Journal of Energy Storage 55 (2022) 105862

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Review article

Overview of compressed air energy storage projects and regulatory framework for energy storage

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ARTICLE INFO

Keywords:
Compressed air energy storage projects
Energy storage regulatory framework
Benchmarking
Energy storage barriers

ABSTRACT

Energy storage (ES) plays a key role in the energy transition to low-carbon economies due to the rising use of intermittent renewable energy in electrical grids. Among the different ES technologies, compressed air energy storage (CAES) can store tens to hundreds of MW of power capacity for long-term applications and utility-scale. The increasing need for large-scale ES has led to the rising interest and development of CAES projects. This paper presents a review of CAES facilities and projects worldwide and an overview of the ES regulatory framework and policies. It performs two benchmarking procedures: first, a benchmark of CAES worldwide, and second a benchmark of ES regulatory frameworks, policies, drivers and barriers. It tries to understand whether the development or cancellation of CAES projects globally is in any way related to the development of ES policies.

This study addresses policy perspectives and specific ES regulatory framework recommendations, contributing to public policy design in the attempt to overcome the regulatory barriers to the ES sector and influencing the deployment of ES and, specifically, CAES. Removing current regulatory barriers and establishing new and broader policies are essential to provide ES and CAES technologies with the right opportunities to develop, enhance efficiency, increase operational experience, and reduce costs.

1. Introduction

As the share of renewable energy sources (RES) in power systems grows, energy grids and policy-makers are facing new challenges. On the one hand, an important part of energy policy relies on regulatory measures being developed to foster the penetration of renewable energy. On the other hand, to allow high shares of RES and ensure the needed flexibility in the electricity system, several methods can be adopted, such as grid reinforcement, smart grids, demand response, and energy storage (ES) solutions. Thus, ES has become a key necessity in recent years, bringing regulatory framework concerns on such matters.

Among the different ES technologies available nowadays, compressed air energy storage (CAES) is one of the few large-scale ES technologies which can store tens to hundreds of MW of power capacity for long-term applications and utility-scale [1,2]. CAES is the second ES technology in terms of installed capacity, with a total capacity of around 450 MW, representing 0.3 % of the total ES capacity worldwide [3], and an alternative to the first ES technology, Pumped Hydro Storage (PHS). A CAES facility converts electrical energy into mechanical energy by using electricity to compress the air [4,5]. In a CAES plant, excess or off-peak power is used to compress ambient air stored under pressure in underground geological reservoirs. Later, when electricity is required, the pressurized air is heated and expanded in a turbine, driving a generator for power production. For instance, when demand is low excess energy generated from RES can be stored by applying this technology [6]. The growing need for large-scale ES has fostered interest and development of CAES projects.

CAES systems are categorized into large-scale compressed air ES systems and small-scale CAES. Large-scale systems are capable of producing >100 MW, while the small-scale systems only produce 10 MW or

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https://doi.org/10.1016/j.est.2022.105862
Received 31 May 2022; Received in revised form 3 October 2022; Accepted 7 October 2022
Available online 19 October 2022

less [6]. Moreover, the reservoirs for large-scale CAES are underground geological formations such as salt formations, host rocks and porous media. In contrast, small-scale CAES usually use storage tanks, vessels or pipes above the ground [2,4].

In this paper, two benchmarking insights are provided: a) A benchmark analysis of CAES systems and projects, with their location, evaluation, costs (when disclosed), the status of the project, and other criteria; b) Benchmarking of ES regulatory framework aiming to understand better the current ES policies, their development and implementation, and the identification of main incentives and barriers. The idea behind these benchmark procedures is to understand if the ES policies and regulatory framework can be one of the causes of the development or the discontinuity of CAES projects in the world.

Concerning the regulatory framework and policies for ES and the CAES benchmark, an approach to a potential correlation between the regulation and policies for ES and CAES is assessed to answer the following questions: What is the ES regulatory framework? Does it impact the development of CAES projects worldwide? Does it dictate their deployment or cancellation? Does it have any influence on the geographical location of CAES projects? Which regulatory measures and barriers can impact large-scale ES technologies such as CAES?

Technical issues such as the cost of technology, device efficiency, and other technical characteristics are already known as capable of impacting the deployment of ES technologies and some of the barriers to storage. In addition, however, a set of non-technical and policy-related issues seem to hinder the implementation of storage, particularly CAES. Thus, this paper's contribution provides an overview of policy outlooks and specific ES regulatory framework recommendations, which may significantly impact the deployment of ES technologies such as CAES systems, allowing policy-makers to benefit from these insights.

This paper is structured as follows: Section 2 presents the methodology; Section 3 provides the benchmark of CAES projects; Section 4 provides an overview of the benchmarking procedure of the ES regulatory framework; Section 5 discusses the results of crossing both benchmark analyses; and Section 6 draws some conclusions about this overview.

2. Methodology

The methodology for answering the previous questions and linking ES policies and CAES was developed by correlating a two-step benchmark procedure.

First, we conducted a benchmark analysis of CAES systems and projects focusing mainly on Europe and USA and briefly overview other countries with CAES projects, systematizing and collecting the available data and information on CAES projects from international reports, scientific journals, books, internet websites, and news (because private companies own most of those projects). Thus, the analysis focuses on CAES facilities that exist already and CAES projects under active development or even just in evaluation. Second, the data gathered was classified, and the CAES were ordered according to scale (large-scale and small-scale), continent, country and type of information available. Therefore, this overview was also systematized into five categories (organized in tables presented as Supplementary material): general data (Table A.1); technical data (Table A.2); reservoirs data (Table A.3); economics (Table A.4) and project status (Table A.5). The five categories are shown in Fig. 1.

Next, a benchmark of the ES regulatory framework aiming to understand policy perspectives on the subject was desktop-based. We analyzed a significant number of scientific articles on regulatory measures and market frameworks for ES, published reports from international entities and policies derived from European directives and the European Commission. The benchmark research focused primarily on Europe. However, the ES regulatory framework for North America (USA and Canada) and some other countries such as Australia, China, and Japan are addressed more generally. This choice was made since most of the policy development activities for ES have been taking place in liberalized or semi-liberalized markets.

The two-phase benchmark is linked since the systematization of CAES projects may eventually help establish a connection with the countries or continents where the regulatory framework for ES is further developed.

3. Compressed air ES benchmark

A benchmark analysis of CAES systems is essential to understand the following: To what extent CAES technologies are deployed; which facilities have been implemented; which projects are being developed; how they were evaluated; how much did they cost (where available); what are the main drivers; and how may they or may they not be

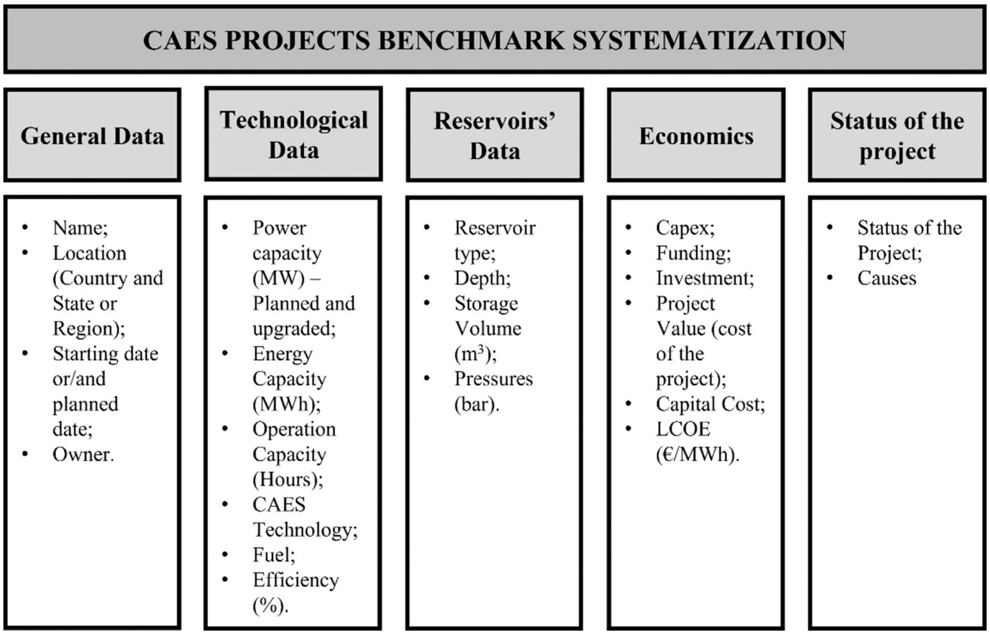

Fig. 1. Methodology of systematization of CAES project benchmark organized by category and type of data.

integrated into the energy market.

Information on many of these CAES projects is scarce. For those projects where scientific articles were not found, the information was collected from company websites and news media.

Next, this benchmark was compared with the Department of Energy (DOE) Global ES Database to check the collected information. It is worthy of note that this CAES benchmark has more information than the information provided by the DOE ES Database.

3.1. *Large-scale CAES power plants*

So far, there are two large-scale commercial CAES plants globally, Huntorf in Germany and McIntosh in the USA. Neither were built at the beginning to integrate RES.

3.1.1. *Huntorf*

The world's first CAES plant was Huntorf, in the North of Germany. It was built in 1978 and consists of two solution-mined salt caverns with a total storage volume of about 310,000 m^3 and a power capacity of 290 MW upgraded to 321 MW in 2006 (over 2 h) [4,7]. In the beginning, Huntorf provided black-start services to nuclear units near the North Sea and furnished inexpensive peak power. Nowadays, it is typically used as a minute reserve and for peak shaving in the evening, when no more PHS capacity is available [7]. In recent years it also has an additional application associated with the substantial increase in the number of wind power plants in North Germany. It is increasingly used to help balance the rapidly growing wind output and can compensate any unexpected shortage in wind power [1,2]. According to [7] this unit's availability and starting reliability are 90 % and 99 %, respectively, operating successfully for >20 years with an efficiency of 42 %.

At the Huntorf power plant, an engine consumes power to compress and store the air during low-cost off-peak periods in two salt caverns (between 650 and 800 m deep). Later, this process is reversed and the compressed air returns to the surface at peak load periods. The air is drawn out and burned together with natural gas in the combustion chambers. Then, the resulting combustion gas is expanded in a 2-stage gas turbine to spin the generator and produce power. The gas turbine is capable of black starts, i.e., it can start without the support of external energy and can reach the full output of 321 MW within six (6) minutes [8].

3.1.2. *McIntosh*

McIntosh CAES plant in Alabama, USA, has been operating since 1991 with a power capacity of 110 MW (over 26 h). Its typical startup sequence can start and be brought to full load within 10 min [9,10]. It consists of one large salt cavern with a total volume of 570,000 m^3, built as a source of inexpensive peak power to rising oil and gas prices [11]. Starting reliabilities achieved are 91.2 % and 92.1 % average for the generation cycle, while the average running reliabilities are between 96.8 % and 99.5 % for the compression cycle, and its efficiency is approximately 54 % [1,2].

The McIntosh facility uses excess electricity generated by a Power South coal-fired plant during off-peak hours (when electricity costs are lowest) to compress air for storage. Then it is used to generate electricity and sell it at a higher price during peak periods [10]. [11] describes that when energy is less expensive during off-peak hours, the air is pumped into the cavern in "compression mode". As a result, air pressure in the cavern reaches nearly 76 bar at full charge. When energy demand is at its highest during peak demand periods, the plant is put into "generation mode", where air from the cavern is released through pipes going through a heat recuperator, heating the air to approximately 315 °C. The hot air then enters a high-pressure combustion chamber, where natural gas is used to further heat the air to around 537 °C before entering the high-pressure expander. Next, the exhaust in the high-pressure expander is re-heated to around 871 °C before it enters the low-pressure expander, where it is fed back through the recuperator and provides an efficient heat source for this stage of the process. Finally, excess heat is discharged into the atmosphere at a temperature of around 178 °C. Together, the high-pressure and low-pressure expanders rotate the generator to produce enough electricity to supply nearly 110,000 homes for up to 26 h [10,11].

3.1.3. *Comparison between CAES power plants*

Although Huntorf and McIntosh CAES power plants are both diabatic technology-based, their main difference is that Huntorf is a simple diabatic CAES[1] (D-CAES) system, while McIntosh is a D-CAES system with a heat recuperator which improves the efficiency in the expansion phase. The comparison of key characteristics of Huntorf and McIntosh CAES facilities can be seen in Table 1.

Thus, the primary design difference between the German and the USA CAES plants is that McIntosh has an exhaust gas heat exchanger and recuperator to heat the air after it comes from storage, reducing the plant's fuel use by 25 % [12]. This difference allows the McIntosh facility to increase its efficiency up to 54 %, compared with only 42 % efficiency at Huntorf. As a result, these CAES plants burn roughly one-third of the natural gas per kWh of output compared to a conventional combustion turbine, thus producing only about one-third of the pollutants [7].

Table 1
Comparison of the key characteristics of Huntorf (Germany) and McIntosh (USA) CAES facilities.

Characteristics of CAES facilities	Huntorf	McIntosh
Location	Germany	USA (Alabama)
Built in	1978	1991
Owner	E.N. Kraftwerke	Power South Energy Cooperative
Power capacity	290 MW Upgraded to 321 MW (in 2006)	110 MW (≥26 h)
Number of storage hours	3	26
Lithology of the storage reservoir	Salt	Salt
Number of air caverns	2	1
Single air cavern volumes	140,000 m^3 170,000 m^3	570,000 m^3
Total air cavern volumes	310,000 m^3	570,000 m^3
Depth of caverns		
(Top)	650 m	125 m
(Bottom)	800 m	459 m
Total depth		808 m
Maximum diameter	60 m	72.5 m
Well spacing	220 m	not applicable
Caverns pressures		
Minimum permissible	1 bar	
Minimum operational (exceptional)	20 bar	
Minimum operational (regular)	43 bar	
Maximum permissible and operational	70 bar	76 bar (at full charge)
Type of CAES. Technology	Diabatic/conventional	Diabatic with heat recuperator
Fuel	Gas	Gas / Fuel Oil
Efficiency	42 %	54 %
Availability	90 %	95 %
Starting reliability	99 %	91.2 % and 92.1 %
Investment ($ 2002)	116 M(400/kWe)	45,1 M (410/kWe)
Specific capital costs	…	727 $/KW

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[1] In Diabatic CAES (D-CAES), the heat resulting from air compression is wasted in the environment by cooling down the compressed air and an external heat source (usually a fossil fuel such as natural gas) is needed for the discharging process [4].

3.2. *CAES projects*

Industry sources estimate that >40 CAES projects are being contemplated worldwide for the next 5 to 10 years [13]. However, this paper provides detailed information mainly on the U.S.A., Canada, and Europe, and briefly approaches other countries' CAES projects.

Detailed CAES projects data from the U.S.A., Canada, and Europe were organized into large or small-scale projects in five tables (as Supplementary material), according to their category: a) general data (Table A.1); b) technical data (Table A.2); c) reservoir data (Table A.3); d) economic data (Table A.4) and e) project status (Table A.5). These tables depict all the information collected from public sources. In addition, the current sub-section provides a summary of the main key characteristics, known investments, and status of CAES projects.

3.2.1. *North America*

Several CAES projects are researched, evaluated, and developed in the USA or Canada. For instance, the Electric Power Research Institute (EPRI) sponsored several studies over the last 20 years to determine the technical and economic feasibility of CAES plants in the USA [14,15]. As a result, it is now known that about three-quarters of the USA have potentially suitable geological resources for sitting compressed air ES facilities [15]. An example of those evaluation studies was the study of CAES in California to enhance California's wind power and other RES utilization. This study focused on attractive underground reservoirs such as depleted gas and oil fields. Although there are other options, such as porous rock saline aquifers, hard or host rock formations, e.g., granites or sedimentary rocks with an extensive cap-rock, or even abandoned coal mines (salt formations seem unavailable in the region). However, storing compressed air in most of California's depleted oil and gas fields (about 400 separate oil and gas production fields, active or abandoned) offers less expensive sitting opportunities.

Next, we provide a summary of the available information on CAES projects in North America, divided into large-scale and small-scale projects. We start by describing the large-scale CAES projects and then address CAES startups with small-scale projects.

3.2.1.1. *Large-scale CAES projects*

3.2.1.1.1. Norton CAES project. The Norton CAES project (in Ohio, USA) was researched for air storage by constructing conventional gas-type wells into the Norton limestone mine for air injection and withdrawal [16], which could operate within the pressure range of 55 bar to 110 bar [1,2]. With 9.6 million cubic meters of potential storage, the Norton ES project would be built in several phases, from about 270 MW to a total capacity of up to 2700 MW [17]. However, in July 2013, it was reported that FirstEnergy Corp delayed building the proposed CAES project due to market conditions, including low energy prices and insufficient demand [17]. To date, the facilities have not been built.

3.2.1.1.2. Iowa Stored Energy Park. The Iowa Stored Energy Park Project (ISEP) was a proposed 270 MW coupled with 75 MW to 100 MW of wind capacity and a $400 million CAES electric generation facility to be located at Dallas Center, Iowa (USA) [18,19]. It was scheduled to start operating in 2015, using as a reservoir a unique sandstone aquifer geologic structure, 91.4 m underground [19]. However, the ISEP project was discontinued in 2011 after eight years of development due to geological limitations, because the geological surveys of the project site showed that the storage reservoir (porous sandstone aquifer) was not suitable for the scale of the intended CAES project [19,20].

3.2.1.1.3. Matagorda Energy Center. Ridge ES & Grid Services LP [21], a Houston-based CAES company, was planning to develop the Matagorda Energy Center, a 540 MW (4 × 135 MW) facility located in Matagorda County, Texas (USA). This facility would be an upgraded version of the McIntosh Dresser-Rand design [21]. This proposed facility aimed at utilizing a previously developed brine cavern with the unique capability of providing bulk ES, enhancing the performance of both renewable (wind and solar facilities) and conventional fossil fuel energy generation [18]. However, the status of this project is currently uncertain because there has been no news of the project since 2017.

3.2.1.1.4. Bethel Energy Center. Bethel Energy Center, owned by APEX CAES company [22], is a planned 317 MW CAES facility (with possible expansion up to 476 MW) located in a cavern salt dome in Anderson County, within Texas' ERCOT power market. The project is fully licensed and is ready to be built [22]. It will be operated using Siemens AG CAES technology. The construction phase (for three years) was scheduled to start in the 4th quarter of 2021, with an anticipated commercial operation date scheduled for the spring of 2025 [22].

3.2.1.1.5. New York State Electric & Gas CAES Project. New York State Electric & Gas (NYSEG) intended to build an advanced CAES plant with a rated capacity of 150 MW (with the possibility of increasing the plant's capacity to 360 MW or more) using an existing 127,425.8 m^3 underground salt cavern in Reading, New York [23,24]. The plant would have the capacity to operate 16 h a day and would provide energy arbitrage for approximately 2300–2500 h per year [24]. The objectives of the New York CAES were [24]: a) create storage and dispatch wind energy; b) refine CAES technology and approach; c) integrate with New York's Smart Grid; d) provide black-start capability and e) accelerate commercialization of CAES plants. NYSEG and NETL [25] conducted an evaluation study on the Engineering and Economics of the project and they concluded that the project's economics was not favorable for development in the economic environment of New York State. Specifically, the cost of building the cavity, the conditions of the energy market, and the low cost of electricity produced in the natural gas plants were reasons for discontinuing the project.

3.2.1.1.6. Dakota Salts CAES project. Dakota Salts engaged with the Electrical Power and Research Institute (EPRI) and Schlumberger Limited subsidiary Schlumberger Water Services (SWS) to carry out the CAES feasibility study for North Dakota wind capture utilization and optimal full system integration [26,27]. The scope of their study was to determine the technological and economic potential of using underground salt formations in North Dakota for CAES. Unfortunately, except for the EPRI newsletters of 2014 [28], there are no more references to this CAES project in recent literature, raising some uncertainty about its development.

3.2.1.1.7. Pacific Northwest Region. Pacific Northwest National Laboratory (USA) and Bonneville Power Administration (BPA) evaluated the technical and economic feasibility of developing a CAES project in the geological setting of Washington and the Oregon States [12,29]. It identified five candidate locations belonging to the Columbia Plateau Province (CPP), which predominantly consists of a set of continental flood basalt deposits, two of which were selected for detailed assessment [12]: a) Columbia Hills (Washington state), analyzed for a conventional CAES plant, using an anticline structure of a porous aquifer as the storage reservoir, which may offer 231 MW of load during storage and 207 MW of generation, translated into a storage capacity of approximately 1,5 million metric tons of air, which may provide a storage capacity of 40 continuous days; b) Yakima Minerals, near Yakima Canyon north of Selah, analyzed for a no-fuel hybrid geothermal CAES plant (Geothermal Hybrid Adiabatic CAES), which could offer 150 MW of load during storage and 83 MW of generation. Based on geology and infrastructure suitability factors for CAES technologies adapted for each site, this study demonstrated the economic grid-scale feasibility of CAES as an ES solution for Pacific Northwest [29].

3.2.1.1.8. Hydrostor. Hydrostor is a Canadian, Toronto-based private company founded in 2010, developing Advanced Adiabatic CAES (A-CAES)[2] technology [30]. Hydrostor has proven A-CAES to be

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[2] In adiabatic CAES (A-CAES) no net external heat source is used, meaning that a Thermal ES (TES) device is used to avoid additional energy requirements and to capture the heat expelled in the compression process and later uses the stored thermal energy to preheat the air during the expansion process [4].

commercially viable, demonstrating its ability to play a significant role in the long-duration ES market [31].

Hydrostor has a variety of A-CAES projects (small to large-scale). However, this section addresses only the large-scale projects [32], namely:

a) Gem ES Center, a utility-scale A-CAES facility under active development in Kern County, northeast of Los Angeles (California, USA). The proposed facility will provide around 500 MW of on-demand peaking capacity for 12 h once it starts off in 2024 and becomes fully operational by 2026. The goal is to store excess generation from California's solar and wind resources into on-demand emission-free peaking capacity while maximizing transmission system utilization [33].
b) Pecho ES Center, a utility-scale A-CAES facility that is under active development near the City of Morro Bay (California, USA), which plans to provide up to 400 megawatts (MW) of new electrical capacity [34,35]. This project will store excess power produced by solar and wind projects in California and generate electricity for at least 8 h at full capacity. It should be operational by 2027 [34]. This project will play a critical role in helping meet California's future electrical supply and reliability needs, particularly as fossil-fueled plants continue to retire due to age and regulatory requirements [34].
c) Silver City ES Center, a utility-scale A-CAES facility under active development by Hydrostor and Energy Estate in Broken Hill, New South Wales (NSW), Australia. It is planned to be in service by 2025 with an expected design life of fifty years [36]. The proposed facility will be accommodated in a local decommissioned mine. It is expected to provide 200 MW of capacity and up to 8 h of electricity discharge (i.e., up to 1600 MWh). It will provide RES integration in the grid and eliminate the need for investments in expensive transmission lines and ongoing reliance on highly polluting diesel generators. This center is the first large-scale, long-duration ES project in Australia to be selected as a preferred solution in the first stage of a regulatory transmission planning process of a major utility [36].

3.2.1.2. Small-scale CAES projects

3.2.1.2.1. SustainX. SustainX was an Isothermal CAES (ICAES) technology startup founded in 2007 [37]. It was trying to build a cost-effective CAES system with tanks or structures above the ground to store compressed air and remove the need for an underground cavern as a storage medium or add gas fuel using isothermal cycling to improve the efficiency of the process [38]. However, this was a costly and unscalable solution, and SustainX merged in 2015 with General Compression [39]. Both companies have built a 2 MW by 300 MWh project in Gaines, Texas [40]. They have turned on the new GCX ES focused on combining fuel-free CAES technology with low-cost, existing, and developable salt caverns, but its state is uncertain, and it seems they have wound down [37,38].

3.2.1.2.2. LightSail Energy. LightSail Energy was a Berkeley (USA) CAES startup. It promised to capture the heat generated while compressing air through a method that vaporizes a water spray which rapidly absorbs the heat energy of compression and provides it during expansion and regenerates useful energy from it through a quasi-Isothermal CAES[3] process [41]. However, it had only two announced projects: a) a California Energy Commission-funded project to store solar power at Ventura County naval base, and b) a project to store energy from a wind turbine in Nova Scotia, Canada [42]. However, the company ran out of cash before reaching commercialization. As a result, it closed down operations, announcing in December 2017 that it is hibernating while figuring out the future [42].

3.2.1.2.3. Hydrostor. As already mentioned in large-scale projects, Hydrostor also has two small-scale A-CAES facilities [32]:

a) Toronto Island ES Facility (Canada) which is the first grid-connected adiabatic-CAES facility with utility host Toronto Hydro [43]. It was commissioned in 2015 with a 0.7 MW of power rate where the air was stored in underwater air storage vessels, approximately 180 ft below the surface of Lake Ontario. This facility was built to demonstrate the A-CAES technology and provide an ongoing testbed with a potential long-term role as reserve power for Toronto Island [43].
b) Goderich ES facility, located in Goderich, Ontario, Canada, in service since 2019, is the world's first commercially contracted A-CAES facility by Ontario's Independent Electricity System Operator (IESO) [44]. It is used for peaking capacity, ancillary services, and full participation in the merchant energy market to support grid reliability. This facility is entirely fuel-free with zero GHG emissions, it has a discharge power rate of 1.75 MW, and a charge power rate of 2.2 MW. Although it was contracted to provide 7 MWh of storage capacity to the Ontario grid operator, it can store >10 MWh [44].

3.2.2. Europe

In Europe, there are also several CAES projects being researched and evaluated in countries such as Ireland, Germany, Switzerland, and Austria.

3.2.2.1. Larne (Ireland). The Larne CAES project, located in the Islandmagee peninsula near Larne, East of Northern Ireland, was being developed by Gaelectric [45]. It would have a storage capacity of 330 MW for 6 to 8 h [46]. The planned reservoirs would be two underground storage caverns (around 150 m × 60 m) in salt deposits at depths between 1400 and 1700 m [45–47]. In 2016, the European Union invested €8,28 million from the Connecting Europe Facility (CEF) plus € 90 million with an estimated cost of about £300 million and a timeline to be constructed by the end of 2021 [47]. However, the Gaelectric company was bought in 2016 by a Chinese nuclear company, and in January 2018 it was winding down [48,49].

3.2.2.2. ADELE project (Germany). The ADELE CAES project was the first adiabatic CAES project for electricity supply worldwide. It started at the beginning of 2010 with a joint venture between RWE Power, General Electric, Zublin AG, and the German Aerospace Centre (DLR). The construction was set to start in 2013 [50]. This Advanced Adiabatic CAES (AA-CAES) project was an EU CORDIS project, and it was the first emission-free CAES technology [51]. Its goal was to develop an adiabatic CAES power station up to bidding maturity for a first demonstration plant, aiming at an overall efficiency of 70 %, approaching PHS plant efficiency of 75 % to 85 % for the first time [52]. Unfortunately, despite all of the investment and joint ventures between different companies and institutes (altogether, project stakeholders contributed € 10 million), the project was canceled for non-technical reasons [53].

3.2.2.3. ALACAES (Switzerland). ALACAES is a privately held Swiss company that is developing an AA-CAES solution for large-scale electricity storage in partnership with research institutes (such as the Federal Institutes of Technology in Lausanne (EPFL) and ETH Zurich) [54]. The project's objectives were to demonstrate a combined sensible/latent-heat storage at an industrially relevant scale for use in AA-CAES and to assess the environmental and economic potential of AA-CAES as an alternative to PHS in Switzerland [55]. As a result, ALACAES developed a $4.1 million ES project [56], built and tested successfully in 2016, the first pilot plant of a small-scale AA-CAES [54], located in the

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[3] Isothermal CAES (I-CAES) is a nearly ideal CAES system that decreases GHG emissions and substantially increases efficiency, theoretically close to 100 %, where the heat of compression is minimized or even prevented, so isothermal compression allows air to reach high pressures without the inherent challenges in temperature, delivering electrical energy without natural gas combustion when power is needed [4,5].

Swiss Alps near the city of Biasca. It exploits a transportation tunnel of the AlpTransit project as a pressure cavern and has a capacity of 1 MWh [54]. The plant was built in an unused tunnel with a diameter of 4.9 m in which two concrete plugs circumscribe a mostly unlined 120-meter-long cavern [57]. The estimated efficiencies were between 63 % and 74 %, consistent with the usually quoted values of AA-CAES plant efficiencies of 60–75 % [57]. Furthermore, the patented technology uses caverns in the mountains as the pressure chamber and proprietary thermal ES (TES) technology to achieve an overall round-trip storage efficiency of >72 %, with <5 min of ramping time. It also eliminates GHG emissions, meaning that this ALACAES plant has zero emissions and a low environmental footprint and has one of the lowest capital expenditures (CAPEX) per kWh of any storage technology [55].

3.2.2.4. Ricas2020 (Austria). The RICAS2020 Design Study for the European Underground Research Infrastructure related to AA-CAES was financed by the European Union's Horizon 2020 research and innovation program [58]. This study focused on the technical, legal, institutional, and financial requirements to get approval as a future research facility. So, it was open to the whole European Research Area, especially for all research fields close to Energy Providers and Suppliers [58,59]. This four-year project aimed to create an underground research infrastructure for AA-CAES, especially targeting the research areas of TES, Advanced Materials for the lining of caverns considering high pressure and high temperature, drilling technologies supported by laser, safety, and security issues of underground ES [60].

RICAS2020 provided concepts for a research infrastructure dedicated to underground storage of extremely high amounts of green energy, based on a small-scale test facility with an estimated power output of 5 MW. The advantages were that the underground ES could be performed irrespective of the geological conditions found and at all places where high energy demand exists [58,59], meaning it should be location-free. Finally, it should also increase high round-trip system efficiency using TES [59].

3.2.3. China

China has several CAES projects under research, for example in Dong Sheng, Inner Mongolia, where a demonstration CAES project comprising a 10 MW advanced unit was officially operational [61]. An advanced CAES comprehensive experimental platform consisting of compression, expansion, and thermal storage subsystem can produce 1.5 MW of power, with 32 MPa maximum pressure, heat storage temperature of 150 °C, cold storage temperature of −196 °C, and aiming to achieve 50–65 % of cycle efficiency [61].

Currently, China has announced the beginning of operation of the newly built salt cavern CAES Project named Jiangsu Jintan, located in Changzhou, Jiangsu province [62]. It has a storage capacity of 300 MWh and a power generating capacity of 60 MW for peak shaving energy of the local grid and its roundtrip efficiency is >60 % [63]. The facility features a salt cavern, situated 1000 m underground and it is owned by China National Salt Industry Group and co-developed also by electricity generation company China Huaneng Group and Tsinghua University [62,63].

3.2.4. Other countries in the world

Besides the US and Europe, there are CAES projects in Australia (such as the Hydrostor Silver City A-CAES mentioned before in large-scale projects), China, Japan, and Israel.

For instance, [64,65] mentioned an experimental project of a CAES pilot plant operating since 1990 at the Sunagawa Coal Mine (Japan); [65] stated that a CAES 30 MW pilot plant was being constructed on Hokkaido Island in Japan; and a 300 MW CAES plant was also being planned for construction in Mount Sodom, Israel. However, any additional information about these projects could not be found, which suggests that they may no longer exist.

3.2.5. Summary of CAES projects

Table 2 provides a summary of the primary key characteristics, known investments, and status of all the regarded CAES projects, showing the main information on CAES projects worldwide for comparison purposes.

It should be pointed out that this CAES benchmark only covers CAES technologies, such as diabatic, adiabatic and isothermal CAES. It does not include any hybrid CAES projects, where CAES technology is joined together with other energy sources, for instance, hydrogen, geothermal energy, or others.

4. Benchmarking of regulatory framework and policies for ES

ES is increasingly seen as an essential part of grid balance, providing for a higher penetration of variable renewable energy. According to [66], interest in ES has been growing significantly, alongside enhanced maturity, over the past five years. Several drivers support the increasing use of ES technologies, such as the shift towards decarbonization, increasing energy access, emphasis on energy security, aging energy infrastructure, increasing energy produced by RES, and emphasis on decentralized energy production due to rapidly declining solar PV costs [67]. Despite factors such as technology cost and performance influencing ES deployment, one of the key issues which impact further development of electricity storage are regulatory and market framework conditions [68]. Unique to each electricity market, the regulatory policy on storage operation significantly impacts ES systems [69].

Although many energy-related policies (e.g., renewable energy policies and market reforms) have been implemented in many parts of the world [70], only recently ES policies have started to be adopted and promoted in some countries for reasons such as supporting renewable energy integration, emergency power, and grid stability [70,71]. Nowadays, utilities and regulators have begun to recognize the value of ES for different services, since it benefits various stakeholders such as electric utilities, customers, and renewable power producers [71] Moreover, ES cuts across electricity systems, including generation, transmission, distribution, and end-users [72]. Thus, different management strategies have been laid out to optimize the operation of ES systems [71] Winfield et al. [66] studied the development of ES in the European Union (EU), Canada, and the United States (US), and they state that private capital is increasingly interested in storage technology developments and commercial-scale investments, but they are waiting to clarify regulatory and policy frameworks.

ES industry associations have been formed in the US (ES Association - ESA), Canada (ES Canada), and Europe (European Association for Storage of Energy - EASE). In addition, ES roadmaps have been published as development strategies by prominent players in the field, such as the technology roadmap of the International Energy Agency [67], the US 2025 vision for ES [73], and the EU with European ES Technology Development Roadmap towards 2030 [74,75].

In this paper, a benchmark of the ES regulatory framework and policies is performed, focusing mainly on European countries and the US, but also briefly addressing other countries such as Australia, China, Japan and South Korea. Furthermore, the drivers of the ES policies and the main ES barriers are identified.

4.1. USA

ES investment is growing in the USA, encouraged by the Energy Independence and Security Act of 2007. In 2016, it reached approximately 23 GW (where 95 % of that ES capacity was PHS), representing 18 % of world storage [76,77].

The efforts for the deployment of ES have been actively pursued by US regulators. According to [70] both federal and state-level governments have pursued policies to promote investment, reduce taxes, subsidize support, and expand public supplies to boost and create new markets for ES.

Table 2
Summary of the key characteristics, costs & investments, and status of CAES projects worldwide.

CAES projects		Location	Power capacity	CAES technology	Reservoir type	Costs & investments	Status of the project
Scale	Name						
Large-scale	GEM	USA,	500 MW	A-CAES	Underground hydrostatic compensated reservoir	$335,959,300	Under active development
	PECHO	California	400 MW			$800 million	Operational by 2024 and 2027
	Norton	USA, Ohio	270 MW	D-CAES	Underground hard rock cavern, Limestone mine with shale cap-rock	Undisclosed	Project delayed
	Iowa	USA, Iowa	270 MW	D-CAES	Sandstone aquifer	$ 400 million	Discontinued in 2011
	Matagorda	USA, Texas	540 MW (4 × 135 MW)	N.S.	Brine cavern	Undisclosed	Unknown
	Apex (Bethel Energy Center)	USA, Texas	317 MW	N.S.	Salt dome	Undisclosed	Construction phase: 4th quarter of 2021; anticipated commercial operation date: spring of 2025
	New York	USA, New York	150 MW	A-CAES	Underground salt cavern	$125,006,103.00	Announced in 2010 and discontinued
	Dakota Salts	USA, Colorado	N.S.	D-CAES	Underground salt formations	$129.700,00 (Phase 1)	Uncertain (Last news in 2014)
	Pacific Norwest	USA, Washington St.	231 MW (storage), 207 MW (generation)	1) D-CAES	1) Porous and permeable rock structures - aquifer	Undisclosed	Uncertain
		USA, Oregon St.	150 MW (storage), 83 MW (generation)	2) Hybrid geothermal CAES	2) Continental flood basalt deposits	Undisclosed	Uncertain
	Larnes	Ireland	330 MW 250 MW (demand)	NS.	Salt deposits	£ 300 million	Announced but Never built
	Adele	Germany	200 MW	A-CAES	Salt caverns	12 million €	Announced but never built
	Silver City	Australia	200 MW	A-CAES	Decommissioned mine	Aus $ 600 million	Under active development operational by 2024
	Israel	Israel	300 MW	NS.	NS.	Undisclosed	Uncertain
	China	China,		AA-CAES	N.S.	Undisclosed	Uncertain
		Mongolia	10 MW	A-CAES	Salt cavern	Undisclosed	Active – under operation
		Jiangsu Jintan	60 MW				
	Japan	Japan, Hokkaido Island	30 MW	NS.	NS.	Undisclosed	Uncertain
Small-scale	SustainX + General Compression = GCX	USA, (Gaine) Texas	1) 1,5 MW 2) 2 MW	Isothermal CAES	1) Tanks or pressure vessels 2) Salt cavern	$10,792,045	1) Unknown 2) Operational
	LightSail Energy	USA, California	NS.	Isothermal CAES.	Carbon fiber tanks	$70 million	Uncertain
	Hydrostor	Canada, Toronto Island	1) 0,7 MW	AA-CAES	HydroPods	Undisclosed	1) In Service (Nov 2015)
		Canada, Goderich	2) 1,75 MW	(With TES)	Build underground cavern		2) In Service 2019
	ALACAES	Switzerland	1 MW (Small CAES.)	AA-CAES	5 m-Diameter tunnel (Swiss Alps)	$4.1 million	Operational (But not ready to be used)
	RICAS 2020	Austria	5 MW (test facility)	AA-CAES	N.S.	1.373.637,50 €	Research ended in 2018
	China	China	1,5 MW	AA-CAES	N.S.	Undisclosed	Uncertain

NS - Not Specified.

In 2020, the American Energy Innovation Act (AEIA) authorized $1.4 billion for ES RD&D at the US Department of Energy (DOE) [70].

The Federal Energy Regulatory Commission (FERC) individually addresses issues concerning ES classification for use on the grid, since they do not fall under conventional generation, transmission, or distribution functions. It also amended its regulations under the Federal Power Act (FPA) to remove barriers to the participation of electric storage resources in the capacity, energy, and ancillary service markets operated by Regional Transmission Organizations (RTO) and Independent System Operators (ISO) (RTO/ISO markets) [78]. For instance, FERC implemented a series of related orders (755, 784, and 792) applicable to the electric power markets of Pennsylvania, Jersey, Maryland (PJM), Midcontinent Independent System Operator (MISO), California Independent System Operator (CAISO), New York Independent System Operator (NYISO), and Independent System Operator for New England (ISO-NE) [69]. FERC order 755 ensures system operators develop pay-for-performance tariffs for ancillary services [79] promoting the ES used for frequency regulation by giving it reasonable rates [70]. FERC order 784 requires system operators to consider speed and accuracy in formulating requirements for ancillary services, opening these markets for ES [70]. In contrast, order 792 places ES on the same level as conventional generators by considering it a power source [80]. In 2018, FERC order number 841 was approved, and it requires that storage be made eligible to participate in all deregulated electricity markets in the US, removing any barriers to the entry of ES technologies by ISO and RTO [70,81]. Thus, several inter-connection regions and ISOs have already established ancillary service markets for services like frequency regulation and voltage support [82], such as PJM - an RTO that coordinates the movement of wholesale electricity in 13 States and the District of Columbia, and also the New York Independent System

Operator (NYISO) [82]. This means that enhancing the value-generating potential of ES by expanding access to ancillary and other markets is a powerful mechanism for building a storage-based smart grid network. Moreover, it works better in deregulated electricity markets which offer the best potential for developing storage services [82].

In 2016, the ES tax incentive bill, S.3159, was proposed with the purpose of allowing ES tax credits with a minimum capacity of 5 kWh, covering different types of ES systems, such as chemical, electrical, thermal, electrochemical, mechanical, and other systems identified by internal revenue services, as long as they store energy by charging and can also discharge when needed [70].

The Pacific Northwest National Laboratory identified five types of state-level ES policies, such as procurement targets, regulatory adaptation, demonstration projects, financial incentives, and consumer protection [83].

Some states in the US, such as Hawaii, California, Oregon, Arizona, Massachusetts, and New York, also pass laws that enforce competitive ES procurement targets, setting minimum requirements for utilities to adopt storage systems [70,73]. According to [70], Hawaii has been investing in ES to integrate RES, which has a goal of reaching 100 % by 2045; California drove the ES grid-scale in the US through its state procurement mandate and had a 2020 target for state ES of 1325 MW plus 500 MW; Oregon required a minimum of 5 MW of ES by utilities in service in 2020; Arizona proposed a target of 3000 MW of ES by 2030; Massachusetts intends to achieve 1000 MWh by the end of 2025, and New York's ES goal is to reach 1500 MW by 2025.

Other states, such as Maryland, have a dedicated tax credit program for ES [73]. Zame et al. [82] state that implementing short-term policies addresses the high cost of capital associated with many ES options. For instance, investment tax credits (ITCs) are a highly effective method of reducing capital costs and limiting exposure to technological and capital risk [82]. An example for CAES shows that within seven years, nearly 2500 MW of new CAES capacity is possible with 20 % ITC compared to only 700 MW without any ITC [84].

4.2. Europe

The EU has been increasing its RES technologies to reduce the carbon output from fossil fuels. Thus, Europe has set goals and regulations to establish policies, incentives, and rules governing the energy markets, renewable energy and ES.

European investment in ES covered around 20 % of the ES market worldwide [76,77]. In addition, the Strategic Energy Technology Plan (SET-Plan) was set up by the European Union (EU) to develop and implement an energy technology policy for the transition to a low carbon economy. In this SET-Plan, ES is referred to as one of the solutions to manage the challenges of a smarter grid [85].

Storage is classified as a generation asset in most electricity markets [72]. Directive 2009/28/EC27 of the European Parliament and the Council of April 2009 provides common rules for the internal electricity market and sets ambitious targets for all Member States. Although the Directive includes definitions on power generation, transmission, distribution, and supply systems, it misses the concept of ES systems as a separate component in the energy model, leading to the treatment of electrical ES as an electricity generator and resulting in differences among EU countries [68,71,86]. The European Commission proposed a definition of ES in 2016 as the "act of deferring an amount of energy that was generated to the moment of use, either as final energy or converted into another energy carrier" [87]. More recently, the Directive (EU) 2019/944 of the European Parliament and the Council of June 5, 2019, on common rules for the internal market for electricity, Article 2 (59), states that: a) 'ES' means deferring the final use of electricity to a moment later than when it was generated, and b) the conversion of electrical energy into a form of energy which can be stored, and the subsequent reconversion of such energy into electrical power or use as another energy carrier [88]. The same Directive refers to long-term storage as a timespan of several months.

Directive 2009/28/EC27 states that transmission system operators (TSOs) cannot control the supply or generation of electricity, meaning that TSOs cannot own or manage an electricity storage system [86]. There is a debate in the European Commission about whether distribution network operators (DNOs) or TSOs should own ES [72,89]. In most EU countries, it is currently not clear if TSOs and DNOs can directly operate ES for grid balancing [71,90]. This ownership issue is also one of the most critical barriers to ES development [72,77,91], especially for large-scale storage, such as CAES.

For instance, [72] stated that for DNO-owned storage in the UK and other major world markets, a third party must handle electricity flows when storage is used to support the network or provide broader system-wide services. In the UK, ES works both as a load or generator. However, it was considered a generator under licensing conditions [76] since there was no clarity in the role, no specific regulation for ES, and no particular license conditions for its ownership and operation [77]. Although the development of ES in the UK is not linked to subsidies, regulatory and policy barriers are being removed, for example in the form of tax breaks to ES systems, and they are funding research, development, and demonstration (RD&D) projects for ES [70].

Scandinavian countries are another example where ES is considered an essential element, but the specific regulation is still insufficient. For instance, in Denmark, ES is treated as a load by present regulation. In Norway, there are grid charges for pumped hydro storage (PHS) as load or generator with an additional charge for energy consumption during peak periods [76,77].

In Germany, although ES is considered a key component in a reliable, economically stable, and efficient power system, regulations, opportunities, and mechanisms are still insufficient to support the competitive use of ES, affecting its uptake [77,92]. However, the German Federal Ministry for Economic Affairs set out low-interest subsidy and loan schemes for ES (e.g., batteries) integrated with distributed photovoltaic (PV) installations connected to the grid. This increased the adoption of ES for PV [70]. However, under the German Renewable Energy Sources Act (EEG), these ES facilities were exempted from grid tariffs and levies; this EEG promotes mainly RES and may act as a barrier to ES as they support negative price periods [70]. So, these laws need to be adjusted.

In the Netherlands, the government is promoting power generation from RES, but the uptake of ESS is discouraged as adequate legislation to support ESS does not exist, so ES facilities still do not attract much interest in the country [70].

France has identified ES as a means of achieving the RES target by 2030 (under the energy transition law). It also set up a hydrogen plan to develop the technology and its ES potential. However, there are several barriers, such as the absence of an ES regulatory framework for its development, ES facilities are charged twice as consumer (when charging) and producer (when discharging into the grid), and feed-in-tariffs favor the direct injection of electricity into the grid instead of storing it [70].

In Italy, the rapid increase of RES led to the adoption of Legislative Decree 28/11 implementing Directive 2009/28/EC calling on Terna. In addition, Italian TSO identifies network reinforcements, including ES, to enable energy from RES to be fully dispatched [77,93]. Furthermore, the National Energy Strategy (NES) considers ES related to smart grids and sustainable transport [70]. However, one of the barriers to ES in Italy is the high grid charges which discourage their deployment [70].

There is also no specific regulation for ES in Spain as a whole since it has seventeen autonomous regions with their own energy policies [70]. Legislative initiatives have been restricted to some regions, such as the Canary Islands, where compensation is done by regulated capacity and energy payments [77,93] or Malaga and Barcelona, which set up initiatives for smart grids [70]. The main barriers to ES in Spain include the classification as generation and not being regulated separately [70].

For Portugal, the report on energy regulation states that the emergence of RES, with a high fixed cost structure and decentralized production, made it necessary to exploit flexibility mechanisms, such as ES and demand management [94]. However, until now, and despite the existing Pumped Hydro Storage (PHS) facilities, there was no known specific regulation for ES systems in the country. But in 2021, new regulations on the electricity system are being reviewed and updated according to the latest European Directives on the internal market of energy and renewables, where new paths and regulations for ES will be pointed out [95]. These new laws are based on a study about ES for Portugal [3], conducted by ADENE, the Faculty of Sciences of Lisbon University (FCUL), and the Technical Superior Institute (IST).

The CEER "European Green Deal" White Paper about long-term storage recommends that regulations establish a level playing field between long-term storage and other seasonal adequacy approaches (i.e., excess generation assets, flexibility, and storage). It also states that storage and sector coupling technologies should be integrated in a more detailed way in planning models (e.g., integrated electricity and gas market and network model) [96].

The present European benchmark analysis of the ES regulatory framework shows that the EU must study its ES needs in depth, clarify its classification and harmonize its regulatory framework across member states (since policies are not homogeneous).

4.3. China

China has a vertically integrated electricity market, and ES technologies such as PHES, CAES and batteries are being researched. Their use is motivated by the need to increase grid efficiency by integrating RES [76,77]. China's Central Government promoted ES policies targeting different aspects that can progress and ensure its rapid development, such as market development, grid-connected operation management, development pattern and environmental protection, and financial support [70,97]. In addition, it encouraged the demonstration projects to be continuously carried out as long as there are new technological innovations [70].

4.4. Other countries

Screening other countries for decarbonization targets, Australia, China, Japan, and South Korea, may be referred to due to the need for ES with the increased use of RES.

Australia has the highest GHG emissions in the Organization for Economic Co-operation and Development (OECD) and is one of the highest globally. Moreover, it targets 20 % electricity production from RES by 2020 [76,77]. Thus, it needs ES solutions. The Australian Renewable Energy Agency (ARENA) is the key mechanism supporting ES development to achieve the country's RES goal [70]. This is corroborated by investments in the ES field, such as battery storage and the Silver City ES project, a utility-scale A-CAES facility located in Broken Hill (New South Wales), developed by Hydrostor in a joint venture with Energy Estate [30].

South Korea supports innovative energy systems, including ES technologies, by laying down the ES Technology Development and Industrialization Strategies (K-ESS 2020), and propelling technological development and demonstration projects [70].

In Japan, power generation and retail sectors of the power industry are liberalized. There is growing interest in ES technologies (especially batteries) as stable suppliers, although they have been around for decades (since the 1980s) [68]: The target is 15 % of ES capacity to be deployed on the grid [76,77].

4.5. Energy storage drivers and barriers

According to [70] ES policies are the reason storage technologies are developing and being utilized at a remarkably high rate. The main driver of the ES policies is the target to obtain more clean and sustainable energy, such as RES, moving towards decarbonization processes. Thus, drivers, such as mitigating climate change, increasing energy security and reliability and energy efficiency, are helping to boost the development of ES. Furthermore, ES regulatory framework and policies are intimately linked to the transition to a low-carbon economy by helping to integrate high levels of intermittent RES, such as wind or solar, allowing a more resilient, reliable, and flexible energy grid, and promoting more energy production [98].

However, the deployment of ES and its regulatory framework still has a long way to go, especially to overcome its barriers. In this benchmark procedure, the identified barriers to ES could be classified into three main types: a) technological barriers (e.g., capacity, efficiency, deployability, and technological costs); b) market and regulatory issues; and c) strategic framework. Furthermore, according to [76,77], the market and regulatory issues can be divided into storage regulatory barriers and storage market design barriers. Thus, this study provides an overview of ES regulatory barriers which is systematized based on several authors [71,72,77]:

a) The current renewable integration policy gives little incentive to invest in ES, meaning a lack of any form of direct support or clear investment incentives;
b) Undetermined ES asset classification or classification only as a generation asset or a load. Since ES is multifunctional, it does not fall under conventional functions of generation, transmission, or distribution;
c) Transmission and distribution use of system charges, since grid ES is usually subject to T&D charges as a generator, consumer, or both.
d) Uncertainty regarding ownership and operation of storage assets, since in many energy regulatory frameworks, TSOs and DSOs cannot own and operate ES systems;
e) Lack of recognition of ES system-wide benefits, related to lack of public and government awareness of the importance of storage for the energy chain, affecting the profitability of investing in storage technologies;
f) Lack of framework and incentives for the provisioning of storage services to network operators, since there are no incentives or rewards for improved power quality;
g) Lack of unified and conclusive legal and regulatory frameworks towards ES, leading in the case of EU countries or US states to differences and distortions in national energy markets;
h) Unwillingness to take risks or innovate correlated to lack of experience and high investment costs for most ES technologies, making ES a risky venture;
i) Lack of standards and practices for ES technologies to carry out through economic assessments, system design and deployment since, most ES technologies are quite new;
j) Policies for other flexible solutions which compete directly with ES, such as interconnections or gas-fired peaking power plants;
k) Considering ES as part of RES schemes, however, the energy stored is not always from RES, leading to the difficulty of including ES in RES subsidies;

Regulatory barriers to ES greatly depend on the extent of unbundling practiced in the electricity system [76]. On the one hand, it is easier for utilities to deploy ES in countries with bundled markets and vertical integration. On the other hand, in countries with an unbundled system, deployment of ES is more difficult, since multiple factors are involved, from generation to consumers, with different goals, practices, and regulation systems. However, natural monopolies can complicate electricity market operation, providing regulated network operators with a way of influencing electricity market price, providing a biased advantage, and going against the principles of unbundling [76]. Thus, T&D operators can potentially distort the electricity market by participating in wholesale and retail markets with ES assets.

The European ES Technology Development Roadmap Towards 2030 [75] mentions impediments and encourages ES deployment, stating that it should be recognized as the fourth element of the energy system, preventing it from being classified as either generation or consumption. On the other hand, [71] defend that ES should be considered a unique technology, with its characteristics and services offered to the power system. Thus, one of the most critical regulatory barriers to ES is classification as a generation asset [72] falling under network codes for generation facilities [68,71], which underestimates the flexibility and set of services that storage can offer [71]. So, the lack of a distinct classification of storage assets contributes to the most significant number of other barriers [72].

Dusonchet et al. [71] state that grid fees and taxation for ES should be reduced as they can offer the necessary balancing services to the electrical grid. They also argue that grid operators and service providers have a significant interest in controlling and operating ES facilities, offering balancing services to the power system, and participating directly in the balancing market. Therefore, ownership of ES should be clarified.

Winfield et al. [66] analyzed the energy policy regime and advanced ES in the U.S., Canada and the EU. They defend the need for adjustments to existing market rules and structures addressing barriers to full utilization of ES resources, such as removing technical barriers of storage resources to market participation, facilitating storage participation in multiple markets simultaneously, and establishing new categories of market participants. [72] also conclude that removing storage barriers is directly associated with its treatment as an integral part of the electricity system, stating that it is a complement to the network and not a competitor.

Zame et al. [82] state that creating a new asset class for ES systems will open storage technologies up to providing multiple services and generating greater value. They also say that a purely market-based system does not offer price signals to the full range of ES services, such as transmission and distribution relief and is currently incapable of pricing all energy services. They mention that appropriate policy support with regulations and incentives for ES would attract more investment. According to the same authors [82], ITCs will accelerate investment in storage projects, and continued market deregulation will augment revenue streams, enhance competition and, more precisely, price storage services. The same authors defend that continuous RD&D policies for new ES technologies and larger-scale applications of existing ES technologies would increase operational experience and reduce costs, which should be crucial for promoting advanced ES development. So, they also defend that pilot and demonstration projects are especially critical to show the viability of newer technologies and successful demonstrations, reducing the risk of investing in these technologies and helping to secure private investor funding for large-scale ES systems. One example they mention is precisely CAES.

The IEA Technology Roadmap [67] states that the key to achieving widespread storage technology deployment is enabling compensation for multiple services delivered across the energy system. [99] defends that security of supply which storage can offer must be adequately remunerated, whether through capacity markets, reliability options, or very well-functioning balancing markets.

The European ES Technology Development Roadmap Towards 2030 [75] states that deployment and system integration of ES technologies depends mainly on the strength of R&D effort. However, enabling a regulatory environment that allows ES to compete on an equal basis with other flexibility providers will be essential for sustained growth in the ES industry [75].

ESA believes that policy-makers, regulators, utilities and other stakeholders must all act to enable ES [73]. Therefore, identifying and removing ES barriers will unleash the opportunities that ES policies can bring [70], and regulators are critical to the energy market's advancement and adoption of advanced ES systems [73].

5. Results and discussion

5.1. *Influence of regulatory framework for ES on CAES projects*

The location of storage assets is critical for understanding their value on the grid since load profiles and storage system needs differ according to location [73].

Therefore, to answer questions raised at the beginning of this study and understand the influence that a developed ES regulatory framework may have on deploying CAES technologies, results were organized by systematizing the analyzed countries with some developed ES policies and CAES projects and facilities by country or continent. Therefore, Table 3 outlines ES policies by country and the number and scale of CAES facilities and projects worldwide.

Twenty-eight CAES projects (Table 3) were addressed in the CAES benchmark analysis involving large and small-scale systems, including five in Europe, fourteen in the USA, two in Canada, one in Israel, three in China, two in Japan, and one in Australia. Among them, three large-scale D-CAES facilities are working globally, one in Germany (Huntorf), one in the USA (McIntosh), and more recently one in China (Jiangsu). In addition, two small-scale A-CAES facilities are in service in Canada (Toronto and Goderich). Three utility-scale A-CAES facilities are under active development, and are scheduled to start operating in 2024, 2026, and 2027; two are in California (USA) and another in New South Wales (Australia) all of which are being developed by Hydrostor.

The table makes it clear that most CAES projects and facilities are located in the Northern hemisphere. For example, North America has sixteen in total, fourteen in the USA and two in Canada, Europe has five CAES projects and China has three (Table 3). However, apart from a utility-scale A-CAES facility project under development in Australia, the significance of the other countries with CAES projects is still small, compared mainly to North America.

The fact is that most CAES projects unfold in countries where ES policies and regulatory framework seem to be more developed and energy markets are liberalized.

Table 3
Systematization of countries with ES regulatory framework benchmark presence and CAES facilities and project benchmark, linking both issues by location.

ES regulatory framework benchmark	CAES benchmark (number and scale of projects)				Total
Countries with some ES policies	CAES facilities	Scale	CAES projects	Scale	CAES
Europe	1	Large	4	Both	5
Denmark	N.A.	N.A.	N.A.	N.A.	N.A.
Norway	N.A.	N.A.	N.A.	N.A.	N.A.
UK	N.A.	N.A.	N.A.	N.A.	N.A.
Ireland (not studied)	N.A.	N.A.	1	Large	1
Germany	1	Large	1	Large	2
Netherlands	N.A.	N.A.	N.A.	N.A.	N.A.
Switzerland (not Studied)	N.A.	N.A.	1	Small	1
Austria (not studied)	N.A.	N.A.	1	Large	1
France	N.A.	N.A.	N.A.	N.A.	N.A.
Italy	N.A.	N.A.	N.A.	N.A.	N.A.
Spain	N.A.	N.A.	N.A.	N.A.	N.A.
Portugal	N.A.	N.A.	N.A.	N.A.	N.A.
USA	1	Large	13	9 large; 3 small	14
Canada	2	Small	N.A.	N.A.	2
Israel	N.A.	N.A.	1	Large	1
China	1	Large	2	2 large, 1 small	3
Japan	N.A.	N.A.	2	1 large, 1 small	2
Australia	N.A.	N.A.	1	1 large	1
South Korea	N.A.	N.A.	N.A.	N.A.	N.A.
Total	5		23		28

N.A. Not Applicable.

There may be several reasons for the correlation between countries with CAES projects and ES policies. For example: a) the concentration of more liberalized energy markets in the Northern hemisphere; b) deeper concerns with climate change, proposed targets, and incentives for the use of RES; c) more significant ES needs, as well as greater awareness of them; d) higher financial availability for investments in ES; e) greater availability of suitable geological sites for underground CAES storage, among other potential reasons. For instance, when considering technical reasons such as geology, some countries may not have CAES projects because they lack the underground lithologies needed for large-scale CAES deployment. The question is: Is this concomitance only a coincidence?

The fact is that ES policies are predominantly made by countries with developed economies [70], and CAES projects (as the majority of ES technologies) are also being deployed in the same economies.

In addition, another question raised at the beginning of this study was if the ES regulatory framework dictates the deployment or cancellation of CAES projects? In fact, out of the twenty-eight CAES projects, there are five operational CAES facilities (three large and two small-scale), four CAES projects under development (three Hydrostor large-scale A-CAES projects, and Bethel Energy Center), and nineteen CAES projects which were canceled or have finished for several reasons. Among the reasons advanced in the literature for the cancellation of CAES, the direct lack of ES policies was not pointed out. Except for the New York State Electric & Gas CAES Project, where the energy market conditions were highlighted. However, this justification is very general and may comprehend several other factors besides the regulatory framework. Actually, the only references to the regulation in the CAES projects benchmark were found under the Hydrostor A-CAES projects in progress, Pecho ES Center in California and Silver City ES Center in Australia, as a positive influencing factor for their deployment.

ES deployment is linked to the goals for increasing RES production [70]. Therefore, ES policies and regulations also seem to be related to the deployment of CAES projects since, as seen, most CAES projects are or were taking place in countries where regulatory policies for energy, RES and ES are more developed. However, the regulatory framework is not the only factor to consider. Although the ES policies seem to motivate increasing interest in CAES, investment and demonstration projects, this may also be true for other ES technologies. Thus, it should be noted that although these benchmarking procedures indicate the concomitance of CAES projects and ES policies, giving clues as to the reasons for this coincidence, this analysis may not be sufficient to demonstrate a direct correlation between the two. This means that future work may be developed with other methodologies.

5.2. *Recommendations for ES regulatory framework applied to CAES*

This benchmark showed that deployment of ES is proceeding at quite different rates worldwide due to factors such as different regulatory frameworks, awareness of ES needs, and investment in technologies, among others. On the one hand, prospects are better in the USA (especially California), because regulation is more advanced and favorable to ES and also because regulators collaborate with developers and utilities to analyze and eliminate ES barriers and find solutions for the technologies. On the other hand, Europe must understand its ES needs in greater depth, clarify its classification, create new markets for ancillary services, design technology-neutral market rules [100], and harmonize its regulatory framework across member states. In addition, China is developing its ES strategy and implementing solutions such as CAES.

For instance, [70] hints at the key challenges for ES adoption, stating that market and regulatory guidelines, cost-effectiveness, safety and performance perception, and cooperation from multiple stakeholders are the principal factors to be addressed.

Several authors and reports indicate the need to adjust existing market rules and structures to overcome barriers, fully utilize ES resources, and address ES as a unique technology, distinct from generation, transmission, or distribution assets.

This policy perspective helped to understand the recommended measures and policies that policy-makers should adopt to stimulate ES deployment in general and, particularly, increase CAES development.

As a result, common policy and regulatory recommendations to most ES technologies are systematized and adapted to CAES according to the ES regulatory framework as follows:

a) Clarify ES definition and role in the energy system, also benefiting large and small-scale CAES;
b) Create a new asset class for ES, achieving its full potential in the energy system as an asset available to generation, transmission, distribution and end users. This measure will positively impact on CAES further;
c) Clarify rules governing ES access to the markets, ownership, and operation of ES facilities. In the case of CAES, this measure is essential to allow TSOs and DSOs to own and operate CAES facilities due to their large-scale utility applications;
d) Ensure that procurement of ES and ancillary services is market-based;
e) Eliminate unwarranted or double charging of ES to decrease costs and increase the competitiveness of storage;
f) Support CAES demonstration projects, endorsing funding of innovative RD&D, and streamlining the financing process for new large-scale CAES systems;
g) Facilitate the licensing and authorization process for new ES processes, such as CAES facilities, removing regulatory barriers that add storage system costs. For instance, regulatory use of underground in case of large-scale CAES should be considered and updated;
h) Establishing ES incentives, subsidies, and rebate programs (for example, ITCs) will benefit CAES deployment.

The significant importance and impact that the regulatory framework has on the deployment of all ES systems and on large-scale ES such as CAES are recognized, with regulation and policies being critical factors for the advancement of energy markets.

Therefore, breaking down barriers to ES and capturing its value for the grid should be the main focus of regulatory reforms and strategic frameworks. These procedures should be technologically neutral and ensure fair competition between different technologies. However, they also directly support the development of CAES projects, meaning that CAES systems have space to grow worldwide.

6. Conclusions

ES is nowadays recognized as a key component of energy systems, where the development of storage technologies can provide multiple services and generate greater value. However, current regulations can still prevent storage from achieving its full potential to integrate RES in the grid and as a main flexible option for electricity systems and markets.

This study provides an overview of CAES projects and insights on regulatory framework and policies from different countries and identifies drivers and barriers to ES. A two-step benchmarking procedure collects quantitative and qualitative data about CAES facilities and projects, as well as ES policy outlooks. Thus, it underlines drivers, barriers, challenges, and opportunities for regulations to better adapt to the ES system development and grid challenges brought by increasing integration of RES.

Removing current regulatory barriers and establishing new and broader policies are essential factors to provide ES technologies with the right opportunities to develop, enhance efficiency, increase operational experience and reduce costs.

Thus, in terms of ES regulatory framework, the main suggestions from this study are the adoption of the following measures to remove barriers to ES: 1) the new classification of ES in the energy market as an asset that cuts across the entire energy chain (e.g., generation, transmission, distribution and end-users); 2) the authorization for the operation and ownership of large-scale facilities by TSOs and DSOs; 3) eliminating double charging of ES systems; and 4) establishing incentives, subsidies and rebate programs for ES. These measures were found to be the main ones to impact large-scale ES technologies, such as CAES. Therefore, although it can be argued that removing the barriers will benefit all ES technologies (which is also true), they were considered in this two-step benchmark procedure as the most significant for large-scale CAES.

On the one hand, widespread CAES deployment seems to be linked with countries where the regulatory framework for ES is more developed, hindering a connection between the regulatory framework for ES and CAES projects. This happens in countries like the USA, where ES deployment is encouraged by several policy measures, better integration in markets has been implemented, and the number of CAES projects is most significant (thirteen CAES projects and one CAES facility). It also happens in European countries (with four CAES projects and one CAES facility). On the other hand, CAES project implementation or cancellation does not refer specifically to the ES policies as a unique driver.

However, despite this link between ES policy development and CAES deployment, the current study is not sufficiently extensive to allow us to conclude that they are directly correlated. Moreover, several factors beyond the regulatory framework may contribute to the zonation of CAES projects in some areas of the globe, i.e., the Northern Hemisphere. These factors may be, for instance, countries with developed economies, deeper concerns over climate change, specific targets and more incentives for the use of RES, the concentration of more liberalized energy markets, greater awareness of ES needs, higher financial availability for investments in RD&D and ES projects, more technical knowledge or even availability of suitable geological sites for underground CAES storage.

Therefore, regulatory framework and policies are not the only factors that should be considered for CAES deployment. For a complete analysis of factors influencing CAES development, other factors beyond regulation and policies should be further addressed. For example, investments in RD&D for ES and particularly CAES, costs and economic aspects of CAES systems, geographical factors, geological limitations, technical factors, and technology efficiencies, among other technical characteristics for CAES, should also be considered.

Despite the previous argumentation, adequate ES policies are a promising opportunity and were recommended in this paper to help motivate ES deployment and CAES development. However, it should be noted that energy and ES regulatory framework and policies are in constant evolution worldwide, so this paper does not claim to be watertight in its overview of ES policies. Furthermore, ES policy revision work has not been exhausted by any means and should be constantly updated.

Regulators and governments need to understand all ES benefits and see it as an opportunity to reach their full potential. Policy-makers can benefit from the insights of this overview, which contribute to public policy for overcoming the regulatory barriers to ES and specifically to CAES.

Future work may deeply understand the existing legislation and market design for ES, especially across the EU, since there is no homogenization between countries. In addition, it would be essential to bring together governments, policy-makers, and key decision leaders to adopt global ES regulation, helping to improve ES implementation worldwide.

CRediT authorship contribution statement

Catarina R. Matos: Conceptualization, Methodology, Investigation, Data curation, Writing - Original draft preparation, Validation, Writing - Review & Editing.

Patrícia P. Silva: Validation, Supervision, Writing - Review & Editing.

Júlio F. Carneiro: Validation, Supervision, Writing - Review & Editing.

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.

Data availability

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

Acknowledgments

Catarina R. Matos acknowledges the funding provided by the Portuguese Foundation for Science and Technology (FCT) under doctoral research grant SFRH/BD/117722/2016 and the Energy for Sustainability Initiative of the University of Coimbra.

Patrícia P. Silva acknowledges that this work has been partially supported by the FCT project grant UID/MULTI/00308/2020 and the Energy for Sustainability Initiative of the University of Coimbra.

The authors Catarina R. Matos and Júlio F. Carneiro acknowledge that this work has been co-funded by National funds through FCT - Fundação para a Ciência e a Tecnologia, I.P. (projects UIDB/04683/2020 and UIDP/04683/2020).

This work was partially supported by the Portuguese Foundation for Science and Technology through projects ID/MULTI/00308/2020 and UIDB/05037/2020 and the European Regional Development Fund in the framework of COMPETE 2020 Programme within project T4ENERTEC (POCI-01-0145-FEDER-0298).

Funding

This work was supported by the Portuguese Foundation for Science and Technology (FCT) under the doctoral research grant SFRH/BD/117722/2016.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.est.2022.105862.

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