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*Review*

# Cryogenics in Renewable Energy Storage: A Review of Technologies

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**Abstract:** The increase in the exploration of renewable energy sources intensifies the need for efficient storage solutions to mitigate the inherent intermittence of these sources. Among the available technologies, cryogenic energy storage (CES) systems stand out as a major and promising technology due to their high scalability, energy efficiency, and potential for integration with other systems. This paper deals with cryogenic approaches, focused on Liquid Air Energy Storage (LAES). Several topics are addressed, including the characterization of the CES systems, their working principle, with special relevance to efficiency and temperature/entropy diagram, the conception and the technical challenges, design, and construction of CES. LAES demonstrates energy efficiencies ranging from 45% to 70%, potentially reaching up to 75% with the integration of complementary technologies, with capital costs ranging from 900 EUR/kW to 1750/EUR/kW. Carbon dioxide ($CO_2$)-based systems, while more energy-efficient (40% to 60%), face significant barriers due to high infrastructure costs. Additionally, hybrid configurations that combine advanced thermal cycles and waste heat management achieve efficiencies between 55% and 80%, showing adaptability in complex energy scenarios. In comparison with alternatives such as batteries and Compressed Air Energy Storage (CAES), despite economic and technological limitations, CES systems have a promising role in the global energy transition, particularly with anticipated advancements that will enhance their competitiveness and economic viability.

**Keywords:** cryogenic energy storage (CES); energy storage; liquid air energy storage (LAES); electric energy storage; liquefied gases



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## 1. Introduction

In the current global energy landscape, renewable energy sources are playing an increasingly pivotal role, driven by the pressing need to mitigate the impacts of climate change and reduce dependence on fossil fuels [1]. However, the intermittent nature of sources such as solar and wind poses significant challenges for their effective integration into power systems [2]. In this context, the search for efficient energy storage solutions has become a priority to ensure the stability and reliability of energy grids. Cryogenic systems have emerged as a promising approach to renewable energy storage [3]. These systems rely on extremely low temperatures to liquefy and store gases such as air or hydrogen, offering high energy density and the potential for large-scale energy recovery [4]. Moreover, cryogenics provides unique opportunities for integration with industrial processes, enhancing overall efficiency and promoting sustainability. Cryogenic energy storage has emerged as a promising solution to address the challenges associated with the intermittence of renewable energy sources [5]. Among the available technologies, Liquid Air Energy Storage (LAES) systems stand out for their innovation, scalability, and high potential for large-scale applications [6]. These systems offer high energy storage capacity, feasibility for large-scale operations, and integration with diverse renewable energy sources, positioning themselves as a strategic solution to ensure the stability and reliability of electrical grids [7,8]. In the scientific literature, LAES systems have gained increasing attention and are widely recognized as a viable alternative for mitigating the challenges posed by intermittent renewable energy sources. Over recent years, numerous studies have utilized review methodologies to analyze the progress of research in this field. Noteworthy contributions include "Liquid Air Energy Storage (LAES): A Review on Technology State-of-the-Art, Integration Pathways and Future Perspectives" [9], "A Review on Liquid Air Energy Storage: History, State of the Art and Recent Developments" [10], "Comprehensive Review of Liquid Air Energy Storage (LAES)" [11], "Liquid Air Energy Storage (LAES) as a Large-Scale Storage Technology for Renewable Energy Integration—A Review of Investigation Studies and Near Perspectives of LAES" [12], "Comprehensive Review of Liquid Air Energy Storage (LAES) Technologies" [11], "Liquid Air Energy Storage Systems: A Review" [13], and "Liquid Air Energy Storage (LAES)—Systematic Review of Two Decades of Research and Future Perspectives" [14]. These studies provide a comprehensive overview of the state-of-the-art developments, technological advancements, and challenges associated with the integration and optimization of LAES systems.

The concept of Liquid Air Energy Storage (LAES) was first proposed in 1977 and subsequently explored experimentally by entities such as Mitsubishi Heavy Industries and Hitachi [15]. Early developments included the implementation of an air-driven Rankine cycle, which demonstrated high operational stability and achieved a power output of 2.6 MW by Kishimoto et al. [16]. Concurrently, Hitachi investigated configurations involving the integration of gas combustors and concrete regenerators designed to enhance the efficiency of the liquefaction process, with projections indicating overall efficiencies of up to 70% [17]. In 2010, a collaboration between Highview Power and the University of Leeds led to the construction of the first fully integrated LAES pilot plant, with a capacity of 350 kW and 2.5 MWh [18,19]. This system was validated in 2013 and later transferred to the University of Birmingham, where it spurred further research. In 2018, Highview Power made a significant advancement with the launch of a pre-commercial 5 MW, 15 MWh plant, paving the way for the deployment of CRYOBattery systems—50 MW installations connected to electrical grids in the United Kingdom and the United States, marking a global milestone in grid integration [20,21]. Recent studies emphasize the critical role of cold thermal energy storage in improving LAES performance [20,22,23]. Notable contributions include Hamdy et al. [24], who analyzed the effect of cold storage on six liquefaction processes. Among the systems studied, the Heylandt, Claude, and Kapitza cycles stood out [25–28]. In addition, initiatives such as the CryoHub project and the IEA Energy Storage Task 36 have deepened technical and operational insights into LAES, highlighting its value in mitigating renewable energy intermittency and integrating with industrial processes, such as utilizing waste heat to improve efficiency and reduce operational costs. Despite these advancements, challenges remain, including optimizing efficiency, minimizing thermal losses, and reducing implementation costs. Nevertheless, the progress achieved underscores the potential of LAES as a strategic solution for developing more sustainable and resilient electrical grids, emphasizing the need for further research to enable large-scale deployment in the context of the energy transition. This review article aims to explore the growing role of cryogenics in renewable energy storage, analyzing the technological advancements and challenges associated with cryogenic systems. By focusing on key aspects such as thermodynamic performance and energy efficiency, the objective is to provide a critical overview of emerging cryogenic solutions, their practical applications, and their potential to contribute to the stability and efficiency of electrical grids within the context of the energy transition.

## 2. Methods and Materials

The systematic review was conducted following the guidelines of the PRISMA framework, ensuring a rigorous and transparent process in the selection of the analyzed studies [29]. The research was performed using the Scopus and ScienceDirect databases, employing the keywords: "cryogenics" OR "cryogenic" and "renewable energy storage" OR "energy storage", with the publication period restricted to 2014–2024. Articles were included that addressed the application of cryogenic systems in renewable energy storage, with a particular focus on thermodynamic aspects, energy efficiency, and grid integration. The ScienceDirect platform was chosen for its extensive coverage and relevance in the field of scientific research. Figure 1 presents the research flow diagram adopted in the systematic review, outlining the stages of the literature screening and selection process.

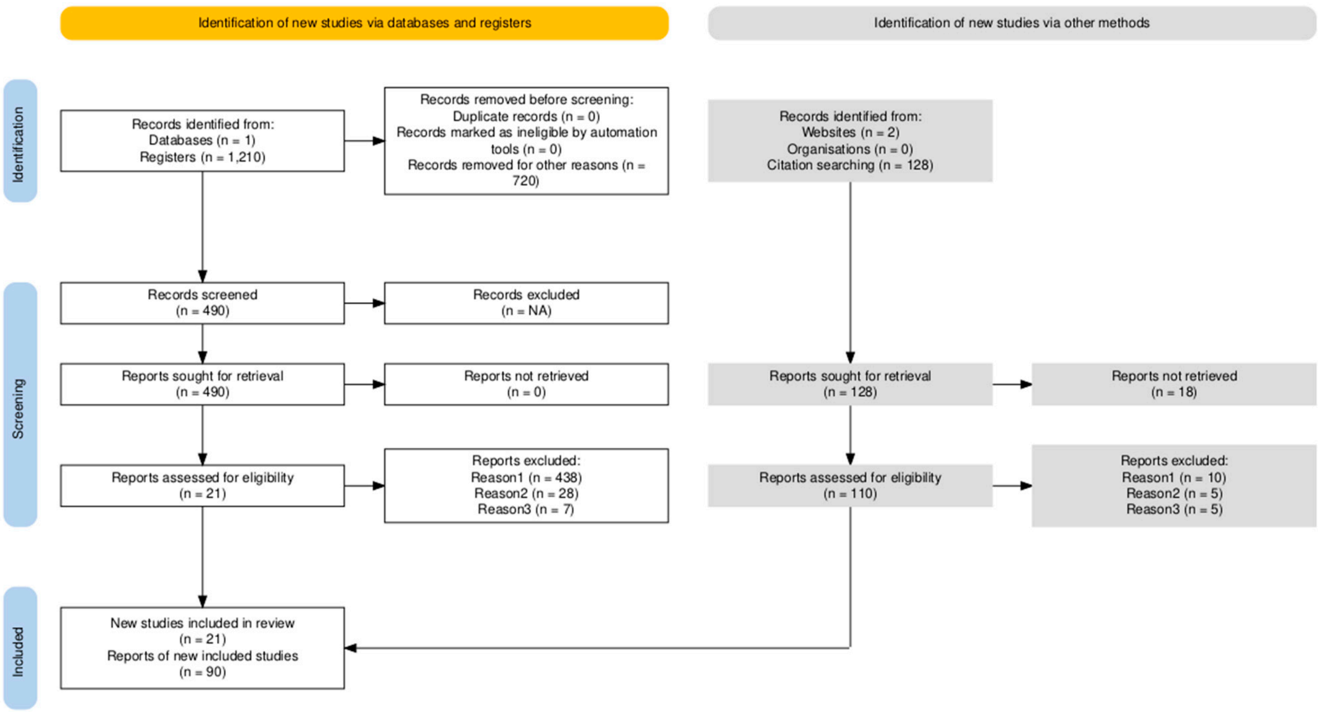


**Figure 1.** Flowchart adopted in the systematic review process.

To ensure the representativeness and comprehensiveness of the selected studies, only articles published in indexed scientific journals with high impact factors were considered, ensuring the reliability and rigor of the sources. The screening process was carried out in three sequential stages. (1) The first stage involved reading the titles to eliminate irrelevant studies. (2) In the second stage, abstracts were analyzed, excluding articles that did not explicitly mention the application of cryogenics in renewable energy storage. Finally, a full review of the content was conducted, ensuring the inclusion of only studies aligned with the research objectives. The quality of the selected studies was assessed based on criteria such as scientific relevance, methodology applied, robustness of the presented data, and impact within the field of study. Articles that presented rigorous quantitative and qualitative analyses, as well as widely recognized review studies in the literature, were prioritized. This meticulous process ensured that only high-quality works contributing to the synthesis of the state-of-the-art in cryogenic systems in the context of sustainable energy transition were included.

## 3. Theoretical Background

### *3.1. Principle of Cryogenic Systems*

Cryogenic systems are based on the application of extremely low temperatures for the processing and storage of gases in a liquid state [13,30,31]. This process consists of essential stages, including gas compression, expansion, and refrigeration, ultimately leading to their liquefaction [32]. Liquefied gases, such as air or hydrogen, are subsequently stored in thermally insulated reservoirs to preserve the critical temperatures required to maintain the liquid state and minimize energy losses [8]. These technologies are distinguished by their high energy density, which grants them significant potential for large-scale applications. Figure 2 illustrates the basic working principle of a cryogenic energy storage system, highlighting the key stages involved in the liquefaction and storage of gases.

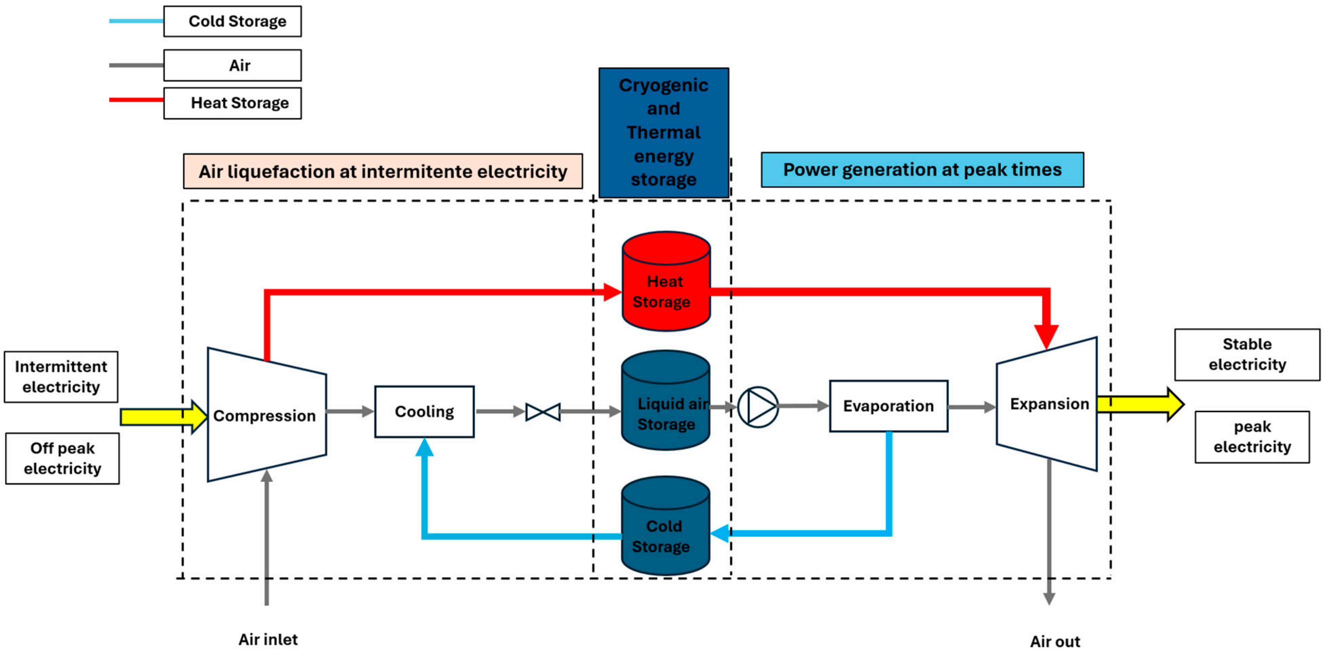


**Figure 2.** Basic working principle of cryogenic energy storage.

### *3.2. Performance Metrics in Cryogenic Energy Storage Systems*

Cryogenic energy storage (CES) systems, specifically Liquid Air Energy Storage (LAES) systems, are distinguished by their ability to store significant amounts of energy using liquefied air as the medium. The performance analysis of these systems is crucial for assessing their feasibility and optimizing their integration into renewable energy grids. Several thermodynamic metrics are employed for this purpose, as outlined below.

#### 3.2.1. Round-Trip Efficiency

Round-trip efficiency (RTE) is a key metric used to quantify the overall performance of Liquid Air Energy Storage systems. It is defined as the ratio of the network produced during the discharge cycle to the network consumed during the liquefaction cycle [13,26,33]:

$$RTE = \frac{Net\ work\ consumed\ (liquefaction)}{Net\ work\ produced\ (discharge)} \quad (1)$$

This definition applies to both conventional Liquid Air Energy Storage systems and integrated systems, making it a useful metric for evaluating efficiency in contexts where stored energy is converted back into electricity to meet demand.

#### 3.2.2. Liquid Yield

The liquid yield (Y) quantifies the efficiency of converting compressed air into liquid air, which is critical for the performance of cryogenic systems. It is defined as [13,26,33]:

$$Y = \frac{m_{la}}{m_{ca}} \quad (2)$$

where $m_{la}$ and $m_{ca}$ represent the mass of liquid air produced and the total mass of compressed air, respectively. This parameter reflects the efficiency of the liquefaction process and the storage capacity of the system.

#### 3.2.3. Exergy and Exergy Efficiency

Exergy analysis is particularly relevant for cryogenic systems due to the significant impact of thermodynamic irreversibility on their operation. The exergy ($E$) and exergy efficiency ($\eta_E$) are calculated as [13,26,33]:

$$E = (h - h_0) - T_0(s - s_0) \quad (3)$$

$$\eta_E = \frac{Useful\ exergy\ of\ the\ process}{Total\ available\ exergy} \quad (4)$$

where $h$ and $h_0$ are the enthalpy of the stream and the reference enthalpy, respectively, and $s$ and $s_0$ are the entropy of the stream and the reference entropy. These metrics enable the evaluation of the quality of stored energy and the effectiveness of thermodynamic processes.

#### 3.2.4. Specific Consumption

Specific consumption (SC) measures the energy required in the liquefaction cycle per unit mass of liquid air produced, serving as an essential parameter for operational efficiency [13,26]:

$$SC = \frac{W_c - W_e}{m_{la}} \quad (5)$$

where $W_c$ is the work required by the compression process, and $W_e$ is the work produced by the expansion process. This parameter is particularly useful for identifying improvements in the liquefaction cycle and energy utilization. The metrics described above are crucial for assessing the efficiency and performance of cryogenic energy storage systems. Optimizing RTE, increasing liquefaction yield, reducing exergy losses, and minimizing specific consumption are key factors that position LAES systems as promising solutions for integrating renewable energy, especially in scenarios characterized by variability and intermittency in energy production.

### *3.3. Thermodynamics of Cryogenic Systems*

Cryogenic systems operate based on fundamental thermodynamic principles, employing refrigeration cycles such as the Claude, Kapitza, and Linde–Hampson cycles to achieve cryogenic temperatures [13]. These cycles involve gas compression, heat exchange, and expansion, all of which are essential processes that determine the efficiency of the system [34]. Analyzing heat transfer and associated energy losses is critical for optimizing the overall system performance. This is influenced by factors such as thermal insulation, the effectiveness of heat exchangers, and the reduction of thermodynamic irreversibility. Comparative studies of liquefaction cycles demonstrate that the Claude cycle and its variants exhibit significantly higher efficiencies than the Linde–Hampson cycle [25,26,28]. This advantage is primarily due to the use of more efficient bypass turbines, which provide the necessary cooling while generating work. Furthermore, the efficiency difference between these cycles can be explained by analyzing the sources of entropy generation in each case. In the Linde–Hampson cycle, the irreversibility associated with the Joule–Thomson expansion, performed without the production of useful work, significantly contributes to increased entropy and a reduction in overall efficiency [35–37]. In contrast, the Claude cycle utilizes expansion through a turbine, allowing for the partial conversion of the fluid's internal energy into work, thereby reducing entropy generation and improving the system's exergy efficiency [12,38]. Additionally, thermal losses in heat exchangers and the irreversibility associated with gas compression affect both cycles; however, the lower operating pressure of the Claude cycle mitigates some of these losses compared to the Linde–Hampson cycle [38,39].

According to Borri et al. [25], the Linde–Hampson system operates at higher pressures (24–26 MPa), resulting in substantially higher specific energy consumption (2.5–2.6 kWh/kg), whereas the Claude and Kapitza cycles exhibit significantly lower specific consumptions (0.72–0.73 kWh/kg and 0.71–0.72 kWh/kg, respectively). Moreover, the exergy efficiency of the Linde cycle is considerably lower, reaching only 2.47%, compared to 12.16% and 12.1% for the Claude and Kapitza cycles, respectively [25].

In a parametric analysis conducted by Borri et al. [25], specific energy consumption was optimized for microgrid systems. For a single-stage compression cycle, the Claude and Kapitza cycles demonstrated the lowest specific consumption (0.52 kWh/kg) at a pressure of 1 MPa. Two-stage compression reduced specific consumption by approximately 20%. Additionally, in the Claude cycle, the third heat exchanger can be eliminated, making the Kapitza cycle slightly more efficient. Although the Heylandt cycle exhibits superior performance, its higher operating pressures require more expensive equipment, making the Claude and Kapitza cycles more viable options in terms of both cost and efficiency [25,26,28]. Notably, the Claude cycle is the most widely used system in practical applications due to its favorable balance between efficiency and operational feasibility [9].

### 3.4. Integration with Renewable Energy Sources

The integration of cryogenic systems with renewable energy sources, such as solar and wind, represents a promising approach to energy storage and a viable solution to mitigate the challenges associated with the intermittency of these sources [3,13,34]. During periods of energy surplus, when electricity generation from renewable sources exceeds demand, this excess energy can be utilized to liquefy gases, enabling storage in the form of cryogenic potential (Figure 1) [13,34]. This process not only efficiently harnesses surplus energy but also provides a safe and reliable solution for energy storage.

During periods of high energy demand, the stored energy is recovered by expanding the liquefied gases in turbines, thereby converting the resulting mechanical energy back into electricity [40]. This technological approach plays a crucial role in stabilizing fluctuations inherent to renewable energy production, reducing reliance on fossil fuel-based resources to compensate for variability. Furthermore, it enhances the efficiency and sustainability of energy grids by enabling more flexible and optimized management of energy resources [41]. In this context, the integration of cryogenic systems with renewable sources emerges as an innovative and effective technological solution to address energy storage challenges. This advancement facilitates the transition toward more sustainable and efficient energy systems, reinforcing the viability of renewable energy within the global energy matrix [13,34,40].

## 4. Cryogenic Systems for Energy Storage

Cryogenic systems represent a strategic solution for large-scale energy storage, particularly in response to the increasing integration of renewable energy sources, such as solar and wind, into the electrical grids. Over the past decades, various cryogenic technologies have been developed, each with specific characteristics tailored to meet distinct energy and industrial demands. This section provides a technical review of the main cryogenic systems currently in use, highlighting their applications, advantages, and limitations within the context of renewable energy storage.

### *4.1. Cryogenic $CO_2$ Storage*

Cryogenic carbon dioxide ($CO_2$) storage was developed within the framework of carbon capture and storage (CCS) technologies to mitigate greenhouse gas emissions [42–44]. This process involves capturing $CO_2$ from industrial or energy generation sources, cooling it to cryogenic temperatures, and storing it in liquid or solid form. In addition to reducing emissions, the stored $CO_2$ can be utilized in various industrial or energy applications [45–47]. Among the advantages, the high energy density of liquid $CO_2$ stands out, facilitating compact storage and efficient transportation. When integrated with carbon capture systems, cryogenic $CO_2$ storage contributes to decarbonization efforts and can be combined with Power-to-X solutions to produce synthetic fuels and chemicals, fostering a low-carbon economy [48–50]. However, this technology has significant drawbacks, such as high operational and implementation costs due to the cooling process and the need for specialized infrastructure [51–53]. The system's technical complexity increases maintenance costs and limits its scalability compared to other storage solutions, such as Liquid Air Energy Storage (LAES), which are simpler and less expensive [54,55]. Therefore, despite the substantial potential of cryogenic $CO_2$ storage for climate change mitigation and renewable energy storage, its limitations in terms of cost and technical complexity still restrict large-scale adoption, requiring technological advancements to become a viable and competitive alternative [56–61].

### *4.2. Liquid Air Energy Storage (LAES)*

Liquid Air Energy Storage (LAES) is a technology developed in the 2000s, proposed as an efficient solution for storing large amounts of surplus energy generated by intermittent renewable sources, such as solar and wind [13,14]. This system leverages excess electricity to liquefy atmospheric air, cooling it to cryogenic temperatures of approximately −196 °C [12,62]. The liquefied air is stored in thermally insulated reservoirs and, when needed, is re-expanded through a reheating process to generate electricity via turbines [18]. A key advantage of LAES compared to cryogenic $CO_2$ storage lies in its operational simplicity, as it relies on atmospheric air as a primary resource, thereby eliminating the need for complex $CO_2$ capture and transportation processes [63]. Furthermore, the infrastructure required for LAES is generally less costly and technically demanding, as it does not involve corrosive materials or extreme pressures associated with carbon dioxide [64,65]. However, LAES is less efficient in terms of energy density, requiring larger storage volumes to achieve the same energy capacity as $CO_2$-based systems [10,66].

When compared to hybrid cryogenic systems, LAES emerges as a more mature technology with well-defined applications [9,11]. Nonetheless, hybrid systems can offer greater flexibility by combining various technologies to meet specific requirements, providing an advantage in more complex scenarios [9,11]. On the other hand, LAES is distinguished by its reliability and scalability, making it particularly suited for stationary applications and grid support.

Given the increasing demand for efficient and sustainable storage solutions to facilitate the energy transition, LAES stands out as a promising option, particularly in contexts where the availability of renewable resources and operational simplicity are critical factors [12,67,68]. However, its limitations suggest that complementary technologies, such as hybrid systems, may be essential to maximize efficiency and economic feasibility in large-scale cryogenic energy storage [20,69–71].

### *4.3. Cryogenic Hybrid Systems*

Cryogenic hybrid systems combine cryogenic technologies with other energy solutions to improve energy efficiency and operational flexibility [9,22,72,73]. These systems optimize thermal resources and reduce energy losses, making them viable candidates for large-scale energy storage and grid stabilization [74–77]. Although promising, these systems still face technical and economic barriers that hinder their widespread adoption [78]. Addressing these challenges will require continued research and development to facilitate large-scale deployment and fully harness their potential in the transition to sustainable energy systems [72,78,79].

#### LAES Technological Integrations

The integration of Liquid Air Energy Storage (LAES) systems with other energy technologies has emerged as a promising strategy to enhance efficiency and broaden the applicability of these systems across various contexts [9,80–82]. This hybrid approach seeks to maximize the capabilities of LAES by leveraging synergies with complementary technologies, addressing inherent limitations such as high energy consumption and economic feasibility challenges [40,72,78]. The specialized literature identifies several integration strategies, among which the most notable are [13]:

- Liquefied Natural Gas (LNG) Regasification: The utilization of residual cold generated during the LNG regasification process presents an opportunity to reduce the energy consumption associated with air liquefaction in LAES systems, significantly improving the overall system efficiency [40,79–81,83–85]. This integration enables optimized use of thermal resources, but its thermodynamic limits are defined by the heat transfer rate between LNG and liquefied air, which directly influences the efficiency of the air liquefaction process. The system efficiency is strongly dependent on factors such as the LNG temperature and the heat transfer rate, as a higher thermal differential between the two fluids can enhance heat transfer efficiency. However, this thermal differential also presents challenges related to thermal control and flow rate management, as a significant temperature difference may result in difficulties in maintaining stable operating conditions. Furthermore, thermodynamic limitations, such as the need to ensure an optimal thermal balance, are critical for minimizing energy losses that could compromise the overall system effectiveness [40,79–81,83–85].
- Cryogenic Rankine Cycles: The incorporation of cryogenic Rankine cycles minimizes exergy losses during thermal exchanges. Studies show that this strategy significantly reduces the levelized cost of storage (LCOS) while improving system efficiency [24,74,86].
- Air Separation Units (ASUs): Integration with ASUs enables LAES systems to directly supply cryogenic gases such as oxygen and nitrogen for industrial applications, fostering synergies between energy storage and industrial production [9,67,87–90].
- Nuclear Energy: Residual thermal energy from nuclear power plants can be utilized to optimize thermal processes in LAES systems, offering an integrated solution for energy storage while reducing reliance on fossil fuels [9,13,76,91].

Cryogenic hybrid systems hold significant promise in the context of the energy transition, offering flexibility and the ability to integrate with a wide range of technologies [9,13,92].

However, challenges remain, including high initial costs, technical complexity, and the need for effective management of multiple subsystems. Continued research and development of complementary technologies will be essential for enabling large-scale implementation of these innovative systems.

## 5. Energy Efficiency in Cryogenic Systems

The analysis of energy efficiency is a key aspect in evaluating cryogenic technologies for energy storage, including Liquid Air Energy Storage (LAES), $CO_2$ cryogenic systems, and hybrid configurations. The scientific literature highlights significant variations in the efficiency of these systems, often influenced by operational methodologies, thermodynamic conditions, and technological integration strategies [9,13,30,68,93].

### *5.1. LAES Systems*

Liquid Air Energy Storage (LAES) systems exhibit energy efficiencies ranging between 45% and 70%, largely depending on their ability to recover and utilize residual heat and cold during compression and expansion cycles [9]. The integration of complementary technologies, such as cryogenic Rankine cycles, can enhance energy efficiency by up to 15%, reaching values near 75% [94,95]. These improvements are attributed to reduced exergy losses and optimized thermal resource management [23,78]. To surpass this efficiency limit, advancements in liquefaction and expansion processes are crucial. In the liquefaction stage, the implementation of advanced precooling techniques using high thermal capacity gases, regenerative heat exchangers, and high-conductivity materials can significantly reduce energy consumption. In the expansion process, high-efficiency turbines, multi-stage expansion cycles, and thermal energy recovery systems can minimize thermodynamic irreversibility and enhance energy conversion. The integration of these optimizations has the potential to increase LAES efficiency beyond 75%, improving its competitiveness compared to other long-duration energy storage technologies.

### *5.2. $CO_2$ Cryogenic Systems*

The efficiency of $CO_2$ cryogenic systems is primarily associated with the energy-intensive compression and liquefaction stages. The overall efficiency of these systems typically ranges from 40% to 60% [53,96,97]. Efficiency optimization is influenced by factors such as operating pressure and the quality of thermal insulation, which are crucial for minimizing thermal losses. The $CO_2$ capture efficiency is also affected by the exhaust gas temperature. While reducing the temperature increases the $CO_2$ concentration, enhancing capture efficiency, it also leads to higher energy consumption, which negatively impacts both the energy efficiency and exergy of the process [97,98].

### *5.3. Hybrid Cryogenic Systems*

Hybrid cryogenic systems, which integrate cryogenic technologies with solutions such as Rankine cycles, air separation units (ASUs), and liquefied natural gas (LNG) regasification processes, achieve efficiencies ranging from 55% to 80%, depending on the technological configuration adopted [23,70,87,89]. For instance, utilizing residual cold from LNG regasification can lead to an efficiency increase of up to 10%. Additionally, the operational flexibility of these systems is a significant advantage, enabling them to respond efficiently to fluctuations in grid demand [70,84]. However, achieving the highest efficiencies (close to 80%) presents significant technical challenges. Among the primary constraints is the complexity of integrating multiple technologies, which can lead to efficiency losses due to difficulties in optimizing the energy flow between the different system components. The need for precise and dynamic control of various operational units, such as LNG regasification and Rankine cycles, can result in operational losses, particularly if the system is not designed to maintain an optimal thermal and energy balance under all operating conditions. Furthermore, material and thermal limitations, such as fatigue and brittleness of materials at cryogenic temperatures, can affect the durability and reliability of more complex hybrid systems, particularly at larger scales [99,100]. The increased complexity of these hybrid systems can, in fact, lead to diminishing returns in large-scale applications. As the system scale increases, the integration of different technologies and the management of cryogenic, thermal, and energy flow processes becomes more challenging, potentially resulting in higher operational costs and reduced overall efficiency. Continuous maintenance and monitoring also become more costly and complex, which directly impacts the economic feasibility of large-scale applications. Therefore, while hybrid systems offer high efficiencies, the added complexity presents significant challenges that must be carefully evaluated to ensure long-term feasibility in large-scale applications.

## 6. Comparative Analysis of Energy Storage Technologies

Cryogenic energy storage systems, including Liquid Air Energy Storage (LAES), $CO_2$ cryogenic systems, and hybrid systems, exhibit distinctive features when compared to alternative energy storage technologies such as batteries and Compressed Air Energy Storage (CAES) storage systems. A comparative analysis focusing on scalability, durability, environmental impact, energy efficiency, and financial cost is presented below.

### *6.1. Scalability*

Liquid Air Energy Storage (LAES) systems are characterized by their high scalability, with installed power capacities ranging from 1 MW to 300 MW, making them robust solutions for industrial applications and integration into large-scale energy grids [9,93,101]. In contrast, Battery Energy Storage (BES) systems, such as lithium-ion (Li-ion) batteries, have limited capacities, ranging from 0 to 100 kW, making them more suitable for decentralized and small-scale applications [93]. On the other hand, vanadium redox flow batteries (VRFBs) exhibit a capacity range between 30 kW and 3 MW, offering greater flexibility to meet a wider range of requirements, from small-scale applications to large-scale energy storage solutions [94]. Compressed Air Energy Storage (CAES) systems, with power capacities ranging from 5 MW to 300 MW, offer moderate scalability and are often deployed in conjunction with renewable energy sources [9,93,101]. On the other hand, Pumped Hydroelectric Storage (PHS) systems exhibit the highest scalability, with installed capacities between 100 MW and 3000 MW, making them the leading solution for large-scale power grids [101]. In this comparison, LAES systems emerge as an intermediate alternative, providing a balance of flexibility and performance to meet medium- and large-scale energy storage requirements. In addition to scalability, factors such as response time and frequency regulation are critical in the comparison of energy storage systems. Response time is essential for applications that require rapid power adjustments, such as load-following. LAES systems exhibit slower response times due to the cryogenic process of liquefaction and expansion of air, in contrast to lithium-ion batteries, which provide near-instantaneous responses due to their electrochemical nature [19,81]. In dynamic frequency regulation, which demands rapid adjustments to maintain grid stability, LAES and CAES systems face challenges due to their slower ramp-up times [3,25,28]. These systems are not well-suited for functions that require immediate responses [21]. On the other hand, lithium-ion batteries and PHS systems stand out for their fast response capabilities, making them more suitable for frequency regulation and ensuring immediate grid stability. Despite these limitations, LAES, CAES, and PHS systems, due to their higher scalability, are more suitable for long-duration energy storage and stable energy management, where constant rapid adjustments are not necessary. These systems are ideal for supporting intermittent renewable energy sources and ensuring a stable long-term energy supply. Technological advancements in LAES systems, such as optimizing liquefaction and expansion processes and implementing more efficient thermal recovery systems, could improve response times, enhancing their viability for applications that demand greater flexibility. However, LAES systems may still not be ideal for real-time dynamic frequency regulation due to inherent limitations in their response times.

### *6.2. Environmental Impact*

Liquefied Air Energy Storage (LAES) systems exhibit a relatively low environmental impact, particularly when integrated with carbon capture technologies, contributing to the mitigation of greenhouse gas emissions [53]. However, the high energy consumption during the air liquefaction process necessitates the use of renewable energy sources to minimize associated emissions. In contrast, Battery Energy Storage (BES) systems, such as lithium-ion (Li-ion) batteries, face substantial environmental challenges due to the extraction of materials like lithium, cobalt, and nickel, resulting in significant $CO_2$ emissions and ecological impacts, in addition to inefficient recycling processes [102,103]. Compressed Air Energy Storage (CAES) systems have a moderate environmental impact, as the compression process may involve fossil fuels, leading to $CO_2$ emissions, although integration with renewable energy sources can significantly reduce these emissions [104,105]. Pumped Hydro Storage (PHS) systems have a low carbon footprint, operating without direct emissions; however, the construction of large infrastructure may lead to considerable environmental impacts, such as ecosystem disruption and displacement of populations [104,106].

In conclusion, LAES systems, despite their high energy consumption, offer environmental benefits when combined with renewable energy sources and carbon capture technologies, while BES and CAES face more significant environmental challenges, and PHS, although environmentally friendly, can cause considerable impacts due to the large infrastructure required [101,107].

### *6.3. Energy Efficiency*

Energy storage systems exhibit significant variations in terms of energy efficiency, which plays a crucial role in determining their applicability in various operational contexts. Among these systems, Battery Energy Storage Systems (BES), particularly lithium-ion batteries, stand out due to their high efficiency, often exceeding 90%. This high efficiency is attributed to the minimal losses during charge and discharge cycles, resulting in almost direct conversion of electrical energy into stored energy. The exceptional efficiency of lithium-ion batteries is a key feature for applications where space and operational time are limited, such as in portable devices and electric vehicles, where the need for compact and efficient energy storage is critical [9,93,101,108]. In contrast, Cryogenic Energy Storage Systems (LAES), which operate at extremely low temperatures, exhibit moderate efficiency, ranging from 40% to 70%. The efficiency of these systems is influenced by multiple factors, including thermal losses associated with cryogenic processes, such as liquefaction and vaporization of the gas, as well as losses resulting from the compression and expansion cycles. Although LAES systems have lower efficiency compared to BES, their main advantage lies in their ability to operate at large scales and over extended periods. Cryogenic systems are, therefore, particularly suited for large-scale and long-duration energy storage scenarios, making them an attractive solution to support the integration of intermittent renewable energy sources, such as solar and wind, which require large-scale and long-term energy storage [8,9,70,95,109]. Compressed Air Energy Storage Systems (CAES) have average efficiencies similar to those of LAES, ranging from 40% to 70%. The efficiency of CAES systems is impacted by inherent losses in the compression and expansion processes, where part of the energy is dissipated as heat during compression, and during expansion, the compressed air cannot be fully reused without losses. Despite these limitations, the integration of CAES systems with renewable energy sources, such as solar or wind, can lead to optimized utilization of the available energy, improving both performance and economic viability. Furthermore, CAES systems can operate at large scales and be installed in geographically favorable locations, such as caves or former natural gas reservoirs, making them a viable option for large-scale energy storage [93,101,110,111]. Finally, Pumped Hydro Storage Systems (PHS) are widely recognized for their high efficiency, ranging from 70% to 85%. The efficiency of PHS systems is primarily influenced by the height of the water fall and the characteristics of the reservoir, such as storage capacity and the volume of available water. This technology, which has been consolidated over time, is primarily applicable in specific geographic regions where the terrain is suitable for the construction of dams and reservoirs. The main advantage of PHS systems lies in their ability to store large quantities of energy at a relatively low cost, making them one of the most sought-after solutions for large-scale energy storage [112]. When comparing these energy storage technologies, energy efficiency emerges as one of the most important parameters, although other factors such as scalability, operational costs, required infrastructure, and the ability to integrate with renewable energy sources also play crucial roles in determining the most suitable technology. While LAES systems exhibit moderate efficiency, their operational flexibility and ability to operate at large scales over long periods make them a favorable solution in scenarios requiring long-term energy storage. In summary, the selection of the most appropriate storage technology should be based on a detailed analysis of the specific needs of the system, taking into account the advantages and limitations of each technology. The final decision will depend on the application context, considering factors such as the need for large-scale storage, operational flexibility, and integration with renewable energy sources to optimize the performance and economic viability of the energy storage system.

### 6.4. Financial Cost

Cryogenic energy storage systems (LAES) exhibit moderate capital costs, ranging between 830 EUR/kW and 1750 EUR/kW, depending on the technological configuration and operational scale [9,40,63,93,101,113]. In terms of energy efficiency, LAES systems offer a significant advantage, as the energy losses associated with liquefaction and cryogenic storage are relatively low, resulting in higher efficiency over time. However, it is important to also consider operational and maintenance costs, which may be higher due to the technological complexity involved in operating cryogenic systems and controlling extremely low temperatures. When considering the total cost per cycle, LAES can be a cost-effective solution depending on operational conditions and the scale of deployment. While the initial costs may be high, the system's efficiency and lower energy losses compared to other technologies make it competitive in the long run. Nevertheless, the operational and maintenance costs of LAES should also be considered. It is estimated that the operational and maintenance costs for LAES are around 0.0046 EUR/kWh [9,40,63,93,101,113], which is relatively competitive, although still higher than some other technologies, such as Compressed Air Energy Storage (CAES). The energy losses associated with LAES are lower than those found in other technologies, such as lithium-ion batteries (BES), which have higher costs, ranging between 1200 EUR/kW and 4000 EUR/kW [9,40,63,93,101,113]. Lithium-ion batteries face similar challenges in terms of efficiency, as their lifespan is limited, and as they age, their efficiency decreases, resulting in increased costs per cycle. Additionally, the energy losses during the charge and discharge processes also contribute to the higher cost per cycle of lithium-ion batteries.

The operational and maintenance costs of lithium-ion batteries are also a significant factor. Maintenance and operational costs for lithium-ion batteries are estimated to range between 0.01 EUR/kWh and 0.03 EUR/kWh [9,40,63,93,101,113], which are considerably higher than those for LAES. This is due to the need for periodic replacements and the higher material and manufacturing process intensity. Furthermore, the efficiency of lithium-ion batteries decreases over time, causing the cost per cycle to increase as the batteries age. On the other hand, Compressed Air Energy Storage (CAES) systems, with costs ranging between 370 EUR/kW and 740 EUR/kW [9,40,63,93,101,113], stand out as a more economical option for large-scale applications, especially when the necessary infrastructure is already in operation. The cost per cycle for CAES tends to be more competitive due to its higher durability and longer lifespan, resulting in lower operational costs over time. However, CAES systems face challenges in terms of efficiency, as the compression and expansion of air lead to thermal losses that can compromise the overall efficiency of the system. In terms of operational and maintenance costs, CAES presents a significant advantage, with costs estimated at 0.0028 EUR/kWh, which is relatively low compared to other technologies [93]. Pumped hydro storage (PHS), with costs ranging from 2300 EUR/kW to 3960 EUR/kW, offers excellent scalability but requires substantial investment in large-scale infrastructure [9,40,63,93,101,113]. While the profitability of PHS in terms of cost per cycle is high at large scales, the need for large infrastructure projects makes it more suitable for large-scale applications and less economically viable for smaller scales. The operational and maintenance costs of PHS are estimated at 0.0037 EUR/kWh, which is higher than CAES but still more competitive compared to lithium-ion batteries [93]. In summary, LAES represents an intermediate solution in terms of cost per cycle, offering good efficiency and lower energy losses compared to lithium-ion batteries but with potentially higher maintenance and operation costs. CAES emerges as the most economical option for large-scale applications, with competitive operational and maintenance costs, while PHS stands out for its scalability but comes with higher costs and requires large infrastructure investments. Therefore, the choice of the most suitable long-duration storage technology should be based on a detailed evaluation of operational conditions, total cycle costs, system lifespan, and available infrastructure.

## 7. Challenges and Opportunities in the Development of Cryogenic Energy Storage Systems

### *7.1. Technical Challenges*

The implementation and operation of cryogenic systems for energy storage pose a series of technical challenges that require the development of highly advanced solutions. One of the main obstacles lies in the precise control of extremely low temperatures, a critical factor in ensuring that cryogenic materials remain in optimal conditions, thus guaranteeing not only the safety of storage but also the efficient utilization of energy [12,74,114,115]. Furthermore, the selection of appropriate cryogenic materials plays a decisive role in the performance of these systems. These materials must exhibit high mechanical strength and chemical stability under low-temperature conditions. Fatigue and brittleness of materials used in storage tanks and piping present significant additional challenges. Under cryogenic operating conditions, materials undergo extreme thermal cycles, which can induce pressure and temperature variations and generate repetitive mechanical stresses, leading to the gradual degradation of their structural properties. Fatigue results from repeated exposure to intense thermal changes, causing microcracks and compromising the material's integrity over time. Brittleness, in turn, is related to the reduction in ductility at cryogenic temperatures, increasing the likelihood of fractures, especially under thermal shock or high-pressure conditions. Therefore, the selection of cryogenic materials must consider not only their resistance to low temperatures but also their ability to withstand the impact of thermal cycles, preventing structural failures that could compromise the safety and performance of the storage system [99,100]. Another significant challenge concerns the implementation of effective thermal insulation solutions. Minimizing thermal losses is essential to ensure the overall system efficiency and prevent the undesirable evaporation of cryogenic fluids. Technologies such as vacuum insulation and cryogenic foams have shown great effectiveness in reducing thermal losses while maintaining the necessary cryogenic temperatures for storage. However, selecting the most suitable insulation solution requires a careful analysis of factors such as cost, durability, and long-term thermal performance. The adopted solutions must be robust enough to withstand operational conditions and resist failures, making continuous monitoring and maintenance essential to ensure optimized performance throughout the system's lifetime. The development of new materials resistant to fatigue and brittleness, along with innovations in thermal insulation technologies, is crucial for the feasibility and expansion of large-scale cryogenic energy storage systems. These advancements are essential to ensure the safe and efficient operation of these systems, promoting the successful integration of renewable energy sources into the global power grid.

### *7.2. Opportunities for Improvement*

Despite the significant challenges associated with cryogenic systems, there are numerous technological opportunities that can be explored to enhance their efficiency and performance. The development of innovative materials, particularly advanced composites and metal alloys with specific properties for cryogenic conditions, presents a promising approach to address the mechanical and thermal challenges posed by extremely low temperatures. Materials with high resistance to fatigue and brittleness are essential to withstand the intense thermal cycles that cryogenic systems undergo, thereby minimizing structural degradation over time. The use of advanced metal alloys and fiber-reinforced composites, for instance, can significantly increase the durability of components under repetitive thermal and mechanical loading conditions while also improving their resistance to thermal shock and fracture, which are critical for ensuring the safety and longevity of cryogenic systems [116,117]. Regarding thermodynamic efficiency, the optimization of thermodynamic cycles, such as the Claude, Kapitz, and Stirling cycles, holds substantial potential for increasing energy efficiency. These cycles can be adapted and improved to minimize thermal losses associated with the compression and expansion of cryogenic gases, thereby enhancing energy conversion. Advanced modulation and control of thermodynamic variables, such as temperature and pressure during liquefaction and vaporization processes, are essential for improving the efficiency of energy storage and release processes. Further research into the ideal operating conditions, including the integration of combined or hybrid thermodynamic cycles, may lead to significant improvements in reducing energy losses and optimizing operational costs [118]. Another promising area lies in the integration of emerging technologies, such as high-density thermal storage materials and energy management systems powered by artificial intelligence. Advanced thermal materials, such as ceramics with high heat capacity or composites designed for large-scale heat storage, can be used to improve energy retention and reduce the need for expensive and heavy thermal insulation systems. Additionally, artificial intelligence-based energy management systems can optimize the operation of cryogenic systems by adjusting operational conditions in real-time to maximize the efficiency of the energy storage and delivery cycles, as well as predict preventive maintenance and long-term system behavior [119]. The ability to monitor, control, and autonomously adapt operations significantly enhances the flexibility and efficiency of cryogenic systems, making them more resilient to fluctuations in energy demand and price variations. These technological innovations not only enhance the performance of cryogenic systems, making them more efficient and economically viable but also strengthen their competitiveness in the global energy storage market. With the increasing role of intermittent renewable energy sources, such as solar and wind, cryogenic systems could emerge as a key solution in the energy transition, providing long-term storage capacity with minimal environmental impact and low operational costs. Continued development in these areas will not only contribute to the optimization of cryogenic systems but also enable the more efficient integration of renewable energy sources into the global power grid.

### *7.3. Future Prospects*

Cryogenic energy storage systems are poised for significant growth, with increasing expectations for technological advancements in the coming years [5,14]. As the demand for efficient and sustainable solutions within the renewable energy sector rises, these systems are anticipated to play an increasingly vital role in energy management, particularly in large-scale storage applications that require high energy density [6,8,10,12,80]. There is an expected intensification in the research and development of more efficient thermodynamic cycles, such as the Claude, Kapitza, and Stirling cycles, aimed at improving performance and reducing thermal losses [23,47,63]. Optimizing these cycles and utilizing cryogenic fluids with superior thermodynamic properties are areas that are likely to experience substantial investment and technological breakthroughs. The combination of these advancements will enhance the competitiveness of cryogenic systems relative to other energy storage technologies. Furthermore, growing international collaboration and an increase in investment in technological innovation are expected to accelerate the development and viability of cryogenic systems. As a result, cryogenic energy storage is set to become an increasingly relevant and sustainable solution for the future of energy storage.

## 8. Key Studies Utilized

Table 1 provides a summary of the most relevant articles utilized in the development of this work, highlighting the respective authors, year of publication, main topics covered, and their relevance to the study of cryogenic systems applied to renewable energy storage. The selection of articles adhered to the established inclusion criteria, prioritizing those that offered significant contributions to the analysis of technological advancements, challenges, and potential practical applications within the context of a sustainable energy transition.

**Table 1.** Summary of Key Studies Utilized in the Development of this Work.

| Authors | Years | Title | Main Topics Covered |
|---|---|---|---|
| Gandhi et al. [33] | 2022 | Cryogenic energy storage: Standalone design, rigorous optimization and techno-economic analysis | The article investigates the optimization of cryogenic energy storage (CES) systems, addressing challenges related to thermodynamic properties and complex modeling. The optimization approach achieved 52% efficiency and a levelized cost of storage (LCOS) of 144.82 EUR/MWh; however, it reveals that, when accounting for all direct and indirect costs, the LCOS could exceed 251.18 EUR/MWh. |
| Mousavi et al. [120]. | 2023 | Techno-economic assessment of an efficient liquid air energy storage with ejector refrigeration cycle for peak shaving of renewable energies | The article examines the integration of a CCHP system with LAES to enhance its efficiency. Utilizing the Organic Rankine Cycle (ORC) and an ejector refrigeration system, the system optimizes LAES performance while fulfilling heating and cooling requirements. Energy and exergy analyses reveal that the system generated 34,927 kWh of electricity, 424 kW of cooling power, and 729 kW of heating power, achieving 13% higher efficiency compared to the standalone LAES. The return on investment is 2.98 years, considering California as a case study. |

**Table 1.** *Cont.*

| Authors | Years | Title | Main Topics Covered |
|---|---|---|---|
| Rabi et al. [11] | 2023 | Comprehensive Review of Liquid Air Energy Storage (LAES) Technologies | The article examines Liquid Air Energy Storage (LAES) as an alternative to large-scale systems like CAES and PHES, noting its high volumetric energy density and ability to overcome geographical constraints. It includes thermodynamic and economic analyses, highlighting the potential of hybrid solutions with waste energy recovery to optimize LAES efficiency. |
| Tan et al. [116] | 2022 | Optimization of a cryogenic liquid air energy storage system and its optimal thermodynamic performance | The article explores Liquid Air Energy Storage (LAES) for large-scale electricity storage using a process model combining the Linde liquefaction process and an open Rankine cycle. Performance optimization was conducted via single-factor analysis and genetic algorithm (GA) in MATLAB. The study examined the impact of charging, storage, and discharging pressures and compressor/turbine isentropic efficiency. GA optimization achieved a 53.33% round-trip efficiency, 86.96% liquefaction ratio, 81% energy efficiency, and a 10.02% reduction in compressor power consumption. |
| Gandhi et al. [3] | 2022 | Integration of cryogenic energy storage with renewables and power plants: Optimal strategies and cost analysis | The article explores cryogenic energy storage (CES) as a solution to the intermittence of renewable energy sources, highlighting its high technological readiness and moderate efficiency. It employs a mixed-integer nonlinear programming (MINLP) model to calculate daily storage costs across different annual scenarios. The study addresses key issues related to the integration of CES with renewable sources, the amount of storage required for the transition to renewable energy, and optimal storage designs for various energy scenarios. |
| O'Callaghan et al. [13] | 2021 | Liquid air energy storage systems: A review | The article reviews Liquid Air Energy Storage (LAES) systems, covering liquefaction, power generation, integrated systems, and practical demonstrations. It identifies the gap between existing literature and the optimal performance of large-scale systems. The article suggests that future research should investigate LAES systems under dynamic conditions, aiming to optimize the design and assess their operational and economic viability at a large scale. |
| Borri et al. [10] | 2021 | A review on liquid air energy storage: History, state of the art and recent developments | The article explores Liquid Air Energy Storage (LAES), highlighting its high volumetric energy density and potential for integration with thermal systems. It discusses air liquefaction, low round-trip efficiency (50–60%), and suggests that hybrid solutions with waste energy recovery are promising for optimizing the techno–economic performance of LAES. |
| Incer-Valverde et al. [31] | 2021 | Improvement perspectives of cryogenics-based energy storage | The article evaluates an adiabatic cryogenic energy storage system (100 MW/400 MWh) using exergy analysis to identify improvements in inefficiencies, costs, and environmental impacts. Simulation in Aspen Plus® indicates that the heat exchangers are the main cost drivers and that increasing the temperature difference is necessary to minimize costs. The expander and the second heat exchanger are the primary sources of avoidable inefficiencies. The applied recommendations render the technology both thermodynamically and economically viable. |

**Table 1.** *Cont.*

| Authors | Years | Title | Main Topics Covered |
| --- | --- | --- | --- |
| Legrand et al. [68] | 2019 | Integration of liquid air energy storage into the Spanish power grid | The article presents a transient thermodynamic model of a 100 MW LAES plant, incorporating a packed-bed cold storage system to optimize efficiency. Thermocline affects the cycle's efficiency. The economic study, based on simulations, analyzes renewable integration scenarios and calculates the levelized cost of energy. The results show that storing photovoltaic energy during daytime peak hours and discharging at night reduces costs to 150 EUR/MWh and 50 EUR/MWh, respectively. |
| Damak et al. [12] | 2020 | Liquid Air Energy Storage (LAES) as a large-scale storage technology for renewable energy integration—A review of investigation studies and near perspectives of LAES | The article reviews the properties of cryogens, different CES processes, and key ways to integrate the system with other facilities to enhance energy efficiency, particularly through combining refrigerated warehouses and thermal energy recovery from cryogen evaporation. |
| Vecchi et al. [9] | 2021 | Liquid air energy storage (LAES): A review on technology state-of-the-art, integration pathways and future perspectives | The article discusses Liquid Air Energy Storage (LAES) as a solution for decarbonizing the energy system and mitigating the volatility of renewable energy sources, with a capacity range of 10–100 MW and storage of GWh. It highlights the advantages of LAES, such as high energy density and ease of deployment, as well as its evolution since 1977. The paper proposes a methodology for comparing literature results, reviews the operation of LAES within the energy system, and suggests future research directions based on over 120 references. |
| Agyekum et al. [14] | 2024 | Liquid air energy storage (LAES)—Systematic review of two decades of research and future perspectives | The article emphasizes the importance of electrical energy storage systems in optimizing grids with higher penetration of renewable energy sources, presenting a literature review from 2000 to 2023. The review highlights improvements in cycle efficiency, with some configurations achieving up to 70%, and the potential for integration with gas power plants and renewable energy sources. Heat recovery, including Rankine cycles and heat pumps, contributes to enhanced efficiency. The study suggests future research directions. |

## 9. Conclusions

In summary, the development of cryogenic energy storage (CES) systems, from design to implementation, has proven to be a highly challenging process characterized by technical complexity, high costs, and a relatively slow development pace. However, the progress achieved thus far, both theoretically and numerically, indicates promising advancements, with several cryogenic solutions still under development and optimization. Among these, Liquid Air Energy Storage (LAES) systems stand out due to their scalability, operational flexibility, and competitive cost, making them a viable option for large-scale energy storage. This type of system is particularly advantageous when integrated with renewable energy sources, such as solar and wind, as it helps mitigate the intermittency of these sources and ensures a continuous energy supply. Despite the technological advancements, the cryogenic systems sector still faces substantial challenges, both technical and economic. Issues such as the precise control of extremely low temperatures, the need for specialized and durable materials, and the optimization of thermodynamic cycles remain significant barriers limiting the widespread adoption of this technology. Energy efficiency remains one of the primary concerns, as minimizing thermal losses during the compression and expansion cycles of cryogenic gases is essential for the feasibility and competitiveness of these systems.

However, the current state of technology points to significant growth and innovation potential. Continuous evolution and increased investment in research and development are clear indicators that cryogenic systems are on track to overcome these challenges. For the effective adoption and expansion of cryogenic systems, continuous efforts will be required to improve thermodynamic cycle efficiency, develop new materials with better performance under cryogenic conditions, and create more effective and economically accessible thermal insulation solutions. Additionally, when compared to other energy storage technologies, such as batteries and Compressed Air Energy Storage (CAES) systems, it is evident that cryogenic systems need to become more competitive, both in terms of operational costs and efficiency. In this context, the integration of new technological approaches, such as the use of artificial intelligence for energy management optimization and the employment of advanced materials with specific properties, could drive the efficiency of cryogenic systems and promote their long-term economic viability. This paper makes a significant contribution to the development of the field by presenting a comprehensive overview of the challenges and emerging solutions for cryogenic energy storage systems. In addition to identifying key areas requiring progress, such as improving energy efficiency and developing more resilient materials, this study also proposes specific directions for future research, such as integrating cryogenic systems with other renewable energy sources and implementing new technologies for thermodynamic cycle and energy management optimization. The contribution of this paper is essential for a deeper understanding of the challenges and opportunities associated with cryogenic systems, serving as a foundation for future research and innovations in the field. Future research perspectives should focus on three key areas: improving energy efficiency through the optimization of thermodynamic cycles and thermal loss control; developing innovative materials, particularly composites and metallic alloys capable of withstanding extreme thermal cycles; and exploring new strategies for integrating cryogenic systems with renewable energy sources, focusing on adaptation to a more sustainable and resilient energy matrix. These areas are crucial for ensuring the expansion and success of cryogenic systems, which have the potential to play a central role in the transition to a greener and more efficient energy future. In conclusion, cryogenic energy storage systems represent a promising technology for large-scale energy storage, particularly in the context of integrating renewable energy sources. Despite the challenges that still exist, technological evolution and ongoing increases in research and development investments open new possibilities for overcoming the current limitations. The future of cryogenic systems will depend on their ability to adapt to the needs of a more sustainable and resilient power grid, positioning them as a key solution in the global energy transition. This study, by addressing technological issues and development perspectives, provides a solid foundation for future research that can accelerate the successful implementation and continuous improvement of this innovative technology.

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