include the United States (US), Japan (JP), Germany (DE), South Korea (KR), and China (CN). This distribution reflects these countries' innovation and research activities, highlighting their contributions to developing energy optimization technologies. By examining the regional distribution of patents and comparing the rankings, stakeholders can identify the countries at the forefront of energy innovation and analyze the factors contributing to their success. Table 2 presents a comprehensive overview of energy-building patents in the top 8 countries. The most noteworthy finding is the substantial number of patents filed in wind energy, indicating its prominence and potential for growth in the renewable energy sector. Globally, a staggering total of 1,379,707 wind energy patents have been filed, with China emerging as the dominant player with 907,887 patents, followed by the United States with 203,225 patents. This data underscores the strong commitment of these countries toward advancing wind energy technologies and signifies the significant investment and research efforts dedicated to harnessing wind power as a renewable energy source.

Furthermore, the table reveals the diverse range of energy types that have garnered considerable attention regarding patent filings. These include solar photovoltaic, wave energy, biomass energy, hydro energy, hydrogen energy, and hydrogen fuel cells. The substantial number of patents in these areas highlights the global emphasis on developing and implementing a wide array of renewable energy sources to mitigate climate change and reduce reliance on fossil fuels. Collectively, the findings from Table 2 underscore the international focus on renewable energy innovation and provide valuable insights into the evolving energy landscape. Additionally, analyzing building energy patents offers further insights into the advancements and trends specifically related to energy optimization in the building sector. Global Distribution of Building-Energy Patents (2000–2023) shown in Fig. 5 presents a worldwide distribution map of building energy patents, highlighting the concentration of innovative activity across different regions. The map reveals the top-ranking countries in each energy group, providing valuable information on the geographic hotspots for specific building energy patent categories. Table 3 presents a detailed comparison of the top ten countries regarding energy patents. The table showcases the number of patents filed by each country in various energy technology groups, including renewable energy, energy storage, energy management, energy efficiency, and smart grid technologies. This detailed comparison allows a more nuanced understanding of each country's specialization and expertise in different energy sectors. For instance, the United States leads in energy storage patents, while Germany excels in renewable energy technologies. South Korea demonstrates strength in energy management and efficiency, while China has a strong presence in smart grid technologies. These rankings provide valuable insights into the areas where each country has focused its research and development efforts, enabling stakeholders to identify potential collaboration and technology transfer areas.

Several cause-and-effect relationships and patterns can be identified by analyzing the distribution of energy patents and comparing the rankings across countries. For instance, the high number of energy storage patents in the United States reflects the country's emphasis on developing advanced storage technologies to support the integration of renewable energy sources and enhance grid stability. Similarly, Germany's focus on renewable energy patents aligns with its ambitious transition to a low-carbon economy and its commitment to reducing carbon emissions. As seen in South Korea's ranking, the regional strengths and specialization in energy management and efficiency technologies can be attributed to the country's efforts to optimize energy usage and reduce energy consumption in buildings and industries. China's dominance in smart grid technologies indicates its commitment to building a modern and efficient power grid incorporating advanced communication, control, and optimization systems.

The analysis of energy patents reveals technological advancements and provides insights into the policy landscapes and regional energy challenges. The countries leading in energy patents often have supportive policies and regulatory frameworks that incentivize innovation and research in the energy sector. They also tend to have unique energy challenges, such as energy security, grid stability, or environmental concerns, which drive their focus on specific energy technologies.

Examining the global distribution of building energy patents in conjunction with the corresponding timeline provides deeper insights into the geographic dynamics of innovation in the field. Stakeholders can identify regions that have emerged as leaders in specific building energy technologies and analyze the factors contributing to their success. For example, the United States and China demonstrate significant activity across multiple energy groups, showcasing their leadership and commitment to energy optimization in buildings. Japan's prominence in energy-efficient building design and smart building automation reflects its focus on technological advancements and sustainability in the built environment. South Korea's strong presence in energy management and optimization highlights its efforts to enhance energy efficiency and occupant comfort in buildings.

The analysis of building energy patents also reveals cause-and-effect relationships and patterns within the sector. The concentration of energy storage patents in countries like the United States and China indicates the growing importance of incorporating energy storage technologies into building design, enabling efficient use of renewable energy and grid integration. The emphasis on energy-efficient building design and smart building automation in various countries reflects the recognition of the significant energy-saving potential in these areas, leading to increased research and development efforts.

Comparing building energy patents among nations uncovers best practices and collaboration prospects. For example, countries excelling in energy-efficient building design can share insights, promoting global sustainability. Collaborations among energy-specialized countries spur innovation. In sum, patent analysis offers a panoramic view of global energy optimization. Stakeholders discern hotspots, aiding informed decisions, international cooperation, and sustainable solutions.

Utilizing the AHP analysis to examine energy in buildings provides a systematic and rigorous approach to evaluating and prioritizing alternative solutions. AHP enables stakeholders, including building engineers, architects, construction managers, and energy economists, to objectively assess the feasibility and desirability of various energy-related options. The comprehensive evaluation of alternatives ensures that decisions are based on solid factual data, leading to informed and evidence-based choices. By employing AHP, decision-makers can identify the most viable strategies for energy-efficient building design and renewable energy systems integration, fostering sustainable and environmentally friendly practices. This scientific and academic methodology enhances the decision-making process in the construction industry, paving the way for energy optimization and the promotion of green building initiatives on a broader scale.

6. Conclusions

The energy research literature review provides a comprehensive overview of academic research, emphasizing the growing importance of renewable energy sources and sustainable systems. Transitioning from fossil fuels to cleaner alternatives like solar, wind, and hydropower is crucial for mitigating climate change and achieving environmental sustainability. The review also underscores the significance of energy efficiency, storage, and grid integration, highlighting the need for innovative solutions to optimize energy use and reduce waste. Additionally, occupant behavior plays a vital role in achieving energy conservation goals, emphasizing the importance of promoting energy-aware habits. Building automation systems and smart grid technologies are recognized as effective tools for achieving substantial energy savings. However, it's important to acknowledge limitations such as reliance on a single search engine and potential publication bias.

The patent analysis reveals the global landscape of renewable energy innovation, with countries like China, the United States, Japan, Germany, and South Korea leading in renewable energy patents. Solar photovoltaic technologies emerge as a prominent focus, indicating a strong interest in harnessing solar energy for power generation. Collaboration and knowledge sharing among nations are evident, accelerating innovation and promoting the dissemination of renewable energy solutions. Energy consumption and efficiency are critical in shaping sustainable building practices, emphasizing the adoption of energy-efficient technologies and design strategies to reduce greenhouse gas emissions.

The synthesis of insights from the literature review, patent analysis, and energy assessment in buildings presents pivotal implications for the global construction landscape. The consensus on renewable energy transition, underscored by academic discourse and patent filings, guides policy and investment priorities. Enhanced energy efficiency regulations and incentives are crucial for sustainable building practices. Integrating renewable energy systems and advanced management technologies transforms buildings into sustainable entities, reducing reliance on fossil fuels and enhancing grid stability. Global collaboration in patent filings underscores the importance of knowledge exchange for clean energy adoption. Additionally, employing AHP offers a systematic approach for stakeholders to evaluate energy options, albeit with sample size limitations. Policymakers, stakeholders, and researchers can leverage these insights to drive policy, innovation, and awareness, fostering a sustainable built environment. Strategies include incentivizing renewables, enhancing efficiency standards, fostering collaboration, and investing in R&D. Future research should focus on addressing gaps, particularly in advancing building energy systems and employing comprehensive surveys integrated with Multi-Criteria Decision Making (MCDM) techniques. In conclusion, this research emphasizes sustainable energy practices' significance, urging ongoing research and development for a sustainable built environment.

Ethics approval

All procedures performed in studies involving human participants were under the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Omar Alharasees: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Utku Kale:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation. **Jozsef Rohacs:** Writing – review & editing, Visualization, Supervision, Project administration. **Daniel Rohacs:** Writing – review & editing, Visualization, Supervision, Project administration. **Muller Enetta Eva:** Writing – review & editing, Visualization, Supervision, Project administration, Investigation. **Anita Boros:** Writing – review & editing, Visualization, Validation, Project administration, Investigation.

Declaration of competing interest

The authors 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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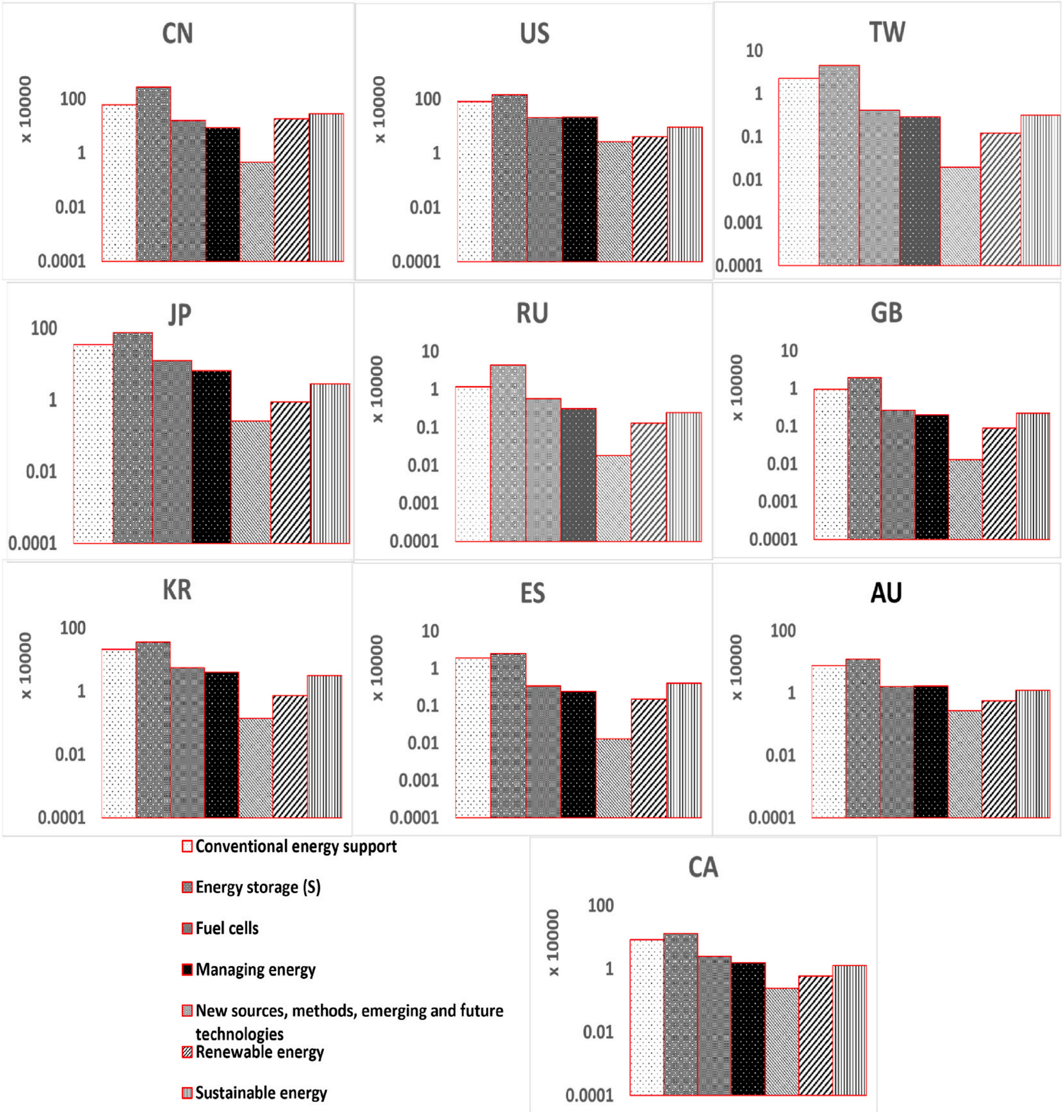
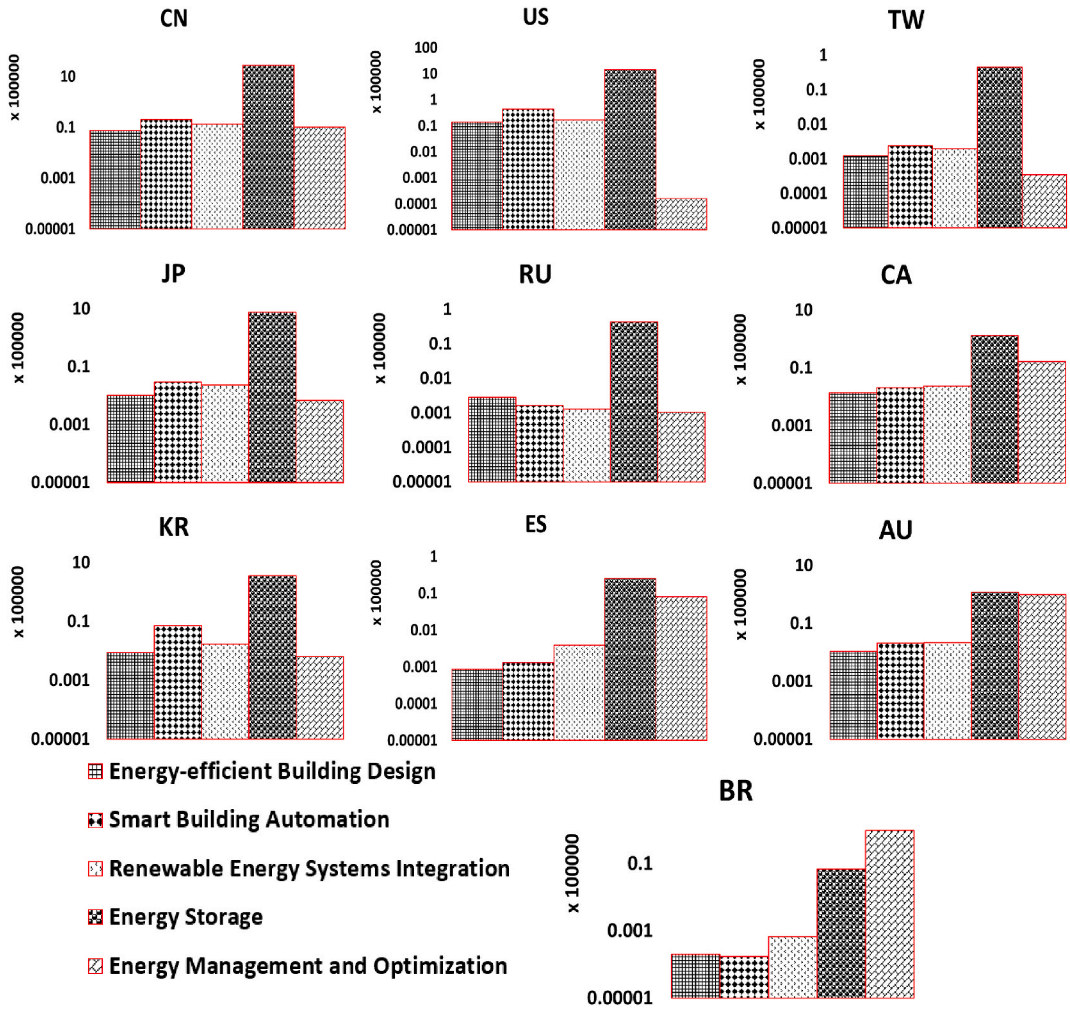
Appendix 1. Global patent analysis for energy (The top 10 countries) based on the world intellectual property organization (WIPO) database



Appendix 2. Building-energy patents (The top 10 countries) based on the world intellectual property organization (WIPO) database



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