Journal of Energy Storage 103 (2024) 114339

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Review article

A bird's eye view of pumped hydro energy storage: A bibliometric analysis of global research trends and future directions

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A R T I C L E I N F O

Keywords:
Bibliometric analysis
Energy storage
Pumped hydro energy storage
Renewable energy
Sustainable development

A B S T R A C T

Large-scale energy storage solutions have become increasingly critical as the global energy sector shifts towards renewable sources. This study conducted a comprehensive bibliometric analysis of global research trends in pumped hydro energy storage (PHES) from 2003 to 2023. Using data extracted from the Scopus database, the study applied various bibliometric techniques, including publication trend analysis, keyword co-occurrence, thematic mapping, and collaboration network analysis. The results reveal a significant surge in PHES research, with annual publications increasing from 1 in 2003 to 146 in 2023. China emerges as the leading contributor, followed by India and the United States. The analysis identifies key research themes, including integration with other renewable sources, operations optimisation, and techno-economic feasibility studies. Emerging topics such as hybrid storage systems and off-river PHES highlight new directions in the field. The study also uncovers strong international collaborations among developed nations, indicating a global recognition of PHES's importance in future energy systems. These findings provide key insights for researchers, policy-makers, and industry stakeholders, offering a comprehensive understanding of the current state and future directions of PHES research. This study contributes to informed decision-making in renewable energy strategies and identifies potential areas for further investigation and international cooperation in PHES development.

List of abbreviations

$/kW	US dollar per kilowatt-hour
€/kWh	Euro per kilowatt-hour
AC	Alternating current
CAES	Compressed air energy storage
CAPEX	Capital expenditure
CO_2	Carbon dioxide
DC	Direct current
EES	Electrical energy storage
GIS	Geographic information system
GW	Gigawatt
GWh	Gigawatt-hour
IEEE	Institute of Electrical and Electronics Engineers
IHA	International Hydropower Association
kW	Kilowatt
kWh	Kilowatt-hour
LCC	Life cycle cost
MCP	Multiple country publication
MW	Megawatt

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https://doi.org/10.1016/j.est.2024.114339
Received 23 August 2024; Received in revised form 16 October 2024; Accepted 20 October 2024
Available online 25 October 2024

O&M Operating and maintenance
OPEX Operational expenditure
PHES Pumped hydro energy storage
PHS Pumped hydro storage
PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSO Particle swarm optimization
PSS Pumped storage systems
PV Photovoltaic
RE Renewable energy
SCP Single country publication
SMES Superconducting magnetic energy storage
TRL Technology readiness level
USD United States dollar

1. Introduction

The global community increasingly recognises the urgent need to address climate change and its associated environmental impacts. This awareness has led to a significant shift towards clean and renewable energy sources, moving away from fossil fuels [1]. Among the various renewable energy alternatives, such as wind, solar, geothermal, and biofuels, hydropower has emerged as a crucial player in the global energy sector.

Hydropower contributes approximately 16 % to the global electricity generation portfolio, making it a significant source of renewable electricity [2]. Beyond its role in energy provision, hydropower enhances grid stability and security through various mechanisms, including frequency regulation, voltage support, and load-following capabilities [3]. Compared to other renewable sources, its cost-competitiveness and reliability further underscore its importance in the clean energy transition [4].

Energy storage technologies have become increasingly critical as the world struggles to integrate intermittent renewable sources such as wind and solar into the grid. Pumped hydro energy storage (PHES) has emerged as a vital component for grid-scale energy storage, facilitating balancing services for these variable renewable sources [5]. PHES operates by storing energy in the form of gravitational potential energy. During periods of low electricity demand, the system uses electricity to pump water from a lower reservoir to a higher one. When electricity demand increases, the stored water is released through turbines to generate power [6]. This cyclical process allows PHES to act as a large-scale, long-duration energy storage solution, potentially storing and releasing energy on a scale of gigawatt-hours [7].

As reported in the International Hydropower Association's (IHA) 2024 World Hydropower Outlook, the global installed capacity for PHES reached 179 GW in 2023 [8]. Due to renewed interest in the technology and over 100 projects in development, the IHA anticipates that PHES capacity will grow by nearly 50 %, reaching approximately 240 GW by 2030. As the only commercially validated large-scale energy storage technology, PHES provides the flexibility, reliability, and grid stability required to integrate variable renewable energy sources [9]. In recent years, there has been a significant revival in both commercial and technical interest in PHES, primarily linked to the growing prevalence of variable renewable energy generation and deregulated electricity markets [10,11]. The technology has been explored in various regional contexts, including China, the United States, and island regions, highlighting its adaptability to diverse geographical and energy challenges [12–14]. Advancements in PHES technology, including integrating reversible pump-turbine machines and hybridising with other storage technologies, have further improved system reliability, flexibility, and performance [15,16]. However, operational challenges associated with pump-turbine instabilities and optimised control strategies require further research [17,18].

In recent years, numerous researchers have conducted studies on PHES systems, with several employing conventional review approaches to analyse the progress in this field. Notable examples include Alnaqbi et al. [19], who reviewed the technological feasibility and geographical distribution of hydropower generation and pumped hydro storage, particularly emphasising installations in the Middle East and North Africa region. Debanjan and Karuna [20] reviewed the challenges posed by the increasing share of on-grid renewable energy in India, mainly focusing on the implications for grid inertia and frequency response as the renewable energy share approaches 80 % by 2040. Ming et al. [12] comprehensively reviewed the development of PHES in China, focusing on its role in ensuring the safe and steady operation of the power grid amid increased variable renewable energy generation and a liberalised electricity market. Ali et al. [21] systematically reviewed and categorised the various techno-environmental and socio-economic drivers and barriers to the development of PHES. Toufani et al. [22] provided an overview of research on optimising PHES systems under uncertainty. Blakers et al. [23] examined the role of PHES in addressing the growing need for energy storage in electricity systems, mainly as large amounts of variable solar and wind generation capacity are being deployed globally. Barbour et al. [24] historically outlined the development of PHES in several key electricity markets and compared various mechanisms for rewarding PHES within different international market frameworks. Lohani and Blakers [25] demonstrated that Nepal could achieve energy self-sufficiency in the twenty-first century by utilising its significant solar potential and moderate hydroelectric resources.

Though previous reviews have provided key insights into various aspects of PHES systems, this study introduces a novel approach using bibliometric analysis to provide a comprehensive and data-driven overview of the field. This method allows quantitative examination of publication trends, influential authors and institutions, key research topics, and emerging focus areas in PHES research. This study provides a unique and up-to-date presentation of the state of the art in PHES systems, helping to identify research gaps and future directions in PHES technology and applications by complementing existing conventional reviews with this bibliometric perspective. This bibliometric analysis of PHES research aims to provide a comprehensive, data-driven overview of the field beyond presenting mere data trends. The main objective is to identify key research trends, influential contributors, and emerging focus areas in PHES systems research. The study seeks to uncover potential research gaps, highlight collaborative networks, and discern the evolution of research themes over time by mapping the intellectual structure of the field. This approach allows us to complement existing conventional reviews with a quantitative perspective, providing researchers, policymakers, and industry professionals with a strategic view of the research field. Finally, this analysis aims to guide future research directions, inform funding decisions, and facilitate more targeted collaborations in the rapidly evolving field of PHES.

The remaining sections of this paper are organised as follows: Section 2 presents a brief overview of the working principle of PHES systems; Section 3 details the methodology employed in this study; Section 4 highlights results and discusses its implications; and Section 5 highlights the conclusions and directions for future research.

2. Brief overview of the working principle of the PHES system

PHES operates by conserving gravitational potential energy derived from water elevated from a lower reservoir to a higher elevation reservoir. The comparatively low energy density in PHES systems necessitates a significantly large body of water or a considerable elevation differential. This system uses economically cheap electrical power (electricity available during off-peak periods such as nighttime) to operate the pumps that facilitate the ascent of water from the lower reservoir to the upper reservoir [26]. The fundamental principle underlying PHES is depicted as two reservoirs and the associated pumping/generation cycle [27]. PHES systems can be designed to utilise various power sources to pump water from the lower reservoir to the upper reservoir during periods of low demand. These power sources include solar photovoltaic (PV) arrays, wind turbines, grid power, or a hybrid system combining multiple energy sources. For example, Fig. 1 depicts a grid-powered PHES system with two modes of operation. In the storage-pumping mode, the upper basin is filled with water while the lower basin is empty. The motor-generator acts as a motor, using electricity from the power grid to drive the pump-turbine and pump water from the lower basin to the upper basin, storing energy in the form of gravitational potential energy. In the generation-turbine mode, the upper basin is filled, and the lower basin is also filled. The motor-generator then acts as a generator, using the flow of water from the upper basin to the lower basin to spin the pump-turbine, generating electricity that is fed back into the power grid. This system allows for energy storage during periods of low demand and electricity generation during periods of high demand, effectively acting as a large-scale energy storage system.

Fig. 2 displays a grid-connected solar-powered PHES system. It includes a PV array that generates electricity, which can be used to charge the system during periods of low demand. The direct current (DC)/alternating current (AC) converter and inverter convert the electricity to a form that can be fed into the grid. The control station manages the flow of electricity and the system's operation. The upper and lower reservoirs store and release the water, with the pump/motor device moving the water from the lower to the upper reservoir during periods of low demand and the generator converting the flow of water from the upper to the lower reservoir into electricity during periods of high demand.

A wind-powered PHES system shown in Fig. 3 includes a wind farm that generates wind energy, which can also be used to charge the system during periods of low demand. The electricity generated by the wind farm is transmitted to the control station, where it is used to power the pump and move water from the lower reservoir to the upper reservoir. When electricity is needed, the flow of water from the upper reservoir to the lower reservoir is used to spin a turbine, which in turn generates electricity that is fed back into the grid. Fig. 4 illustrates a solar PV/wind-powered hybrid PHES system. The PV array generates electricity, which can be used to charge the system during periods of low demand. The DC/AC converter and inverter convert the electricity to a form that can be fed into the grid. The control station manages the flow of electricity and the system's operation. The upper and lower reservoirs store and release the water, with the pump/motor device moving the water from the lower to the upper reservoir during periods of low demand and the generator converting the flow of water from the upper to the lower reservoir into electricity during periods of high demand. The wind turbine also generates energy that can be used to charge the system.

However, the configuration of nearly all PHES power facilities is intricately linked to the site's characteristics. A location with adequate water resources is deemed suitable for establishing a PHES installation, provided the region's topography and geological conditions are advantageous [28].

3. Methodology

Fig. 5 displays the approach used to conduct the bibliometric analysis of global research trends on PHES. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was utilised to ensure a systematic and transparent data extraction process [33–35]. The data was extracted from the Scopus database, which is one of the largest abstract and citation databases of peer-reviewed literature. The search string comprises the following terms: ("pumped hydro energy storage" OR "pumped energy storage" OR "pumped hydro storage" OR "pump hydro energy storage" OR "pump hydro storage" OR "PHES"). The search was conducted from 2003 to 2023, on August 1, 2024. This yielded 1065 documents, which were further refined to 1020 after applying the inclusion and exclusion criteria, as shown in Fig. 5. These criteria help to ensure the quality and relevance of the literature included in the analysis.

We performed the bibliometric analysis using the bibliometrix

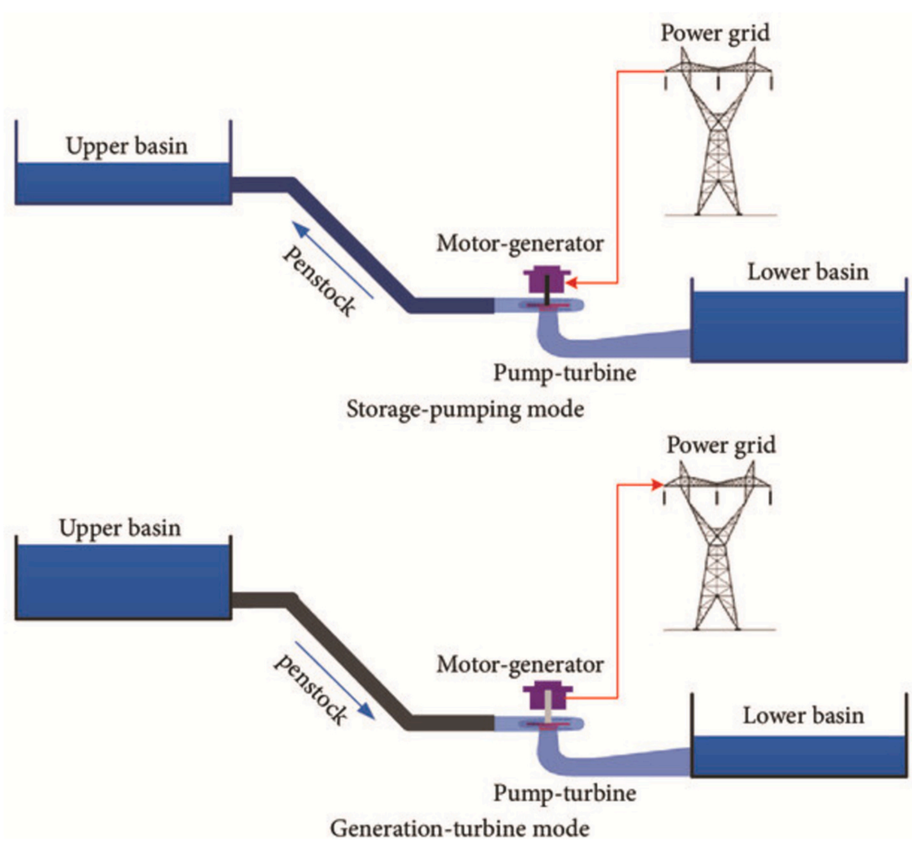

Fig. 1. Grid-powered PHES system [29] (Published under open access).

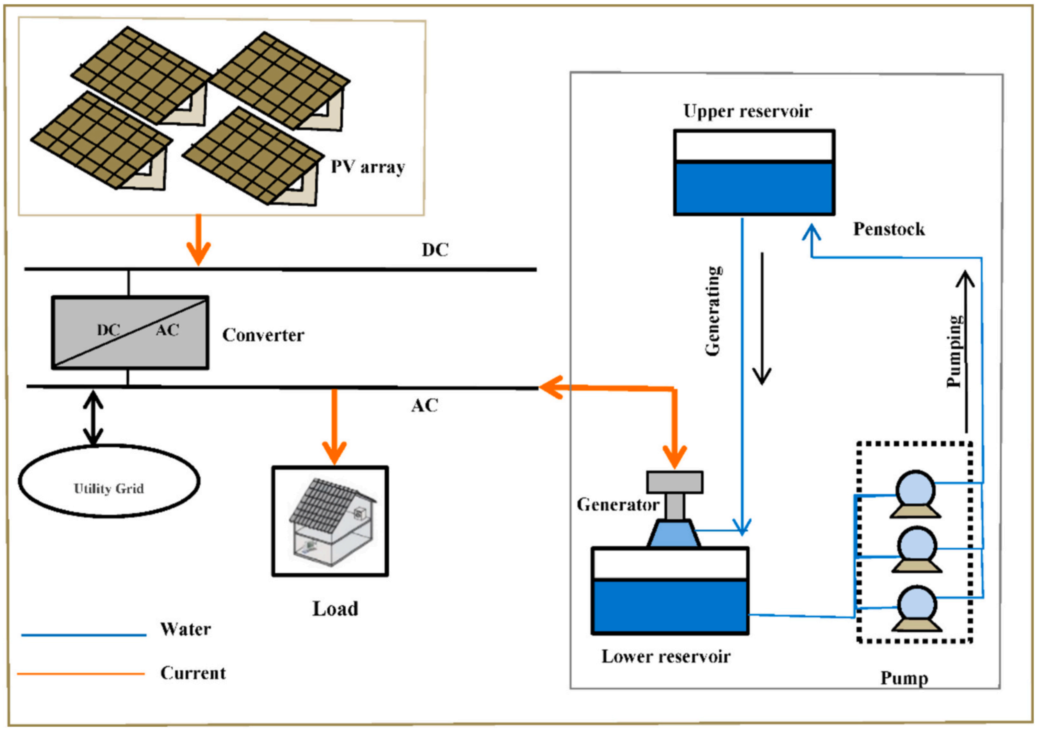

Fig. 2. Grid-connected solar-powered PHES system [30] (Published under open access).

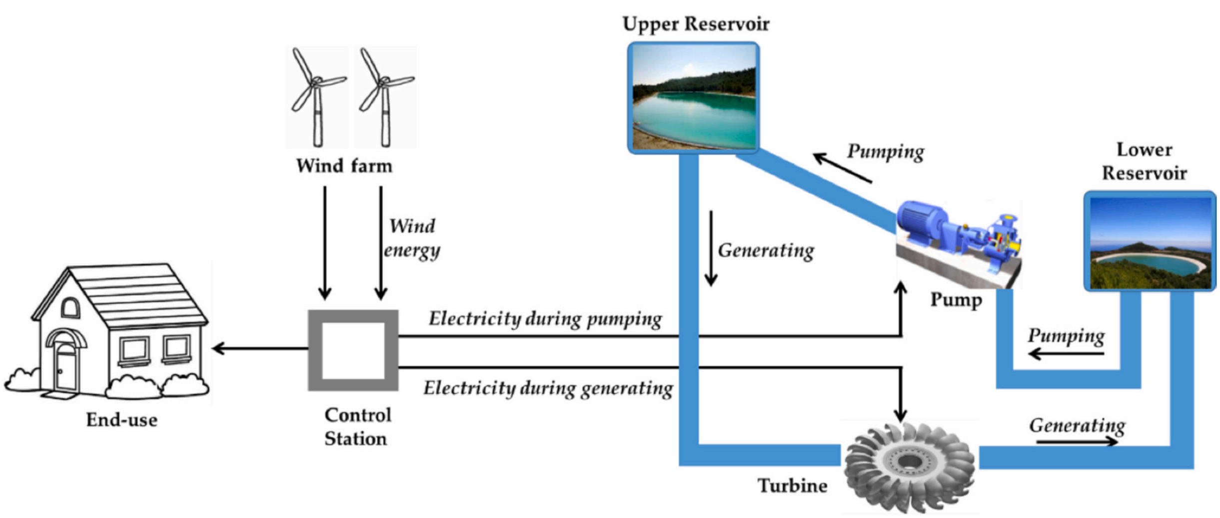

Fig. 3. Wind-powered PHES system [31] (Published under open access).

package in R software and the biblioshiny library, a powerful tool for statistical computing and data visualisation [36–40]. The bibliometric analysis performed involved several key components. First, the publication trends were examined to understand the temporal evolution of research activities in PHES. Next, the most frequently occurring keywords were identified to uncover the prevalent themes and emerging research topics. The conceptual structure of the research area was explored through co-occurrence analysis, thematic mapping, thematic evolution analysis, and factorial analysis, which provided insights into the intellectual structure and the relationships between different research themes. Likewise, the analysis also focused on identifying the leading countries, research institutions, and journals contributing to the field of PHES to gain a comprehensive understanding of the global research field. Also, the collaboration patterns between countries were examined to understand international research collaborations and knowledge sharing. Furthermore, the most cited works were reviewed to identify the seminal publications that have significantly impacted the field.

It is worth mentioning that the methodological approach adopted in this study ensures the reproducibility and transparency of the research findings. The use of the Scopus database, the PRISMA approach, and the well-established bibliometric techniques in the R software environment provide a robust and reliable framework for the analysis. The comprehensive nature of the bibliometric analysis, covering publication trends, keyword analysis, conceptual structure, leading actors, and highly cited works, provide a holistic understanding of the global research area on PHES, paving the way for informed decision-making and future research directions in this critical field of renewable energy.

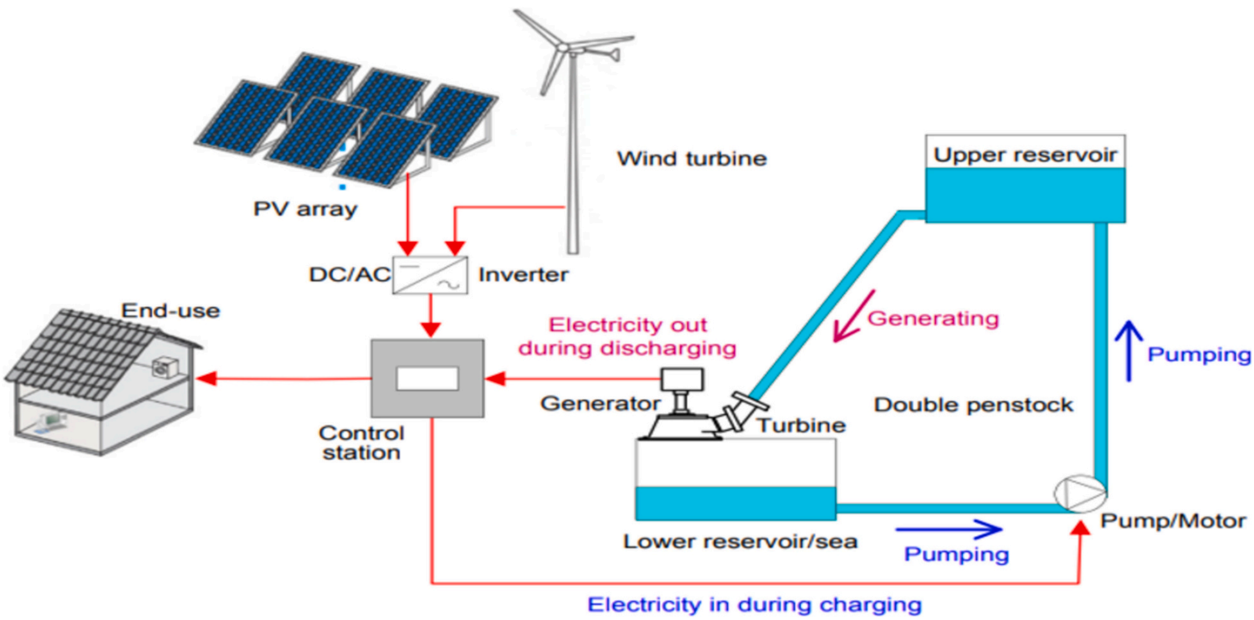

Fig. 4. PV/wind-powered hybrid PHES system [32] (Reproduced with permission from Elsevier, License number: 5854400955904).

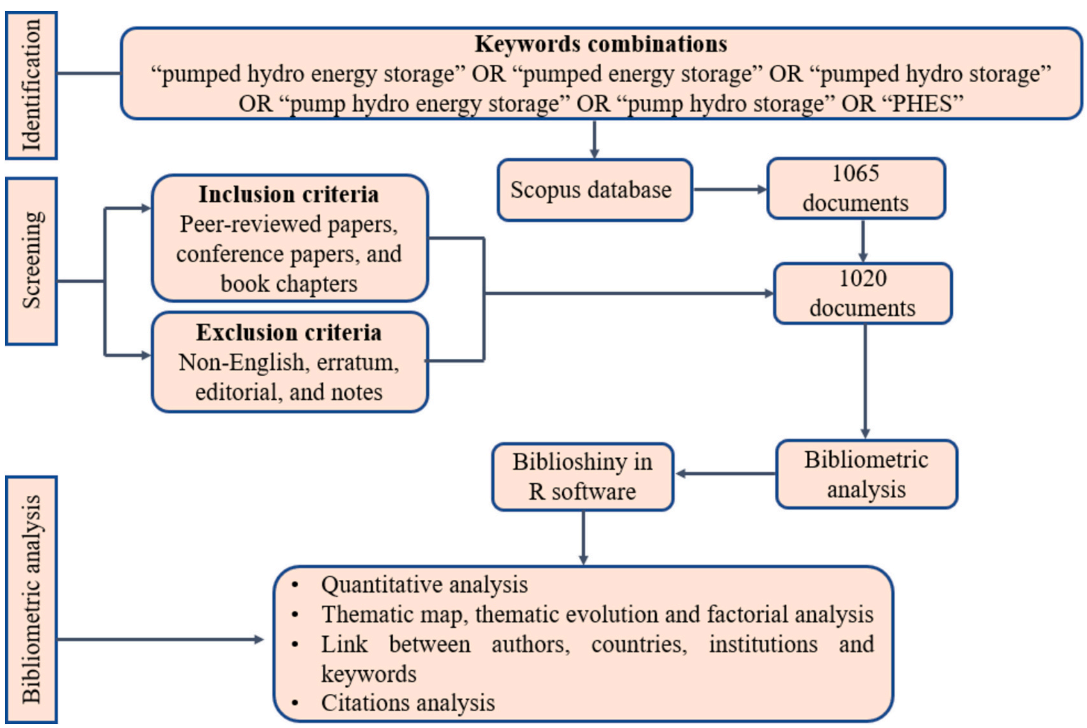

Fig. 5. Methodology used for the bibliometric analysis.

4. Results and discussion

This section discusses the findings from the bibliometric analysis conducted.

4.1. Overview of bibliometric data

Fig. 6 summarises the key bibliometric data used for the bibliometric analysis. The timespan from 2003 to 2023 indicates a comprehensive 20-year review period, during which 1020 documents were published from 429 sources. The annual growth rate of 28.3 % suggests rapidly increasing interest and investment in pumped hydro research. With 2516 authors contributing to these publications, a substantial and diverse research community is engaged in this area. It can be seen that only 55 authors produced single-authored works, implying that collaboration is the norm in this field. This is further supported by the average of 3.7 co-authors per document. The international nature of the research is evident from the 23.92 % rate of international co-authorship, indicating global cooperation on pumped hydro topics. The presence of 2581 author keywords (DE) points to a rich and varied vocabulary within the field, likely covering multiple aspects of pumped hydro technology, economics, and environmental impacts. The 34,781

Fig. 6. Summary of key bibliometric parameters.

references used across these publications demonstrate the depth of background knowledge being incorporated into new research. The relatively young average document age of 5.22 years suggests that much of the research is recent and likely highlights current technological advancements and policy considerations. The high average of 32.33 citations per document indicates that these publications are influential and frequently referenced by other researchers, emphasising the importance and relevance of PHES in the broader context of renewable energy and grid stability discussions.

To provide a more comprehensive view of the field, discussing the industrial implementation of PHES technology and its connection to current research is essential. The Technology Readiness Level (TRL) of PHES is generally high, with most components at TRL 9 indicating full commercial readiness [41]. In addition, Nikolaos et al. [5] alluded that PHES systems have reached a TRL of 11/11, as outlined in the International Energy Agency guide. However, ongoing research continues to push the boundaries of efficiency and application, particularly in variable speed technology and pump-turbine design optimisation [42–44].

The industrial sector of PHES is diverse and global. Genex Power is developing the 250 MW Kidston PHES project in Australia, which uniquely repurposes an abandoned gold mine [45]. This project exemplifies the innovative application of PHES in non-traditional settings, aligning with research trends on off-river pumped hydro storage [46]. In Europe, Energy Vault in Switzerland is pioneering gravity-based energy storage systems inspired by pumped hydro principles, demonstrating how PHES concepts can inspire novel storage technologies [47]. Their system, which uses concrete blocks and cranes instead of water, showcases the potential for PHES principles to be adapted to different environments and resources.

Rye Development is pursuing several pumped storage projects in the United States, including the 1200 MW Goldendale Energy Storage Project in Washington state [48]. This project, designed to integrate with wind and solar generation, signifies the research focus on hybrid renewable energy systems incorporating PHES. China remains at the forefront of PHES development in Asia, with state-owned utilities like State Grid Corporation of China investing heavily in large-scale projects [49]. This aligns with the bibliometric data showing China's dominance in PHES research output. These commercial endeavors demonstrate the practical application of research findings and highlight the ongoing industrial relevance of PHES technology.

The interplay between academic research and industrial implementation is vital for advancing PHES technology and its role in future energy systems. For instance, research into advanced control strategies and grid integration techniques [50] is being incorporated into modern PHES installations to enhance their flexibility and grid support capabilities. Additionally, the growing interest in seawater PHES, seen in projects like the Okinawa Yanbaru Seawater Pumped Storage Power Station in Japan [51], represents a new frontier combining research innovation with practical implementation to address geographical constraints. This synergy between research and industry is driving the evolution of PHES from traditional mountain-based systems to more diverse and adaptable configurations, positioning it as a key technology in the global transition to renewable energy systems.

4.2. Publications trend and distribution by journal and subject

Fig. 7 shows a clear upward trend in annual article production from 2003 to 2023, with notable patterns and implications. The results show that research output was minimal in the early years (2003–2004), with only one article published annually. A slight increase occurred from 2005 to 2010, with annual publications ranging from 4 to 8 articles. However, a significant shift began in 2011, marking the start of a substantial and sustained growth in research interest. The number of articles more than doubled from 14 in 2011 to 24 in 2012 and then surged to 39 in 2013. This rapid increase continued, with annual publications exceeding 100 for the first time in 2019 and reaching a peak of 165 articles in 2022. This trend is quantitatively captured by the linear regression equation $y = 7.6584\times - 15,368$, where y represents the number of articles and x the year. This equation indicates an average increase of about 7.66 articles per year, highlighting the steady growth in research output. The R^2 value of 0.8547 suggests that 85.47 % of the variance in article numbers can be explained by time, demonstrating a strong correlation between year and research productivity. This mathematical model confirms the observed trend and provides a tool for potential future predictions. The consistent growth in research output, particularly from 2011 onwards, suggests a growing recognition of pumped hydro energy storage's importance in the renewable energy sector. The rapid increase in PHES research output from 2011 onwards can be attributed to several interconnected factors. Firstly, the global push towards renewable energy integration intensified during this period, spurred by international agreements such as the 2015 Paris Agreement [52]. This shift highlighted the need for large-scale energy storage solutions to address the intermittent of renewables like wind and solar. Secondly, technological advancements in variable speed pump-turbines and power electronics enhanced the flexibility and efficiency of PHES systems, making them more attractive for grid stabilisation [53]. Policy changes also played a crucial role; for instance, the European Union's Renewable Energy Directive of 2009 set binding targets for 2020, indirectly boosting interest in energy storage research [54]. In the United States, the Department of Energy's Hydropower Vision report in

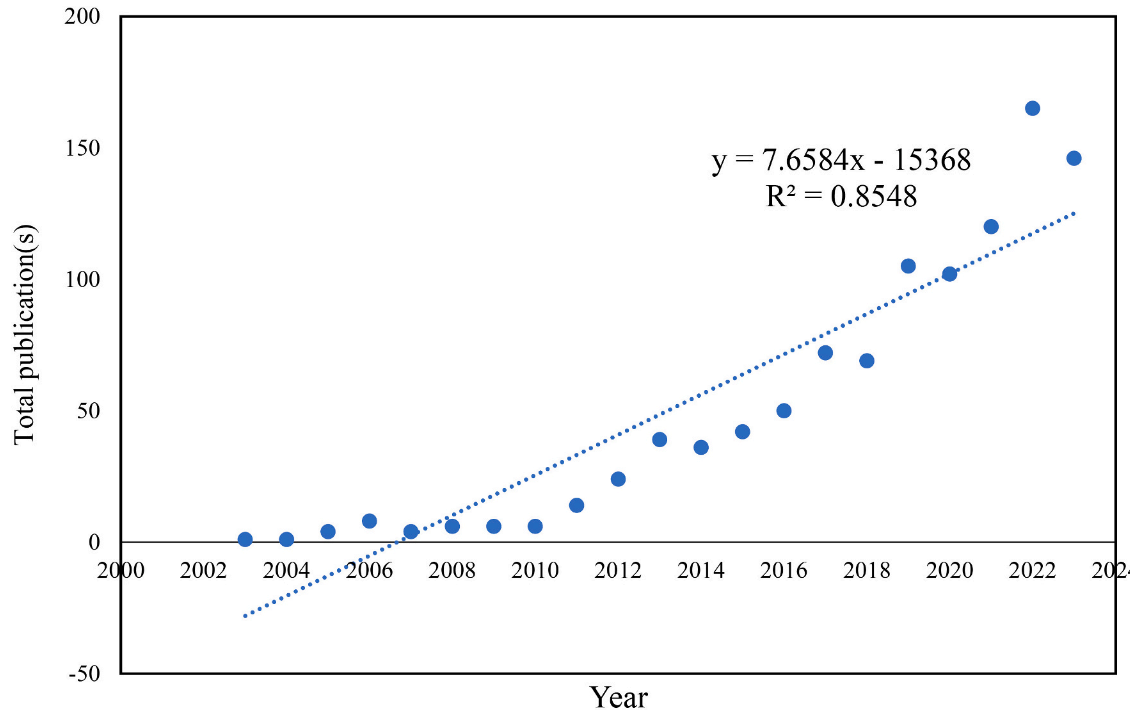

Fig. 7. Number of publications per year in the period 2003–2023.

2016 emphasised the role of pumped storage in future energy systems, likely contributing to increased research attention [55]. China's 12th Five-Year Plan (2011–2015) explicitly supported PHES development, aligning with the country's dominance in research output [56]. Additionally, the increasing volatility in electricity markets due to higher renewable penetration created new economic opportunities for PHES, spurring research into novel operational strategies and market mechanisms [24]. The convergence of these factors, including policy support, technological progress, economic incentives, and the pressing need for grid-scale storage, collectively might drive the surge in PHES research from 2011 onwards, suggesting the technology's growing importance in the global energy transition.

4.3. Cost trends of PHES systems

Capital expenditure (CAPEX) and operational expenditure (OPEX) are vital financial metrics in assessing energy projects' viability and long-term profitability [57]. CAPEX represents the initial investment required to build or upgrade facilities, while OPEX comprises the ongoing operation and maintenance costs. Fig. 8 displays the trend in CAPEX for PHES over time. The figure illustrates a wide spread of CAPEX values, particularly in recent years, ranging from approximately

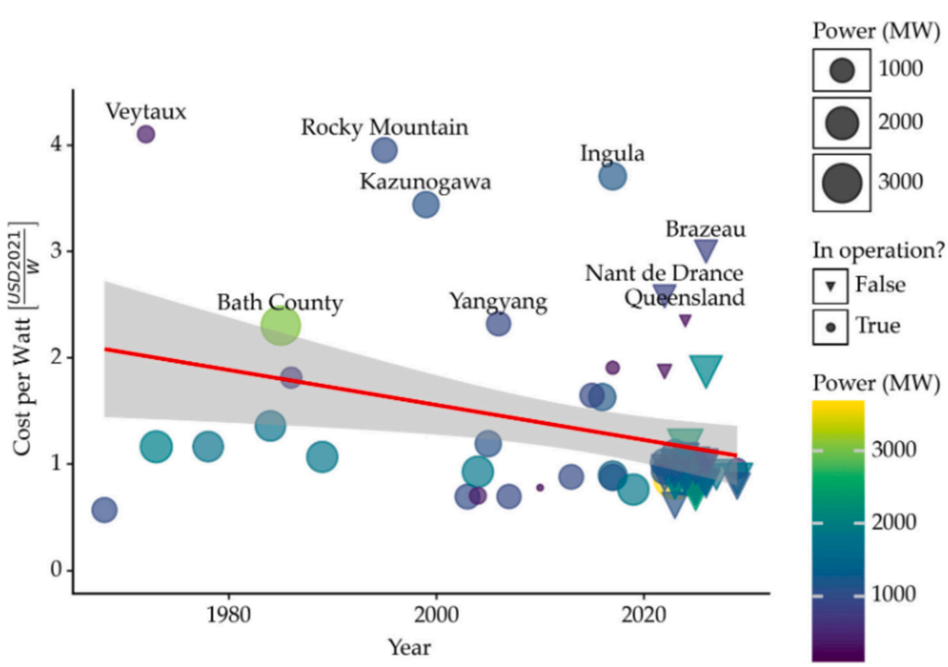

Fig. 8. Trend in CAPEX for PHES systems [5] (Published under open access).

0.7 to 3.0 USD/W in 2020, compared to a tighter cluster around 0.7–1.2 USD/W in the early 2000s. This distribution suggests that project-specific factors such as location, scale, and site conditions significantly impact costs more than time alone. Although the trend line indicates a slight overall decrease in CAPEX, the substantial variability in recent data highlights the absence of a consistent cost reduction. Some modern projects have achieved lower costs than their early 2000s counterparts. In contrast, others remain more expensive, indicating that rising material and labour costs may offset technological advancements and potential economies of scale.

On the other hand, OPEX has remained relatively stable as a percentage of CAPEX, typically ranging from 0.5 % to 1 % annually throughout the period [58]. Nikolaos et al. [5] alluded that for a 100 MW system, the total fixed operating and maintenance (O&M) cost is 30.4 USD/kW-year, representing 2.0 % of the capital cost. In contrast, a 1000 MW system shows economies of scale with a lower total fixed O&M cost of 17.8 USD/kW-year, accounting for 1.4 % of the capital cost. This breakdown reveals that labour-related fixed O&M costs decrease significantly with system size (from 15.7 to 3.1 USD/kW-year), while refurbishment-related costs remain constant at 9.0 USD/kW-year regardless of system size. These figures explain how operational costs scale with system capacity, highlighting the potential cost advantages of larger PHES installations. The long operational lifespan of PHES systems contributes to their competitive annualised costs despite potentially high initial investments [12].

4.4. Countries' distribution and collaborations

The countries that published more studies on PHES from 2003 to 2023 in the Scopus database are shown in Fig. 9. It can be observed that China has the highest publications of 754 articles, more than double the output of the next highest contributor, India, with 289 articles. The United States follows closely behind India with 282 articles, while Australia and Germany round out the top five with 189 and 174 articles, respectively. European nations, particularly Germany, Italy, Greece, Spain, and Switzerland, also show strong research interest, indicating a continent-wide focus on pumped hydro as part of their energy strategies. The presence of countries like Brazil, South Africa, and Iran in the top 20 accentuates the global relevance of pumped hydro storage across different geographical and economic contexts. Notably, some countries known for their hydroelectric resources, such as Norway and Canada, have relatively lower article counts, suggesting either a focus on traditional hydropower or a saturation of existing knowledge. The long tail of countries with fewer than 10 articles indicate a broader, although less intensive, global interest in technology. This distribution highlights the dominance of major economies and technologically advanced nations in PHES research. China, India, and the United States emerging as leading contributors to PHES research might be due to the following reasons. For example, in 2023, pumped hydro emerged as the leading segment in China's energy storage industry, receiving the highest investment with a total allocation of USD 47 billion [59]. China is constructing pumped-storage hydropower facilities to enhance grid flexibility and integrate increasing amounts of wind and solar power. By May 2023, China had achieved 50 GW of operational pumped-storage capacity, representing 30 % of the global total and surpassing any other country [60]. Recently, China just commissioned the largest PHES plant in the world [61].

Likewise, India's contribution may be driven by the need for at least 18.8 GW of PHES capacity to support the planned integration of wind and solar power into the grid by 2032, with the possibility of requiring more if other energy storage systems prove financially unviable. The Indian government has recently revised its estimated pumped-storage hydropower potential from 96 GW to 106 GW [62]. Similarly, the United States government allocated USD 13 million to fund seven research and development initiatives to enhance hydropower as an essential clean energy resource. With PHES currently making up 93 % of utility-scale energy storage in the country, it is poised to be a critical asset in stabilising a grid that increasingly relies on variable energy sources like wind energy and solar energy [63].

This distribution of research output in Fig. 9 suggests that knowledge and expertise in pumped hydro storage are concentrated in a handful of countries, potentially leading to technological leadership and economic advantages in the renewable energy sector. It also highlights potential areas for international collaboration and knowledge transfer, particularly between high-output countries and those with fewer publications but significant hydropower potential. The results may also indicate varying national priorities in energy research and development, with some countries potentially focusing more on other energy storage or generation forms.

Fig. 10 presents a world map illustrating international collaborations on PHES research, with countries highlighted in various shades of blue and interconnected by orange lines representing collaborative links. This visualisation provides significant insights into the global nature of research efforts in this critical area of renewable energy technology. It can be observed that the map shows a complex network of collaborations crossing multiple continents, with particularly dense connections between North America, Europe, and East Asia. The thickness of the

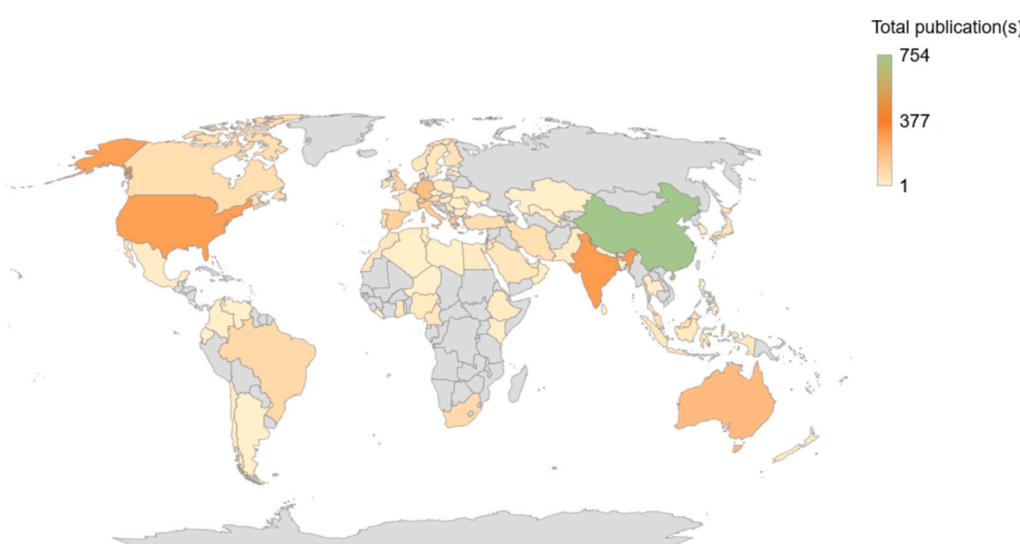

Fig. 9. Total publications distribution per country.

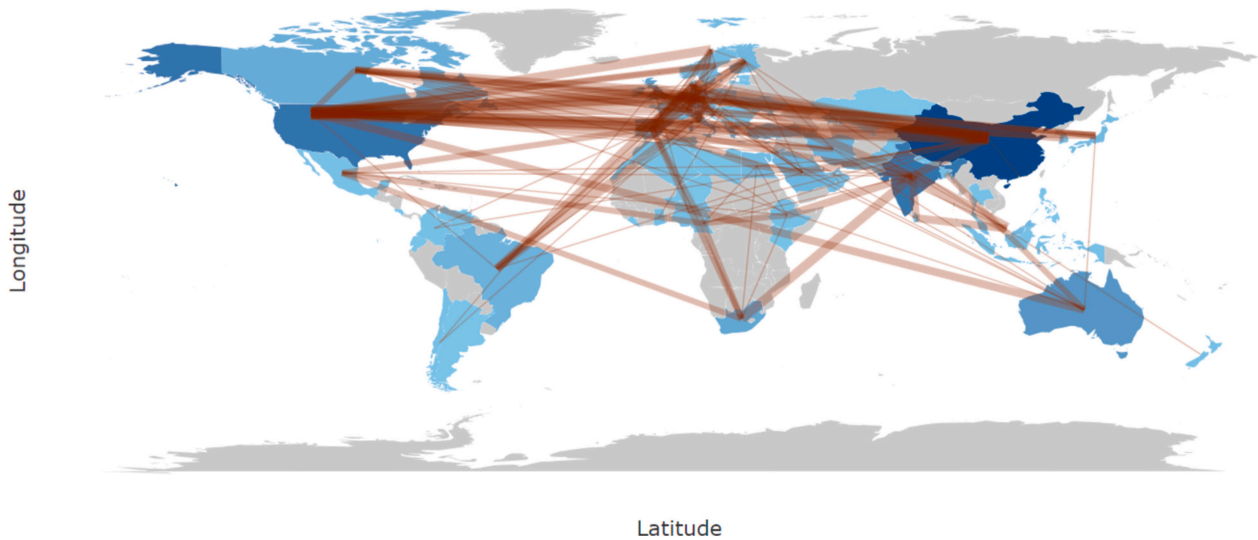

Fig. 10. Countries collaboration map.

lines likely indicates the strength or frequency of collaborations between countries. Notably, there appear to be strong collaborative ties between the United States, several European countries, China, and Australia, suggesting these nations are at the forefront of PHES research and development. The prominence of these connections aligns with the technological capabilities and research output of these countries in the renewable energy sector.

The map also shows collaborations extending to South America, Africa, and South Asia, though with less intensity, indicating a growing global interest in PHES technology beyond the traditional research powerhouses. This global spread of collaborations has significant implications for advancing and disseminating PHES technology. It suggests that knowledge transfer is occurring worldwide, potentially accelerating innovation and adaptation of the technology to diverse geographical and economic contexts. The strong collaborative networks between developed nations may lead to faster technological breakthroughs.

In contrast, including developing countries in these networks could facilitate the transfer of expertise to regions where PHES is pivotal in future energy systems. The pattern of collaborations also indicates geopolitical and economic relationships, with stronger ties evident between traditional allies and major trading partners. This collaborative pattern has implications for policy-making, international relations, and the global renewable energy market. It suggests that PHES is seen as a critical technology for addressing global energy challenges, requiring international cooperation to realise its full potential fully. However, the varying intensities of collaboration also highlight potential disparities in access to cutting-edge research and technology, which could impact the global adoption of pumped hydro storage solutions.

Fig. 11 displays the countries of corresponding authors involved in PHSE research over the two decades. This result provides vital insights into the nature of research collaboration and leadership in this field. It can be observed that China stands out as the dominant force, with 106 single country productions (SCPs) and 31 multiple country productions (MCPs). This implies a high volume of domestic research and significant international collaboration. India follows with 56 SCPs but only 5 MCPs, suggesting a strong domestic research programme but limited international engagement. The United States, Germany, and Greece round out the top five in total publications, each showing a mix of domestic and collaborative research. Australia, interestingly, has a high number of SCPs (30) but only 1 MCP, indicating a robust national research programme but minimal international collaboration in this result.

European countries like Italy, Spain, the United Kingdom, and

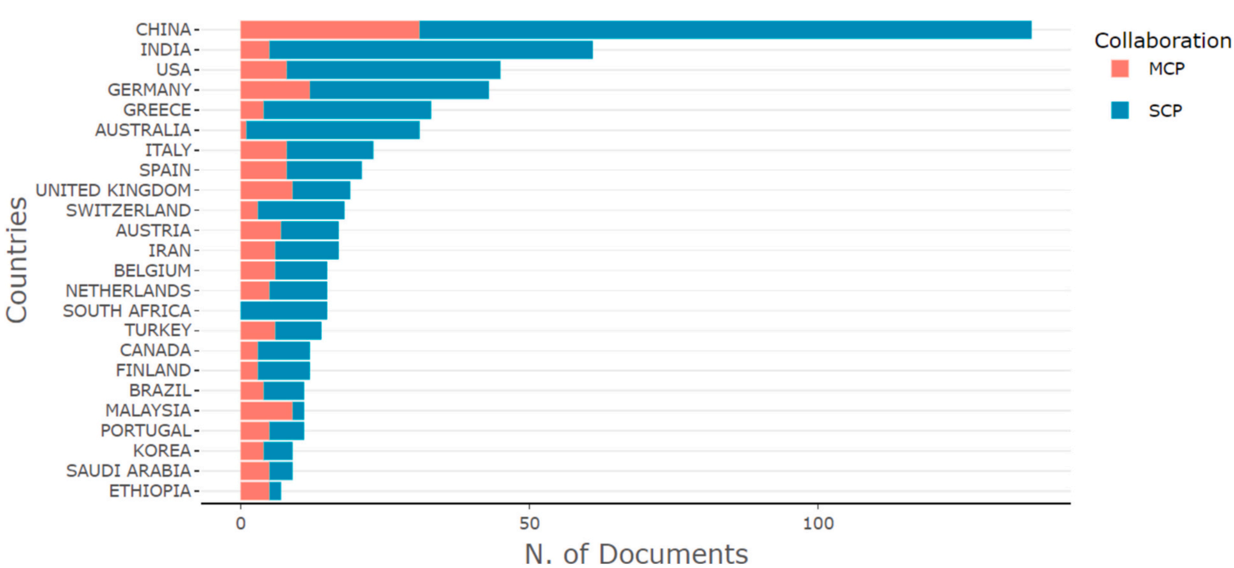

Fig. 11. Corresponding authors' countries.

Switzerland demonstrate a more balanced approach between SCP and MCP, signifying the interconnected nature of European research. Some countries, such as Malaysia, show a higher proportion of MCPs to SCPs, suggesting they may be leveraging international collaborations to enhance their research capacity. South Africa has 15 SCPs and no MCPs, indicating a purely domestic research focus. The results highlight the global distribution of expertise in PHES research, with a clear concentration in China, followed by other major economies and technologically advanced nations. The varying ratios of SCP to MCP across countries reveal different research strategies and capacities.

Countries with high SCP numbers may have more developed domestic research ecosystems, potentially leading to faster implementation of pumped hydro technologies tailored to their needs. Conversely, countries with more MCPs may benefit from knowledge transfer and international best practices. However, they might face challenges in developing solutions uniquely suited to their local contexts. The results also suggest potential areas for increased international collaboration, particularly for countries with low MCP numbers. Enhanced collaboration could lead to more innovative solutions and accelerated global adoption of PHES technologies. Furthermore, the dominance of certain countries in both SCP and MCP might indicate their potential to shape global standards and practices in PHES. However, it also raises questions about equitable access to cutting-edge research and technology for countries with lower research output. This disparity could affect the global transition to renewable energy systems, potentially widening the gap between nations regarding energy infrastructure development.

4.5. Analysis of trend topics

The trend topics in Fig. 12 provide a comprehensive overview of this field's evolution and current focus areas from 2009 to 2022. The visualisation reveals several key insights and implications for the renewable energy sector. Notably, "pumped storage" and "pumped hydro storage" consistently appear as prominent topics throughout the timeline, indicating their enduring significance in energy storage discussions. The increasing frequency and recency of terms like "renewable energy," "wind energy," and "battery storage" suggest a growing integration of pumped hydro systems with other renewable technologies and storage solutions. This trend implies a shift towards more holistic and diversified approaches to energy management. The emergence of "optimisation" as a high-frequency term in recent years points to a focus on improving the efficiency and performance of PHES systems.

Similarly, "uncertainty" near the top of the figure in recent years highlights the challenges and complexities in implementing and managing these systems in a rapidly evolving energy sector. The appearance of "hydrogen" as a recent trend indicates a potential new direction in energy storage, possibly exploring synergies between pumped hydro and hydrogen technologies. The consistent presence of "energy storage" throughout the timeline indicates the central role of storage solutions in the renewable energy transition. Topics like "100% renewable energy" and "renewable integration" suggest an increasing ambition towards fully sustainable energy systems, with PHES playing a critical role. The figure also shows a progression from broader concepts like "CAES (compressed air energy storage)" and "wind power" in earlier years to more specific and technical topics in recent years, such as "hybrid system" and "power system economics." This shift implies a maturing field with a growing emphasis on practical implementation and economic viability. The presence of "modeling" and "simulation" indicates the importance of advanced analytical tools in planning and optimising pumped hydro systems. This trend analysis reveals a dynamic and evolving field, with PHES adapting to new challenges and opportunities in the renewable energy sector and playing an increasingly crucial role in the transition to sustainable energy systems.

4.6. Conceptual structure

4.6.1. Co-occurrence network analysis

The co-occurrence network visualisation centred on pumped hydro storage reveals a complex web of interconnected concepts and technologies within the energy sector, as shown in Fig. 13. At the core, pumped hydro storage appears as the central node, indicating its significant role in energy storage discussions and research. The network shows a dense cluster of red nodes closely linked to pumped hydro storage, suggesting a strong association with various aspects of renewable energy, particularly wind and solar power. This connection highlights the critical role of pumped hydro in addressing the intermittent challenges of renewable sources. The presence of terms like "energy management," "grid stability," and "load balancing" in proximity to the central node emphasises pumped hydro's importance in maintaining power system reliability and flexibility. The network also illustrates

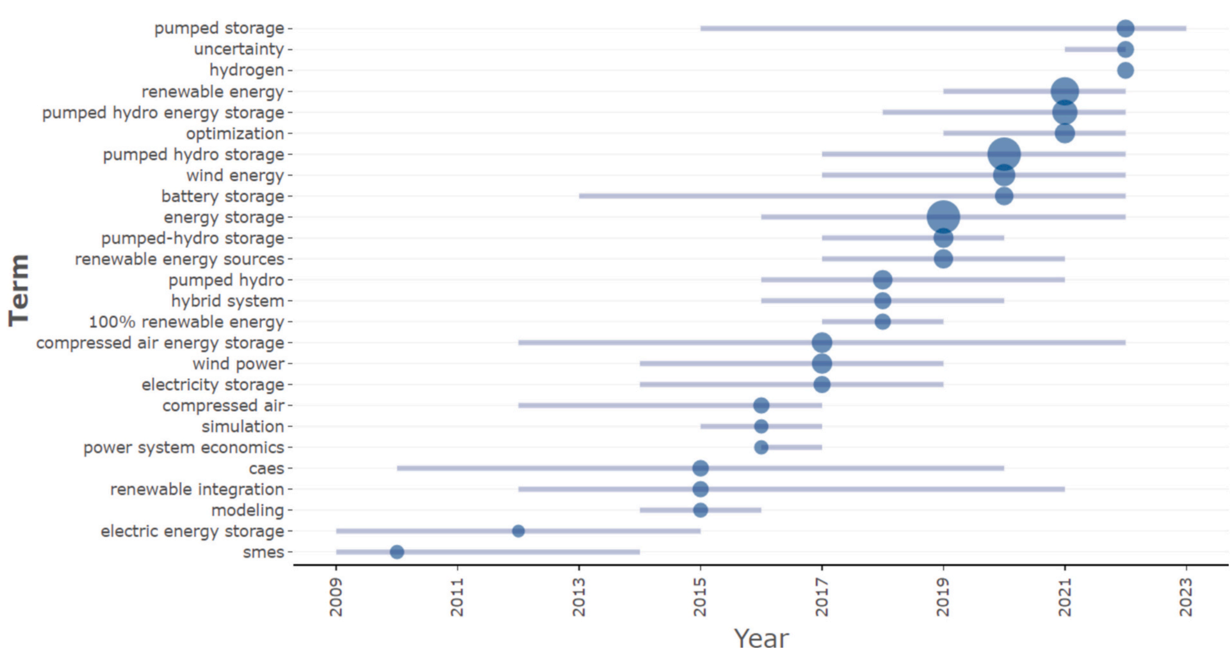

Fig. 12. Trend topics from 2009 to 2023.

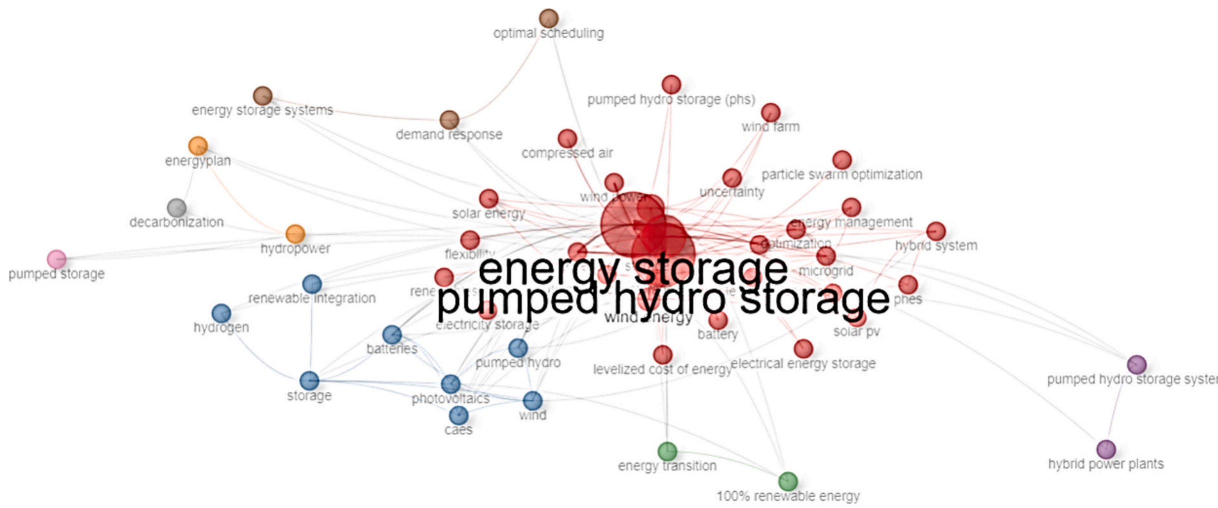

Fig. 13. Co-occurrence network.

connections to other energy storage technologies, such as batteries and hydrogen, implying a complementary rather than competitive relationship between storage solutions. The appearance of economic and policy-related terms (e.g., "energy market," "regulatory framework") indicates that pumped hydro storage is not just a technical solution but also a subject of market dynamics and policy considerations. Environmental factors are represented in the network, suggesting ongoing discussions about the ecological impacts and sustainability of pumped hydro projects. The presence of nodes related to optimisation and efficiency improvements points to active research and development efforts to enhance the technology's performance.

Interestingly, the network shows links to concepts like "demand response" and "smart grids," hinting at pumped hydro's potential role in future, more dynamic energy systems. The diversity of connected nodes, spanning technical, economic, environmental, and policy domains, signifies the complex nature of pumped hydro storage and its wide-ranging implications for energy systems. This comprehensive network suggests that pumped hydro storage is a key technology for enabling higher penetration of renewable energy and a focal point for broader discussions on energy transition, grid modernisation, and sustainable development. The implications of these results demonstrate that pumped hydro storage will likely remain a critical component of the future energy sector, requiring interdisciplinary approaches to leverage its potential and address associated challenges fully.

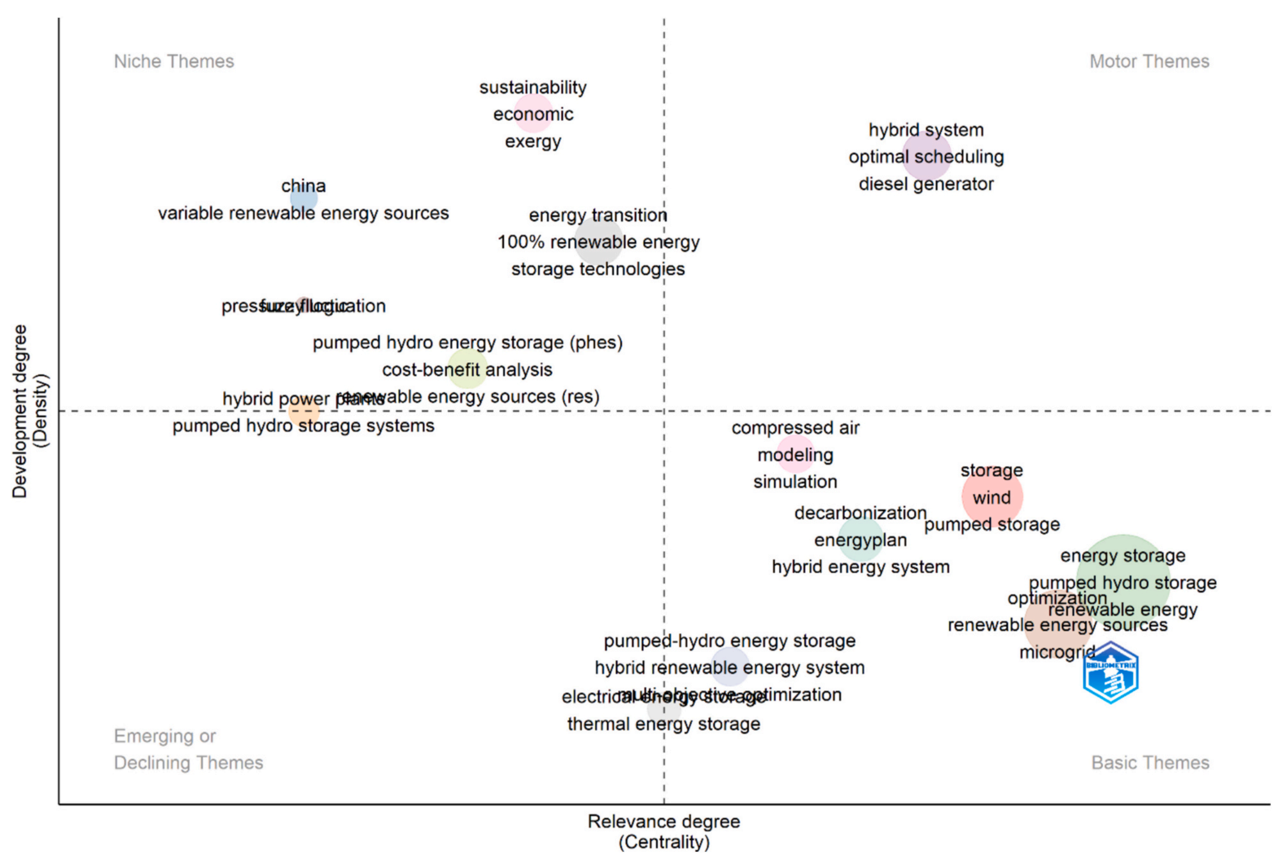

Fig. 14. Thematic map of keywords.

4.6.2. Thematic mapping

Fig. 14 displays the thematic map of keywords that evolved over the study period. The thematic map is divided into four quadrants: basic themes, niche themes, motor themes, and emerging/declining themes. The map provides valuable insights into the current state and future directions of PHES research. The niche themes quadrant comprises topics like "sustainability," "economic," and "exergy," positioned prominently, indicating their specialised but potentially impactful nature in the field. The presence of "China" in this quadrant suggests a significant focus on pumped hydro developments in this country.

The motor themes quadrant, representing high development and centrality, includes "hybrid system," "optimal scheduling," and "diesel generator," highlighting the integration of pumped hydro with other energy systems and the importance of operational optimisation. The basic themes quadrant is densely populated, featuring concepts like "storage," "wind," "pumped storage," "energy storage," and "renewable energy sources." This concentration indicates a strong research foundation on core aspects of pumped hydro technology and its role in renewable energy integration.

The emerging/declining themes quadrant shows promising areas like "pumped-hydro energy storage," "hybrid renewable energy system," and "thermal energy storage," suggesting evolving research directions that may gain prominence in the future. The map also reveals interesting cross-cutting themes such as "energy transition" and "100% renewable energy," positioned at the intersection of multiple quadrants, highlighting their relevance across different aspects of PHES research. The prominence of "variable renewable energy sources" in the niche themes quadrant emphasises the critical role of pumped hydro in addressing intermittency challenges. The positioning of "cost-benefit analysis" near the centre of the map highlights its pervasive importance across various research areas.

The implications of these results are significant for researchers, policymakers, and industry stakeholders. The map suggests that future research could focus on integrating pumped hydro with hybrid systems, optimising scheduling, and operations, and exploring innovative storage technologies. The emphasis on sustainability and economic aspects in the niche themes indicates a need for more studies on pumped hydro projects' long-term viability and cost-effectiveness. "China" as a niche theme implies the potential for international collaboration and knowledge exchange in pumped hydro development. The map also highlights the importance of addressing technical challenges related to grid integration, as evidenced by themes like "microgrid" and "decarbonisation." The positioning of "energy transition" and "100% renewable energy" themes highlights the vital role of pumped hydro in achieving broader energy and climate goals. Researchers should consider exploring the intersections between basic themes and emerging concepts to drive innovation in the field. For policymakers, the map suggests the need for supportive frameworks that encourage the development of hybrid systems and the integration of pumped hydro with variable renewable sources. Industry stakeholders can use these insights to guide investment decisions, focusing on areas with high potential development potential, such as optimal scheduling and hybrid systems.

4.6.3. Thematic evolution

The thematic evolution of keywords in Fig. 15 shows a fascinating progression in research focus and technological development. It can be seen that, in the initial period (2003–2017), the emphasis was primarily on fundamental concepts and broad applications, with keywords such as "pumped-hydro energy storage," "compressed air energy storage," and "electricity storage" dominating the discourse. This suggests a period of establishing the basic principles and potential of pumped hydro storage within the broader context of energy systems. "wind energy" and "power system economics" indicate early recognition of pumped hydro's role in supporting renewable integration and its economic implications.

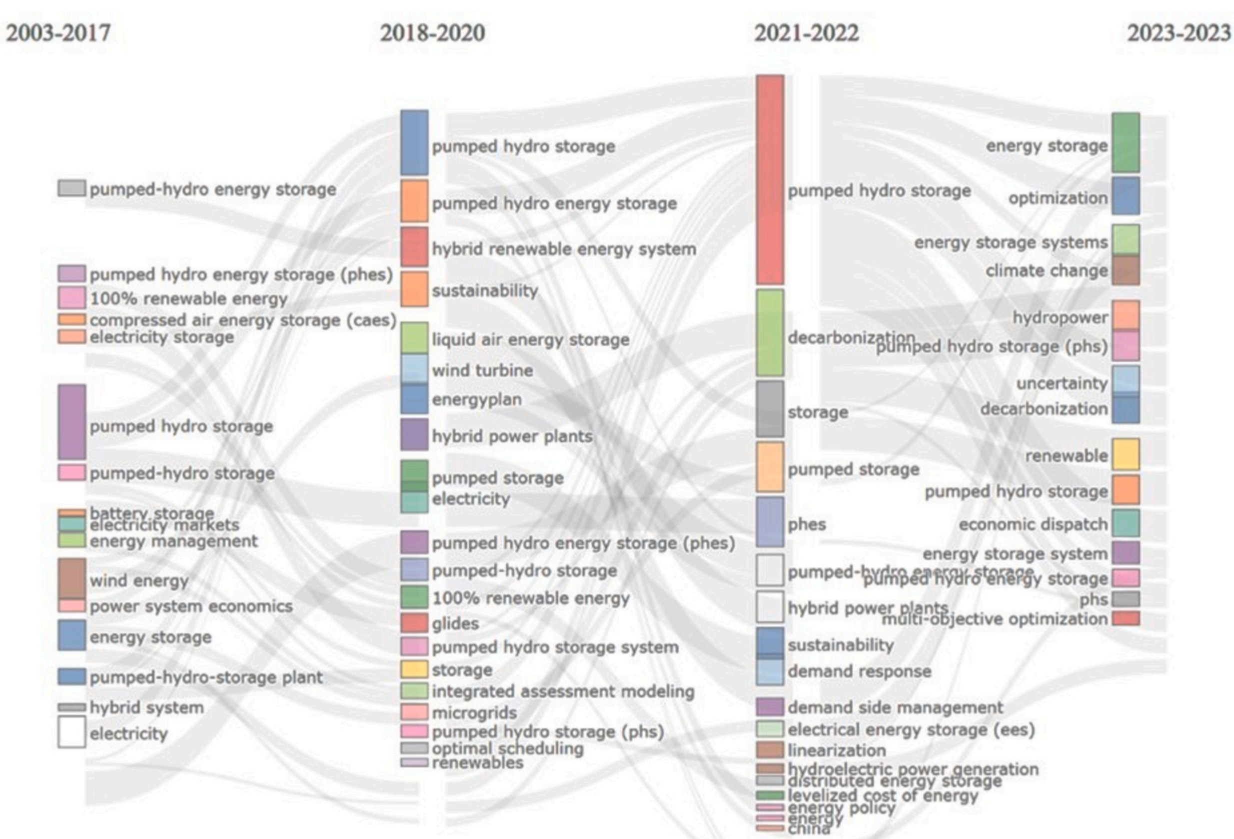

Fig. 15. Thematic evolution of keywords.

Moving into the 2018–2020 period, observed a shift towards more specific and advanced applications. The emergence of the "hybrid renewable energy system" and "sustainability" keywords signifies a growing interest in integrating pumped hydro storage with other renewable technologies to create more sustainable energy solutions. The appearance of "liquid air energy storage" and "wind turbine" suggests a diversification of energy storage technologies and a closer focus on wind power integration. "EnergyPlan" and "hybrid power plants" emphasise comprehensive energy system planning and hybrid solutions. The 2021–2022 period marks a significant transition, with "pumped hydro storage" becoming the dominant keyword, suggesting a renewed focus on this technology as a central solution for energy storage. The prominence of "decarbonisation" and "climate change" signifies the growing urgency of addressing environmental concerns through energy storage solutions. "Demand response" and "sustainability" highlight the evolving role of pumped hydro in grid flexibility and sustainable energy practices. The appearance of "multi-objective optimisation" indicates more sophisticated system design and operation approaches. The most recent period (2023) shows a further diversification and specialisation of topics. "Energy storage" remains prominent, but new keywords like "optimisation," "uncertainty," and "economic dispatch" suggest a focus on refining and improving the efficiency and economic viability of pumped hydro systems. Including "renewable" and "decarbonisation" reinforces the ongoing importance of pumped hydro in the transition to clean energy. "Hydropower" appears as a distinct keyword, possibly indicating a renewed interest in the synergies between conventional hydropower and pumped storage.

This thematic evolution has several important implications. Firstly, it signifies the growing recognition of PHES as an essential technology for enabling high penetration of renewable energy and achieving decarbonisation goals. The shift from general concepts to more specific and advanced topics suggests a maturing field, with research now focusing on optimising performance, addressing uncertainties, and improving economic viability. The consistent sustainability-related keywords throughout the periods highlight the long-term commitment to environmental considerations in energy storage development. The evolution also points to the increasing integration of pumped hydro storage with other technologies and energy system components, as evidenced by the recurring themes of hybrid systems and grid integration. This suggests a future where pumped hydro plays a central role in complex, multi-technology energy systems. The emergence of keywords related to optimisation and economic dispatch in recent years indicates a growing focus on making pumped hydro storage more competitive and efficient in energy markets. Additionally, the thematic progression highlights pumped hydro storage's expanding role beyond energy arbitrage. Its evolving applications in grid stability, demand response, and supporting various renewable technologies demonstrate its versatility and importance in the future energy sector. The recent focus on uncertainty and optimisation techniques suggests acknowledging the challenges in predicting and managing energy systems with high renewable penetration and the critical role pumped hydro can play in addressing these challenges.

4.6.4. Factorial analysis

Fig. 16 presents the factorial analysis, which reveals a complex interplay of factors and concepts within the field. At the top of the map is a cluster of renewable energy sources and storage technologies, including "photovoltaics," "wind," "CAES" (compressed air energy storage), and "batteries." This grouping suggests a strong association between pumped hydro and other renewable energy and storage solutions, indicating its role in a diverse energy mix. The proximity of "solar photovoltaics" and "wind energy" to "pumped hydro" and "PHS"

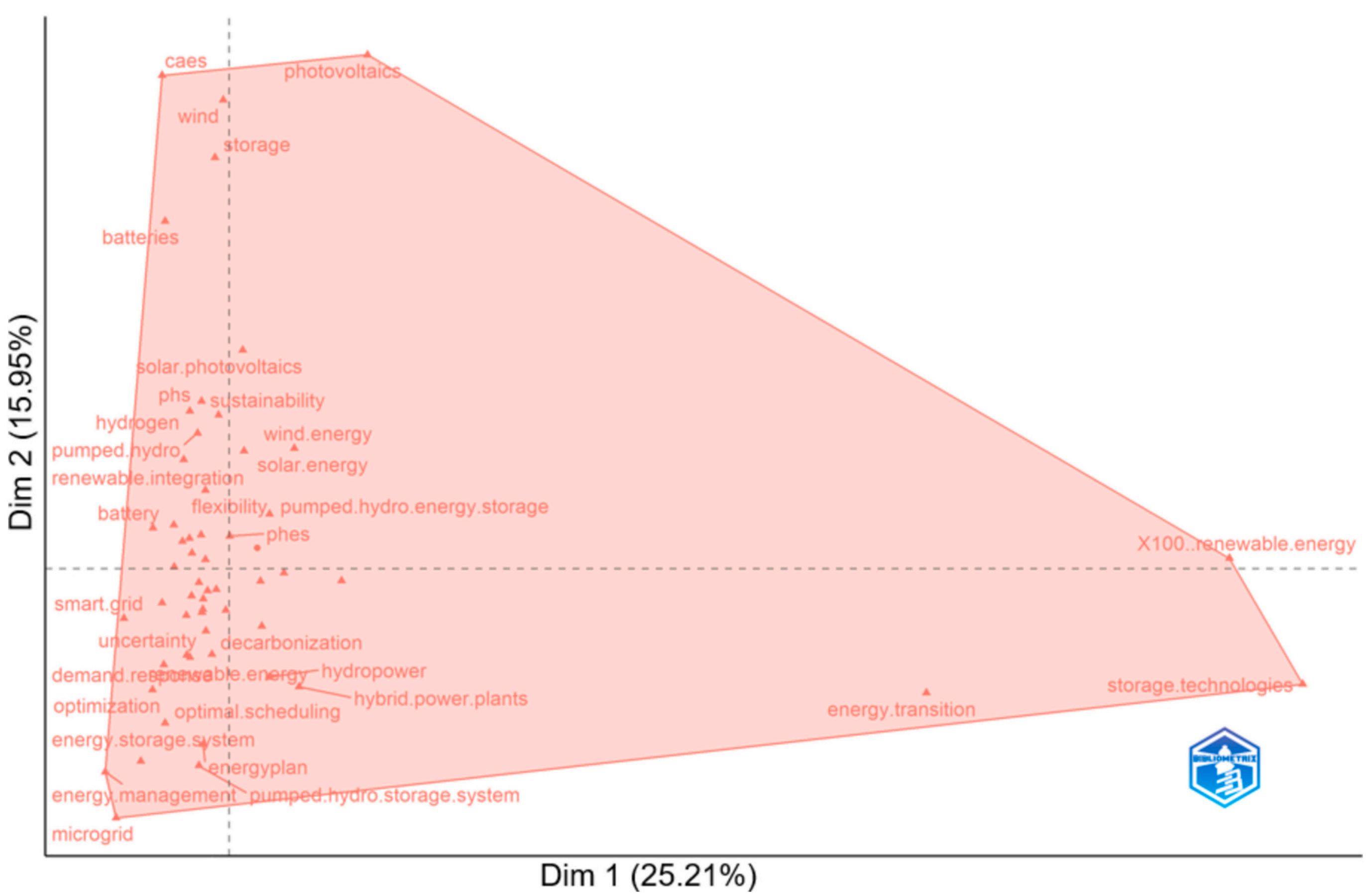

Fig. 16. Factorial analysis of keywords.

(pumped hydro storage) emphasises the synergistic relationship between these technologies in managing intermittent renewable sources.

The central region of the map contains concepts like “sustainability,” “renewable integration,” and “flexibility,” highlighting the critical role of pumped hydro in enabling a more sustainable and flexible energy system. The presence of “smart grid” and “energy management” in the lower portion of the map emphasises the importance of pumped hydro in grid stabilisation and overall energy system management.

Interestingly, “100% renewable energy” appears as an outlier on the right side of the map, connected to “storage technologies” and “energy transition.” This positioning suggests that pumped hydro is viewed as a key enabler in pursuing fully renewable energy systems but also indicates that achieving this goal involves complex interactions with various storage and transition strategies. The lower left quadrant includes operational and planning concepts such as “optimal scheduling,” “demand response,” and “energy storage system,” emphasising the technical and logistical challenges in integrating pumped hydro into existing energy infrastructures. The presence of “decarbonisation” in this area links these operational aspects to broader climate goals.

The implications of these results are significant for the future of energy systems and climate change mitigation efforts. The analysis suggests that pumped hydro energy storage is not viewed in isolation but as part of a broader ecosystem of renewable energy technologies and grid management strategies. Its central position in relation to various renewable sources, storage technologies, and grid management concepts indicates its potential as a linchpin in the transition to sustainable energy systems. The results also imply that future research and development in pumped hydro should focus on enhancing its flexibility and integration capabilities with other renewable sources and smart grid technologies. The emphasis on sustainability and decarbonisation suggests that environmental considerations will continue to be a driving force in developing and deploying pumped hydro systems. Furthermore, the analysis highlights the need for interdisciplinary approaches in addressing the challenges of energy transition, combining technical innovations with policy frameworks that support the integration of pumped hydro into comprehensive energy strategies.

4.7. Author productivity, journals, institutions, and citations analyses

Fig. 17 illustrates authors’ productivity in the field using Lotka’s law, which describes the frequency distribution of scientific productivity. The figure shows a steep decline in the percentage of authors as the number of documents written increases, following a typical power law distribution. This pattern reveals that a few highly productive authors contribute a large proportion of the publications in this field. At the same time, most researchers publish only one or a few papers. The solid and dashed lines likely represent observed and expected distributions, respectively, with close alignment indicating that author productivity in PHES research largely conforms to Lotka’s Law. This distribution has significant implications for the field. It suggests that PHES research is characterised by a core group of specialised experts who consistently contribute to the knowledge base, potentially driving innovation and setting research agendas. These prolific authors may serve as key opinion leaders, mentors, and collaboration hubs within the research community. However, the steep drop-off in productivity also indicates a large pool of researchers who contribute occasionally or are new to the field, which could bring fresh perspectives and interdisciplinary insights. The long tail of low-productivity authors might represent practitioners, graduate students, or researchers from adjacent fields who publish on PHES sporadically. This diversity can benefit the field’s development, fostering cross-pollination of ideas and linking academic research with practical applications. The observed distribution also has implications for research evaluation and funding allocation, highlighting the need to balance support between established experts and emerging researchers. Furthermore, it highlights the importance of collaboration and knowledge sharing to leverage the collective expertise of both high-productivity authors and the broader research community.

The ranking of the top 20 journals with the most publications in the field is presented in Table A1. The Journal of Energy Storage has the highest publications, followed closely by Applied Energy and Energy. Energies and Renewable and Sustainable Energy Reviews round out the top five with 46 and 36 articles, respectively. This distribution highlights the interdisciplinary nature of PHES research, spanning dedicated energy storage journals, broader energy-focused publications, and sustainability-oriented outlets. The prominence of journals like Renewable Energy and Energy Conversion and Management emphasises the technology’s relevance to renewable energy integration and efficient energy management. The appearance of policy-oriented journals such as Energy Policy indicates that the socio-economic and regulatory aspects of pumped hydro storage are also being explored. The presence of the Encyclopedia of Energy Storage, with 11 articles, demonstrates the consolidation of knowledge in this area. Journals focusing on cleaner production and sustainability, like the Journal of Cleaner Production and Sustainability (Switzerland), each with 11 and 10 articles, respectively, highlight the environmental considerations in pumped hydro research. The inclusion of IEEE publications and conference proceedings

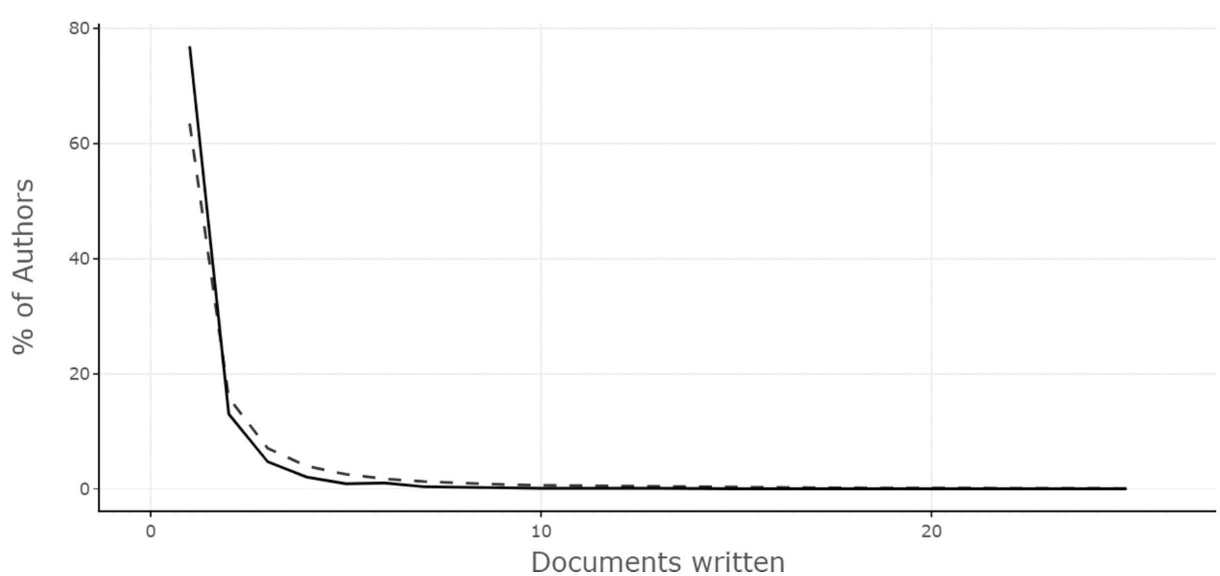

Fig. 17. Author Productivity through Lotka’s Law.

points to this technology's electrical engineering and power systems aspects. This distribution of publications across various journals implies a holistic approach to PHES research, comprising technical, environmental, economic, and policy dimensions. The results indicate a robust and diverse research ecosystem, suggesting that PHES is recognised as a critical component in the transition to sustainable energy systems, with implications spanning from technological advancements to policy formulation and environmental impact assessment.

Table A2 shows the ranking of the top 20 institutions actively involved in PHES research over the two decades. The results show a global distribution of research efforts, with a notable concentration in China and significant contributions from institutions across Asia, Europe, and Australia. North China Electric Power University has the highest publications, followed closely by the Australian National University. Chinese institutions dominate the top ranks, with Xi'an Jiaotong University, Shanghai Jiao Tong University, and Hohai University contributing 40, 39, and 33 articles, respectively. This strong Chinese presence signifies the country's significant investment in renewable energy and energy storage technologies. The Australian National University's high ranking highlights Australia's focus on pumped hydro as a solution for its renewable energy integration challenges. European institutions also feature prominently, with the Delft University of Technology, the National Technical University of Athens, and the University of Padova among the top contributors. This suggests a robust European research ecosystem, likely driven by the continent's ambitious renewable energy targets. The presence of Universiti Tenaga Nasional from Malaysia, which has 24 articles, indicates a growing interest in PHES in Southeast Asia. The table also includes institutions from Denmark (Aalborg University), South Africa (Central University of Technology), India (National Institute of Technology), Greece (Hellenic Mediterranean University), Cameroon (University of Buea), and Croatia (University of Zagreb), highlighting the global nature of PHES. The diversity of institutions suggests that PHES is being studied in various geographical and climatic contexts, potentially leading to a rich body of knowledge on its application in different environments. The strong representation of universities known for their engineering programmes implies a focus on the technical aspects of PHES. However, the presence of institutions from developing countries like Cameroon indicates a growing interest in this technology for addressing energy challenges in diverse economic contexts. This global distribution of research efforts has significant implications for the future of PHES. It suggests that a broad base of expertise is being developed worldwide, which could accelerate technological advancements, policy formulation, and implementation strategies. The research concentration in China and other Asian countries may lead to these regions becoming leaders in pumped hydro technology and deployment. Meanwhile, the contributions from European and Australian institutions could drive innovations in integrating pumped hydro with advanced grid systems and variable renewable energy sources. This diverse research sector bodes well for the future of PHES as a critical component of global energy transition strategies.

Fig. 18 displays the top 20 most cited countries. It can be observed that China leads in total citations with 5527, indicating its substantial research output in this field. However, its average article citation of 40.30 suggests that while prolific, the impact per article is moderate compared to other countries. The United States follows with 2293 total citations and a higher average of 51 per article, indicating a strong balance between quantity and impact. Surprisingly, several countries with fewer total citations show remarkably high average citation rates. Hong Kong stands out with an exceptional average of 305.5 citations per article, although with a lower total citation count. This suggests that while Hong Kong may produce fewer papers, they are highly influential.

Similarly, Ireland, Malaysia, Canada, and Finland demonstrate high average citation rates, indicating that their research, though less voluminous, has a significant impact. European countries like Germany, Italy, the Netherlands, Greece, and Spain show a mix of total and average citation performance, demonstrating the continent's diverse research area in PHES. Australia's presence underlines its commitment to this technology, which is likely driven by its unique geographical and energy challenges. The appearance of developing economies like India, Iran, and South Africa in the top 20 highlights the global relevance of PHES research, spanning both developed and emerging markets. These results have several implications for the field of PHES. Firstly, they suggest that while the quantity of research is essential, as demonstrated by China's leading position, the quality and impact of research can vary significantly. Countries with high average citation rates may produce particularly innovative or relevant research that resonates widely in the field. The strong showing of smaller countries like Finland, Ireland, and Hong Kong implies that targeted, high-quality research can have a substantial impact regardless of a country's size or total research output. The global distribution of research efforts indicates that pumped hydro storage is recognised as a crucial technology for energy transition worldwide, with established and emerging economies contributing

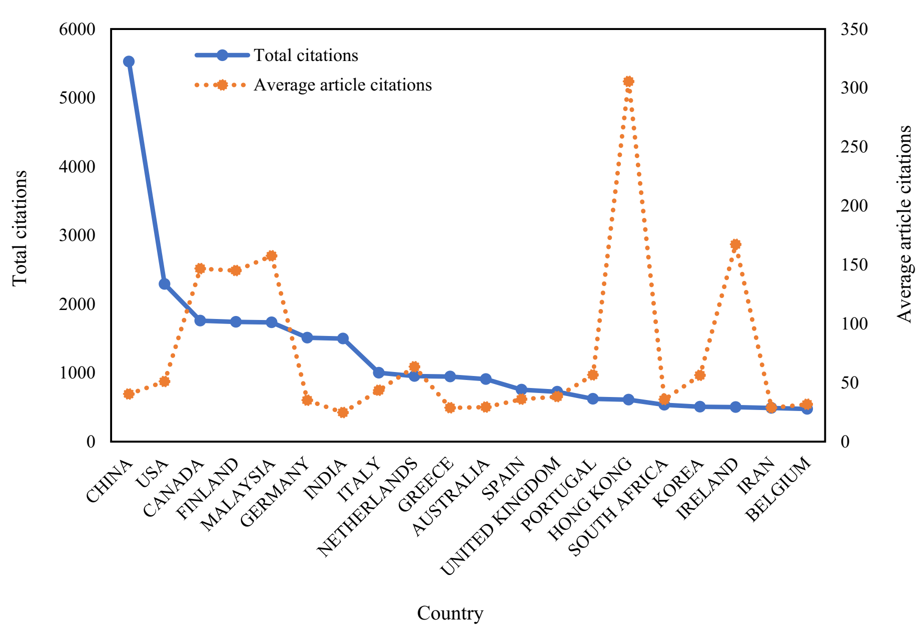

Fig. 18. Top 20 most cited countries.

significantly. This diversity of research sources could lead to a rich tapestry of approaches and solutions, potentially accelerating the development and deployment of pumped hydro storage technologies. Furthermore, the varying citation patterns might reflect different research priorities or areas of expertise across countries, suggesting opportunities for international collaboration to leverage complementary strengths.

4.8. Analysis of the top 50 most relevant cited papers

This section discusses the findings and recommendations from the most relevant top-cited papers in the study period, as shown in Table A3. The high citation counts of these papers, led by Rehman et al.'s technological review with 814 citations, indicate their influence and importance in advancing knowledge and understanding in the field. Table A3 shows a wide range of research topics related to PHES, including technical reviews, techno-economic analyses, feasibility studies, optimisation of operations, and integration of pumped hydro with other renewable energy sources like solar and wind. This diversity of research indicates the growing importance and complexity of pumped hydro storage in the broader context of renewable energy systems. Likewise, the high citation counts, ranging from 814 to 79, suggest that these papers have had a significant impact on the field and have been widely recognised by the research community.

PHES has emerged as a vital technology for large-scale electricity storage, particularly in the context of increasing renewable energy integration. In view of this, several authors have highlighted its significance, efficiency, and potential for future development. For instance, Rehman et al. [64] emphasised that PHES remains the most commercially viable and suitable technology for large-scale electricity storage, especially for stabilising grids with high renewable energy penetration. The authors alluded that PHES systems typically achieve energy efficiencies between 70 % and 80 %, with some systems claiming up to 87 %. Deane et al. [65] observed a renewed commercial and technical interest in PHES, with over 7 GW of capacity expected to be added in Europe within eight years, alongside developments in the USA and Japan. The study noted a trend towards repowering, enhancing, or building 'pump-back' PHES projects in liberalised markets. Depending on site-specific factors, capital costs for new PHES projects vary widely between €470/kW and €2170/kW. The authors also highlighted adopting variable speed technology, which offers greater operational flexibility and efficiency at a slightly higher cost.

Several studies have focused on integrating PHES with renewable energy sources, particularly in remote or isolated areas. For example, Ma et al. [66] found that PHES is a viable technology for integrating solar energy into small, autonomous systems in remote areas. Their study used genetic algorithms and Pareto optimality for techno-economic optimisation, achieving zero loss of power supply probability in a real remote island scenario. Bueno and Carta [14] proposed a wind-powered PHES system for Gran Canaria that could increase renewable energy share by 1.93 % at a competitive cost. Utilising existing reservoirs, the system would lead to significant environmental benefits, yearly reductions of 13,655 metric tonnes in fossil fuel usage, and a decrease of 43,064 metric tonnes in carbon dioxide (CO_2) emissions. Ma et al. [67] demonstrated that incorporating PHES into a hybrid solar-wind system can mitigate the variability of renewable energy sources. The hour-by-hour simulation showed that this combination provides a stable and sustainable power solution, enabling 100 % energy self-sufficiency for isolated communities.

In comparing storage options, Ma et al. [54] found that combining pumped storage with a battery bank reduces life-cycle costs (LCC) to 55 % of advanced deep cycle batteries alone. The most cost-effective solution was purely pumped storage with a hydraulic controller, with the lowest LCC, representing 29–48 % of the LCC for advanced deep cycle batteries. Barbour et al. [68] revealed that despite PHES being a well-established bulk electrical energy storage (EES) technology with a global installed capacity of approximately 130 GW, bulk EES deployment remains limited. The study emphasised the need for effective reward mechanisms to make bulk EES more attractive to investors and discussed the role of public-sector investment in overcoming private-sector hesitance.

Javed et al. [15] reviewed recent advances in PHES technology, noting improved flexibility, response time, and performance. The authors highlighted the potential of hybrid storage systems, such as PHES-battery combinations, for overcoming individual limitations. They suggested areas for future research in modeling and techno-economic optimisation of RE-based PHES systems. Yang and Jackson [13] highlighted that the primary barriers to PHES development are environmental issues and financial uncertainties rather than the lack of technically viable sites. Ardizzon et al. [69] observed a resurgence in global interest in PHES and the refurbishment of older small hydropower plants. The study emphasised the importance of advancements in turbine technology to enhance plant efficiency and flexibility and the need for innovative approaches to optimise storage capacity and increase profitability.

Zhang et al. [70] modelled scenarios combining PHES with electric boilers and wind capacity. The analysis revealed that combining 3.6 GW of PHES, 6.2 GW of electric boilers, and 40 GW of wind capacity could lower CO_2 emissions by 43.5 million tonnes compared to the business-as-usual scenario. Javed et al. [71] studied a hybrid pumped hydro-battery storage system and found that PHES is the primary storage for high energy demands. In contrast, battery storage covers very low energy shortfalls. The authors achieved a storage usage factor of 7.3 % for pumped storage and an energy utilisation ratio of 16.5 % for the entire system. de Boer et al. [72] found that large-scale energy storage techniques generally reduce economic costs in the electricity system, with PHES showing the greatest cost reductions. However, storage technologies increased fuel use and greenhouse gas emissions in some scenarios.

Blakers et al. [23] emphasised that PHES dominates global energy storage capacity and remains the most cost-effective solution for large-scale, long-term energy storage. The study highlighted the potential of closed-loop off-river PHES systems for low-cost, large-scale storage without the environmental impacts associated with river-based systems. Kapsali and Kaldellis [73] investigated the technical and economic viability of a wind-hydro solution on the island of Lesbos, significantly increasing renewable energy contribution to nearly 20 % of the island's total electricity consumption while enhancing grid stability. Fan et al. [74] explored the feasibility of hybrid PHES systems using coal mine goafs, and found an average system efficiency of 82.8 % and a regulating-energy density of 1.06 kWh/m^3. The authors concluded that such systems could be developed in the short term for daily energy regulation in China. Ding et al. [75] showed that coordinating wind farms and PHES plants significantly mitigates the negative effects of wind power fluctuations on the power grid and enhances profitability. Their proposed models successfully balanced profit from energy sales with penalties for output deviations.

Stoppato et al. [76] developed an optimisation model based on particle swarm theory. They revealed that incorporating a pump as a turbine can save about 4 % of diesel fuel costs in a hybrid system. The study showed that when striving for a fully renewable system, the optimal size of the photovoltaic plant is about 16 times larger than in a mixed system. Wang et al. [77] introduced the bat algorithm simulated annealing for solving unit commitment problems, showing that while increasing renewable energy power forecast error leads to higher load fluctuations and operating costs, PHES effectively mitigates these negative impacts, enhancing system stability. Bruninx et al. [78] found that both deterministic and interval unit commitment models, which account for the hydraulic constraints of PHES, achieved significant operational cost reductions due to the regulating capabilities of PHES. Kusakana [79] demonstrated that integrating pumped hydro storage with photovoltaic and wind power sources and a diesel generator can achieve fuel savings and reduce operational costs compared to relying solely on the diesel generator.

Guezgouz et al. [16] showed that a hybrid storage system (combining pumped hydro and batteries) enables higher reliability at lower cost than systems using a single storage technology. For a system with 97.5 % reliability, the hybrid storage cost was €0.162/kWh, compared to €0.207/kWh for battery-only and €1.462/kWh for pumped storage-only systems. Hozouri et al. [80] developed a posterior multi-objective optimisation framework that effectively addresses wind energy curtailment cost, total social cost, and storage units' revenue. Chaudhary and Rizwan [81] proposed a hybrid model that outperforms existing methods like artificial neural networks for solar power forecasting accuracy. They also demonstrated that integrating a demand response programme and a pumped hydro storage system helps enhance grid reliability and flexibility. Bhayo et al. [82] found that integrating a rainfall-based hydropower system with a photovoltaic-battery system reduces the installed photovoltaic capacity by about 13 %, with the lowest levelized cost of energy at 0.443 USD/kWh achieved when hydropower serves as the primary backup.

Pérez-Díaz & Jiménez [83] showed that incorporating a pumped-storage hydropower plant can reduce system scheduling costs by 2.5–11 %, facilitate wind energy integration, and potentially reduce the reliance on inflexible thermal generating units. Makhdoomi and Askarzadeh [84] proposed a modified crow search algorithm with adaptive chaotic awareness probability that outperforms other optimisation techniques, resulting in more accurate and robust solutions for optimal sharing of deficit power between diesel generators and PHES. Segurado et al. [85] demonstrated that applying their proposed optimisation methodology to the island of S. Vicente in Cape Verde can increase renewable energy penetration to 84 %, reduce power and water production costs by 27 %, and decrease CO_2 emissions by 67 %. Kapsali et al. [86] found that a proposed wind-based pumped hydro storage system can increase the contribution of renewable energy by 15 % on an island, covering 25 % of the island's energy needs. The most economically viable configuration achieved a payback period of less than 10 years.

Ming et al. [12] highlighted China's significant progress in PHES development, projecting a future target of 50.02 GW by 2020. They recommended the temporary operation and scheduling of PHES by grid companies and emphasised the importance of government subsidies in supporting renewable energy integration. Lu et al. [87] successfully identified potential dry-gully and turkey's nest sites for off-river pumped hydro storage in South Australia, demonstrating the effectiveness of GIS-based site search algorithms for large-scale assessments. Foley et al. [88] found that the incentive to invest in capital-intensive pumped hydro storage to firm wind power is limited unless significant external market costs are involved. They also highlighted the growing importance of ancillary services in future power systems with increased wind power. Katsaprakakis et al. [89] showed that introducing pumped storage systems (PSS) in Crete results in nearly a 10 % reduction in annual electricity production costs and eliminates wind energy rejection. However, they found that PSS introduction in Rhodes was not economically attractive, concluding that PSS benefits isolated power systems with specific energy production costs higher than approximately €0.05/kWh.

Das et al. [90] identified the PV/diesel/PHES system as the most cost-effective configuration, with an energy cost of 0.27 USD/kWh, compared to other combinations. They also found that the genetic algorithm method offers a more cost-effective and sustainable solution than the HOMER software tool used in their analysis. Zhang et al. [91] studied vibrations in pumped storage power stations, identifying three distinct regions of vibrational characteristics based on load conditions. They found that vibrations of the top cover are primarily induced by fluid flow within the turbine. In contrast, vibrations of the upper and lower brackets are less influenced by load and water head variations.

Yimen et al. [92] identified an optimal system configuration for a hybrid renewable energy system in sub-Saharan Africa, resulting in a cost of energy of €0.256/kWh and a total net present cost of €370,426. Their study is notable for using HOMER's pumped-hydro component and considering seasonal agricultural demand variations. Kocaman and Modi [93] demonstrated that pumped hydro storage can significantly reduce the reliance on diesel in isolated systems, keeping its contribution below 10 % compared to more than 50 % in conventional systems with limited streamflow. They also suggested that conventional hydropower stations could be converted to pumped hydro stations with a smaller upper reservoir, reducing diesel use and lower system costs. Stocks et al. [46] identified 616,000 potential closed-loop PHES sites globally with a combined storage potential of 23,000 TWh, significantly more than needed to support large-scale renewable electricity integration. This vast and widely distributed resource is well-suited to support extensive solar and wind deployment for grid decarbonisation.

Hunt et al. [7] proposed combined short and long-term cycles for pumped-hydro storage as a viable solution for energy storage in regions with flat topography and arid climates, such as the upper Zambezi water basin. Their approach significantly reduces the cost of water storage to near zero. Cavazzini et al. [17] identified behaviour instabilities in pump turbines when operating at part loads and frequently switching between pump and turbine modes. These instabilities limit the ability of PHES to provide effective regulation services over a wide operational range, highlighting the need for a comprehensive design strategy that optimises pump-turbine geometry for stability in both modes. Vasudevan et al. [18] reviewed power converter topologies and control techniques for variable speed PHES systems. They identified specific domains that need further research to enhance the efficiency and effectiveness of PHES systems.

Schill and Kemfert [94] found that the utilisation of pumped hydro storage and its associated welfare effects are influenced by the storage ownership and the operator's involvement in conventional generation. They noted that strategic operators often under-utilise their storage capacity, leading to welfare losses, especially if an oligopolistic generator controls both storage and conventional generation. Kusakana [95] developed and presented the operation principle, mathematical model, and simulation model for a hydrokinetic system combined with pumped hydro storage. Their techno-economic analysis showed that integrating PHES with hydrokinetic systems is cost-effective, reliable, and environmentally friendly compared to traditional battery storage in rural South Africa. Kotb et al. [96] identified an optimal hybrid renewable energy system configuration for a specific application consisting of wind turbines, a photovoltaic array, a diesel generator, batteries, and a converter. This system demonstrated the best economic performance with the lowest net present cost and cost of energy while also achieving a high renewable energy share of 95.55 %.

Shabani et al. [97] found that the optimal design for meeting full power demand is the hybrid PV-wind-battery storage system, which outperforms the hybrid PV-wind-micro PHES system by offering lower life cycle costs and oversupply. De Oliveira and Hendrick [98] concluded that small-scale PHES applications are not competitive due to the absence of economies of scale that make large PHES installations viable. However, they suggested that costs could be significantly reduced if synergies with existing reservoirs can be identified. Padrón et al. [99] developed a dynamic model of Gran Canaria's power system. This demonstrates that a properly managed PHES installation can significantly enhance network stability, reduce fossil fuel consumption, and lower CO_2 emissions while enabling increased wind energy penetration.

5. Conclusions and future research directions

This comprehensive bibliometric analysis of global research trends in PHES from 2003 to 2023 provides valuable perspectives into the evolving landscape of this critical technology. The study reveals a significant surge in research interest, particularly since 2011, indicating the growing recognition of PHES as a crucial component in the transition to renewable energy systems. The dominance of China in research output, followed by India and the United States, highlights the global nature of PHES development and the potential for knowledge transfer between nations.

The major new key findings from this analysis include:

The rapid growth in publications, from 1 in 2003 to 165 in 2022, highlights the increasing importance of PHES in addressing energy storage challenges.

The emergence of themes such as hybrid storage systems, off-river PHES, and integration with variable renewable sources points to new directions in PHES research and development.

Strong international collaborations, particularly among developed nations, suggest a global recognition of PHES's importance and the potential for shared innovation.

The diversity of research topics, ranging from technical optimisations to economic feasibility studies, indicates the multifaceted nature of PHES research and its broad implications for energy systems.

These findings have significant implications for researchers, policymakers, and industry stakeholders, providing a roadmap for future research and development efforts in PHES. In charting this future roadmap, it is crucial to consider PHES's position relative to other energy storage technologies. Although PHES remains the most widely deployed large-scale storage solution globally [23], emerging technologies like lithium-ion batteries, flow batteries, and compressed air energy storage are rapidly evolving. PHES maintains advantages in terms of capacity, longevity, and proven reliability, but faces challenges in site availability and environmental impact [5,68]. Researchers should focus on enhancing PHES's compatibility with these emerging technologies, potentially in hybrid systems, to leverage the strengths of each. Additionally, innovations in reversible pump-turbines, variable speed technology, and underground PHES could further cement its role in future energy systems. In view of this, several concrete policy recommendations can be offered to guide future decisions regarding PHES development and renewable energy integration. Firstly, policymakers should prioritise the development of comprehensive regulatory frameworks that incentivise PHES projects, particularly those that integrate with variable renewable energy sources. This could include implementing feed-in tariffs or capacity payments for PHES systems that provide grid stability services. Secondly, governments should fund research and development in emerging PHES technologies, such as variable speed systems and hybrid storage solutions, to enhance efficiency and flexibility. Thirdly, environmental policies should be updated to streamline the approval process for off-river PHES projects, which have shown potential for reduced ecological impact. Additionally, international cooperation in PHES research and development should be encouraged through joint funding programs and knowledge-sharing initiatives. Finally, energy market reforms should be considered to properly value the multiple services PHES can provide, including long-duration storage, frequency regulation, and grid inertia. These policy recommendations aim to accelerate the development and deployment of PHES technologies, thereby supporting the broader transition to renewable energy systems.

Based on the findings from the bibliometric analysis, the following future research directions are proposed:

- Integrating PHES with hydrogen storage to create more efficient and flexible energy storage solutions.
- Developing strategies to minimise the ecological footprint of PHES installations, particularly for off-river systems.
- Refining models to improve the economic viability of PHES in various market structures and geographical contexts.
- Enhancing the role of PHES in smart grids, including advanced control algorithms for optimal dispatch and grid stability.
- Investigating effective policy mechanisms to incentivise PHES development and integration with renewable energy sources.
- Exploring the potential of smaller, more widely distributed PHES systems for local energy management and resilience.
- Investigating the role of PHES in providing seasonal storage capabilities to address long-term variability in renewable energy generation.
- Focusing on the potential and challenges of PHES implementation in developing countries and emerging economies.
- Investigating new materials and innovative designs for pump turbines to improve efficiency and operational flexibility.
- Conducting comparative studies assessing the long-term economic and environmental impacts of PHES versus other storage technologies in various grid scenarios.

As the energy sector evolves, PHES's ability to provide ancillary services, long-duration storage, and grid stability will likely become increasingly valuable, particularly in systems with high renewable energy penetration. This bibliometric analysis has comprehensively provided an overview of the current state of PHES research and identified key areas for future investigation. Thus, as the global energy sector evolves, PHES could enable high penetration of renewable energy sources. The identified research directions offer a roadmap for addressing the challenges and opportunities in this field, potentially leading to more efficient, economical, and environmentally friendly energy storage solutions. Moreover, continued international collaboration and interdisciplinary research will be crucial in realising the full potential of PHES in the global transition to sustainable energy systems.

CRediT authorship contribution statement

Flavio Odoi-Yorke: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Agnes Abeley Abbey:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Theophilus Adu Frimpong:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Investigation. **Enoch Asante:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology. **Ernestina Mawushie Amewornu:** Writing – review & editing, Writing – original draft, Visualization, Validation. **John Eshun Davis:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Ephraim Bonah Agyekum:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Lawrence Atepor:** Writing – review & editing, Writing – original draft, Supervision.

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.

Acknowledgements

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A

Table A1
Ranking of top 20 journals with most publications.

Ranking	Journals	Publisher	Articles
1	Journal of Energy Storage	Elsevier	58
2	Applied Energy	Elsevier	49
3	Energy	Elsevier	49
4	Energies	MDPI	46
5	Renewable And Sustainable Energy Reviews	Elsevier	36
6	Renewable Energy	Elsevier	33
7	Energy Conversion And Management	Elsevier	29
8	Energy Procedia	Elsevier	24
9	Energy Reports	Elsevier	13
10	Sustainable Energy Technologies And Assessments	Elsevier	13
11	Energy Policy	Elsevier	12
12	Encyclopedia of Energy Storage	Elsevier	11
13	Journal of Cleaner Production	Elsevier	11
14	International Journal of Energy Research	Wiley	10
15	Journal of Physics: Conference Series	IOP Publishing	10
16	Sustainability (Switzerland)	MDPI	10
17	IEEE Power And Energy Society General Meeting	IEEE (Institute of Electrical and Electronics Engineers)	9
18	IEEE Transactions On Power Systems	IEEE	9
19	International Conference On The European Energy Market	IEEE	9
20	Pumped Hydro Energy Storage For Hybrid Systems	Elsevier	9

Table A2
Ranking of top 20 institutions with most publications.

Ranking	Institution	Country	Articles published
1	North China Electric Power University	China	62
2	Australian National University	Australia	58
3	Xi'an Jiaotong University	China	40
4	Shanghai Jiao Tong University	China	39
5	Hohai University	China	33
6	Delft University of Technology	Netherlands	26
7	National Technical University of Athens	Greece	25
8	University of Padova	Italy	25
9	Universiti Tenaga Nasional	Malaysia	24
10	University of Electronic Science and Technology of China	China	23
11	Tianjin University	China	22
12	Tsinghua University	China	22
13	Aalborg University	Denmark	20
14	Central University of Technology	South Africa	20
15	National Institute of Technology	India	20
16	Hellenic Mediterranean University	Greece	19
17	Northwest A&F University	China	16
18	Sichuan University	China	16
19	University of Buea	Cameroon	16
20	University of Zagreb	Croatia	16

Table A3
Top 50 most relevant cited papers in Scopus database.

S/n	Author(s)	Title of paper	Total citations in Scopus
1	Rehman et al. [64]	Pumped hydro energy storage system: A technological review	814
2	Deane et al. [65]	Techno-economic review of existing and new pumped hydro energy storage plant	461
3	Ma et al. [66]	Pumped storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization	324
4	Bueno and Carta [14]	Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands	320
5	Ma et al. [67]	Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong	318
6	Ma et al. [100]	Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island	293
7	Barbour et al. [68]	A review of pumped hydro energy storage development in significant international electricity markets	272
8	Javed et al. [15]	Solar and wind power generation systems with pumped hydro storage: Review and future perspectives	271
9	Yang and Jackson [13]	Opportunities and barriers to pumped-hydro energy storage in the United States	231
10	Ardizzon et al. [69]	A new generation of small hydro and pumped-hydro power plants: Advances and future challenges	219

(continued on next page)

Table A3 (*continued*)

S/n	Author(s)	Title of paper	Total citations in Scopus
11	Zhang et al. [70]	Reducing curtailment of wind electricity in China by employing electric boilers for heat and pumped hydro for energy storage	213
12	Javed et al. [71]	Hybrid pumped hydro and battery storage for renewable energy-based power supply system	174
13	De Boer et al. [72]	The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels	164
14	Kim et al. [101]	Operating characteristics of constant-pressure compressed air energy storage (CAES) system combined with pumped hydro storage based on energy and exergy analysis	163
15	Steffen et al. [102]	Prospects for pumped-hydro storage in Germany	158
16	Blakers et al. [23]	A review of pumped hydro energy storage	152
17	Kapsali and Kaldellis [73]	Combining hydro and variable wind power generation by means of pumped-storage under economically viable terms	149
18	Fan et al. [74]	Preliminary feasibility analysis of a hybrid pumped-hydro energy storage system using abandoned coal mine goafs	145
19	Ding et al. [75]	Stochastic optimization of the daily operation of wind farm and pumped-hydro-storage plant	144
20	Stoppato et al. [76]	A PSO (particle swarm optimization)-based model for the optimal management of a small PV(Photovoltaic)-pump hydro energy storage in a rural dry area	136
21	Bruninx et al. [78]	Coupling pumped hydro energy storage with unit commitment	130
22	Kusakana et al. [79]	Optimal scheduling for distributed hybrid system with pumped hydro storage	128
23	Guezgouz et al. [16]	Optimal hybrid pumped hydro-battery storage scheme for off-grid renewable energy systems	121
24	Hozouri et al. [80]	On the use of pumped storage for wind energy maximization in transmission-constrained power systems	120
25	Kaldellis et al. [103]	Energy balance analysis of wind-based pumped hydro storage systems in remote island electrical networks	117
26	Chaudhary and Rizwan [81]	Energy management supporting high penetration of solar photovoltaic generation for smart grid using solar forecasts and pumped hydro storage system	110
27	Wang et al. [77]	Study on unit commitment problem considering pumped storage and renewable energy via a novel binary artificial sheep algorithm	110
28	Bhayo et al. [82]	Power management optimization of hybrid solar photovoltaic-battery integrated with pumped-hydro-storage system for standalone electricity generation	102
29	Pérez-Díaz and Jiménez [83]	Contribution of a pumped-storage hydropower plant to reduce the scheduling costs of an isolated power system with high wind power penetration	102
30	Makhdoomi and Askarzadeh [84]	Optimising operation of a photovoltaic/diesel generator hybrid energy system with pumped hydro storage by a modified crow search algorithm	101
31	Segurado et al. [85]	Optimization of a wind powered desalination and pumped hydro storage system	100
32	Kapsali et al. [86]	Wind powered pumped-hydro storage systems for remote islands: A complete sensitivity analysis based on economic perspectives	100
33	Ming et al. [12]	Overall review of pumped-hydro energy storage in China: Status quo, operation mechanism and policy barriers	95
34	Lu et al. [87]	Geographic information system algorithms to locate prospective sites for pumped hydro energy storage	94
35	Foley et al. [88]	A long-term analysis of pumped hydro storage to firm wind power	94
36	Katsaprakakis et al. [89]	Pumped storage systems introduction in isolated power production systems	94
37	Das et al. [90]	Optimal sizing of a grid-independent PV/diesel/pump-hydro hybrid system: A case study in Bangladesh	93
38	Zhang et al. [91]	Experimental study on the vibrational performance and its physical origins of a prototype reversible pump turbine in the pumped hydro energy storage power station	93
39	Yimen et al. [92]	Analyzing of a photovoltaic/wind/biogas/pumped-hydro off-grid hybrid system for rural electrification in Sub-Saharan Africa—Case study of Djoundé in Northern Cameroon	93
40	Kocaman and Modi [93]	Value of pumped hydro storage in a hybrid energy generation and allocation system	90
41	Stocks et al. [46]	Global atlas of closed-loop pumped hydro energy storage	89
42	Hunt et al. [7]	Existing and new arrangements of pumped-hydro storage plants	87
43	Cavazzini et al. [17]	Unstable behaviour of pump-turbines and its effects on power regulation capacity of pumped-hydro energy storage plants	87
44	Vasudevan et al. [18]	Variable speed pumped hydro storage: A review of converters, controls and energy management strategies	84
45	Schill and Kemfert [94]	Modeling strategic electricity storage: the case of pumped hydro storage in Germany	82
46	Kusakana [95]	Feasibility analysis of river off-grid hydrokinetic systems with pumped hydro storage in rural applications	81
47	Kotb et al. [96]	A fuzzy decision-making model for optimal design of solar, wind, diesel-based RO desalination integrating flow-battery and pumped-hydro storage: Case study in Baltim, Egypt	80
48	Shabani et al. [97]	Techno-economic comparison of optimal design of renewable-battery storage and renewable micro pumped hydro storage power supply systems: A case study in Sweden	80
49	De Oliveira and Hendrick [98]	Pumped hydro energy storage in buildings	79
50	Padrón et al. [99]	Analysis of a pumped storage system to increase the penetration level of renewable energy in isolated power systems. Gran Canaria: A case study	79

Data availability

Data will be made available on request.

References

[1] W. Strielkowski, L. Civín, E. Tarkhanova, M. Tvaronavičienė, Y. Petrenko, Renewable Energy in the Sustainable Development of Electrical Power Sector: A Review, 2021.

[2] Å. Killingtveit, 8 - Hydropower, in: T.M. Letcher (Ed.), Managing Global Warming, Academic Press, 2019, pp. 265–315, https://doi.org/10.1016/B978-0-12-814104-5.00008-9.

[3] S. Amiri, Comprehensive Review and Comparative Analysis of Hydropower Integration Strategies and Energy Storage Technology, 2023.

[4] G.R. Timilsina, Are renewable energy technologies cost competitive for electricity generation? Renew. Energy 180 (Dec. 2021) 658–672, https://doi.org/10.1016/j.renene.2021.08.088.

[5] P.C. Nikolaos, F. Marios, K. Dimitris, A review of pumped hydro storage systems, Energies 16 (11) (Jun. 2023) 4516, https://doi.org/10.3390/en16114516.

[6] A. Oymak, I.H. Demirel, M.R. Tur, Conversion of reservoir dams to pumped storage dams: a case study batman dam, J. Energy Storage 95 (Aug. 2024) 112417, https://doi.org/10.1016/j.est.2024.112417.

[7] J.D. Hunt, et al., Existing and new arrangements of pumped-hydro storage plants, Renew. Sust. Energ. Rev. 129 (Sep. 2020) 109914, https://doi.org/10.1016/j.rser.2020.109914.

[8] International Hydropower Association, 2024 World Hydropower Outlook [Online]. Available: https://acrobat.adobe.com/id/urn:aaid:sc:us:6ba5f8fc-5ad3-4d52-a83c-0931ce5fa119?viewer%21megaVerb=group-discover, 2024.

[9] T.M. Gür, Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage, Energy Environ. Sci. 11 (10) (2018) 2696–2767, https://doi.org/10.1039/C8EE01419A.

[10] S. Ali, R.A. Stewart, O. Sahin, Drivers and barriers to the deployment of pumped hydro energy storage applications: systematic literature review, Clean. Eng. Technol. 5 (Dec. 2021) 100281, https://doi.org/10.1016/j.clet.2021.100281.
[11] J.P. Deane, B.P.Ó. Gallachóir, E.J. McKeogh, Techno-economic review of existing and new pumped hydro energy storage plant, Renew. Sust. Energ. Rev. 14 (4) (May 2010) 1293–1302, https://doi.org/10.1016/j.rser.2009.11.015.
[12] Z. Ming, Z. Kun, L. Daoxin, Overall review of pumped-hydro energy storage in China: status quo, operation mechanism and policy barriers, Renew. Sust. Energ. Rev. 17 (Jan. 2013) 35–43, https://doi.org/10.1016/j.rser.2012.05.024.
[13] C.-J. Yang, R.B. Jackson, Opportunities and barriers to pumped-hydro energy storage in the United States, Renew. Sust. Energ. Rev. 15 (1) (Jan. 2011) 839–844, https://doi.org/10.1016/j.rser.2010.09.020.
[14] C. Bueno, J.A. Carta, Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands, Renew. Sust. Energ. Rev. 10 (4) (Aug. 2006) 312–340, https://doi.org/10.1016/j.rser.2004.09.005.
[15] M.S. Javed, T. Ma, J. Jurasz, M.Y. Amin, Solar and wind power generation systems with pumped hydro storage: review and future perspectives, Renew. Energy 148 (Apr. 2020) 176–192, https://doi.org/10.1016/j.renene.2019.11.157.
[16] M. Guezgouz, J. Jurasz, B. Bekkouche, T. Ma, M.S. Javed, A. Kies, Optimal hybrid pumped hydro-battery storage scheme for off-grid renewable energy systems, Energy Convers. Manag. 199 (Nov. 2019) 112046, https://doi.org/10.1016/j.enconman.2019.112046.
[17] G. Cavazzini, J.-B. Houdeline, G. Pavesi, O. Teller, G. Ardizzon, Unstable behaviour of pump-turbines and its effects on power regulation capacity of pumped-hydro energy storage plants, Renew. Sust. Energ. Rev. 94 (Oct. 2018) 399–409, https://doi.org/10.1016/j.rser.2018.06.018.
[18] K.R. Vasudevan, V.K. Ramachandaramurthy, G. Venugopal, J.B. Ekanayake, S. K. Tiong, Variable speed pumped hydro storage: a review of converters, controls and energy management strategies, Renew. Sust. Energ. Rev. 135 (Jan. 2021) 110156, https://doi.org/10.1016/j.rser.2020.110156.
[19] S. Alnaqbi, S. Alasad, H. Aljaghoub, A. Alami, M. Abdelkareem, A. Olabi, Applicability of hydropower generation and pumped hydro energy storage in the Middle East and North Africa, Energies 15 (7) (Mar. 2022) 2412, https://doi.org/10.3390/en15072412.
[20] M. Debanjan, K. Karuna, An overview of renewable energy scenario in India and its impact on grid inertia and frequency response, Renew. Sust. Energ. Rev. 168 (Oct. 2022) 112842, https://doi.org/10.1016/j.rser.2022.112842.
[21] S. Ali, R.A. Stewart, O. Sahin, Drivers and barriers to the deployment of pumped hydro energy storage applications: systematic literature review, Clean. Eng. Technol. 5 (Dec. 2021) 100281, https://doi.org/10.1016/j.clet.2021.100281.
[22] P. Toufani, E.C. Karakoyun, E. Nadar, O.B. Fosso, A.S. Kocaman, Optimization of pumped hydro energy storage systems under uncertainty: a review, J. Energy Storage 73 (Dec. 2023) 109306, https://doi.org/10.1016/j.est.2023.109306.
[23] A. Blakers, M. Stocks, B. Lu, C. Cheng, A review of pumped hydro energy storage, Prog. Energy 3 (2) (Mar. 2021) 022003, https://doi.org/10.1088/2516-1083/abeb5b.
[24] E. Barbour, I.A.G. Wilson, J. Radcliffe, Y. Ding, Y. Li, A review of pumped hydro energy storage development in significant international electricity markets, Renew. Sust. Energ. Rev. 61 (Aug. 2016) 421–432, https://doi.org/10.1016/j.rser.2016.04.019.
[25] S.P. Lohani, A. Blakers, 100% renewable energy with pumped-hydro-energy storage in Nepal, Clean Energy 5 (2) (Jun. 2021) 243–253, https://doi.org/10.1093/ce/zkab011.
[26] M. Alam, S. Rehman, L.M. Al-Hadhrami, Pumped Hydro Energy Storage System: A Technological Review, 2015.
[27] J.D. Hunt, B. Zakeri, A. Nascimento, R. Brandão, Pumped hydro storage (PHS), in: Storing Energy, Elsevier, 2022, pp. 37–65, https://doi.org/10.1016/B978-0-12-824510-1.00008-8.
[28] A. Rogeau, R. Girard, G. Kariniotakis, A generic GIS-based method for small pumped hydro energy storage (PHES) potential evaluation at large scale, Appl. Energy 197 (Jul. 2017) 241–253, https://doi.org/10.1016/j.apenergy.2017.03.103.
[29] G. Li, Y. Wang, P. Cao, J. Zhang, J. Mao, Effects of the splitter blade on the performance of a pump-turbine in pump mode, Math. Probl. Eng. 2018 (Oct. 2018) 1–10, https://doi.org/10.1155/2018/2403179.
[30] H.M.K. Al-Masri, S.K. Magableh, A. Abuelrub, O. Saadeh, M. Ehsani, Impact of different photovoltaic models on the design of a combined solar array and pumped hydro storage system, Appl. Sci. 10 (10) (May 2020) 3650, https://doi.org/10.3390/app10103650.
[31] J.I. Sarasúa, G. Martínez-Lucas, C.A. Platero, J.Á. Sánchez-Fernández, Dual frequency regulation in pumping mode in a wind–hydro isolated system, Energies 11 (11) (Oct. 2018) 2865, https://doi.org/10.3390/en11112865.
[32] T. Ma, H. Yang, L. Lu, J. Peng, Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong, Renew. Energy 69 (Sep. 2014) 7–15, https://doi.org/10.1016/j.renene.2014.03.028.
[33] F. Odoi-Yorke, R. Opoku, F. Davis, G.Y. Obeng, Optimisation of thermal energy storage systems incorporated with phase change materials for sustainable energy supply: a systematic review, Energy Rep. 10 (Nov. 2023) 2496–2512, https://doi.org/10.1016/j.egyr.2023.09.044.
[34] M.J. Page, et al., Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement, J. Clin. Epidemiol. 134 (Jun. 2021) 103–112, https://doi.org/10.1016/j.jclinepi.2021.02.003.
[35] M.L. Rethlefsen, et al., PRISMA-S: an extension to the PRISMA statement for reporting literature searches in systematic reviews, Syst. Rev. 10 (1) (Jan. 2021) 39, https://doi.org/10.1186/s13643-020-01542-z.
[36] F. Odoi-Yorke, A systematic review and bibliometric analysis of electric cooking: evolution, emerging trends, and future research directions for sustainable development, Sustain. Energy Res. 11 (1) (Jun. 2024) 24, https://doi.org/10.1186/s40807-024-00119-x.
[37] M. Aria, C. Cuccurullo, Bibliometrix: an R-tool for comprehensive science mapping analysis, J. Inf. Secur. 11 (4) (Nov. 2017) 959–975, https://doi.org/10.1016/j.joi.2017.08.007.
[38] F. Odoi-Yorke, R. Opoku, F. Davis, G.Y. Obeng, Employing bibliometric analysis to identify the trends, evolution, and future research directions of sand-based thermal energy storage systems, J. Energy Storage 94 (Jul. 2024) 112343, https://doi.org/10.1016/j.est.2024.112343.
[39] E.B. Agyekum, F. Odoi-Yorke, A.A. Abbey, G.K. Ayetor, A review of the trends, evolution, and future research prospects of hydrogen fuel cells – a focus on vehicles, Int. J. Hydrog. Energy 72 (Jun. 2024) 918–939, https://doi.org/10.1016/j.ijhydene.2024.05.480.
[40] E.B. Agyekum, C. Nutakor, T. Khan, O.R. Adegboye, F. Odoi-Yorke, P. C. Okonkwo, Analyzing the research trends in the direction of hydrogen storage – a look into the past, present and future for the various technologies, Int. J. Hydrog. Energy 74 (Jul. 2024) 259–275, https://doi.org/10.1016/j.ijhydene.2024.05.399.
[41] T.-T. Nguyen, V. Martin, A. Malmquist, C.A.S. Silva, A review on technology maturity of small scale energy storage technologies, Renew. Energy Environ. Sustain. 2 (2017) 36, https://doi.org/10.1051/rees/2017039.
[42] S.V. Jain, R.N. Patel, Investigations on pump running in turbine mode: a review of the state-of-the-art, Renew. Sust. Energ. Rev. 30 (Feb. 2014) 841–868, https://doi.org/10.1016/j.rser.2013.11.030.
[43] Z. Lan, J. Gu, J. Liu, J. Hu, S. Liu, H. Xie, Benefits of variable speed pumped hydro storage technology for increasing renewable integration in regional power grids, in: 2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2), IEEE, Taiyuan, China, Oct. 2021, pp. 660–664, https://doi.org/10.1109/EI252483.2021.9712853.
[44] D. Li, Y. Qin, J. Wang, Y. Zhu, H. Wang, X. Wei, Optimization of blade high-pressure edge to reduce pressure fluctuations in pump-turbine hump region, Renew. Energy 181 (Jan. 2022) 24–38, https://doi.org/10.1016/j.renene.2021.09.013.
[45] Genex Power, '250MW Kidston pumped storage hydro project'. Accessed: Sep. 25, 2024. [Online]. Available: https://genexpower.com.au/250mw-kidston-pumped-storage-hydro-project/.
[46] M. Stocks, R. Stocks, B. Lu, C. Cheng, A. Blakers, Global atlas of closed-loop pumped hydro energy storage, Joule 5 (1) (Jan. 2021) 270–284, https://doi.org/10.1016/j.joule.2020.11.015.
[47] Energy Vault, 'Gravity energy storage'. Accessed: Sep. 25, 2024. [Online]. Available: https://www.energyvault.com/products/g-vault-gravity-energy-storage.
[48] Rye Development, 'Goldendale energy storage project'. Accessed: Sep. 25, 2024. [Online]. Available: https://www.ryedevelopment.com/projects.html.
[49] R.J. Mahfoud, N.F. Alkayem, Y. Zhang, Y. Zheng, Y. Sun, H.H. Alhelou, Optimal operation of pumped hydro storage-based energy systems: a compendium of current challenges and future perspectives, Renew. Sust. Energ. Rev. 178 (May 2023) 113267, https://doi.org/10.1016/j.rser.2023.113267.
[50] J.I. Pérez-Díaz, M. Chazarra, J. García-González, G. Cavazzini, A. Stoppato, Trends and challenges in the operation of pumped-storage hydropower plants, Renew. Sust. Energ. Rev. 44 (Apr. 2015) 767–784, https://doi.org/10.1016/j.rser.2015.01.029.
[51] A. Pradhan, M. Marence, M.J. Franca, The adoption of Seawater Pump Storage Hydropower Systems increases the share of renewable energy production in Small Island Developing States, Renew. Energy 177 (Nov. 2021) 448–460, https://doi.org/10.1016/j.renene.2021.05.151.
[52] H. Onodera, R. Delage, T. Nakata, The role of regional renewable energy integration in electricity decarbonization—a case study of Japan, Appl. Energy 363 (Jun. 2024) 123118, https://doi.org/10.1016/j.apenergy.2024.123118.
[53] J.I. Pérez-Díaz, et al., Technological developments for pumped-hydro energy storage, in: Technical Report, 2014 [Online]. Available: https://www.cedren.no/Portals/Cedren/Technological%20Developments%20for%20Pumped-Hydro%20Energy%20Storage_EERA%20report%202014.pdf.
[54] Directive 2009/28/EC on the promotion of the use of energy from renewable sources, Off. J. Eur. Union (2009) [Online]. Available: https://faolex.fao.org/docs/pdf/eur88009.pdf.
[55] N. U.S. Department of Energy, Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source (Full Report), DOE/GO–102016-4869, 1330494, Jul. 2016, p. 7496, https://doi.org/10.2172/1330494.
[56] National Development and Reform Commission, The Twelfth Five-Year Plan for National Economic and Social Development of the People's Republic of China, 2011.
[57] Y. Kikuchi, T. Ishihara, Assessment of capital expenditure for fixed-bottom offshore wind farms using probabilistic engineering cost model, Appl. Energy 341 (Jul. 2023) 120912, https://doi.org/10.1016/j.apenergy.2023.120912.
[58] IEA, Hydropower Special Market Report [Online]. Available: https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf, 2021.
[59] D. Slotta, Leading energy storage segments in China in 2023, based on investment value [Online]. Available: https://www.statista.com/statistics/1465042/china-i

nvestment-value-of-leading-energy-storage-segments/, 2024. (Accessed 16 August 2024).
[60] U.S. Energy Information Administration, New pumped-storage capacity in China is helping to integrate growing wind and solar power [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=57360, 2023. (Accessed 16 August 2024).
[61] C. Murray, China: Largest pumped hydro energy storage plant in the world fully operational [Online]. Available: https://www.energy-storage.news/china-largest-pumped-hydro-energy-storage-plant-in-the-world-fully-operational/, 2024. (Accessed 16 August 2024).
[62] International Hydropower Association, India trailblazing pumped storage development with new draft guidelines [Online]. Available: https://www.hydropower.org/blog/india-trailblazing-pumped-storage-development-with-new-draft-guidelines, 2023. (Accessed 16 August 2024).
[63] ENERGY.GOV, Biden-Harris Administration Invests More Than $13 Million to Enhance Continued Deployment of Hydropower [Online]. Available: https://www.energy.gov/articles/biden-harris-administration-invests-more-13-million-enhance-continued-deployment, 2023.
[64] S. Rehman, L.M. Al-Hadhrami, Md.M. Alam, Pumped hydro energy storage system: a technological review, Renew. Sust. Energ. Rev. 44 (Apr. 2015) 586–598, https://doi.org/10.1016/j.rser.2014.12.040.
[65] J.P. Deane, B.P.Ó. Gallachóir, E.J. McKeogh, Techno-economic review of existing and new pumped hydro energy storage plant, Renew. Sust. Energ. Rev. 14 (4) (May 2010) 1293–1302, https://doi.org/10.1016/j.rser.2009.11.015.
[66] T. Ma, H. Yang, L. Lu, J. Peng, Pumped storage-based standalone photovoltaic power generation system: modeling and techno-economic optimization, Appl. Energy 137 (Jan. 2015) 649–659, https://doi.org/10.1016/j.apenergy.2014.06.005.
[67] T. Ma, H. Yang, L. Lu, J. Peng, Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong, Renew. Energy 69 (Sep. 2014) 7–15, https://doi.org/10.1016/j.renene.2014.03.028.
[68] E. Barbour, I.A.G. Wilson, J. Radcliffe, Y. Ding, Y. Li, A review of pumped hydro energy storage development in significant international electricity markets, Renew. Sust. Energ. Rev. 61 (Aug. 2016) 421–432, https://doi.org/10.1016/j.rser.2016.04.019.
[69] G. Ardizzon, G. Cavazzini, G. Pavesi, A new generation of small hydro and pumped-hydro power plants: advances and future challenges, Renew. Sust. Energ. Rev. 31 (Mar. 2014) 746–761, https://doi.org/10.1016/j.rser.2013.12.043.
[70] N. Zhang, et al., Reducing curtailment of wind electricity in China by employing electric boilers for heat and pumped hydro for energy storage, Appl. Energy 184 (Dec. 2016) 987–994, https://doi.org/10.1016/j.apenergy.2015.10.147.
[71] M.S. Javed, D. Zhong, T. Ma, A. Song, S. Ahmed, Hybrid pumped hydro and battery storage for renewable energy based power supply system, Appl. Energy 257 (Jan. 2020) 114026, https://doi.org/10.1016/j.apenergy.2019.114026.
[72] H.S. de Boer, L. Grond, H. Moll, R. Benders, The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels, Energy 72 (Aug. 2014) 360–370, https://doi.org/10.1016/j.energy.2014.05.047.
[73] M. Kapsali, J.K. Kaldellis, Combining hydro and variable wind power generation by means of pumped-storage under economically viable terms, Appl. Energy 87 (11) (Nov. 2010) 3475–3485, https://doi.org/10.1016/j.apenergy.2010.05.026.
[74] J. Fan, et al., Preliminary feasibility analysis of a hybrid pumped-hydro energy storage system using abandoned coal mine goafs, Appl. Energy 258 (Jan. 2020) 114007, https://doi.org/10.1016/j.apenergy.2019.114007.
[75] H. Ding, Z. Hu, Y. Song, Stochastic optimization of the daily operation of wind farm and pumped-hydro-storage plant, Renew. Energy 48 (Dec. 2012) 571–578, https://doi.org/10.1016/j.renene.2012.06.008.
[76] A. Stoppato, G. Cavazzini, G. Ardizzon, A. Rossetti, A PSO (particle swarm optimization)-based model for the optimal management of a small PV (photovoltaic)-pump hydro energy storage in a rural dry area, Energy 76 (Nov. 2014) 168–174, https://doi.org/10.1016/j.energy.2014.06.004.
[77] W. Wang, C. Li, X. Liao, H. Qin, Study on unit commitment problem considering pumped storage and renewable energy via a novel binary artificial sheep algorithm, Appl. Energy 187 (Feb. 2017) 612–626, https://doi.org/10.1016/j.apenergy.2016.11.085.
[78] K. Bruninx, Y. Dvorkin, E. Delarue, H. Pandžić, W. D'haeseleer, D.S. Kirschen, Coupling pumped hydro energy storage with unit commitment, IEEE Trans. Sustain. Energy 7 (2) (Apr. 2016) 786–796, https://doi.org/10.1109/TSTE.2015.2498555.
[79] K. Kusakana, Optimal scheduling for distributed hybrid system with pumped hydro storage, Energy Convers. Manag. 111 (Mar. 2016) 253–260, https://doi.org/10.1016/j.enconman.2015.12.081.
[80] M.A. Hozouri, A. Abbaspour, M. Fotuhi-Firuzabad, M. Moeini-Aghtaie, On the use of pumped storage for wind energy maximization in transmission-constrained power systems, IEEE Trans. Power Syst. 30 (2) (Mar. 2015) 1017–1025, https://doi.org/10.1109/TPWRS.2014.2364313.
[81] P. Chaudhary, M. Rizwan, Energy management supporting high penetration of solar photovoltaic generation for smart grid using solar forecasts and pumped hydro storage system, Renew. Energy 118 (Apr. 2018) 928–946, https://doi.org/10.1016/j.renene.2017.10.113.
[82] B.A. Bhayo, H.H. Al-Kayiem, S.I.U. Gilani, F.B. Ismail, Power management optimization of hybrid solar photovoltaic-battery integrated with pumped-hydro-storage system for standalone electricity generation, Energy Convers. Manag. 215 (Jul. 2020) 112942, https://doi.org/10.1016/j.enconman.2020.112942.
[83] J.I. Pérez-Díaz, J. Jiménez, Contribution of a pumped-storage hydropower plant to reduce the scheduling costs of an isolated power system with high wind power penetration, Energy 109 (Aug. 2016) 92–104, https://doi.org/10.1016/j.energy.2016.04.014.
[84] S. Makhdoomi, A. Askarzadeh, Optimizing operation of a photovoltaic/diesel generator hybrid energy system with pumped hydro storage by a modified crow search algorithm, J. Energy Storage 27 (Feb. 2020) 101040, https://doi.org/10.1016/j.est.2019.101040.
[85] R. Segurado, J.F.A. Madeira, M. Costa, N. Duić, M.G. Carvalho, Optimization of a wind powered desalination and pumped hydro storage system, Appl. Energy 177 (Sep. 2016) 487–499, https://doi.org/10.1016/j.apenergy.2016.05.125.
[86] M. Kapsali, J.S. Anagnostopoulos, J.K. Kaldellis, Wind powered pumped-hydro storage systems for remote islands: a complete sensitivity analysis based on economic perspectives, Appl. Energy 99 (Nov. 2012) 430–444, https://doi.org/10.1016/j.apenergy.2012.05.054.
[87] B. Lu, M. Stocks, A. Blakers, K. Anderson, Geographic information system algorithms to locate prospective sites for pumped hydro energy storage, Appl. Energy 222 (Jul. 2018) 300–312, https://doi.org/10.1016/j.apenergy.2018.03.177.
[88] A.M. Foley, P.G. Leahy, K. Li, E.J. McKeogh, A.P. Morrison, A long-term analysis of pumped hydro storage to firm wind power, Appl. Energy 137 (Jan. 2015) 638–648, https://doi.org/10.1016/j.apenergy.2014.07.020.
[89] D. Al, D.G. Katsaprakakis, A. Christakis, D. Papantonis Zervos, S. Voutsinas, Pumped storage systems introduction in isolated power production systems, Renew. Energy 33 (3) (Mar. 2008) 467–490, https://doi.org/10.1016/j.renene.2007.03.021.
[90] B.K. Das, M. Hasan, F. Rashid, Optimal sizing of a grid-independent PV/diesel/pump-hydro hybrid system: a case study in Bangladesh, Sustain. Energy Technol. Assess. 44 (Apr. 2021) 100997, https://doi.org/10.1016/j.seta.2021.100997.
[91] Y. Zhang, X. Zheng, J. Li, X. Du, Experimental study on the vibrational performance and its physical origins of a prototype reversible pump turbine in the pumped hydro energy storage power station, Renew. Energy 130 (Jan. 2019) 667–676, https://doi.org/10.1016/j.renene.2018.06.057.
[92] N. Yimen, O. Hamandjoda, L. Meva'a, B. Ndzana, J. Nganhou, Analyzing of a photovoltaic/wind/biogas/pumped-hydro off-grid hybrid system for rural electrification in sub-Saharan Africa—case study of Djoundé in northern Cameroon, Energies 11 (10) (Oct. 2018) 10, https://doi.org/10.3390/en11102644.
[93] A.S. Kocaman, V. Modi, Value of pumped hydro storage in a hybrid energy generation and allocation system, Appl. Energy 205 (Nov. 2017) 1202–1215, https://doi.org/10.1016/j.apenergy.2017.08.129.
[94] W.-P. Schill, C. Kemfert, Modeling strategic electricity storage: the case of pumped hydro storage in Germany, Energy J. 32 (3) (2011) 59–87.
[95] K. Kusakana, Feasibility analysis of river off-grid hydrokinetic systems with pumped hydro storage in rural applications, Energy Convers. Manag. 96 (May 2015) 352–362, https://doi.org/10.1016/j.enconman.2015.02.089.
[96] K.M. Kotb, et al., A fuzzy decision-making model for optimal design of solar, wind, diesel-based RO desalination integrating flow-battery and pumped-hydro storage: case study in Baltim, Egypt, Energy Convers. Manag. 235 (May 2021) 113962, https://doi.org/10.1016/j.enconman.2021.113962.
[97] M. Shabani, E. Dahlquist, F. Wallin, J. Yan, Techno-economic comparison of optimal design of renewable-battery storage and renewable micro pumped hydro storage power supply systems: a case study in Sweden, Appl. Energy 279 (Dec. 2020) 115830, https://doi.org/10.1016/j.apenergy.2020.115830.
[98] G. De Oliveira, E. Silva, P. Hendrick, Pumped hydro energy storage in buildings, Appl. Energy 179 (Oct. 2016) 1242–1250, https://doi.org/10.1016/j.apenergy.2016.07.046.
[99] S. Padrón, J.F. Medina, A. Rodríguez, Analysis of a pumped storage system to increase the penetration level of renewable energy in isolated power systems. Gran Canaria: a case study, Energy 36 (12) (Dec. 2011) 6753–6762, https://doi.org/10.1016/j.energy.2011.10.029.
[100] T. Ma, H. Yang, L. Lu, Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island, Energy Convers. Manag. 79 (Mar. 2014) 387–397, https://doi.org/10.1016/j.enconman.2013.12.047.
[101] Y.M. Kim, D.G. Shin, D. Favrat, Operating characteristics of constant-pressure compressed air energy storage (CAES) system combined with pumped hydro storage based on energy and exergy analysis, Energy 36 (10) (Oct. 2011) 6220–6233, https://doi.org/10.1016/j.energy.2011.07.040.
[102] B. Steffen, Prospects for pumped-hydro storage in Germany, Energy Policy 45 (Jun. 2012) 420–429, https://doi.org/10.1016/j.enpol.2012.02.052.
[103] J.K. Kaldellis, M. Kapsali, K.A. Kavadias, Energy balance analysis of wind-based pumped hydro storage systems in remote island electrical networks, Appl. Energy 87 (8) (Aug. 2010) 2427–2437, https://doi.org/10.1016/j.apenergy.2010.02.016.