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Review

Compressed Air Energy Storage—An Overview of Research Trends and Gaps through a Bibliometric Analysis

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Abstract: Electrical energy storage systems have a fundamental role in the energy transition process supporting the penetration of renewable energy sources into the energy mix. Compressed air energy storage (CAES) is a promising energy storage technology, mainly proposed for large-scale applications, that uses compressed air as an energy vector. Although the first document in literature on CAES appeared in 1976 and the first commercial plant was installed in 1978, this technology started to gain attention only in the decade 2000–2010, with remarkable scientific production output and the realization of other pre-commercial demonstrators and commercial plants. This study applies bibliometric techniques to draw a picture of the current status of the scientific progress and analyze the trend of the research on CAES and identify research gaps that can support researchers and manufacturers involved in this entering technology. Recent trends of research include aspects related to the off-design, the development of thermal energy storage for adiabatic CAES, and the integration of CAES with combined heating and cooling systems.

Keywords: compressed air energy storage; CAES; energy storage; literature review; bibliometric analysis

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1. Introduction

The need to reduce energy consumption and produce energy in a sustainable way are key aspects to reducing carbon emissions and relieving the irreversible consequences of climate change that currently our planet is facing. Although in 2020 a global decrease in energy demand was experienced due to the COVID-19 crisis, worldwide energy needs in 2021 already recovered the ground that was lost in the previous year with a 4% increase [1]. Nevertheless, even with global economies under the burden of COVID-19 lockdowns and disruptions, renewable energy sources (RES) continue to grow rapidly reaching an 85% share of new electricity generating capacity with a record level of 260 GW_e added in 2020, more than four times the capacity from other sources. The increase in energy generated by renewable sources highlights the need for solutions to deal with their intermittent and unpredictable nature. In this context, electrical energy storage (EES) represents the most effective technology to balance and decouple the energy supply and the energy demand, increasing the flexibility of the grid and resulting in both techno-economic and environmental benefits.

As of now, for large-scale applications, pumped hydro energy storage (PHES) is the most widely adopted EES technology due to its low cost (5–100 $/kWh [2]), high round-trip efficiency (65–87% [2]) and high technology readiness level (TRL = 9 [3]). The working principle of this EES is based on the conversion of electricity into potential energy and vice versa during the discharge. Therefore, in PHES, a proper elevation is needed. This characteristic represents the main constraint of this technology, requiring suitable geological and geographical conditions. Nowadays, the main alternative to PHES for large-scale and long duration energy storage is represented by compressed air energy storage (CAES). Indeed, CAES has gained considerable momentum in R&D in recent years being considered one of the most promising solutions offering relatively high round-trip efficiency (~60–70% [4]) and low cost (2–50 $/kWh [2,3]). Operationally, this technology converts electricity into mechanical energy by compressing air and storing it in large volumes. When electrical power is needed, the compressed air is used to drive a turbine connected to an electric generator. Other than high performance and low cost, the main advantages that CAES system offers include the use of off-shelf components, long-life duration (20–40 years [5]), negligible losses and easy scalability. Nevertheless, likewise PHES, geological constraints represent the main drawback. Indeed, due to the low volumetric energy density (~3–6 kWh/m^3 [2]), the CAES system needs large volumes to store the compressed air such as underground cavities, salt caverns, mine shafts, or gas fields. Above-ground pressurized vessels are currently used only in small-scale systems (<10 MW_e [6]).

Currently, only two CAES commercial plants are operating in the world and several demonstrators were developed; although, this technology is often considered mature, there are still barriers to getting CAES into the market for its commercial operation. As a consequence, significant effort was put in recent years to overcome technical and economic challenges with a relevant increase in scientific studies related to this technology. In literature, several systematic reviews on CAES technology were already published to collect scientific documents related to this topic and highlight in detail the contribution of each study. Nevertheless, in those types of reviews, it can be difficult to have a clear picture of research trends and the current gaps that need to be filled.

Bibliometric analysis is a statistical method that allows evaluating the trend and the scientific progress of a topic, offering an overall understanding of the research state-of-the-art. By adopting bibliometrics techniques, it is possible to quantitatively evaluate the number of documents, authors, and institutions publishing documents related to a specific topic. Furthermore, by analyzing the keywords related to papers, a more qualitative analysis can be carried out to identify the hotspots that help to understand the past and the current trend of research, and future perspectives.

In the field of electric and thermal energy storage, Reza et al. [7] performed a bibliometric analysis using trends in the literature related to the integration of energy storage into the grid. Barra et al. [8] used bibliometrics data to evaluate the number of publications related to the use of energy storage with wind power generation. Borri et al. [9] adopted bibliometric techniques to evaluate trends and gaps in the research carried out on liquid air energy storage (LAES). Maldonado et al. [10] combined a systematic review and a bibliometric analysis to collect studies related to the use of heat pipes in thermal energy storage. Similarly, Cardenas-Ramírez et al. [11] carried out a systematic review supported by a bibliometric study on the shape-stabilization and the encapsulation of latent heat (LH) materials. Calderon et al. [12] analyzed through bibliometric methodology the current trends in thermal energy storage, while Mustapha et al. [13] performed a bibliometric analysis on the specific topic of latent heat thermal energy storage (TES) systems. Indeed, as previously shown, bibliometric techniques recently found a high interest in the literature to evaluate trends in the field of energy storage, due to the recent development of this technology in the past 20 years.

Compared to the systematic reviews that were extensively published on CAES, the aim of the present study is to give a concise overview of the progress achieved on CAES and evaluate the research trend and the future perspectives on CAES systems by means of bibliometric analysis methodology. The results of the bibliometric analysis proposed in this study can be useful to delineate the prospects and the new challenges in storing energy through the use of compressed air and at the same time to inspire researchers and manufacturers in helping to grasp the state-of-the-art in the literature, highlighting the hotspots linked to the current CAES technology and future research.

2. Compressed Air Energy Storage General Overview

2.1. CAES Concept and History

CAES is a large-scale commercially available (depending on the CAES configurations, which will be described in detail in Section 2.2) technology that has been operating at grid level for more than 40 years [6]. Based on traditional gas turbine technology, CAES system can be divided into the traditional three phases of an energy storage system: charging, storing and discharging. During the charge phase, CAES utilizes off-peak and low-cost electricity to compress ambient air. Then, the compressed air is stored in a dedicated pressurized reservoir (typically at 40–80 bar), either underground cavern or aboveground tanks. To extract the elastic potential energy stored in the compressed air during the discharge phase, this energy vector is first drawn from the reservoir, heated up and finally expanded in a turbine train at high pressure and temperature generating thus electricity back to the grid (Figure 1).

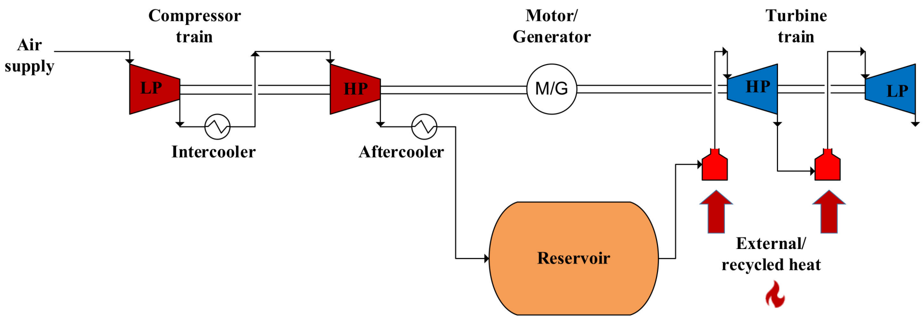

Figure 1. CAES system process flow diagram. Adapted from Huntorf layout [14].

As shown in Figure 2, the concept to use compressed air as an energy storage medium was first proposed in the early 1940s with the patent application "Means for Storing Fluids for Power Generation" submitted by F.W. Gay [15] to the US Patent Office and officially granted in 1948. However, until the end of the 1960s, no further developments were accomplished. Between 1960s and 1980s, the considerable increase in installed baseload electricity generation by nuclear and coal-fired power plants, especially in Europe and United States, led to the potential economic advantage to store inexpensive off-peak electricity production from baseload power plants and shift it to peak hours. Initially fulfilled by PHES but partially hindered by geological limitations, the storage capacity led to the development of other energy storage technologies, such as CAES, characterized by less severe topological conditions. Indeed, due to the availability of underground salt domes already utilized to store compressed natural gas in northern Germany, the first diabatic CAES (D-CAES) plant started to be developed in 1969 mainly to supply a load following service [16] and deal with black start capability for northern German grid [6]. Commissioned nine years later in Huntorf (Germany), the plant has a power and storage capacity of 290 MW_e and 642 MWh, respectively, and uses two salt caverns with a total volume of 310,000 m^3 to store compressed air at a pressure range between 46 and 66 bar. Under design conditions, the plant reaches a round-trip efficiency of around 42% [17]. In 2008, the plant was retrofitted adjusting the turbine inlet pressures and temperatures of the high-pressure and low-pressure turbines, increasing thus the total power capacity up to 321 MW_e [6]. Encouraged by the successful experience of Huntorf plant, the United States started to heavily invest in CAES technology in the late 1970s, developing a robust R&D and pre-demonstration program that principally gave rise to a second generation of CAES technology (first among all adiabatic A-CAES and isothermal I-CAES, whose main technical features will be described in detail in Sections 2.2.2 and 2.2.3). The main outcome of this program was the realization of the first US large-scale D-CAES plant commissioned in 1991 in McIntosh site (Alabama, USA) by the Alabama Electric Cooperative (currently PowerSouth Electric Cooperative [18]). Differently from Huntorf plant, MacIntosh plant makes use of a recuperator that recovers the waste heat from low-pressure turbine and preheats the air before the expansion in the high-pressure turbine, increasing the round-trip efficiency up to 54% [17]. Table 1 summarizes the main technical parameters for both Huntorf and McIntosh plants.

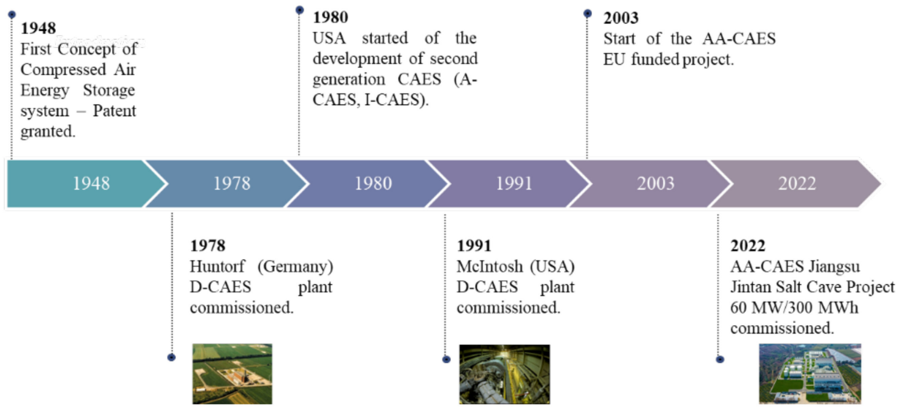

Figure 2. Timeline of cornerstones in CAES R&D.

Table 1. Key technical parameters of Huntorf and McIntosh D-CAES plants ([6,17,19]).

Parameter	Huntorf	McIntosh	Unit
Utility Operator	E.ON Kraftwerke	PowerSouth	-
Status	Operative	Operative	-
Round-Trip Efficiency	42	54	%
Power Capacity	290/321	110	MW_e
Energy Capacity	642	2640	MWh
Cavern volume	310,000	538,000	m^3
N° of Reservoir	2	1	-
Reservoir Typology	Salt cavern	Salt cavern	-
Pressure Range	46–66	46–75	bar

2.2. Variant of Compressed Air Energy Storage and Working Principle

Over the years, different CAES configurations were proposed in order to improve the performance of the first-generation CAES technology, as well as limit the usage of fossil fuel, making CAES environmentally friendly. A general classification of CAES technologies is shown in Figure 3, and the main technical key performance indicators are reported in Table 2.

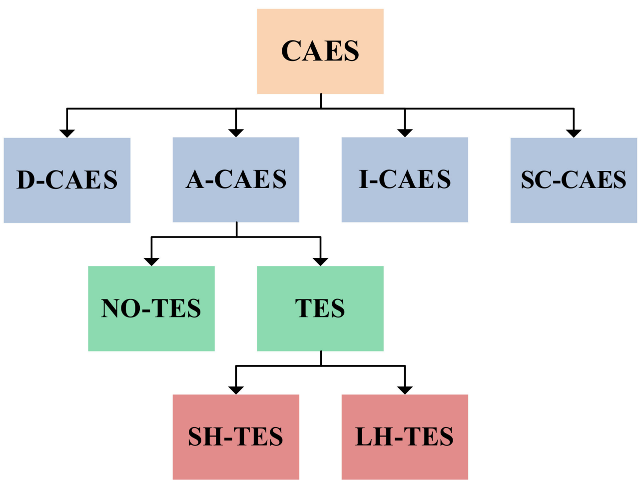

Figure 3. Classification of compressed air energy storage configurations.

Table 2. Key technical parameters of different CAES configurations [2–6,16,20].

Parameters	D-CAES	A-CAES	I-CAES	SC-CAES	Unit
Power rating	10–320	0.5–300	1–2	110–290	MW_e
Discharge time	1–24+	1–24+	1	1–24+	h
Round-trip efficiency	54–60	60–70	35–40	45–70	%
Energy density	3–6	0.5–20	3–6	8–24	kWh/m^3
Maturity (TRL)	9	8	5–7	8	-

2.2.1. Diabatic CAES (D-CAES)

The first generation of CAES technology, also known as diabatic CAES (D-CAES), is simply derived from gas turbine thermodynamic cycles. As shown in the process flow diagram of Figure 1, the ambient air is compressed by a compressor train and the waste heat available due to the compression is rejected to the ambient through intercoolers. During the discharge, the fuel is combusted to heat up the air before the expansion in the turbines generating thus electricity during peak times. The efficiency of these systems can be estimated at around 50% [4] with an energy density in the range of 2–15 kWh/m^3 [5,6]. The main drawbacks related to D-CAES are linked to (1) the significant amount of waste heat lost to the environment, (2) the relatively low round-trip efficiency and energy density and high emissions related to fossil fuel consumption, as well as (3) geological requirements for the reservoir.

2.2.2. Adiabatic CAES (A-CAES)

In order to overcome the disadvantages of D-CAES mainly linked with the thermal energy loss at the intercooling phase, an adiabatic CAES (A-CAES) configuration has been in development since the late 1970s, thanks to the work of Kreid [21], that first started to develop this second generation of CAES technology at the Pacific Northwest Laboratory [22]. Adiabatic CAES system aims to principally store the waste heat of compression and recycle it to increase the turbine inlet temperature of the compressed air, thus reducing or even eliminating the dependance on fossil fuel. Depending on the presence or the absence of a dedicated thermal energy storage to store the waste heat of compression, A-CAES can be further differentiated in:

- **A-CAES without thermal energy storage**. The waste heat of compression is directly stored in the reservoir, acting as a combined compressed air and thermal energy storage system. Despite the technical ease of this configuration, the high temperatures achieved during the compression phase require reservoir material capable to resist thermal stress. Indeed, due to this limitation, A-CAES without TES can be only adopted at low-pressure (<10 bar), thus significantly affecting the energy density and the roundtrip efficiency of the system. As a consequence, as of now, their development has been limited only to lab-scale plants without any commercial application [6].
- **A-CAES with thermal energy storage** (Figure 4). In this configuration, a dedicated thermal energy storage system is employed to store and reuse the waste heat of compression, to increase the turbine inlet temperature before expansion in the turbine train. Compared to A-CAES without TES, significantly higher pressure (>60 bar [6]) and consequently, higher energy density in the range of 0.5–20 kWh/m^3 with round-trip efficiency up to 70% [5]. Based on the concept of a high-temperature A-CAES with storages temperatures above 400 °C, a third generation of CAES, also known as advanced adiabatic CAES (AA-CAES), has gained momentum in literature and has been further developed under the umbrella of different European projects [23]. Grizzini et al. [24] carried out a technical investigation on an optimized AA-CAES reaching a round-trip efficiency of 72% without the support of any fossil fuel. Different solutions and materials for the thermal energy storage were proposed in the literature. Leveraging on the solid technical knowledge and background from solar power plants, sensible heat TES were adopted, either in packed bed or double tanks

configuration. Barbour et al. [25] and Sciacovelli et al. [26] proposed and dynamically studied a AA-CAES based on a sensible heat (SH) packed bed technology, showing how this component is crucial in obtaining round-trip efficiencies of around 70%. Ochmann et al. [27] experimentally and numerically analyzed a packed bed TES filled with slender basalt designed for installations in decommissioned mine shafts. A double tank indirect heat exchange fluid was proposed by Mei et al. [28] Within the project, it aims to develop an AA-CAES demonstrator of 500 kW_e. The two tanks configuration employs a cold and hot TES, an intermediate heat transfer fluid and indirect heat exchangers to cool down and heat up the compressed air during the charging and discharging phases, respectively. Phase change materials (PCMs) were adopted as medium storage for the thermal energy storage of the AA-CAES in order to further enhance the energy density and the round-trip efficiency of the system, by exploiting the buffer effect typically triggered by the phase change process. A PCM based packed bed solution was considered by Peng et al. [29] for a AA-CAES system. The authors conducted a parametric performance study by analyzing the effect of storage media on the TES performance and concluded that a TES filled with single PCM ($NaNO_2$), or multiple heat storage materials has improved charge efficiency compared to sensible heat material (rocks). In order to globally assess the effect of the TES on the performance of the whole system, Tessier et al. [30] proposed a AA-CAES system implementing a cascaded PCM thermal energy storage, revealing that the utilization of additional PCM stages improved the round-trip efficiency of the system. Similar to this work, a packed bed filled with cascaded PCMs was techno-economically analyzed by Mousavi et al. [31]. The authors confirmed the results from the previous study conducted by Tessier et al. [30], achieving a AA-CAES round-trip efficiency of 61.5% with a notable pay-back period lower than 4 years.

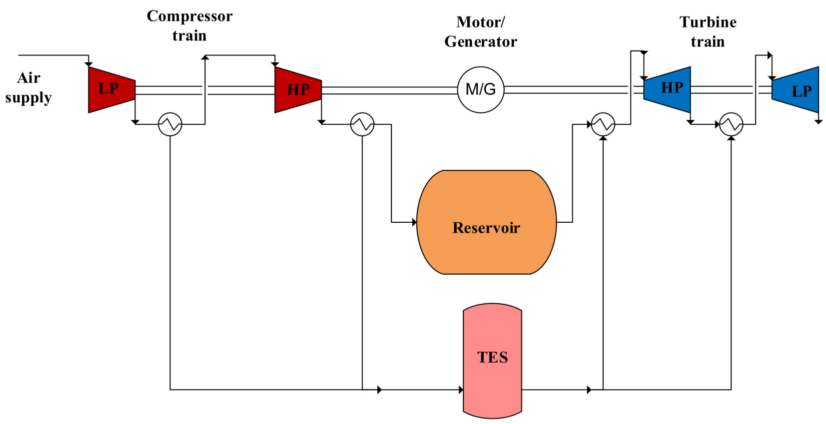

Figure 4. Schematic of AA-CAES with thermal energy storage. Adapted from [32].

Despite the relevant research being carried out, no commercial AA-CAES system was built worldwide due to different limitations mainly linked with the high operational temperatures producing unacceptable thermal and mechanical stresses on both the TES and the compressor, thus requiring advanced materials and complex engineering.

To overcome those shortcomings, a low temperature adiabatic CAES (LTA-CAES) was proposed in the literature demonstrating that similar round-trip efficiency can be achieved by this novel CAES solution providing, at the same time, lower start-up times favorable for energy reserve market services. Luo et al. [33] reported that a LTA-CAES system with a two-stage compression and one-stage relaxation achieves round-trip efficiency up to 68%. Yang et al. [34] analyzed the impact of heat exchangers performance on round-trip efficiency of a LTA-CAES. Guo et al. [35] proposed and compared two off-design control strategies of the LTA-CAES: (1) optimizing the variable inlet guide vane (VIGV) rotation angle of the compression train and (2) guaranteeing equal pressure ratio. However, low temperature A-CAES concepts suffer from lower energy densities and lower roundtrip efficiencies that have currently hindered their further development [36].

2.2.3. Isothermal CAES (I-CAES)

Aiming to stabilize the compression and expansion temperatures of the compressed air during charging and discharging, respectively, an isothermal CAES (I-CAES) was proposed to achieve a quasi-isothermal process. Indeed, by continuously extracting or providing heat transfer during the charge and discharge phases, respectively, the system may achieve significantly higher round-trip efficiency, eliminating the need for an additional thermal energy storage [19]. The concept of I-CAES was firstly realized through the implementation of additional heat exchange surfaces and liquid piston [37–39], where a liquid is used to compress the air. Alternatively, a liquid spray (water or pre-mixed foam) was proposed to achieve quasi-isothermal compression [40,41]. Coney et al. [41] achieved quasi-isothermal compression by injecting water into the cylinder of a reciprocating air compressor, where the air is maintained below 100 °C. Iglesias et al. [42] carried out an experimental analysis of water injection into the co-rotating scroll compressor-expander, showing that the turbine efficiency can reach values up to 70–75%. Adopting water spray into the expander cylinder, Zhang et al. [40] developed an isothermal CAES, enhancing the specific work production and reducing the cylinder size. SustainX [43] introduced the use of pre-mixed foam to achieve quasi-isothermal compression by improving the heat transfer performance.

2.2.4. Supercritical CAES (SC-CAES)

By combining the advantages of AA-CAES and the novel liquid air energy storage (LAES) [5,44], such as environmentally friendly, high energy storage and round-trip efficiency and, above all, no geological/geographical requirements, a novel supercritical CAES (SC-CAES) was proposed in the literature. Based on the patent submitted by Chen [45] and on the work carried out by Guo et al. [46], the system layout takes mainly inspiration from LAES system: Air is first compressed at supercritical thermodynamic status recovering the waste heat of compression in thermal energy storage and then liquefied and stored in a dedicated cryogenic tank. During the discharge phase, the liquid air is re-gasified, heated up by the thermal energy stored and expanded through a turbine train, producing electricity back to the grid. From Guo et al. [46,47] studies, the energy density is calculated to be almost 18 times higher than the D-CAES with a round-trip efficiency of ~67%.

2.3. Overview of the Main CAES Projects

As underlined in the previous section, CAES is a large-scale energy storage technology with a well-established tradition and technical development since the operation of the first D-CAES plant in Huntorf. Consequently, in recent years there were numerous major CAES projects, novel demonstrators or commercial applications. China is currently paving the way for the development of CAES in the 2020s with a considerable amount of research work from several research groups [4] and, above all, the grid connection of a commercial AA-CAES plant (60 MW_e/300 MWh) in Jiangsu [48]. A comprehensive list of the past and current major projects is reported as follows:

- **Seneca Project.** In 2010 a D-CAES commercial plant (130 MW_e/2000 MWh), developed by the New York State Energy Research and Development Authority (NYSERDA), was planned to be commissioned in upstate New York utilizing the local salt mine and the on-site natural gas facility. The project was later dismissed due to increased investment cost and a lack of economic incentives [49].
- **SustainX Project.** An American company (SustainX) designed in 2013 the first and only MW-scale I-CAES demonstrator based on pre-mixed foam to achieve quasi-isothermal compression [50]. Despite the notable round-trip efficiency of 54% reached and the possibility to use above-ground reservoir for compressed air storage, the project was since then discontinued due to the external acquisition of SustainX by General Compression which heavily devested in this technology [51].

- **ADELE Project.** One of the most important European projects related to the development of the AA-CAES technology was proposed under the umbrella of ADELE project. Started in 2009 and aimed to develop an AA-CAES commercial plant of around 200 MW_e in Germany [52], one of the major strengths of the project was to provide high round-trip efficiency up to 70%. Nevertheless, the project was discontinued due to technical issues related to AA-CAES technical limitations and uncertain business potential [6].
- **PG&E Project.** The PG&E D-CAES plant is a 300 MW_e energy storage project located in California, USA. Announced in 2010 and expected to be commissioned in 2021 [53], the plant will make use of porous rock formation to store the compressed air. As of now, no further announcements and updates were published after the end of the first phase of the project related to the techno-economic feasibility study of the project [54].
- **Hydrostor Projects**. Hydrostor is a Canadian company that has recently demonstrated a novel grid scale A-CAES concept through a commercial plant (1.75 MW_e) that become operational in 2019 in Goderich, Canada [19]. The compressed air storage is drilled underground and can be partially flooded by a surface water reservoir to ensure constant pressure of the compressed air during the whole discharge process. Another larger commercial plant rated at 5 MW_e is expected to become operational in the next future in Angas, Australia [55]. In this case, a zinc mine will be used as compressed air storage without any drilling activity involved as occurred in Goderich plant.
- **TICC-500 Project.** In 2014 China Electric Power Research Institute and Tsinghua university successfully connected to the grid a A-CAES multi-stages demonstrator rated at 500 kW_e [28]. Despite the low round-trip efficiency (33.3% [20]), the system is designed to be operated in poly-generation mode providing external heating by waste heat of compression at 80 °C and external cooling by low temperature air at 3 °C at the outlet of the turbine, thus achieving a global efficiency of 72% [4].
- **IET Projects.** The Chinese Academy of Sciences Institute of Engineering Thermophysics (IET) and the Macaoenergy Industrial Park Development Co. Ltd. designed and connected to the grid a novel 1.5 MW_e SC-CAES in 2013 [19]. The plant situated in Langfang, China had successfully run more than 3000 h with an average round-trip efficiency of around 55% [5]. Based on the positive experience gained from the SC-CAES demonstrator, in 2016 IET constructed a 10 MW_e AA-CAES in Bijie, China implementing a series of above-ground compressed air storage and a 22 MWh_{th} thermal energy storage based on sensible heat material to store the waste heat of compression. As of now, the system is still under development with the possibility of further enhancing the capacity to 100 MW_e [56].
- **Jiangsu Project.** The first large scale commercial AA-CAES plant (60 MW_e/300 MWh) was recently commissioned in Xuebuzhen (Jiangsu, China) and became operational in 2022. Aiming at limiting the solar curtailment in Jiangsu province, the system uses an existing salt cavern as compressed air storage. As of now, the system was recently connected to the grid after a series of successful trials [48].

3. Materials and Methods

In this study, the Scopus database was used as a reference due to the higher number of documents and accuracy of results related to technological topics compared to other databases [57,58]. The documents published related to CAES were retrieved with the last access in September 2022. The query used was the following: "TITLE-ABS-KEY ((“compressed air energy storage” OR (“CAES” AND “storage”)))". The bibliometric data were elaborated to obtain the trend of publications per year, the main journals, the top countries, and the authors publishing on the topic. In the evaluation of top countries, Europe was considered as a single territory, including the member states of EU-27. Furthermore, the co-occurrence of keywords of each document was elaborated using the software VOSviewer [59,60] in order to obtain a bibliometric map which shows the main area of studies (clusters) and the network amongst different keywords. In this study, both author and indexed keywords were selected, and the bibliometric map was obtained with keywords appearing in a minimum of 25 documents. In the plots, keywords are grouped in clusters appearing in different colors, indicating the main areas of study. The dimension of the circle of each keyword is proportional to the number of occurrences and the link strength with other keywords. On the other hand, the distance between them is proportional to their relationship. The trend of research was evaluated through the overlay visualization, which shows the year when different keywords had most of the occurrence in literature.

4. Results and Discussion

This section includes the results of the bibliometric analysis conducted on a total of 2542 documents retrieved from the Scopus database.

4.1. Publications Trend and Distribution by Journal and Subject

The number of papers on CAES published per year until the year 2021 is shown in Figure 5.

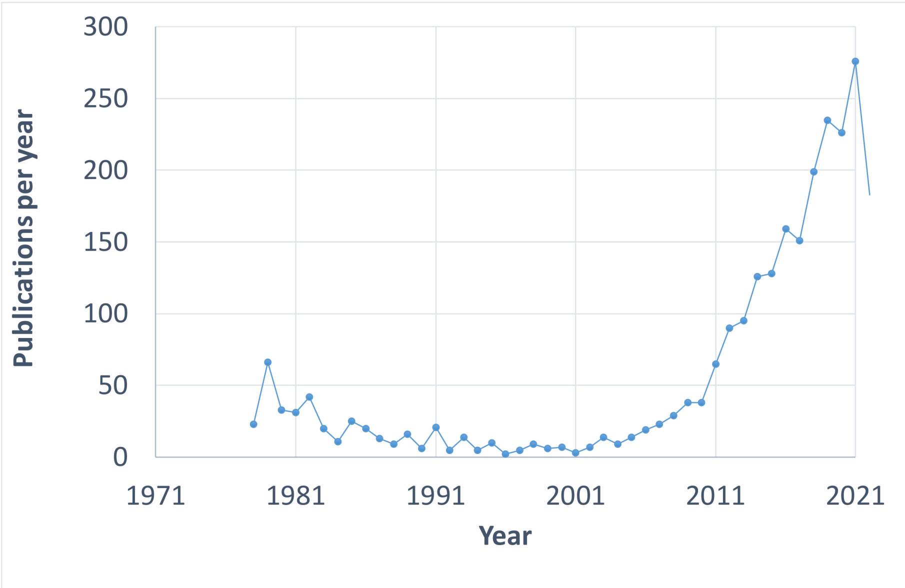

Figure 5. Number of publications per year.

The first documents on this technology were published in the year 1976, including studies related to the Huntorf plant in Germany (Air Storage Energy Transfer—ASSET) [61,62], conceptual designs, economic assessment of CAES, and rock mechanics research and geological issues for underground caverns which can be used to store compressed air [63–70]. Although the main CAES concept was based on a D-CAES configuration, studies on A-CAES started to be published in 1978 [71]. Despite the initial momentum, the number of publications on the topic decreased until the year 2000. From Figure 5 is also possible to notice that CAES started again to gain interest around the year 2002 with a rapid increase in the number of publications per year from the year 2010. The reason for this can be attributed to actions taken by different governments for energy transitions and the integration of renewable sources where electric energy storage has a key role. Indeed, as already reported in Section 2.1, although at the early stages CAES was mainly considered to add black start capability to fossil fuel power plants, the main driver of the research carried out in the last decade was the need to find an alternative solution for large-scale energy storage to support renewable sources integration and peak load management. Figure 5 shows that the literature trend is exponentially increasing with more than 250 documents published in the year 2021. Excluding systematic review papers, the most cited document is a comparative life-cycle cost analysis of different EES, including CAES, published by Zakeri and Syri in the year 2015 [72]. Another highly cited study was published in 2009 by Lund and Salgi on the role of CAES in future sustainable energy systems [73].

Figure 6 shows the type of publication on the CAES topic distinguishing between journal articles, conference papers, book chapters and review papers. Although journal articles represent most of the documents published, a significant number of studies were published as conference papers, giving the possibility to consult them in open access form. Furthermore, there is also a significant amount of review papers which include CAES. The main journals are shown in Figure 7. Energy, Journal of Energy Storage, Applied Energy, and Energy Conversion and Management are considered high-quality journals (Q1) with good impact factors. However, they are not Open Access, meaning that most of the documents are not fully accessible to the research institutions. However, different studies were published in Energy Procedia which in this case allows consulting them without any restrictions or journal subscriptions.

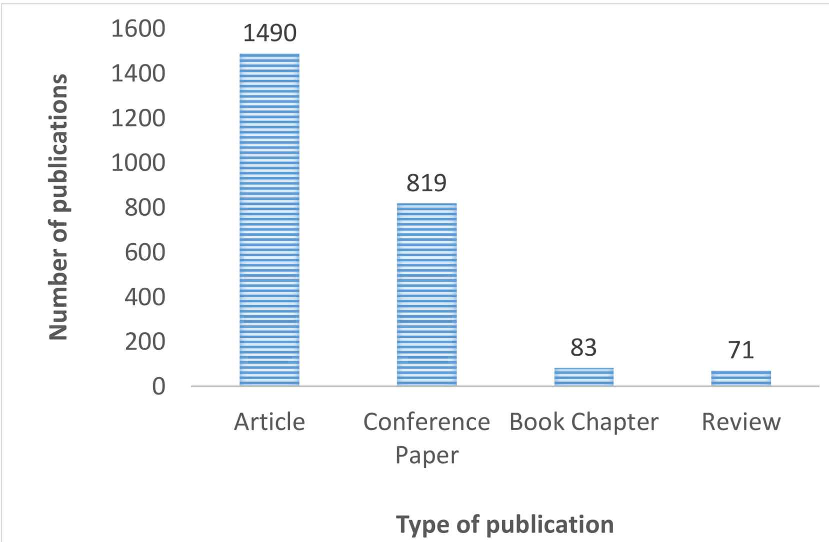

Figure 6. Type of publication of paper published until September 2022.

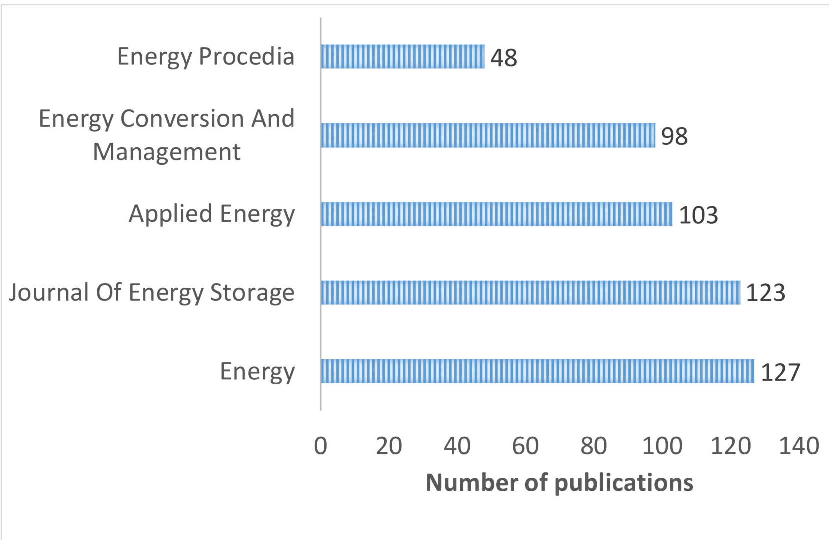

Figure 7. Top journals of paper published until September 2022.

The main countries/territories working on the topic are shown in Figure 8. Although the first plant was constructed in Germany, the USA was the first country to publish on the topic. Indeed, the USA was one of the first countries to invest and develop this technology including a second generation of CAES (A-CAES and I-CAES). Europe (EU27) and China are currently the leading countries/territories that publish on the topic. Indeed, the results show that both territories started to deliver a consistent number of publications only after the year 2004 with a remarkable research output, accounting for almost half of the papers published in the year 2021. In particular, China is today one of the countries that invested more in CAES with different demonstration and commercial plants currently in operation. The potential of CAES in China was recently studied by Tong et al. [4] highlighting that Central and East China are abundant in underground salt cave resources that can be exploited as CAES' reservoirs. One of the most highly cited studies from China was recently published by Cai et al. [74] proposing a new mathematical model to optimize the profit of CAES integration in the electricity market.

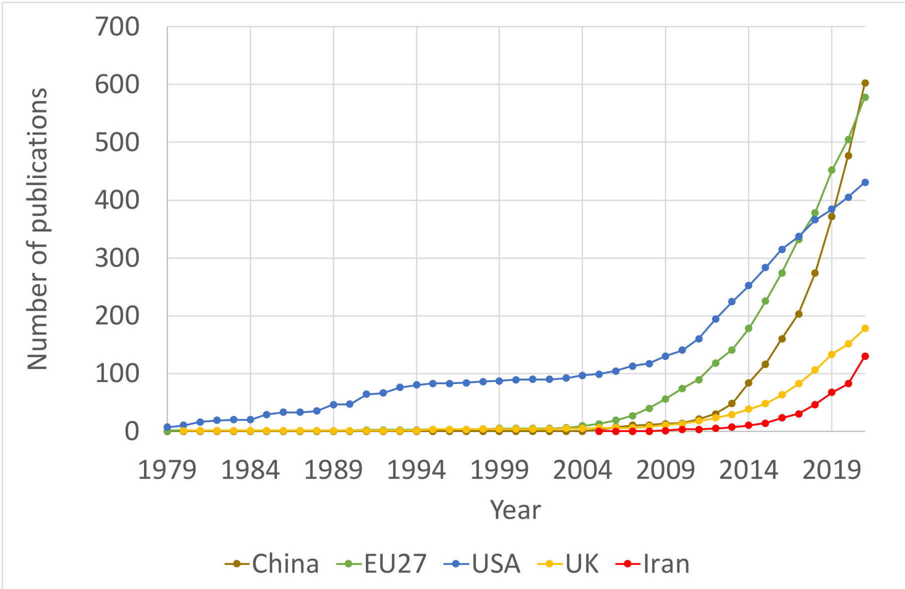

Figure 8. Top countries/territories publishing on CAES.

In Europe, energy storage is recognized as one of the key technologies to support the energy transition toward a carbon-neutral economy addressing several principles of the Clean Energy for all European package [75]. Amongst all European Countries, Germany, Italy, and France account for the larger number of publications. In particular, Germany has authored highly cited documents including a study on the environmental assessment of different storage solutions (mobility, heat, fuels, chemical feedstock, and electrical energy storage) published in 2015 by Sternberg and Bardow [76] and a simulation study on different adiabatic CAES configurations published by Hartmann et al. [77]. Another top country is UK which follows the initial trend of China in terms of number of publications. The most cited studies (excluding reviews) published by British institutions are related to A-CAES integrated with thermal energy storage [25,33]. Although Iran started, only recently, to publish on the topic, nowadays is one of the most prolific countries accounting for more than 100 publications in the year 2021 [25,26,33]. The most cited paper was published in 2017 by Mohammadi et al. [78] and it is focused on an exergy analysis of a CAES integrated with combined cooling, heating and power (CCHP) plant and wind turbine.

The top authors publishing on the topic are shown in Table 3. Haisheng Chen is the top author publishing on the topic. The most relevant document is one of the most cited reviews on energy storage systems. Nevertheless, there are studies on A-CAES which are highly cited [26,33]. From the documents in Scopus, Haisheng Chen has a strong collaboration with Yujie Xu who is also in the top author list. Jihong Wang is also another author of different reviews on CAES [20,79] and the most highly cited studies were done in collaboration with Haisheng Chen. Shengwei Mei from Tsinghua University has different recent publications on CAES integrated into microgrid and energy distribution systems [80–83]. Robert B. Schainker and Michael Nakhamkin have authored publications on CAES between the year 1984 and the year 1998, including a status of the CAES project operating in MacIntosh, Alabama [84].

Table 3. Top list of authors publishing on CAES.

Author	Institution	Country	Number of Publications in This Query	Total Number of Publications	h-Index
Chen, H.	University of Chinese Academy of Sciences	China	97	359	50
Wang, J.	Faculty of Science, Engineering and Medicine, Coventry	UK	48	201	32
Mei, S.	Tsinghua University	China	44	471	50
Xu, Y.	University of Chinese Academy of Sciences	China	44	119	36
Nakhamkin, M.	Energy Storage and Power Consultants, Inc.	USA	43	63	7
Schainker, R.B.	Electric Power Research Institute	USA	38	47	8
Chen, L.	Qinghai University	China	32	194	24
Li, W.	University of Chinese Academy of Sciences	China	32	57	7
Guo, H.	University of Chinese Academy of Sciences	China	30	37	13
Li, P.Y.	University of Minnesota Twin Cities	USA	30	209	29

4.2. Keyword Analysis

The co-occurrence of author keywords obtained with the software VOSviewer [60] is shown in Figure 9. The overlay visualization, which indicated the year when the keywords had the most occurrence is shown in Figure 10.

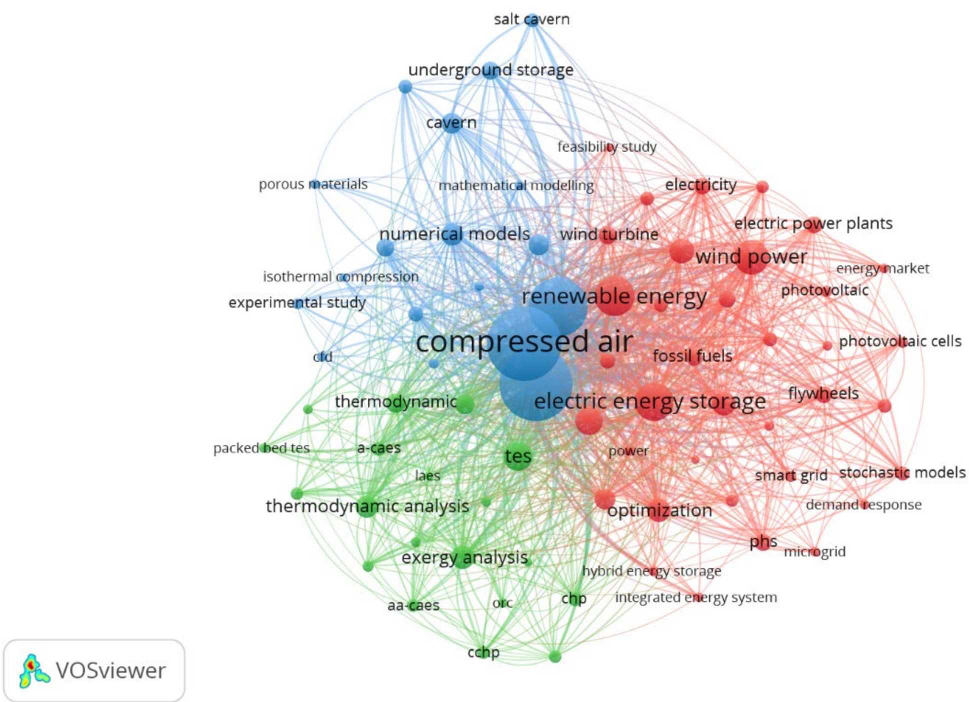

Figure 9. Co-occurency of keywords related to publications on CAES.

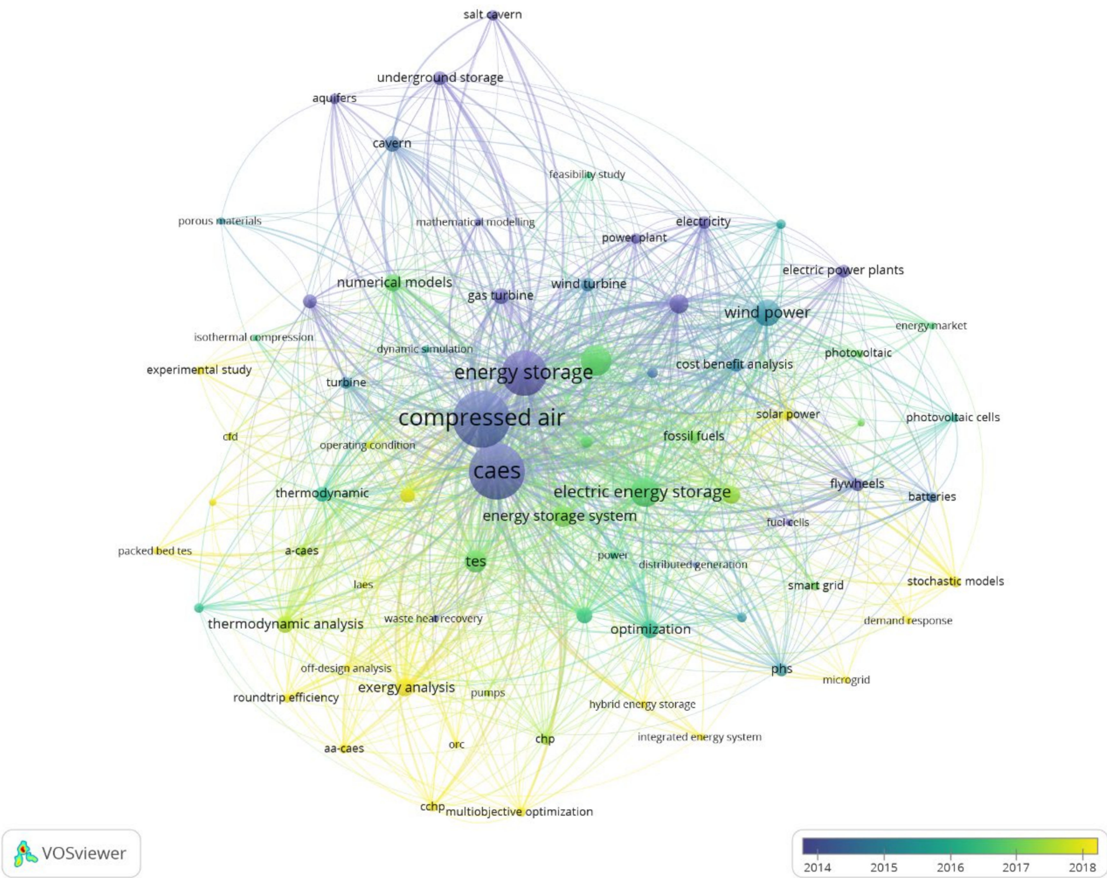

Figure 10. Overlay visualization of keywords related to publications on CAES.

Three main clusters were identified in Figure 9. The red cluster includes all the keywords related to the CAES integration in energy systems/networks. From the map, it is possible to identify keywords related to other EES technologies, such as PHS (pumped hydro storage) and flywheels. These keywords include reviews and comparison studies amongst different EES solutions. The cluster contains also keywords related to "renewable energy" sources. Amongst all, the most relevant is "wind power" indicating the most attractive renewable source to be coupled with CAES due to the large-scale energy production.

Figure 11 shows the network of these keywords, highlighting the main keywords' connections and clusters. Different studies on the integration of the CAES with wind power plant were based on cost-benefit analysis. One of the most cited studies was published by Denholm and Sioshansi [85] on the benefits evaluation of the integration of CAES with a wind power plant to increase transmission utilization and decrease transmission costs. Jeffery et al. [86] studied the economic viability of wind energy using a cost-optimization model comparing two competing systems: "wind + gas" scenario, namely wind energy supplemented by combined cycle natural gas turbines, and "wind + CAES", namely wind energy supplemented by CAES. Marano et al. [87] proposed a model for techno-economic analysis and optimization of a hybrid power plant consisting of CAES, a wind farm and a photovoltaic system.

Bhattarai et al. [88] presented a methodology to quantify the benefits of CAES in wind-integrated power systems considering economic and environmental performance indicators as well as the reliability impact of the storage. The results showed that the benefits are strictly related to the operation strategy, existing markets and incentive mechanisms. Meng et al. [89] evaluated the levelized cost of electricity (LCOE) of a CAES integrated with a wind power plant. The authors concluded that the hybrid system wind + CAES is more cost-effective than other renewable energy sources.

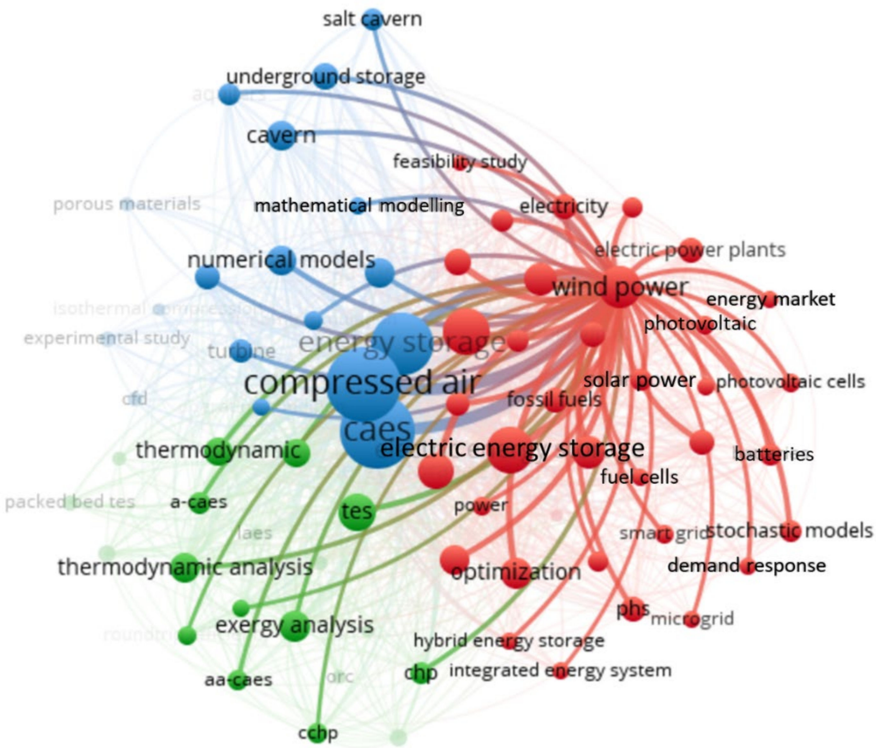

Figure 11. Network of the keyword "wind power".

Although "wind power" is the keyword with the highest occurrence in this cluster, Figure 10 shows that "solar power" is starting to gain interest as a recent topic. Kandezi et al. [90] proposed a hybrid system based on the integration of CAES with a concentrated solar power plant (CSP). The economic analysis, carried out for the case study of San Francisco (USA), shows an interesting payback period lower than 2 years. Arabkoohsar et al. [91] proposed and conducted a techno-economic analysis of a CAES system with an ancillary solar heating system to be integrated in a photovoltaic (PV) farm. Considering Brazil as the main case study, the payback time resulting from the analysis was less than 9 years.

Other interesting keywords in the red cluster, which represent also topics of recent interest, are "microgrid" [92–94], and "demand response" [95–97] including also the use of "stochastic models" [98]. Indeed, the ability of CAES to provide a fast response to the grid makes this EES technology suitable for demand-side management techniques and microgrid integration due to its scalability. Nevertheless, studies related to demand response and microgrid context have a low relevance in terms of occurrence, thus representing a research gap. Furthermore, the overlay visualization in Figure 10 shows that these keywords are recently investigated topics, thus highlighting recent trends in research.

The blue cluster at the top of Figure 9 includes all the keywords related to CAES' components such as "compressors", "turbine" and "gas turbine". On this topic, an interesting study was published by Rhabar et al. [99]. The authors proposed a methodology to develop small-scale radial inflow turbine for CAES applications based on 1-D modeling, 3-D aerodynamic investigation and structural analysis, novel manufacturing techniques (additive layer manufacturing) and experimental results used to validate the CFD model.

In the same blue cluster, it is also possible to identify keywords related to compressed air storage, such as "salt cavern", "underground storage" and "aquifers". Salt caverns and abandoned mines represent the most common reservoir typologies to store compressed air. Different studies in this context were published on rock mechanics of salt rock caverns [100–102]. Aquifers can be also configured as a storage solution for CAES, thus widening the potential of applications. Guo et al. [103] compared two different compressed air storage solutions (cavern and aquifer) for the Huntorf CAES plant. The simulation results showed that aquifers with appropriate reservoir characteristics might enhance the CAES performance compared to solutions opting for caverns as compressed air storage. Another interesting keyword shown in the blue cluster, also representing another important research gap in the CAES topic, is “isothermal compression” which refers to the isothermal CAES configuration (I-CAES). Guanwei et al. [104] carried out a study using a contact heat transfer method used to cool the compressed air with water spray for isothermal compression applied to CAES. Chen et al. [38] conducted a thermodynamic analysis of an open-type I-CAES using spray cooling. Gouda et al. [105] developed and experimentally validated a CFD model to analyze the flow and heat transfer characteristics of an air compressor with liquid piston technology for CAES applications. Zhang et al. [106] analyzed by means of thermal analysis, a compressor with liquid piston technology with two types of porous material to minimize the temperature rise during the compression. Other than CAES main components, the blue cluster also includes the keyword “experimental studies”. Related to both the whole CAES system and the single components, this keyword presents a low occurrence in the cluster, indicating a relevant research gap. Indeed, the lack of experimental data on the CAES system and components represent one of the main barriers hindering the technology deployment in the market.

The green cluster in Figure 9 contains all the keywords related to CAES system design and analysis. Indeed, from the keywords analysis in this cluster, it can be inferred that most of the performance assessments were conducted through thermodynamic and energy analysis. The green cluster also comprises the keyword “LAES”, namely liquid air energy storage technology, representing one of the most attractive variants of CAES system, where the air is not only compressed but also liquefied, thus reducing the specific volume of storage, augmenting the energy density of the system and overcoming the geological constraints related to underground compressed air storages [44]. As shown in Figure 10, off-design analysis of CAES also appears as a recent topic of study since these systems are likely to operate at off-design conditions due to several factors such as load fluctuations and ambient conditions. Most importantly, the off-design operation could also heavily affect the overall performance and the economic feasibility of the system. Recent works on off-design analysis were published by Guo et al. [35,107] and Arabkooshar et al. [108] who investigated the impact of the optimal operation strategies on A-CAES performance and the impact of the off-design operation on a CAES with multi-stage turbines and compressors, respectively. The green cluster includes also keywords related to the thermal energy storage (TES) system, which represents a key component for A-CAES to store the waste heat thermal energy from air compression. In this case, “packed-bed tes” appears to be one of the main technologies analyzed for CAES. Studies on the optimization and modelling of packed bed TES were published by Peng et al. [29] and Cárdenas et al. [109]. The overlay visualization in Figure 10 shows also that packed TES is a recent topic being an important component for the development of A-CAES.

The integration of CAES with ORC using the waste heat of compression is an interesting solution to increase the round-trip efficiency evaluated by different authors for combined heat and power (CHP) systems [110–113]. Furthermore, as highlighted by the keyword CCHP (combined cooling, heat and power) in the green cluster, some studies also analyzed the technical capability of CAES to be operated in cogenerative/trigenerative configuration such as the system proposed by Razmi et al. [114] and based on the integration of CAES, ORC and compression-absorption refrigeration cycle. Figure 10 also highlights that the ORC integration and the possibility to operate CAES as CHP or CCHP system are recent topics which started to gain momentum in recent years, whose low occurrence could pave the way for further investigations.

5. Conclusions

Compressed air energy storage (CAES) has gained momentum in the last few years as an electrical energy storage solution for large-scale applications. Although the first CAES plant was built in 1978 in Germany aiming to introduce black start capability to the grid, nowadays this technology is seen as a potential EES to support the integration of renewable energy sources which drive the current energy transitions. Indeed, in recent years several demonstrators and commercial plants were developed and are currently in operation. The high number of studies published highlights that nowadays research is putting effort to overcome the actual barriers and try to find new potential applications of CAES. The main conclusions of the bibliometric analysis carried out in this study are:

- Despite the fact that the USA was the first country to show interest in CAES technology with the first documented paper in literature published in 1976, nowadays, Europe (EU27) and China lead the research on the CAES topic, accounting for almost half of the documents published. Notably, China is currently the country investing the most in CAES R&D developing and commissioning several demonstrators and commercial CAES plants. Although different studies were published in conference proceedings and can be consulted with no restrictions, most of the literature on CAES were published in Q1 journals, not available in open access form.
- The keyword analysis highlighted that the CAES potential is mostly considered as an EES solution for wind power integration. Nevertheless, recent studies start to investigate CAES systems coupled also with solar power applications. Research gaps can be found in studies related to CAES for demand response and microgrid integration which represent potential applications of CAES.
- In terms of components, the development of isothermal compressors and expanders is a recent trend which could pave the way for the further enhancement of second generation isothermal CAES. Furthermore, novel and advanced solutions for thermal energy storage systems could support the development of adiabatic CAES systems. Other interesting solutions, recently analyzed, include the integration of CAES with organic Rankine cycle for cogeneration or trigeneration purposes.
- The evaluation of the off-design and partial load performance of CAES is also another important topic which was considered by different studies in the literature. However, the main gap in this area is the lack of experimental studies and experimental data which represents one of the main constraints to the demonstration of the feasibility of CAES technology, especially for new generation CAES.
- Furthermore, although some literature studies are already published, the environmental and social aspects of CAES are still not fully explored, representing a potential area of study that could support the technology deployment and increase acceptance from both stakeholders and policymakers.

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