energies

MDPI

Review

Beyond Seasonal Arbitrage—Structured Review on Distributed Long Duration Energy Storage and Its Benefits to the Distribution Grid

Catherine Adelmann * and **Dietmar Graeber**

Smart Grids Research Group, Technische Hochschule Ulm, 89075 Ulm, Germany
* Correspondence: catherine.adelmann@thu.de

Abstract

The rapid rise in variable renewable energy sources such as wind and solar introduces significant volatility and uncertainty into electricity grids, underscoring the critical need for increased system flexibility to ensure stability and reliability. Long-duration energy storage (LDES) technologies are emerging as essential solutions for meeting needs by enabling the storage and dispatch of energy over extended periods—from several hours to days or even weeks. The existing literature and system studies focus predominantly on centralized LDES providing seasonal arbitrage under idealized "copper plate" grid assumptions, while the broader distribution grid services and the specific role of distributed LDES and its benefits to the distribution grid remain largely underexplored. This paper presents a structured literature review on studies published between 2015 and 2025 that explicitly address grid-connected LDES at the distribution level. The review synthesizes the portfolio of services provided by distributed LDES—ranging from seasonal arbitrage, curtailment reduction, and hosting capacity enhancement to T&D deferral, resilience, and hydrogen co-products—and compares techno-economic characteristics, modeling approaches, and optimization objectives across studies. On this basis, the review identifies the main research gaps and contribution areas and gives direction for future research.

Keywords: LDES; distributed storage; distribution grid; grid flexibility; energy systems

Academic Editors: Dario Pelosi and Lorenzo Trombetti

Received: 27 October 2025
Revised: 20 November 2025
Accepted: 23 November 2025
Published: 28 November 2025

Citation: Adelmann, C.; Graeber, D. Beyond Seasonal Arbitrage—Structured Review on Distributed Long Duration Energy Storage and Its Benefits to the Distribution Grid. *Energies* **2025**, *18*, 6256. https://doi.org/10.3390/en18236256

1. Introduction

The ongoing transformation of the energy system is marked by a rapid expansion of variable renewable energy (VRE) sources such as wind and solar, leading to substantial changes in the power system and the switch from centralized, conventional generation to distributed, variable renewable generation [1]. While renewable generation technologies are essential for decarbonization, they introduce significant variability into electricity generation, thereby amplifying the need for system flexibility. Besides short-duration energy storage (SDES), mainly provided by batteries for intra-day balancing, there are long-duration energy storage (LDES) technologies emerging as critical enablers of this flexibility by providing the ability to store and dispatch energy over extended periods, from several hours to days, weeks, or even seasons and bridging the feared "Dunkelflaute" [2–4].

A general, differentiating factor of LDES is the ability to increase energy capacity independently of power capacity [5]: the stored energy (MWh) can be scaled by enlarging the storage medium without proportionally increasing the power conversion system (MW). However, there is no universally accepted definition of LDES in terms of storage duration.

While some sources classify systems with storage durations exceeding 4 h as LDES, the majority defines it as exceeding 10 h [6], with two sub-classes: one up to 20 h to meet daily cycling needs and the other for ultra long durations to address seasonal storage patterns [7,8]. It is also expected that the need for longer-duration storage will increase when more flexibility is added to the system [8,9]. In this paper, we follow the majority of recent LDES studies and roadmaps in using a minimum discharge duration of 10 h as a practical working definition of long-duration energy storage. This choice is not meant as a fundamental boundary from the perspective of flexibility theory, but as a convenient classification to separate technologies focused primarily on short-term, intra-day balancing (up to 4 h) from options that can shift energy across multiple hours to multiple days or weeks. Nevertheless, both the necessity and the appropriate duration of LDES depend on the characteristics of the specific power system, can vary significantly across different contexts [5,7], and is shaped by the unique characteristics of each country's energy system, the generation mix, its CO_2 intensity, the climate, and resulting energy generation potential and demand patterns: a high penetration of wind and solar, as well as ambitious CO_2 reduction goals, are the main drivers for LDES [10], while higher renewable energy potentials, overbuilding of capacity, and high transmission capacity reduce need for LDES [6,11].

Research conducted in different regions illustrates the diverse requirements and deployment potentials: On the pan-European level, LDES has the potential to reduce the need for overcapacity by a factor of two and reduce emissions by 33% [12].

In Switzerland it is projected that 4.5 TWh domestic, seasonal storage will be required [13], which can be covered by existing hydropower [14]. Meanwhile, Spain—with abundant solar potential—could integrate by deploying seasonal storage up to an additional 7.27 TWh of renewable energy, avoiding approximately 2.54 million tons of CO_2 emissions annually [15]. In Finland, seasonal storage in GWh-scale could reduce carbon emissions by up to 69% [16], reflecting the potential for seasonal storage in colder climates.

In Germany, model results suggest that long-term storage options like hydrogen will become the backbone of flexible capacity by 2050. The projections for charging power for long-term storage is estimated at 53 GW total charging capacity, while only 20 GW of discharging capacity will be needed [17]. The studies on the German energy system predominantly favor centralized hydrogen storage in salt caverns as a key strategy for managing renewable energy surpluses and ensuring supply during periods of low generation, such as the Dunkelflaute [18,19]. This approach, however, is still subject to significant uncertainty [20] and relies heavily on coordinated national planning without transmission bottlenecks, which is not considered in most studies [11].

Simultaneously, the ongoing transition from a centralized energy system toward a more decentralized structure—driven by the increasing penetration of distributed and variable renewable energy sources—poses new challenges for distribution system operators (DSOs). They are now tasked with integrating and managing distributed energy resources, including local generation, flexible loads, and decentralized storage [21,22].

Large-scale grid expansion could potentially address both integration issues [6], such infrastructure projects face long implementation timelines and substantial costs. For Germany, total investment requirements are estimated at EUR 730 billion, which would result in a doubling of grid fees [23]. Notably, grid charges already account for approximately 30% of end-user electricity prices.

On the other hand, distributed storage can provide several additional benefits compared to a central storage location [24,25]: The overall efficiency in distributed energy is higher compared to centralized plants by reducing energy waste and avoiding curtailment, transmission loses, and meeting local demand. Capital costs can be distributed over several, smaller investments and scaled according to actual demand and progression of the energy transmission. There is an increased awareness for energy consumption due to visibility of technology closer to the end user and energy justice can be created by allowing communities investments in distributed units [26]. Distributed LDES can also increase the resilience of the power grid, since there is less dependency on higher grid levels, the import of energy is reduced, and demand can be meet locally [26–28].

Several studies highlight the importance of siting of LDES, considering local supply, demand, and network patterns, leading to benefits such as savings in network and generation investment [29,30], less impact on land due to smaller footprint and overall less grid infrastructure necessary [26], resulting in higher implementation speed and quicker decarbonization [31].

In addition, heat from the storing and releasing processes can also be used locally or heat can be directly stored as thermal energy, which can be only transported over small distances reducing waste energy [32].

There are various types of distributed energy systems that incorporate long-term storage. They can be categorized into three main, partly overlapping, groups:

Off-grid/island systems/mini grids are mostly located in remote locations without connection to the national grid. The focus in off-grid systems lays in meeting its energy needs. LDES poses an alternative to fossil fuel energy supply, which must be transported over long—frequently poor—infrastructure, resulting in high supply cost. LDES becomes easily economically attractive, especially if high CO_2 reduction targets are assumed. The level of energy services and accepted outages have a high influence on the costs of the overall system [33]. Because electricity is the dominant energy demand in off-grid systems, storage solutions are usually electrochemical or chemical in nature, providing a reliable and flexible means to store surplus energy and convert it back into electricity during periods of low generation.

District energy systems: District energy systems aim to satisfy local energy demand at the lowest possible cost, often through the integration and coupling of multiple energy vectors, such as electricity, heat, or gas. Given the localized nature of district energy systems, a detailed analysis of the existing energy vectors and their interconnections is essential to optimize system design and operation. As heat represents approximately 50% of total end-use energy demand [34], thermal energy storage is frequently employed to enhance overall system efficiency and economic performance, since thermal energy storage costs are substantially lower than chemical or electric storage options.

In addition to thermal storage, other storage technologies—such as chemical and electrical energy storage—as well as flexible loads, including EV charging, can be integrated to increase system flexibility.

District energy systems are usually connected to the national electricity grid, and in some cases to heat or gas networks, allowing for energy exchanges to manage excess generation or peak demand. They are also applied in weak grid scenarios to improve resilience and reduce dependency on external supply [28].

Grid-connected storage: The storage unit is connected to the grid and either optimized on its own to maximize its own profit or minimize the operation cost of the grid. Most storage is setup to purely provide seasonal arbitrage, but also additional services such as reducing curtailment or transmission constraints, T&D deferral, resilience support, and providing ancillary grid services are possible. In grid-connected applications, rapid response capabilities and cost-effectiveness are critical, leading to a predominance of mechanical and electrochemical storage technologies that can reliably deliver high-frequency and energy-shifting services.

All three system types fall along a continuum, ranging from system-centric configurations (off-grid) to fully grid-integrated solutions (grid-connected storage), as shown in Figure 1. Only systems with a higher degree of grid integration are capable of providing grid services, either because off-grid systems lack access to the grid, or the system was not designed with this function in mind. As the share of decentralized renewable generation grows, grid services become essential to address emerging distribution grid challenges:

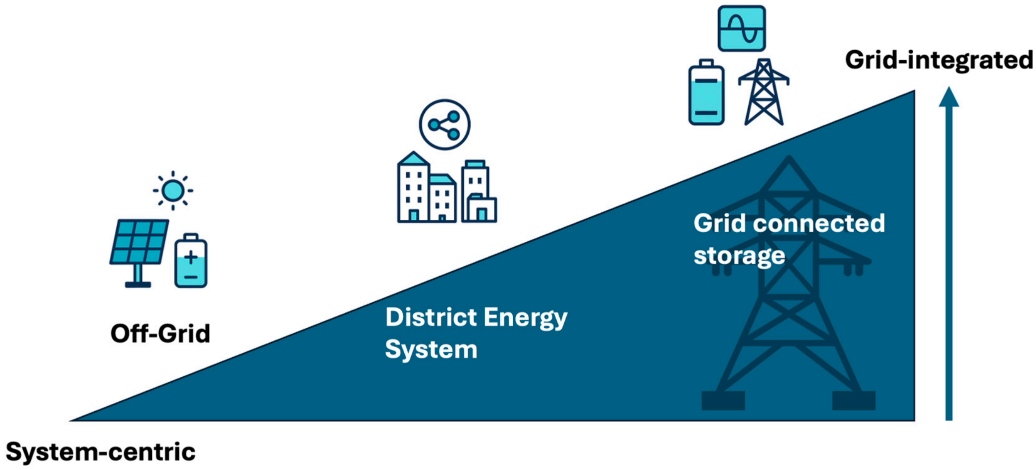

Figure 1. Classification of system types with LDES.

- **Voltage Instability**: High local generation, especially from rooftop PV systems, can cause voltage rise beyond acceptable limits, particularly in weak or rural grids [35,36].
- **Bidirectional Power Flows**: Traditional grids were designed for one-way power flow—from central plants to consumers. With distributed generation, reverse flows complicate protection schemes and load management [37,38].
- **Thermal Overloading**: Lines, transformers, and other components may be stressed by unexpected load/generation patterns, risking overheating and reduced lifespan [35,38].
- **Power Quality Issues**: Fluctuating renewable inputs can lead to voltage flicker, harmonics, and frequency deviations, impacting sensitive equipment and overall grid stability [37].
- **Low System Inertia**: The replacement of conventional synchronous generators with inverter-based renewable sources reduces system inertia, weakening the grid's ability to withstand disturbances and leading to faster frequency changes during imbalances [39].

The variability of solar and wind generation makes it harder to match supply with demand, requiring accurate forecasting and fast-response balancing resources. To maintain stability and flexibility, there is an increased need for flexibility resources, including storage systems, controllable loads, and demand response. Addressing these issues often requires significant infrastructure investment and reinforcement, such as upgrading cables, substations, and implementing smart grid technologies. Also, regulatory and economic barriers can impede progress, as existing frameworks may not yet support or incentivize the level of coordination and modernization required for a high-renewable future.

A lot of those challenges can be addressed by distributed storage systems, located either close to the generation and/or consumption of energy [40]. In this context, three operational modes are often distinguished [41]:

- **Grid-supportive**: The storage system actively stabilizes the grid, e.g., by providing frequency control, voltage support, or peak shaving.

- **Grid-neutral**: The storage system operates without significantly influencing the grid, typically charging and discharging in a way that balances only local generation and consumption.
- **Grid-stressing**: The storage system operates in a way that aggravates grid issues, such as charging during peak demand or discharging during periods of oversupply.

Most of the existing research on LDES emphasizes seasonal arbitrage under idealized assumptions—most notably a copper plate grid model that overlooks transmission constraints. As a result, only a limited number of studies explore the broader benefits of LDES, particularly those that extend beyond the optimization of electricity prices.

This study focuses on grid-connected, distributed, long-duration energy storage systems, including district energy systems that provide additional services to the distribution grid. Off-grid systems, or district energy systems with no grid access are excluded, since the technical and socio-economic motivations driving the deployment of off-grid storage—such as the absence of a central grid, rural electrification objectives, or islanded microgrids—differ fundamentally from those influencing grid-connected contexts.

Thermal long-term energy storage solutions are not considered in this study, as the focus of this study lies on the additional services that LDES can provide directly to the electricity distribution grid. While thermal energy storage may fulfill long-duration requirements in specific contexts, its underlying physical principles, energy conversion mechanisms, and operational dynamics differ significantly from those of electrical storage technologies.

This study aims to address that gap by offering a comprehensive overview of research on grid-connected, distributed LDES, emphasizing the grid services these systems can provide, their system-level benefits, and their potential role in a fully renewable energy system. Furthermore, it identifies key research gaps to inform and guide future investigations into the evolving role of distributed long-duration energy storage in a decarbonized electricity grid.

2. Methodology

To develop a comprehensive understanding of distributed, grid-connected LDES systems, this study adopts a systematic literature review approach. To ensure the relevance, quality, and accessibility of the reviewed literature, a set of inclusion and exclusion criteria was established. First, the temporal scope of the search was limited to publications released between 2015 and May 2025, capturing recent advances and current trends in the field of long-duration energy storage. Only publications written in English were considered.

To align with the core research objective, only studies that included the term "long-duration energy storage" or "LDES" in the title or abstract were selected. This criterion was essential to guarantee that LDES was a central focus of the work rather than a peripheral topic. Furthermore, to narrow the scope specifically to distributed, grid-connected LDES, the studies had to demonstrate a clear association with the distribution grid, either through system architecture, application context, or analytical modeling. Publications were included only if their focus was on distributed LDES, ensuring that centralized or transmission-scale storage systems were excluded unless directly relevant to distribution-level insights. A demonstrable connection between LDES and its functional or strategic role in the distribution grid was also required, such as contributions to grid stability, load management, or local energy autonomy.

To ensure academic rigor and reliability, the selection was restricted to peer-reviewed journal articles, as well as governmental and regulatory sources. Additionally, only publications with full-text availability online were considered, supporting transparency, reproducibility, and accessibility. Finally, the sources had to be available in one of the major academic databases searched during the review process, such as IEEE Xplore, ScienceDirect, Google Scholar, and Springer Link. In parallel with the defined inclusion criteria, several exclusion parameters were applied. Studies centered on off-grid systems were excluded from the review. Including such studies would have introduced significant variability and reduced the comparability of findings. The review also explicitly excluded storage systems based on thermal energy storage technologies.

The literature review process began with a comprehensive search across selected academic databases, yielding a total of 427 publications. This initial set was retrieved using search strings that combined terms such as "long-duration energy storage", "distributed", "grid-connected", and "distribution grid", along with Boolean operators to refine scope and relevance. Following the removal of duplicates across databases, the dataset was reduced to 365 unique entries.

An initial screening based on titles and abstracts was then conducted, guided by the inclusion and exclusion criteria outlined earlier. This step narrowed the pool to 75 potentially relevant studies. A subsequent full-text review and snowballing techniques—both backward (reference lists) and forward (citations)—were employed to identify additional relevant literature that may not have appeared in the initial search results. A final total of 27 studies with a special focus on distributed long-duration energy storage and a grid-supportive behavior have been then compared in detail, as outlined in Table 1. The detailed findings are then discussed in Section 3. The full process of the review is detailed in Figure 2.

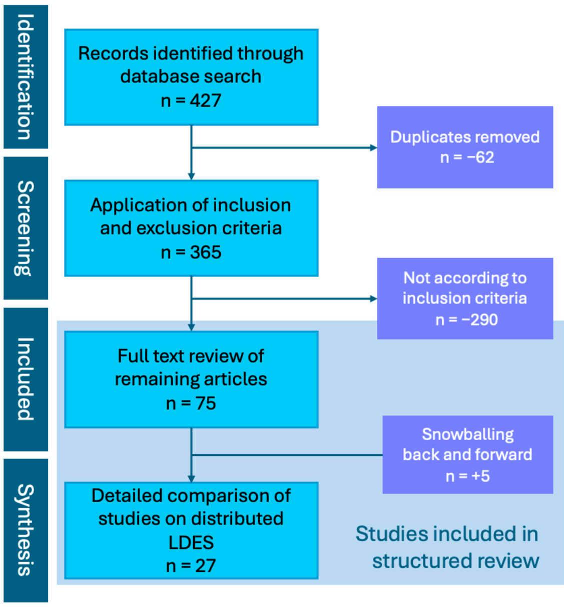

Figure 2. Approach and filtering of the reviewed studies.

Furthermore, a targeted selection of regulatory and policy-oriented publications was included to contextualize the technical findings within broader system integration and governance frameworks.

Table 1. Overview of studies with distributed LDES.

	Source	LDES Technology	SDES	System Type (Classification)	System Optimization	Electricity Grid	Gas Grid	Hydrogen Grid	Location and Siting	Duration	Arbitrage	Curtailment	Hosting Capacity	Selling H2/Gas	Grid Services	Resilience	T&D Constraints	Firm PV Generation	Modeled Country
1	[42]	Hydrogen	Li	MES	System	X	X	-	Consumption	Seasonal	X	X							Switzerland
2	[43]	SNG	Li	Hydrogen	System	X	X	-	-	Gas Grid	X						X		Germany
3	[44]	Hydrogen	Li	MES	Operator	X	-	-	Generation	Seasonal	X	X							The Netherlands
4	[45]	Hydrogen	Li	LDES	System	X			Generation	Seasonal	X	X	X						Finland
5	[26]	Hydrogen	Li	Hydrogen	Operator	X			Consumption	Seasonal	X	X		X	X				Australia
6	[46]	Hydrogen	-	Hydrogen	-	X			Strategic Node	-		X	X		X				US
7	[47]	Hydrogen	Hydrogen	Hydrogen	System	X			Generation	Seasonal	X	X			X	X			India
8	[48]	Hydrogen	-	Hydrogen	System	X			Generation	4–10 h	X	X	X		X		X		Iran
9	[28]	Pumped Hydro	Li	MES	System	X	-	-	Consumption	Seasonal	X					X			Iran
10	[49]	Hydrogen	Li	MES	System	X	-	-	Generation	Seasonal	X							X	China
11	[50]	Hydrogen	Li	MES	System	X	-	-	Consumption	10 h	X			X		X			USA
12	[51]	Hydrogen	-	Hydrogen	System	X	-	X	Strategic Node	Gas Grid				X		X			China
13	[52]	Hydrogen	Li	MES	System	X			-	10 h	X	X		X					China
14	[53]	-	Li	MES	System	X			Consumption	20 h	X	X			X				Switzerland
15	[54]	Hydrogen	Li	MES	System	X			Strategic Node	10 h	X			X					Egypt/Oman/Quatar
16	[55]	Hydrogen	Li	Hydrogen	-	X	-	X	Generation	Seasonal	X	X			X	X			China
17	[56]	Hydrogen	Li	MES	System	X	X	-	Generation	Seasonal	X			X					China
18	[57]	Hydrogen	Li	Hydrogen	System	X	X	-	Generation	Seasonal	X			X					China
19	[58]	Power-to-Methane	Li	Hydrogen	System	X	-	-	Consumption	Seasonal	X			X			X		Germany
20	[29]	-	-	LDES	System	X	-	-	Strategic Node	10 h	X	X	X		X	X	X	X	USA
21	[59]	Hydrogen	-	Hydrogen	System	X	-	-	Several	Seasonal	X				X		X		China
22	[60]	-	-	LDES	System	X	-	-	Strategic Node	100 h+	X	X					X		California—USA
23	[61]	Hydrogen	Li	Hydrogen	Operator	X	-	-	Consumption	Seasonal	X			X					Switzerland
24	[62]	Hydrogen	Hydrogen	Hydrogen	System	X	-	-	Several	4 h+	X				X				Italy
25	[63]	Hydrogen	-	Hydrogen	Operator	X	X	-	Several	Gas Grid	X			X	X		X		The Netherlands
26	[27]	Hydrogen	Li	Hydrogen	System	X			Several	80 h+	X					X			Iran
27	[64]	Hydrogen	-	Hydrogen	Operator	X	X	-	Several	Gas Grid		X		X					Italy

3. Results

The research about distributed LDES is currently scattered between different research fields, which overlap on the topic of distributed LDES, as shown in Figure 3: one aspect is of course the field of long-duration energy storage. It is still a relatively new but quickly growing field. A fraction of the published papers focuses, as well, on distributed system setups. Three of the considered studies fall in this category. The second field is around multi-energy systems, looking at the optimal configuration of energy systems with a limited scope (e.g., a distribution network or district). Nine studies of this country have been found which also consider long-term storage. The third and biggest group focuses on the hydrogen supply chain with 15 studies. The main research objective is to find optimal ways to generate hydrogen. The relevant subsection here is about grid-supportive operation methods and distributed storage.

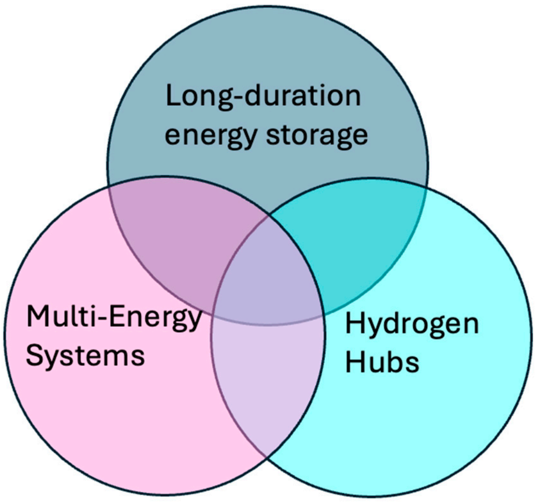

Figure 3. Research fields associated with distributed LDES.

This review gives an overview about the most relevant studies concerning distributed LDES from the various fields. Since each of the three fields is an individual, broad, and complex field of research, only the studies closest to the scope of this review have been considered.

3.1. LDES Technologies

Among the various long-duration energy storage technologies discussed in the literature, only a subset is suitable for distributed applications. Many LDES concepts—such as large-scale pumped hydropower or underground compressed air energy storage—depend on specific geographic conditions or require substantial land area, making them difficult to implement in densely populated or cultivated regions. However, several emerging technologies exhibit strong potential for distributed deployment due to their modularity, scalability, and lower spatial requirements.

Mechanical storage: Traditional pumped-storage hydropower offers substantial potential for cost-effective, long-duration storage. Nevertheless, its reliance on natural elevation differences and large water reservoirs limits its applicability for distributed use. Compressed air energy storage faces similar geographic and land-use constraints [65,66]. Recently, novel mechanical storage systems have been proposed that operate on similar physical principles—storing gravitational potential energy through the movement of water or solid weights—but utilize entirely man-made structures. These can be integrated into existing buildings or built in compact vertical shafts [67]. While these systems currently come at higher costs, they provide clear advantages for distributed, grid-supportive operation due to reduced land-use, rapid response time, and negligible ramp-up or ramp-down delays [68]. Especially when integrated into existing structures and utilizing recyclable materials, mechanical storage systems can achieve much lower environmental impacts over their life-cycle thanks to their long design lifetimes and minimal new civil or material construction [69].

Thermal storage: Thermal storage is inherently well-suited to long-duration applications, though it is primarily employed as heat-to-heat storage rather than electricity storage. Two promising technologies that convert electricity into storable heat and back are Pumped Heat Electrical Storage (PHES) and Electrical Thermal Energy Storage (ETES). PHES systems operate by converting electricity into heat and cold using reversible heat pumps, storing energy in hot and cold reservoirs, and later reversing the process to regenerate electricity when required [70]. ETES, in contrast, stores heat in solid media such as volcanic rock and reconverts it into electricity via steam turbines, often in combination with VRE. Both PHES and ETES exhibit relatively small land footprints, low environmental impact during operation, good recyclability, and are promising for distributed applications, although their round-trip efficiency remains lower compared to electrochemical systems [68,71].

Electrochemical storage: Beyond the widely used lithium-ion batteries—which, due to their high costs and limited cycle life, are less suited for long-duration storage—flow batteries represent a promising alternative. These include vanadium redox flow, zinc-based iron flow, and even emerging organic or metal-free chemistries [72,73]. Flow batteries are characterized by their scalability, long cycle life, and decoupled power and energy capacities. Their environmental impact highly depends on the used chemistry, which can be very toxic or use scarce raw material (vanadium). Organic flow batteries bring a significant improvement but the electrolyte has a significantly lower lifespan and cannot be reused as vanadium based electrolytes [74–76]. Their fast response times make them particularly suitable for grid-supportive operations, such as frequency regulation and peak shaving. Several pilot projects already employ them as replacements for emergency generators or backup power systems, demonstrating their potential for distributed LDES [68].

Chemical storage: Among chemical energy storage options, power-to-gas systems are the most relevant for long-duration applications. These systems convert surplus renewable electricity into hydrogen through electrolysis, or further SNG via methanation. While large-scale deployment often depends on gas infrastructure and salt caverns for storage, advances in modular electrolyzers and small-scale methanation reactors enable distributed configurations. From an environmental perspective, the greatest risk is hydrogen leakage, which has a 100-year global warming potential (GWP_{100}) 11.6 times higher than that of CO_2 [77]. The main recyclability challenges lie in polymer membranes, composite tanks, and high-pressure infrastructure [78,79].

In Figure 4 the size and potential fit for distributed and centralized application of the introduced storage technologies are compared.

The reviewed studies associated with grid benefits of distributed LDES are hydrogen and power-to-gas dominant. Only one study considered pumped hydropower [28], all others focused on hydrogen or power-to-gas as the storage medium. Three studies considered the production of methane (SNG): one from the production with biogas in combination with an electrolyzer and injected into the gas grid and two with a decentralized power-to-methane plant. Nineteen studies used hydrogen as the storage medium, either with decentralized storage systems or connected to the hydrogen grid. Three studies have been setup in a generic way and did not consider any specific storage technology at all.

CO_2 saving and cost benefits are either compared to the status quo or to fossil fuels (mostly gas) with carbon capture and storage as a long-term flexibility option [60].

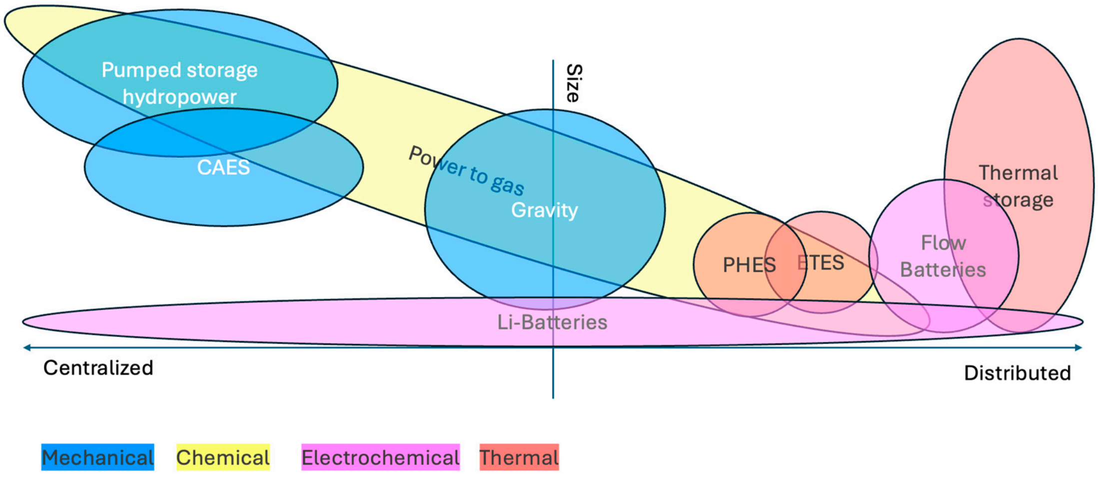

Figure 4. Overview on different LDES technologies.

3.2. Short- and Long-Term Storage: Complementary Roles in Energy Systems

To meet the different flexibility needs in modern energy systems, a combination of different storage and generation technologies that are most effective is required. In the studied publications, nearly all use a combination of SDES and LDES. SDES typically serves as the "work horse" [60] of energy storage, with a high number of full load hours with hourly to daily (diurnal) cycles, mainly to shift PV generation from day to night, while LDES is designed to provide energy over extended periods—ranging from several days to weeks or even entire seasons. Batteries, particularly lithium-based ones, have recently seen a significant drop in price; they offer high efficiency, no ramp-up or ramp-down constraints, and are ideal for applications up to 4 h (discharge time to rated capacity)—but they require a high number of charge cycles to become economically viable.

Two studies used hydrogen to also cover short-term storage needs; seventeen used batteries, mostly lithium; one study was modeled in a generic way, assuming short-term storage but not mentioning a specific technology; while seven studies did not have any short-term storage included in the system setup.

As mentioned earlier, the mix of different storage components and the overall system design is complex and highly dependent on several factors, including the availability of renewable resources, the cost of their exploitation, and the existing generation mix. SDES and LDES technologies can, to some extent, be substituted for one another, depending on their respective costs, efficiencies, and operational characteristics. Chu et al. have developed a substitution ratio, which can be used to quantify the interchangeability of different storage and generation types. Due to its high efficiency and flexibility, SDES remains essential in nearly all modeled scenarios. Even in configurations with very high levels of LDES deployment, SDES continues to deliver substantially larger amounts of energy. Typically, SDES technologies cover around 30–50% of the total delivered electricity, especially in a system with a high solar penetration, primarily by managing intra-day and short-term fluctuation. LDES technologies usually contribute a smaller share, around 3–5%, but play a critical role in balancing seasonal variability and supporting system resilience during extended periods of low renewable generation [60]. Liu found that when LDES and SDES are optimized and operated together, the overall costs can decrease by up to 10% compared to when considering them as separated systems [52].

3.3. Interconnections to Other Grids, Sector Coupling, and General System Setup

While most of the studies consider only electricity, eight studies also consider other energy grids and have an interconnection to either the gas (six) [42,55–57,63,64] or specifically the hydrogen (two) grid [51,55]. The main advantages of interconnections are that additional revenue streams can be integrated by selling hydrogen or synthetic natural gas to other parties. Two studies also considered the gas grid or hydrogen grid as form of storage, where energy can be injected when produced and drawn form later.

However, the costs of maintaining the gas grid have not been considered by any of these studies, which is expected to increase significantly per kWh over the next decades since less gas is transported [80,81]. When these are considered, the economics may change significantly and the economic evaluation of distributed storage solutions has to be reconsidered, especially when gas is mainly reconverted to electricity and injected at specific points.

3.4. Location and Siting Decision

Siting of LDES is a complex task and there is no simple answer to where it should be placed; it highly depends on the grid topology. Several papers explicitly focus on the siting of hydrogen-based and long-duration energy storage systems. For instance, Bragatto et al. examined the location and sizing of hydrogen storage within distribution networks to enable renewable energy integration [62]. Chu et al. analyze the role of long-duration energy storage in transmission-constrained systems with high shares of variable renewable energy [60]. Specific attention has also been given by Lin et al. to the determination of optimal hydrogen storage locations and capacities in power grid planning for large-scale renewable deployment [59]. Jafari et al. found in his review study that geographic location of storage placement makes a big difference: While short-duration storage is advantageous in locations with a high PV-penetration to offer diurnal cycling, LDES is needed for locations with seasonal variations [82]. Also, Cole et al. found in his study on the optimal siting of LDES, considering VRE and load concentration, other storage, transmission availability, and the network topology, but could not identify a simple metric, such as co-locating with load or generation [29].

The transmission capability is one influencing factor: LDES is ideally constructed at nodes which are well interconnected [59], but needs to consider as well the grid development—when the grid changes, the optimal LDES location might change as well—therefore the optimal location in 5 years might be different from the optimal location today [29].

Also, the placement of SDES impacts LDES siting, as well as VRE distribution: with dispersed VRE, the location of VRE is no indication for LDES placement, but for concentrated VRE, location corresponds with the optimal LDES location, due to increased transmission constraints and curtailment reduction benefits LDES can bring [29]. Ideally, the sites are optimized simultaneously to leverage synergy effects.

In the reviewed studies, there are the four siting options examined for the location of distributed LDES in the distribution grid, as outlined in Table 2: Ten studies opted for a co-location with the generation. Motivations could be to increase hosting capacity [45,48], reduce curtailment [44,47], market the produced energy better, or to firm up PV capacity [49]. Seven studies placed the storage close to the consumption, e.g., a district energy system to cover load peaks [26] in an isolated mountain village [42] with only few lines connecting it to the wider grid, or in a weak grid setup, to provide energy in case of outages of the wider grid [28,50,83]. The third option optimized the grid as a wider system and placed the storage in specifically selected, strategic nodes to improve the grid operation, which was chosen by five studies.

Table 2. Overview on location and siting decisions.

Location and Siting	Study
Consumption	[26,28,42,50,53,58,61]
Generation	[44,45,47–49,51,54–57]
Strategic Node	[29,46,60]
Not considered	[43,52]
Several	[27,59,62–64]

Li et al. found in their study on hydrogen storage systems that deploying several, smaller storage locations results in the lowest overall system cost [59]. Similar conclusions were reached by a total of five studies that also examined multiple-location approaches.

3.5. Duration

The discharge duration of LDES can range from just above 4 h to seasonal or even multi-year timescales. There is no universally agreed definition: some sources classify storage systems beyond 4 h as LDES, while most adopt a threshold of more than 10 h.

When looking at the discharge duration in the reviewed studies, seven studies fall into the medium duration of up to 20 h for daily cycling needs, two studies consider discharge durations of up to hundred hours and the majority, thirteen studies, have very long durations of 1000 h, or more for seasonal balancing.

Four studies used the gas grid as more or less unlimited storage.

The required duration of LDES is highly system dependent, varying with the characteristics and needs of each power grid [5,7]. Chu et al. have investigated in their research the long-duration energy storage for transmission constraint systems, with a particular focus on the discharge duration: LDES often operates for over hundreds of hours, averaging about 420 h. When inexpensive, LDES can exceed 1000 h of discharge, while at high costs it is only used sparingly with durations under 100 h, essentially acting as a peaker resource, but with significantly reduced system benefits [60].

Figure 5 gives a quantitative overview of the storage duration applied in the reviewed studies.

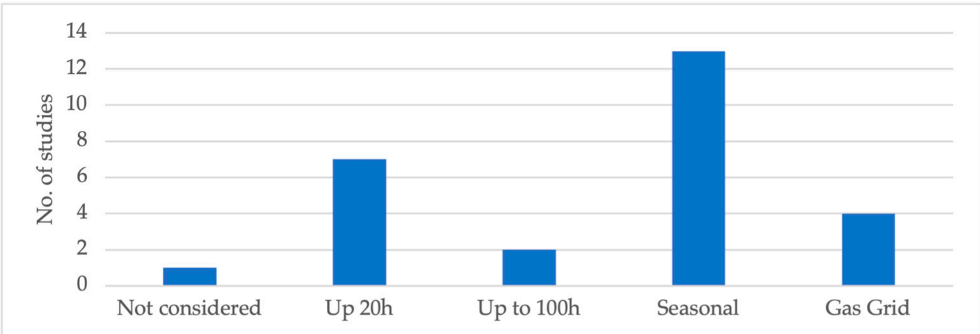

Figure 5. Discharge duration.

3.6. Provided Services

LDES can provide a broad range of services that are increasingly critical as renewable penetration grows and conventional generation assets are phased out [6]. These services can be broadly categorized into energy management services and ancillary services, each serving distinct but complementary roles in modern power systems [1,25]. Energy management services focus on shifting energy across time to balance supply and demand, reduce curtailment, and optimize the use of renewable resources. Ancillary services, on the other hand, are vital for supporting grid reliability, including functions such as frequency regulation, voltage control, and reserve provision.

It is important to mention that different topologies of grids have different needs for flexibility [53].

In the following are the main motivations mentioned which drive the installation of distributed LDES. They are partly overlapping, and a clear separation of the single services is not always possible. While certain services may implicitly encompass others, only those explicitly identified in each study have been included in the count. Since CO_2 reduction is the main driver and a 100% renewable system prerequisite for all studies, it is therefore not explicitly mentioned as a system benefit or service to the energy system.

3.6.1. Curtailment Reduction and Usage of Surplus Energy

The utilization of surplus renewable energy to mitigate curtailment, prevent grid overloading, and as a transmission constraint is a well-established and extensively studied strategy. Numerous studies have explored this scenario, particularly focusing on power-to-X technologies and the distributed generation of hydrogen, which converts at the distribution-level excess electricity into other energy products [64,83,84].

Depending on the siting of LDES, there can also be counter-intuitive impacts on curtailment reduction: it is expected that adding LDES will decrease curtailment, but it can increase due to transmission constraints, if placed at a suboptimal location [28]. Especially if LDES is cheap, it brings significant cost advantages to the system by reducing curtailment; otherwise, building overcapacity of generation power is the lowest cost option [60].

It is also worth mentioning that the charging capacity of LDES is mostly significantly higher than the discharging capacity to absorb peak energy, which is also highlighted by Fonseca et al. Their analysis showed that in most examined hydrogen systems the predominant application identified was the use of surplus renewable energy, particularly for peak shaving, underscored by the relatively large electrolyzer capacities proposed in many of the reviewed systems [84].

Ten of the reviewed studies are charging from surplus energy to reduce curtailment in the range of 8–13% [55], but not all studies adopt this approach and allow charging from the grid or do not specify the charging methodology. This is especially the case when the main purpose of the system is to increase resilience against outages or supply hydrogen as an energy vector.

3.6.2. (Seasonal) Arbitrage

Shifting energy from times of high generation to periods where demand exceeds generation is the most obvious use case of energy storage and applied by nearly all studies. The benefits are mainly described in lower prices, either by higher usage of locally produced energy, avoidance of high prices for purchasing external energy, or a penalty for load shedding. This strategy is applied by 24 of the reviewed studies. Especially systems with a high share of wind energy are benefiting from LDES [49]. The need for LDES for long-term arbitrage evolves with the energy transition as the need for longer term storage increases [26] and becomes inevitable in systems with over 90% renewables [42].

Systems not providing arbitrage services have been built to either increase hosting capacity [46], to reduce curtailment [64], generate hydrogen, or increase resilience against outages [51].

3.6.3. Transmission and Distribution Deferral

Avoiding transmission constraints partially overlaps with the benefits of charging from excess energy: instead of expanding the grid or curtailing surplus generation, the excess can be stored in LDES. Moreover, the growing demand from heating electrification and electric vehicles increases the load on lines and transformers. Since building new transformers and lines is costly and slow, LDES can provide a viable alternative and either reduce the expansion need or even defer it [39]. In this context, SDES is well-suited to alleviate local grid congestions, while LDES can address long-distance transmission limitations and help overcome regional fluctuations [49]. Six of the reviewed studies explicitly focus on the relief of transmission constraints. Especially in the transmission grid, there are several studies which mention the benefits of LDES: LDES can serve as a peaker plant, reducing the need for redispatch [60,85] or allowing higher grid loadings with a net-booster setup [86].

If LDES is used to increase the grids transmission capability, it is ideally constructed at nodes which are well interconnected. The capacity of each line divided by its power transfer distribution gives the transmission capability. The line with the lowest capacity determines capacity of the whole grid [59].

LDES might be an especially good fit, where lines are not permanently overloaded, but grid congestions appear seasonally [44] and the capacity limit is only reached for a few hours each year [5].

Chu et al. have investigated in their study specifically the role of LDES in transmission-constraint energy systems and found that low-cost LDES can significantly reduce both transmission capacity expansion and curtailment. Unless LDES becomes very inexpensive, short-duration energy storage remains more critical under limited transmission, supplying 30–50% of total energy, whereas LDES contributes only 3–5%, particularly in systems with a high share of solar generation [60].

3.6.4. Grid Balancing Services

Grid services include the control of voltage and frequency of the power grid. Ten studies have been optimized to keep the operation of the network within the allowed limits.

Hydrogen systems especially are investigated to provide ancillary services, such as frequency regulation. Fuel cells and electrolyzers are used since they have steeper ramp-up and ramp-down rates and are more flexible than generators with a negligible impact on H2 production. Voltage support can be provided with power electronics converters where the power factor can be adjusted to the grid needs for reactive power and voltage [46].

The grid balancing services are either rewarded with payments for grid services [26,46] or the benefits can be seen in overall lower system costs if the whole energy system is optimized as one. Findings include that in days with high PV generation the voltage in the distribution grid could be improved significantly (−35%) [46] and lower costs for the full system in the range of 15% [47].

3.6.5. Firming up Generation

A particular application of energy storage is firming up PV generation, which is a combination of the above-mentioned services: it involves providing bulk energy services such as arbitrage and peak shaving, as well as ancillary services like frequency regulation, spinning reserve, or voltage support, but also infrastructure services such as upgrade deferral. The aim is to make the output from PV power plants more reliable, predictable, and dispatchable, so that it behaves more like a conventional power source. Firm generation and transmission-constrained systems have need for truly long-duration storage exceeding 100 h [60], but also benefit from the fact that LDES helps to mitigate forecasting errors when dispatching VRE sources [39]. Two studies mentioned the benefits of LDES when firming up PV generation and highlighting the advantages of longer look-ahead windows, which decreased costs by 6.9% when going from a 1 to 3 days look-ahead window since uncertainties could be managed better [29].

3.6.6. Increase Hosting Capacity

In power systems engineering, hosting capacity describes the maximum amount of additional VRE that can be connected to a specific part of the electric grid without violating predefined technical limits. These limits typically relate to power quality (e.g., voltage deviations, harmonic distortion), thermal loading of lines and transformers, and system protection coordination. Traditionally, utilities have addressed these issues through grid reinforcement, such as upgrading transformers, increasing conductor capacity, or expanding feeder lines.

By contrast, LDES offers a flexible, non-wires alternative to expand hosting capacity. When strategically sited, storage systems can absorb surplus generation that would otherwise cause technical violations and re-inject it during periods of higher demand. This mitigates voltage excursions, alleviates congestion, and maintains compliance with operational limits, thereby enabling a higher penetration of VRE without extensive physical upgrades. Two studies explicitly mentioned the increase in hosting capacity as motivation to build LDES [45,48] and an increase in hosting capacity by 10–14%.

3.6.7. Increase Resilience

The increase in resilience is a major driver for the adaption of distributed LDES: it secures energy supply at all times, also during dark doldrums, natural disasters or outages of higher grid levels [39].

Six studies consider the increase in grid resilience, e.g., in case of natural disasters, like typhoons, or grid outages: if there is an outage in the larger grid and some grid parts become islanded, the distributed storage has sufficient capacity to provide power in case of an emergency.

For three studies, resilience has been the primary factor to the system design [28,50,51]; the other three studies did mention resilience as a benefit, but did not consider it as the main, driving factor.

3.6.8. Hydrogen Sales as an Auxiliary Revenue Stream

As mentioned earlier, hydrogen is the most extensively researched storage technology, offering lower costs for large-scale capacities, high versatility, sector coupling advantages, and a higher energy density that facilitates transport compared to electricity. Twelve studies include the supply or selling of hydrogen in their model.

Excess energy can be converted to hydrogen and sold, e.g., to the industry, as fuel to electric fuel cell vehicles, or injected into the gas grid. Selling energy in that way is a veritable side-business for LDES and can improve the economic business case, especially since LDES capacity is dimensioned to cover a worst-case scenario, which might happen, concerning the fluctuation nature of VRE.

3.6.9. Combination of Services

Most popular services are arbitrage, followed by curtailment reduction (thirteen), selling hydrogen (twelve) and grid services. The majority of the twelve studies offer two services. Nine studies offer three services while six studies offer four or more. The most popular combination of two services is seasonal arbitrage and curtailment reduction. An overview of used combinations is given in Figure 6.

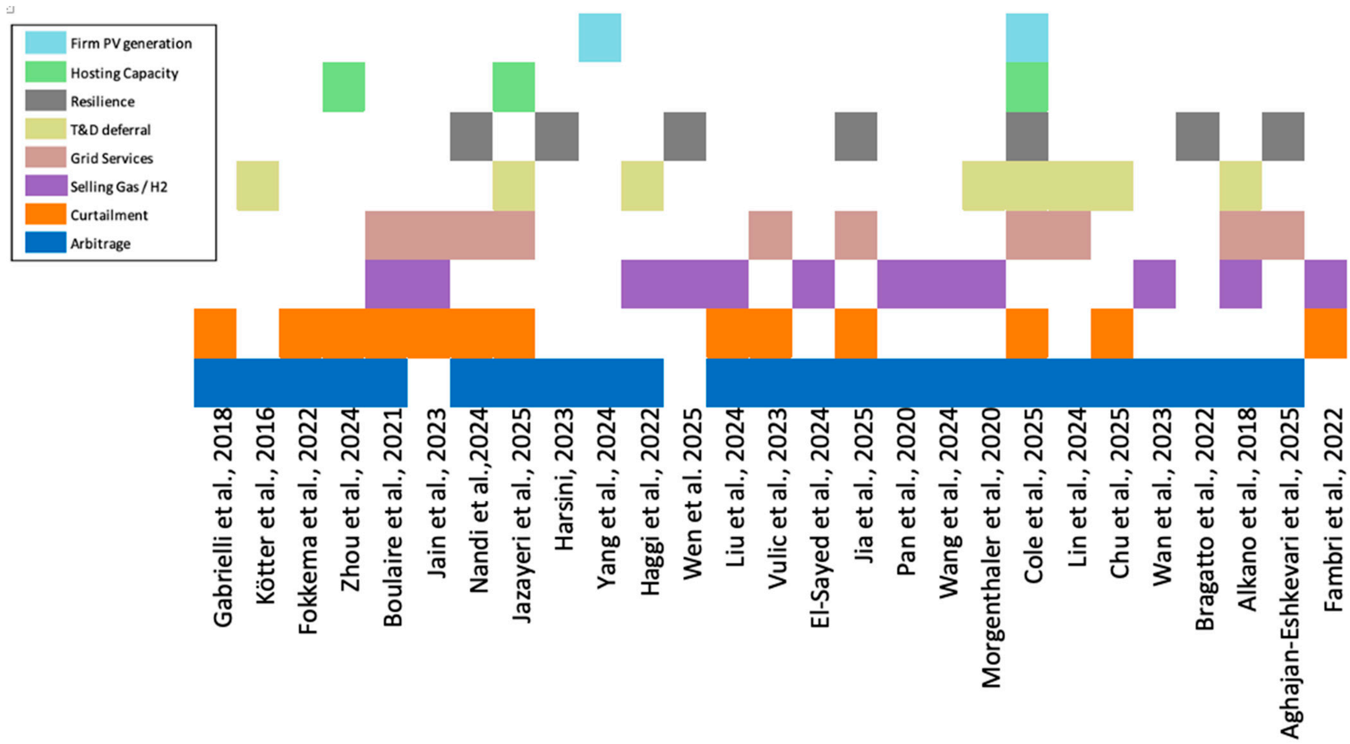

Figure 6. Overview on combination of services [26–29,42–64].

3.7. Modeling

As mentioned earlier, LDES is primarily modeled within the broader system context, with emphasis on its interactions with generation assets and other storage technologies. In particular, Hybrid Energy Systems, which couple different storage technologies, allow the integration of their respective advantages to meet both short-term and long-duration storage requirement [87]. Batteries are highly suitable for short-term demand, providing grid regulation services and on-demand supply; however, their low power-to-capacity ratios limit their use in large-scale balancing. By contrast, LDES can accommodate substantial amounts of energy over extended periods, thereby complementing the role of batteries [12]. In addition, LDES can serve as a substitute for generation capacity, and vice versa, particularly in systems subject to significant seasonal variation [60]. Among the reviewed studies, 17 adopt this hybrid configuration and model it accordingly.

This leads to the special challenge when modeling LDES, which include very large problems due to a large number of variables and long time horizons, ranging from days to several weeks, seasons, or even years. To receive meaningful results, the energy system has to be optimized with a high resolution (hourly or even finer), leading to complex and computationally intense problems [42]. There are several strategies to reduce the complexity of the model:

One approach is the usage of a clustering algorithm. It is important to note that clustering algorithms need to consider continuity of several days, otherwise the SOC does not match. Therefore traditional clustering algorithms cannot be used [42]. One option instead is using typical days by dividing the year into four seasons, each represented by a typical day of 24 h, and optimizing the operation conditions for the specific days and assembling from the results the whole year [61]. While this approach reduces significantly the computational effort and allows one to also optimize the storage location, it is not well-suited for regions with significant variations in weather within a season. Also, the interplay with SDES and LDES cannot be well represented within this approach since the simplification is too big.

It can also be performed by clustering typical design days and coupling them. The year is described as typical days and a sequence σ introduced, which couples successive days by connecting SOC end of days to SOC of the next day. This method has more variables and constraints, but gives the storage optimization flexibility [42]. With this method, more variations within one season can be considered. The storage level can be then optimized over the whole year, using the typical days with a better granularity, but depending how the days are clustered, extreme weather events may not be considered, although of substantial importance for LDES operation.

Another option, instead of optimizing for the whole days, is reducing the high number of variables for each typical day and considering only a certain set of binary variables per day, limiting the possible operation modes [42]—e.g., consider that the long-term storage on a specific day either only charges or discharges [56], which makes the method well-suited to optimize the operation of the LDES, but not suitable to optimize several storage locations or make siting decisions on both LDES or SDES.

Depending on the optimization goal, it is also possible to use two clustering algorithms together to reduce complexity. With a local outlier factor, low and abnormal probability scenarios are eliminated. In a second step a clustering algorithm is used to determine optimal segmentation points and identify with k-means for each period a representative scenario [52]. The challenge with this approach however is that extreme weather events are not considered, which decreases the robustness of the solution significantly and is not suited for situations where the resilience of the overall system should be increased, especially since those events are filtered out.

3.8. Optimization

Concerning the optimization goal, there are two perspectives observed in the literature: minimizing total power system costs and maximizing the profit of the storage operator. These represent fundamentally different problem formulations, which to a certain extend lead to diverging results: Power system cost-minimization, using, e.g., a production cost model, prioritizes overall system efficiency but does not necessarily align with the revenue-maximization objectives of individual operators [29]. In contrast, profit-maximizing approaches focus on market-driven incentives and the commercial viability of storage deployment. For instance, Wan et al. demonstrated that profit optimization for an energy hub, when incorporating grid fees, led to increased local storage utilization and reduced grid trading [61]. Similarly, Alkano et al. proposed a distributed, coordinated supply algorithm between the DSO and a power-to-gas plant operator, which maximized plant revenue while respecting grid capacity constraints through a maximum allowable injection limit [63].

System cost-minimization highlights societal benefits; profit-maximization underscores individual business cases. Well-designed regulations and incentives can bring the two viewpoints together and promote business models that realize the societal welfare potential of LDES.

In the current academic discourse, the focus lays clearly on the optimization of the overall system benefits with 20 studies considering this approach. In the modeled studies, the system is defined as a multi-energy system in a certain neighborhood or district energy system, which minimizes the total operation cost [28,42], a certain distribution grid [47,48,50,54], or a broader region [27,29,43,49,51–53,56–60,62].

Only five studies took the view of the plant operator and maximized their profit. The operator in the reviewed studies can be a PV park operator with a co-located storage [44], the operator of a renewable energy power plant or hydrogen system [26,61,63,64]. Two studies did not use an optimization model.

Depending on the goal of the study, investment versus operation or deterministic versus uncertain environments, different optimization methods are used:

Mixed-Integer Linear Programming (MILP) is the most frequently used method, particularly for siting and sizing case studies in distribution networks, such as locating LDES units at congested nodes, determining optimal power and energy capacities, and co-optimizing day-ahead operation under network constraints [27,42,45,49,54,88]. MILP formulations represent investment decisions as binary variables and system behavior as linear constraints, enabling efficient solutions using branch-and-bound or branch-and-cut algorithms.

Several case studies adopt Markov Decision Processes (MDPs) to model sequential operational decision-making under uncertainty. MDPs represent the system using state transitions (e.g., state-of-charge evolution), probabilistic inputs (e.g., PV output states), and a policy function that maximizes long-run expected rewards. They are commonly solved using dynamic programming or value iteration and are used when studies focus on long-term operational strategies rather than single-period optimization.

To represent uncertainty more explicitly, robust optimization—typically in the form of min–max formulations with column-and-constraint generation—is applied in several LDES dispatch case studies [48,56,89]. These methods compute decisions that remain feasible under all realizations within an uncertainty set. The algorithm iterates between solving a master problem (the "min" problem) and identifying the worst-case scenario (the "max" problem), making it well-suited for applications where reliability is critical, such as congestion management or resilience services.

Big-M linearization is another common technique, used to transform nonlinear or logical constraints into MILP-compatible linear constraints, especially in hydrogen-based or thermochemical LDES studies [48,52,56,57]. By introducing large constant values (the "M" parameters), nonlinear relationships—such as on/off behavior, part-load constraints, or conditional operations—can be reformulated so that binary variables enforce linear logic conditions. This allows otherwise nonlinear models to be solved efficiently using standard MILP solvers.

3.9. Compensation and Business Models

From the literature review, it becomes evident that profitable business models and robust compensation mechanisms for LDES are still underdeveloped. Several studies stress that LDES is still in an early stage of maturity, with market frameworks and policy environments yet to be established [6,90]. While the technical potential is widely recognized, very few studies focus on profitability and operational aspects.

Figure 7 provides a high-level overview of the current business environment for distributed LDES, including actors, market mechanisms, and potential revenue streams.

A key challenge in profitable operation is the high-cost of LDES: system studies suggests that prices must fall below ~10 USD/kWh to support low-cost decarbonization, while costs above 20–30 USD/kWh restrict LDES to niche or peaking roles. Overall, a low cost is more crucial than high efficiency for widespread LDES adoption [60].

At present, the dominant income stream for storage systems is short-term energy arbitrage, which is incentivized by the greater predictability of near-term price fluctuations [5] and therefore dominated by a four-hour storage scale [91], favoring SDES. To compete with short-duration batteries, capital costs need to drop below 2500 EUR/kW [92]. In both isolated and interconnected systems, storage costs account for a substantial share of levelized costs of electricity—up to one-third, or 135–165 EUR/MWh [12]. Levelized costs of electricity are highly cost-sensitive, ranging from ~0.05 USD/kWh at 0.5 USD/kWh storage cost to ~0.11 USD/kWh at 30 USD/kWh [60].

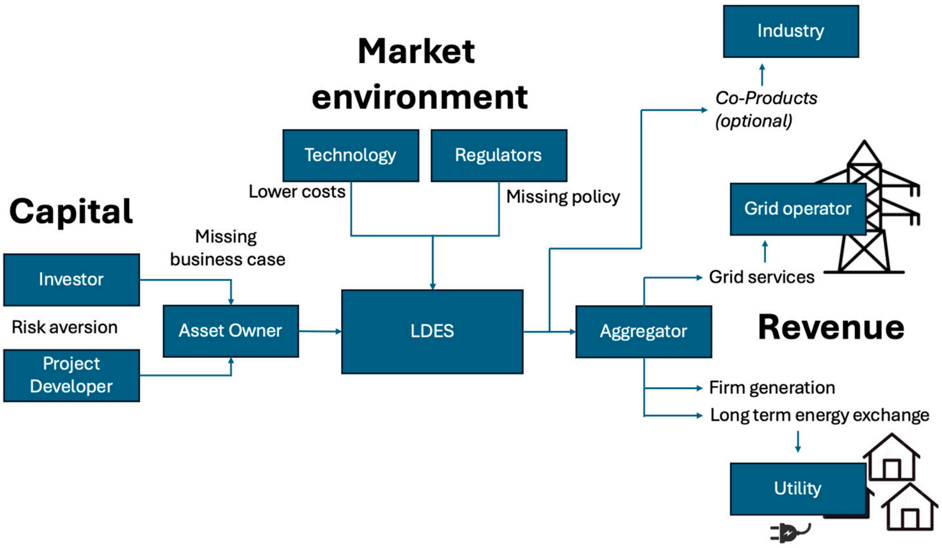

Figure 7. Business environment of LDES.

Long-term energy trading is managed via exchanges, which currently does not offer incentives for LDES participation and are unlikely to self-evolve into supportive markets without policy intervention [6]. Market revenues from arbitrage alone capture only 52–85% of the total operational system value of LDES and remain insufficient to cover the high capital costs of deployment [93].

Similarly, ancillary service markets reinforce the advantage of SDES, making it unlikely that LDES can rely on these mechanisms as major revenue sources [5,12]. Price differentials for long-term pricing for either of those markets are not high enough to compete with other flexibility options such as gas or pumped hydro [5].

Only five of the reviewed studies explicitly examine business models for LDES: Fokkema et al. analyzed a PV park operator with co-located storage, optimizing for long-term operational profit under local demand commitments, stochastic electricity prices, seasonal solar generation patterns, hydrogen conversion efficiencies, and grid distribution limits. The study found a clear benefit in reduced curtailment due to grid constraints and in storing energy for later use to satisfy local demand [44]. A second business model observed in the literature centers on the production and sale of hydrogen or gas [26,61,63,64], either as the sole revenue source or as part of a diversified set of income streams. Seasonal hydrogen storage, in particular, may currently be more profitable when directed toward the transportation or industrial sectors rather than being reintegrated into the electricity market [61].

Despite these niche examples, the current revenue opportunities for LDES remain limited. However, LDES could deliver additional system benefits that are currently uncompensated [6,93]. For example, LDES could defer transmission or distribution line investments in cases where congestion occurs, particularly during PV peaks or EV charging events that last only a few hours per year. Although this represents a clear system benefit, it is unlikely to account for a significant share of LDES revenues [5].

The following factors are improving the profitability of LDES: Dynamic pricing structures tend to yield higher profits compared to fixed tariffs [61] and value stacking, e.g., combining energy arbitrage with capacity market participation, and/or selling hydrogen can significantly enhance profitability [6]. Policies that value long-term resilience are beneficial for LDES, e.g., disaster recovery [6] even though this is consistently identified as a key driver for implementation in the reviewed studies, this service is not economically compensated.

The general consensus is that under current conditions a favorable market environment for LDES is unlikely to emerge before the late 2020s or early 2030s [6]. Until then, project-specific support schemes are expected to play a decisive role, after which broader deployment could accelerate [90].

One key recommendation is the implementation of forward markets, covering all trades beyond the D-1 timeframe, up to several days or even years. Currently, however, market liquidity is limited. Germany demonstrates the highest levels of liquidity, whereas storage operators in other European countries lack access to suitable trading platforms. In addition, transmission rights do not align with the products offered in forward markets [5]. Also multipart payment contracts, regulated rates of return, tax credits, procurement mandates, subsidies, carbon pricing, and novel business models such as the "storage-as-a-service" concept, positioning LDES as a distinct asset class that is compensated for storing—rather than generating—energy are needed [5,6,91,94].

Another emerging opportunity is capacity firming: power purchase agreements (PPAs) could pay premiums for firm capacity, enabling renewable energy producers to improve their participation in arbitrage and ancillary service markets. However, this market remains at an early stage in Europe [5].

Overall, the high capital costs, immaturity of business models, and uncertainty surrounding future market design and regulation undermine the bankability of LDES projects. Current market mechanisms and dedicated marketplaces remain undefined, making it difficult for developers to secure long-term revenue certainty [5,6]. Without targeted policy interventions and the development of robust compensation mechanisms, the technical potential of LDES will remain underutilized.

3.10. Regulations

The development of regulations for LDES is increasingly recognized as critical to defining how LDES can provide grid functions, remove barriers, and create marketplaces where LDES can be properly valued; moreover, policies that value long-term resilience (e.g., disaster recovery) and regulations that limit curtailment (e.g., from residential rooftop solar) as well as demand quick and deep decarbonization further strengthen the case for LDES [6,95]. While the absence of clear market rules, supportive incentives, and predictable revenue streams continues to pose significant deployment barriers. Recent developments at the European Union level illustrate both the progress made and the remaining gaps in creating a favorable environment for LDES.

To create a new regulation within the European Union, the European Network of Transmission System Operators ENTSO-E draft a technical proposal, such as network codes, methodologies, or recommendations, which has then to be reviewed by the Agency for the Cooperation of Energy Regulators ACER which ensures regulatory consistency. Then the European Commission (sometimes with Parliament and Council) adopts them as EU law. If it is a regulation, it is directly binding across Member States; if it is a Directive, national governments must transpose it into national law, which is then implemented by national regulators and system operators.

Currently, there are no regulations on LDES in Europe, but the process has started: ENTSO-E have mentioned within their E RDI Roadmap 2024–2034 the potential and need for LDES. Hydrogen is expected to play an important role in achieving EU climate targets by contributing to climate neutrality, decarbonizing hard-to-decarbonize energy sectors and providing large-scale seasonal energy storage for long periods of time, which can solve the problem of long-term flexibility of the system and its role when planning and expanding the transmission system. In this context, it is also mentioned that market mechanisms to increase the system resilience and security have to be implemented and validated [96].

The Council of the European Union and the European Commission have explicitly recognized the strategic role of energy storage in the Union's decarbonization and energy security agendas:

The rules for storage at the European level are set in the EU directive 2019/944 on common rules for the internal electricity market. It provides a technology-neutral definition of energy storage (Art. 2(59)), defined as the conversion of electrical energy into storable forms and its subsequent re-use either as electricity or another energy carrier. Energy storage is explicitly recognized as a market activity, allowing operators to buy, sell, and provide services in wholesale, balancing, and ancillary markets on a non-discriminatory basis, especially compared to generating units, safeguarding against tariff structures that would discourage storage, notably by prohibiting discriminatory network charges such as double charging electricity during storage and re-injection. It restricts transmission and distribution system operators from owning or operating storage facilities (Arts. 36 and 54), with exception, when no competitive providers are willing to invest, and where storage is essential for grid reliability. It extends also the market rights to active consumers and citizen energy communities, enabling them to own and operate storage in combination with generation and self-consumption. This approach not only democratizes access to energy markets but also embeds storage within decentralized and participatory energy models [97].

An additional recommendation by the European Commission on Energy Storage (14 March 2023) highlights the need for both short- and long-duration solutions to integrate high shares of renewable generation, to reduce dependence on Russian gas, and enable rapid decarbonization. The recommendations suggests that it should be ensured that system operators consider storage in their planning process and its potential compared to grid investments. LDES requires long-term visibility and predictability of revenues to attract financing. The Commission urges Member States to ensure storage's full participation in electricity markets, facilitate revenue stacking, and remove double charging—particularly for front-of-the-meter assets serving energy communities [98].

Progress on implementation across European countries is outlined in the National Energy and Climate Plans (NECPs), which were reviewed by the European Storage Coalition. The assessment shows that most Member States have yet to introduce strong policies and regulatory frameworks for energy storage [99].

In March 2025, the European Commission launched a real-time dashboard tracking storage capacity deployment across EU countries: SDES shows a rapid uptake—especially in Britain and Germany. LDES deployment is still low all over Europe [100].

Favorable instruments under discussion for LDES are a variety of policy tools: Procurement mandates commit future demand to investors, thereby de-risking the supply chain and manufacturing investments; however, their inflexibility and the challenge of defining appropriate energy-to-power ratios pose risks of technology mismatches or insufficient uptake [6].

Subsidies, such as tax credits or exemptions proportional to installed capacity (e.g., per MW) can lower investment costs without raising consumer prices, though they do not influence demand-side behavior and may reduce overall market efficiency [6].

Carbon pricing, whether through direct taxation or emissions trading schemes (ETS), strengthens the competitiveness of LDES relative to fossil fuel-based peaker plants by internalizing the cost of emissions. Nevertheless, while carbon pricing is widely favored by economists and has proven effective in practice [94], it tends to prioritize least-cost solutions rather than fostering technological innovation, which may limit its effectiveness in advancing novel LDES technologies [6].

In the United Kingdom, several mechanisms have been explored to provide stable revenue streams for storage. These include the regulated asset base model, which grants investors a stable rate of return with capped revenues and wheeling charges; the cap-and-floor mechanism, which guarantees revenues within a defined range and compensates for deviations in either direction; and contracts for difference, which ensure a fixed strike price for energy delivered, with compensation payments if market prices fall below or exceed this level. While contracts for difference offer design flexibility, the UK government has considered both the regulated asset base model and contracts for difference inadequate for storage applications. Instead, it is pursuing the implementation of the cap-and-floor approach and evaluating reforms to the capacity market, under which providers receive annual payments for maintaining capacity to cover scarcity situations [5].

In the United States, no comprehensive regulation for LDES has yet been implemented. California has initiated early measures, but the current market design, with revenues largely derived from short-term arbitrage, continues to favor SDES [6]. Nonetheless, positive steps are being taken at the federal level: under the Inflation Reduction Act, the Clean Energy Investment Credit offers tax credits covering between 6% and 70% of the costs of installing energy storage, providing a potentially powerful incentive for LDES deployment [101].

3.11. Research Gaps

Although research on distributed long-duration energy storage has expanded rapidly in recent years, the field remains fragmented. The reviewed literature reveals knowledge gaps that can be grouped into seven key clusters: technical modeling, optimization, siting, sizing, technology development, grid support, and business models and regulation.

Improvement in modeling: Existing models of H_2 systems often fail to adequately capture the dynamic characteristics of real-world operation. In particular, hydrogen systems are costly and poorly suited to rapid changes in dynamic operation, which accelerates component degradation and reduces system lifetime [47]. More accurate modeling approaches are needed to consider constraints such as heat management, leakage, and overall system resilience within decarbonized power systems [50]. Additionally, frequency modulation requirements are frequently overlooked [59], while nonlinear substitution dynamics in complex multi-technology systems remain insufficiently explored [60]. These shortcomings highlight the need for advanced and holistic modeling frameworks that can better represent real-world system behavior.

Optimization: Probabilistic optimization approaches are required to address the inherent uncertainty of load and renewable generation [50]. Most optimization studies to date focus primarily on daily flexibility, with limited attention to seasonal demand and inter-annual variability [53]. Research should expand to consider long-term flexibility requirements.

New methods such as clustering algorithms can be applied to generate representative "typical" days for system studies and so improve the accuracy of the results [61], which has been already achieved in some studies, and metaheuristic approaches—such as harmony search algorithms—show promise in solving cost-minimization problems [49].

Business Modell, Regulation, and Operation: The deployment of LDES also requires supportive business models and regulatory frameworks. Current system optimization often prioritizes minimizing total system costs, but this does not align with the revenue structures of storage operators [29]. New business models, such as cost-sharing or leasing arrangements, could help distribute the high upfront investment burden [49]. At the same time, appropriate regulations and policies must be developed to incentivize deployment and ensure fair market participation.

Siting: Optimal siting of LDES in systems with high shares of VRE is another underexplored area. Additional models are required to identify the best storage locations, likely through a combination of multiple factors such as net load, transmission capacity, storage size, and locational marginal prices [29]. Furthermore, research should investigate multi-stage co-optimization of location and sizing, especially for systems providing ancillary services [52].

Sizing: The sizing of storage systems is a key determinant of both technical feasibility and economic viability. However, most studies overlook the non-marginal, system-level impacts of decentralized power-to-X systems and their scaling effects [61]. Moreover, the implications of larger storage capacities for system integration and flexibility require further investigation [29].

Technology: Technological limitations remain a significant barrier to efficient deployment. Hydrogen-based systems are currently expensive and not designed for rapid dynamic operation, leading to high rates of component degradation [47]. Although other publications on LDES discuss a range of storage technologies, the reviewed studies and modeled systems on grid-supportive, distributed LDES focus almost exclusively on hydrogen, largely neglecting other storage options. Future work should investigate a broader portfolio of storage technologies and examine the interplay between different options and storage technologies. This includes exploring nonlinear substitution dynamics across multi-technology systems, which remain insufficiently studied [60].

Grid support: Most studies look at optimization and modeling of large, centralized storage options. Optimization and siting approaches rarely account for distribution grid constraints, voltage regulation, or local flexibility needs, as well as the interplay with short-term flexibility options, which play a major role in distribution grids with high shares of renewables. From a technology perspective, the dominance of hydrogen in existing studies leaves a significant gap in understanding how alternative distributed LDES technologies—such as flow batteries, thermochemical storage, or modular gravity-based systems—could provide comparable grid services and could be modeled. Finally, business model and regulatory frameworks remain insufficiently developed to enable distributed LDES to participate effectively in local energy markets or ancillary service provision.

3.12. Bibliometric Summary

The growing importance of LDES is reflected in the rising number of academic publications on the topic. As a relatively recent research field, this is evident not only from the publication dates of reviewed papers, as seen in Figure 8, but also from other systematic reviews on similar topics, such as the one conducted by Fonseca et al. on distributed energy systems utilizing hydrogen [84] or the link between VRE levels and LDES adoption [10].

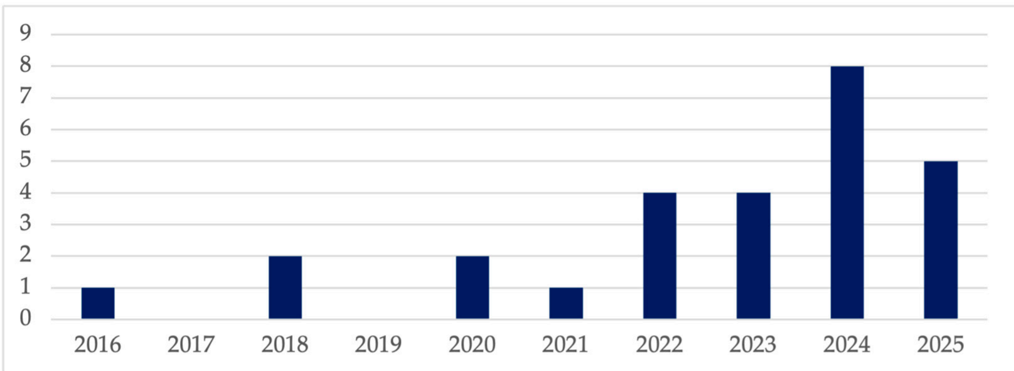

Figure 8. Publication year.

There is also still an inconsistent terminology used in academic literature: while the majority uses the term "long-duration energy storage" which is therefore also adopted in this review, the term "seasonal storage" is widely used, some speak about "long-term storage", making it difficult to find all the relevant literature and obtain an overview on the topic.

Another factor to highlight is the global importance of the topic: The studies published are coming from very different countries, with very different VRE potentials, grid topologies, and challenges in the energy transition, highlighting the universal importance of LDES.

4. Conclusions and Discussion

As VRE penetration increases, the role of LDES becomes increasingly critical in ensuring system stability and flexibility, which is shown by the increasing number of publications for LDES, in general, and distributed LDES in particular. Currently, the research on distributed LDES is still in its early stages, with deployment primarily driven by the wish to increase resilience, strict CO_2-emission reduction targets, increasing shares of VRE and the consequent need to minimize renewable curtailment.

The main findings of this review can be summarized as the following:

Grid and system integration: Distributed LDES rarely operates in isolation. Most studies optimized integrated energy systems that include both short-duration energy storage and LDES. A further, often underestimated advantage is its potential to avoid or defer costly grid reinforcements and extensions. Many existing studies neglect explicit grid restrictions in their models; under such unconstrained assumptions, decentralized options appear less cost-competitive. Energy systems with a high share of fluctuating generation therefore require coordinated operation of both types of storage to achieve full grid-supportive functionality.

Technologies: On the technological side, research on distributed LDES is currently heavily focused on hydrogen due to its comparatively high technological readiness, but also because hydrogen offers additional value streams, such as sales to industrial users or the mobility sector. However, from a grid-support perspective, hydrogen's slower response characteristics and conversion losses highlight the need to explore complementary technologies capable of providing faster, more dynamic services at the distribution level. Overall, the literature highlights a pressing need for cost-effective and scalable technological solutions to enable LDES at meaningful scale—particularly those that can provide both energy-shifting and ancillary services in decentralized grids.

Business models and regulation: Although LDES offers significant benefits for grid stability and flexibility, its economic viability remains a major challenge, as robust business models are still underdeveloped and supportive regulatory frameworks and market signals are not yet in place. Current adoption of LDES is mostly limited to contexts where additional revenue streams can be leveraged, such as selling surplus hydrogen, or where no alternative solutions exist, for example, when enhancing system resilience against natural disasters. Future research should therefore focus on designing appropriate compensation mechanisms for LDES, particularly for the system-level benefits it provides that are not currently remunerated. In parallel, policy design and regulatory frameworks must evolve to enable viable business models, ensuring that distributed LDES can act as an active grid participant rather than a passive storage asset, and thereby play a meaningful role in the energy transition.

Author Contributions: Conceptualization, methodology, formal analysis, investigation, writing—original draft preparation, and visualization: C.A.; methodology, supervision: D.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Acknowledgments: During the preparation of this manuscript, the author used ChatGPT (GPT-5, OpenAI, 2025) to assist with language refinement and correction. All content, analyses, and interpretations of the reviewed literature were conducted by the author. The author has reviewed and edited all text produced with the aid of this tool and takes full responsibility for the final content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ACER	Agency for the Cooperation of Energy Regulators
CO_2	Carbon Dioxide
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	Emissions Trading Scheme
EU	European Union
EV	Electric Vehicle
ETES	Electric Thermal Energy Storage
GW	Gigawatt
GWh	Gigawatt-hour
H_2	Hydrogen
IEEE	Institute of Electrical and Electronics Engineers
kW	Kilowatt
kWh	Kilowatt-hour
LDES	Long-duration energy storage
Li	Lithium-ion
MES	Multi-Energy System
MDP	Markov Decision Process
MILP	Mixed-Integer Linear Programming
MW	Megawatt
MWh	Megawatt-hour
NECP	National Energy and Climate Plan
PHES	Pumped Heat Electrical Storage
PPA	Power Purchase Agreement
PV	Photovoltaic
SDES	Short-duration energy storage
SNG	Synthetic natural gas
SOC	State of Charge
T&D	Transmission and Distribution
UK	United Kingdom
VRE	Variable renewable energy

References

1. Sahoo, S.; Timmann, P. Energy Storage Technologies for Modern Power Systems: A Detailed Analysis of Functionalities, Potentials, and Impacts. *IEEE Access* **2023**, *11*, 49689–49729. [CrossRef]
2. Hunter, C.A.; Penev, M.M.; Reznicek, E.P.; Eichman, J.; Rustagi, N.; Baldwin, S.F. Techno-Economic Analysis of Long-Duration Energy Storage and Flexible Power Generation Technologies to Support High-Variable Renewable Energy Grids. *Joule* **2021**, *5*, 2077–2101. [CrossRef]
3. Blanco, H.; Faaij, A. A Review at the Role of Storage in Energy Systems with a Focus on Power to Gas and Long-Term Storage. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1049–1086. [CrossRef]
4. Albertus, P.; Manser, J.S.; Litzelman, S. Long-Duration Electricity Storage Applications, Economics, and Technologies. *Joule* **2020**, *4*, 21–32. [CrossRef]

5. European Commission. Directorate General for Energy; Fraunhofer Institute for Systems and Innovation Research ISI; Guidehouse; McKinsey & Company, Inc.; Toegepast natuurwetenschappelijk onderzoek.; Trinomics; Utrecht University. *Study on Energy Storage*; Publications Office: Mumbai, India, 2023.
6. McNamara, J.W.; DeAngelis, V.; Byrne, R.H.; Benson, A.; Chalamala, B.R.; Masiello, R. Long-Duration Energy Storage in a Decarbonized Future: Policy Gaps, Needs, and Opportunities. *MRS Energy Sustain.* **2022**, *9*, 142–170. [CrossRef]
7. Denholm, P.; Cole, W.; Frazier, A.W.; Podkaminer, K.; Blair, N. *The Challenge of Defining Long-Duration Energy Storage*; United States Department of Energy location: Washington, DC, USA, 2021.
8. Twitchell, J.; DeSomber, K.; Bhatnagar, D. Defining Long Duration Energy Storage. *J. Energy Storage* **2023**, *60*, 105787. [CrossRef]
9. Schleifer, A.H.; Cohen, S.M.; Cole, W.; Denholm, P.; Blair, N. Exploring the Future Energy Value of Long-Duration Energy Storage. *Energies* **2025**, *18*, 1751. [CrossRef]
10. Selänniemi, A.; Hellström, M.; Björklund-Sänkiaho, M. Long-Duration Energy Storage—A Literature Review on the Link between Variable Renewable Energy Penetration and Market Creation. *Energies* **2024**, *17*, 3779. [CrossRef]
11. Staadecker, M.; Szinai, J.; Sánchez-Pérez, P.A.; Kurtz, S.; Hidalgo-Gonzalez, P. The Value of Long-Duration Energy Storage under Various Grid Conditions in a Zero-Emissions Future. *Nat. Commun.* **2024**, *15*, 9501. [CrossRef]
12. Santecchia, A.; Castro-Amoedo, R.; Nguyen, T.-V.; Kantor, I.; Stadler, P.; Maréchal, F. The Critical Role of Electricity Storage for a Clean and Renewable European Economy. *Energy Environ. Sci.* **2023**, *16*, 5350–5370. [CrossRef]
13. Panos, E.; Kober, T.; Ramachandran, K.; Hirschberg, S. *Long-Term Energy Transformation Pathways*; Joint Activity Scenarios and Modelling: Zürich, Switzerland, 2021.
14. Gabrielli, P.; Garrison, J.; Hässig, S.; Raycheva, E.; Sansavini, G. The Role of Hydrogen Storage in an Electricity System with Large Hydropower Resources. *Energy Convers. Manag.* **2024**, *302*, 118130. [CrossRef]
15. Brey, J.J. Use of Hydrogen as a Seasonal Energy Storage System to Manage Renewable Power Deployment in Spain by 2030. *Int. J. Hydrogen Energy* **2021**, *46*, 17447–17457. [CrossRef]
16. Elberry, A.M.; Thakur, J.; Veysey, J. Seasonal Hydrogen Storage for Sustainable Renewable Energy Integration in the Electricity Sector: A Case Study of Finland. *J. Energy Storage* **2021**, *44*, 103474. [CrossRef]
17. Kondziella, H.; Bruckner, T. Flexibility Requirements of Renewable Energy Based Electricity Systems—A Review of Research Results and Methodologies. *Renew. Sustain. Energy Rev.* **2016**, *53*, 10–22. [CrossRef]
18. Talukdar, M.; Blum, P.; Heinemann, N.; Miocic, J. Techno-Economic Analysis of Underground Hydrogen Storage in Europe. *iScience* **2024**, *27*, 108771. [CrossRef]
19. Thimet, P.J.; Mavromatidis, G. What-Where-When: Investigating the Role of Storage for the German Electricity System Transition. *Appl. Energy* **2023**, *351*, 121764. [CrossRef]
20. Kondziella, H.; Specht, K.; Lerch, P.; Scheller, F.; Bruckner, T. The Techno-Economic Potential of Large-Scale Hydrogen Storage in Germany for a Climate-Neutral Energy System. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113430. [CrossRef]
21. International Renewable Energy Agency. *System Operation—Innovation Landscape*; International Renewable Energy Agency IRENA: Masdar City, United Arab Emirates, 2020.
22. Study on the Effective Integration of Distributed Energy Resources for Providing Flexibility to the Electricity System—European Commission. Available online: https://energy.ec.europa.eu/publications/study-effective-integration-distributed-energy-resources-providing-flexibility-electricity-system_en (accessed on 11 June 2025).
23. Abschätzung Der Netzausbaukosten Und Die Resultierenden Netzentgelte Für Baden-Württemberg Und Deutschland Zum Jahr 2045. Available online: https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2024/04/2024_04_Abschlussbericht_Netzentgelte_BW_DE.pdf (accessed on 6 March 2024).
24. Eyer, J.; Corey, G. *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide: A Study for the DOE Energy Storage Systems Program*; Willis Library: Denton, TX, USA, 2010; p. 1031895.
25. Zhang, J.; Guerra, O.J.; Eichman, J.; Pellow, M.A. Benefit Analysis of Long-Duration Energy Storage in Power Systems with High Renewable Energy Shares. *Front. Energy Res.* **2020**, *8*, 527910. [CrossRef]
26. Boulaire, F.; Love, J.; Mackinnon, I. An Adaptive Renewable Energy Plant (AREP)—To Power Local Premises and Vehicles with 100% Renewables. *Energy Strategy Rev.* **2021**, *38*, 100703. [CrossRef]
27. Aghajan-Eshkevari, S.; Ameli, M.T.; Azad, S.; Pashiri, N.T. Chapter 15: Resilience Enhancement of Distribution Networks by Optimal Scheduling of Hydrogen Systems. In *Future Modern Distribution Networks Resilience: From Passive Operation to Strategic Active Paradigms*; Elsevier: Amsterdam, The Netherlands, 2025; ISBN 978-0-443-16087-5.
28. Harsini, A.E. Resilience-Oriented District Energy System Integrated with Renewable Energy and Multi-Level Seasonal Energy Storage. *J. Energy Storage* **2023**, *72*, 108645. [CrossRef]
29. Cole, D.L.; Dalvi, S.; Zavala, V.M.; Guerra, O.J. Towards Understanding the Complexity of Long-Duration Energy Storage Siting in High Renewable Power Grids. *iScience* **2025**, *28*, 112571. [CrossRef]
30. Pudjianto, D.; Strbac, G. Whole System Value of Long-Duration Electricity Storage in Systems with High Penetration of Renewables. *iEnergy* **2022**, *1*, 114–123. [CrossRef]

31. Andrade, C.; Selosse, S.; Maïzi, N. The Role of Power-to-Gas in the Integration of Variable Renewables. *Appl. Energy* **2022**, *313*, 118730. [CrossRef]
32. Zeng, Y.; Zhou, T.; Wang, T.; Zhang, M.; Zhang, S.; Yang, H. Long-Duration Energy Storage: A Critical Enabler for Renewable Integration and Decarbonization. *Energies* **2025**, *18*, 466. [CrossRef]
33. Groppi, D.; Pfeifer, A.; Garcia, D.A.; Krajačić, G.; Duić, N. A Review on Energy Storage and Demand Side Management Solutions in Smart Energy Islands. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110183. [CrossRef]
34. IEA. *Renewables 2025*; Institute of Estate Agents: Singapore, 2025.
35. Baviskar, A.; Hansen, A.D.; Das, K. Challenges of Future Distribution Systems with a Large Share of Variable Renewable Energy Sources—Review. In Proceedings of the 19th Wind Integration workshop, Ljubljana, Slovenia, 11–13 November 2020.
36. Gevorgian, V.; Booth, S. *Review of PREPA Technical Requirements for Interconnecting Wind and Solar Generation*; NREL: Golden, Colorado, 2013; p. 1260328.
37. Sinsel, S.R.; Riemke, R.L.; Hoffmann, V.H. Challenges and Solution Technologies for the Integration of Variable Renewable Energy Sources—A Review. *Renew. Energy* **2020**, *145*, 2271–2285. [CrossRef]
38. Katiraei, F.; Aguero, J. Solar PV Integration Challenges. *IEEE Power Energy Mag.* **2011**, *9*, 62–71. [CrossRef]
39. De Carne, G.; Maroufi, S.M.; Beiranvand, H.; De Angelis, V.; D'Arco, S.; Gevorgian, V.; Waczowicz, S.; Mather, B.; Liserre, M.; Hagenmeyer, V. The Role of Energy Storage Systems for a Secure Energy Supply: A Comprehensive Review of System Needs and Technology Solutions. *Electr. Power Syst. Res.* **2024**, *236*, 110963. [CrossRef]
40. Energiespeicher. Available online: https://www.bayernwerk-netz.de/de/energie-einspeisen/energiespeicher.html (accessed on 16 June 2025).
41. Zahler, J. Netzverträglicher Ausbau von Großbatteriespeichern. Available online: https://www.ffe.de/veroeffentlichungen/netzvertraeglicher-ausbau-von-grossbatteriespeichern-loesungsansaetze-aus-der-praxis/ (accessed on 16 May 2025).
42. Gabrielli, P.; Gazzani, M.; Martelli, E.; Mazzotti, M. Optimal Design of Multi-Energy Systems with Seasonal Storage. *Appl. Energy* **2018**, *219*, 408–424. [CrossRef]
43. Kötter, E.; Schneider, L.; Sehnke, F.; Ohnmeiss, K.; Schröer, R. The Future Electric Power System: Impact of Power-to-Gas by Interacting with Other Renewable Energy Components. *J. Energy Storage* **2016**, *5*, 113–119. [CrossRef]
44. Fokkema, J.E.; Uit Het Broek, M.A.J.; Schrotenboer, A.H.; Land, M.J.; Van Foreest, N.D. Seasonal Hydrogen Storage Decisions under Constrained Electricity Distribution Capacity. *Renew. Energy* **2022**, *195*, 76–91. [CrossRef]
45. Zhou, S.; Han, Y.; Zalhaf, A.S.; Lehtonen, M.; Darwish, M.M.F.; Mahmoud, K. Risk-Averse Bi-Level Planning Model for Maximizing Renewable Energy Hosting Capacity via Empowering Seasonal Hydrogen Storage. *Appl. Energy* **2024**, *361*, 122853. [CrossRef]
46. Jain, R.; Nagasawa, K.; Veda, S.; Sprik, S. Grid Ancillary Services Using Electrolyzer-Based Power-to-Gas Systems with Increasing Renewable Penetration. *E-Prime Adv. Electr. Eng. Electron. Energy* **2023**, *6*, 100308. [CrossRef]
47. Nandi, S.; Ghatak, S.R.; Sannigrahi, S.; Acharjee, P. Coordinated Planning and Operation of PV- Hydrogen Integrated Distribution Network Incorporating Daily-Seasonal Green Hydrogen Storage and EV Charging Station. *Int. J. Hydrogen Energy* **2024**, *90*, 134–158. [CrossRef]
48. Jazayeri, S.A.; Samiei Moghaddam, M.; Moazzami, M.; Shahgholian, G.; Hashemi, M. Enhancing Renewable Hosting Capacity in Smart Grids: A Robust Optimization Framework Integrating Hydrogen Systems and Demand Response. *Energy Convers. Manag. X* **2025**, *27*, 101063. [CrossRef]
49. Yang, G.; Yang, D.; Liu, B.; Zhang, H. The Role of Short- and Long-Duration Energy Storage in Reducing the Cost of Firm Photovoltaic Generation. *Appl. Energy* **2024**, *374*, 123914. [CrossRef]
50. Haggi, H.; Sun, W.; Fenton, J.M.; Brooker, P. Proactive Rolling-Horizon-Based Scheduling of Hydrogen Systems for Resilient Power Grids. *IEEE Trans. Ind. Appl.* **2022**, *58*, 1737–1746. [CrossRef]
51. Wen, Z.; Zhang, X.; Wang, G.; Li, Y.; Qiu, J.; Wen, F. Data-Driven Stochastic-Robust Planning for Resilient Hydrogen-Electricity System With Progressive Hedging Decoupling. *IEEE Trans. Sustain. Energy* **2025**, *16*, 1545–1561. [CrossRef]
52. Liu, N.; Zhang, K.; Zhang, K. Coordinated Configuration of Hybrid Energy Storage for Electricity-Hydrogen Integrated Energy System. *J. Energy Storage* **2024**, *95*, 112590. [CrossRef]
53. Vulic, N.; Rüdisüli, M.; Orehounig, K. Evaluating Energy Flexibility Requirements for High Shares of Variable Renewable Energy: A Heuristic Approach. *Energy* **2023**, *270*, 126885. [CrossRef]
54. El-Sayed, W.T.; Awad, A.S.A.; Al-Abri, R.; Alawasa, K.; Onen, A.; Ahshan, R. Integrated Planning of Hydrogen Supply Chain and Reinforcement of Power Distribution Network for Accommodating Fuel Cell Electric Vehicles. *Int. J. Hydrogen Energy* **2024**, *81*, 865–877. [CrossRef]
55. Jia, Q.; Zhang, T.; Zhu, Z.; Cai, R.; Song, K.; Yan, F.; Qayyum, A. Harnessing Hydrogen Energy Storage for Renewable Energy Stability in China: A Path to Carbon Neutrality. *Int. J. Hydrogen Energy* **2025**, *118*, 93–101. [CrossRef]
56. Pan, G.; Gu, W.; Lu, Y.; Qiu, H.; Lu, S.; Yao, S. Optimal Planning for Electricity-Hydrogen Integrated Energy System Considering Power to Hydrogen and Heat and Seasonal Storage. *IEEE Trans. Sustain. Energy* **2020**, *11*, 2662–2676. [CrossRef]

57. Wang, S.; Yang, D.; Zhang, L.; Chenmei, L. Robust Planning for Hydrogen-Based Multienergy System Considering P2HH and Seasonal Hydrogen Storage. *Int. Trans. Electr. Energy Syst.* **2024**, *2024*, 1156761. [CrossRef]
58. Morgenthaler, S.; Ball, C.; Koj, J.C.; Kuckshinrichs, W.; Witthaut, D. Site-Dependent Levelized Cost Assessment for Fully Renewable Power-to-Methane Systems. *Energy Convers. Manag.* **2020**, *223*, 113150. [CrossRef]
59. Lin, H.; Zhao, X.; Zhang, R. Analysis of Hydrogen Energy Storage Location and Capacity Determination and Power Grid Planning Suitable for Renewable Energy Large-Scale Development. *IEEE Access* **2024**. [CrossRef]
60. Chu, A.K.; Baik, E.; Benson, S.M. Long-Duration Energy Storage in Transmission-Constrained Variable Renewable Energy Systems. *Cell Rep. Sustain.* **2025**, *2*, 100285. [CrossRef]
61. Wan, Y.; Kober, T.; Schildhauer, T.; Schmidt, T.J.; McKenna, R.; Densing, M. Conditions for Profitable Operation of P2X Energy Hubs to Meet Local Demand with Energy Market Access. *Adv. Appl. Energy* **2023**, *10*, 100127. [CrossRef]
62. Bragatto, T.; Carere, F.; Cresta, M.; Gatta, F.M.; Geri, A.; Lanza, V.; Maccioni, M.; Paulucci, M. Location and Sizing of Hydrogen Based Systems in Distribution Network for Renewable Energy Integration. *Electr. Power Syst. Res.* **2022**, *205*, 107741. [CrossRef]
63. Alkano, D.; Scherpen, J.M.A. Distributed Supply Coordination for Power-to-Gas Facilities Embedded in Energy Grids. *IEEE Trans. Smart Grid* **2018**, *9*, 1012–1022. [CrossRef]
64. Fambri, G.; Diaz-Londono, C.; Mazza, A.; Badami, M.; Sihvonen, T.; Weiss, R. Techno-Economic Analysis of Power-to-Gas Plants in a Gas and Electricity Distribution Network System with High Renewable Energy Penetration. *Appl. Energy* **2022**, *312*, 118743. [CrossRef]
65. Yang, C.-J.; Jackson, R.B. Opportunities and Barriers to Pumped-Hydro Energy Storage in the United States. *Renew. Sustain. Energy Rev.* **2011**, *15*, 839–844. [CrossRef]
66. Budt, M.; Wolf, D.; Span, R.; Yan, J. A Review on Compressed Air Energy Storage: Basic Principles, Past Milestones and Recent Developments. *Appl. Energy* **2016**, *170*, 250–268. [CrossRef]
67. Energy Vault®—Long Duration. Available online: https://www.energyvault.com/solutions/long-duration (accessed on 22 October 2025).
68. Shan, R.; Reagan, J.; Castellanos, S.; Kurtz, S.; Kittner, N. Evaluating Emerging Long-Duration Energy Storage Technologies. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112240. [CrossRef]
69. Berrada, A.; Emrani, A.; Ameur, A. Life-Cycle Assessment of Gravity Energy Storage Systems for Large-Scale Application. *J. Energy Storage* **2021**, *40*, 102825. [CrossRef]
70. Smallbone, A.; Jülch, V.; Wardle, R.; Roskilly, A.P. Levelised Cost of Storage for Pumped Heat Energy Storage in Comparison with Other Energy Storage Technologies. *Energy Convers. Manag.* **2017**, *152*, 221–228. [CrossRef]
71. Wang, P.; Li, Q.; Wang, S.; Xiao, T.; Wu, C. Thermo-Economic and Life Cycle Assessment of Pumped Thermal Electricity Storage Systems with Integrated Solar Energy Contemplating Distinct Working Fluids. *Energy Convers. Manag.* **2024**, *318*, 118895. [CrossRef]
72. Organic-SolidFlow-Energiespeicher | CMBlu Energy AG. Available online: https://www.cmblu.com/de/technologie/ (accessed on 22 October 2025).
73. Cheng, Z. Redox Flow Batteries for Long-Duration Energy Storage: Technology Overview, Market Status, and Sustainable Development Perspectives. *Technol. Eng. Chem. Environ. Prot.* **2025**. [CrossRef]
74. He, H.; Tian, S.; Tarroja, B.; Ogunseitan, O.A.; Samuelsen, S.; Schoenung, J.M. Flow Battery Production: Materials Selection and Environmental Impact. *J. Clean. Prod.* **2020**, *269*, 121740. [CrossRef]
75. Blume, N.; Neidhart, M.; Mardilovich, P.; Minke, C. Life Cycle Assessment of a Vanadium Flow Battery Based on Manufacturer Data. *Procedia CIRP* **2023**, *116*, 648–653. [CrossRef]
76. Zhang, S.; Ramanujam, A.S.; Arvidsson, R.; Michieletto, A.; Schubert, U.S. Prospective Life Cycle Assessment of Organic Redox Flow Batteries. *EES Batter.* **2025**, *1*, 468–481. [CrossRef]
77. Sand, M.; Skeie, R.B.; Sandstad, M.; Krishnan, S.; Myhre, G.; Bryant, H.; Derwent, R.; Hauglustaine, D.; Paulot, F.; Prather, M.; et al. A Multi-Model Assessment of the Global Warming Potential of Hydrogen. *Commun. Earth Environ.* **2023**, *4*, 203. [CrossRef]
78. Uekert, T.; Wikoff, H.M.; Badgett, A. Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy. *Adv. Sustain. Syst.* **2024**, *8*, 2300449. [CrossRef]
79. Haque, N.; Giddey, S.; Saha, S.; Sernia, P. Recyclability of Proton Exchange Membrane Electrolysers for Green Hydrogen Production. In *New Directions in Mineral Processing, Extractive Metallurgy, Recycling and Waste Minimization*; Reddy, R.G., Anderson, A., Anderson, C.G., Fleuriault, C., Spiller, E.D., Strauss, M., Vidal, E.E., Zhang, M., Eds.; The Minerals, Metals & Materials Series; Springer Nature Switzerland: Cham, Switzerland, 2023; pp. 137–150, ISBN 978-3-031-22764-6.
80. Rosenow, J. A Meta-Review of 54 Studies on Hydrogen Heating. *Cell Rep. Sustain.* **2024**, *1*, 100010. [CrossRef]
81. Available online: https://assets.ctfassets.net/mfz4nbgura3g/66utWag5IRGhRziWWRAJXe/5528357b14b461fc12350480ca084146/Locational_20costs_20of_20heat_20technologies_20in_20Great_20Britain_20-_20FINAL_20REPORT.pdf (accessed on 9 September 2025).

82. Jafari, M.; Botterud, A.; Sakti, A. Decarbonizing Power Systems: A Critical Review of the Role of Energy Storage. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112077. [CrossRef]
83. Vivas, F.J.; De Las Heras, A.; Segura, F.; Andújar, J.M. A Review of Energy Management Strategies for Renewable Hybrid Energy Systems with Hydrogen Backup. *Renew. Sustain. Energy Rev.* **2018**, *82*, 126–155. [CrossRef]
84. Fonseca, J.D.; Camargo, M.; Commenge, J.-M.; Falk, L.; Gil, I.D. Trends in Design of Distributed Energy Systems Using Hydrogen as Energy Vector: A Systematic Literature Review. *Int. J. Hydrogen Energy* **2019**, *44*, 9486–9504. [CrossRef]
85. Li, Y.; Xie, Y.; Zhang, X.; Xiao, F.; Gao, W. Grid Variability and Value Assessment of Long-Duration Energy Storage under Rising Photovoltaic Penetration: Evidence from Japan. *Energy* **2024**, *307*, 132607. [CrossRef]
86. Schewe, C.; Graeber, D. *HydrogREenBoost: Wasserstoff für die Sicherstellung des Stromnetzbetriebs*; TransnetBW GmbH: Stuttgart, Germany, 2025.
87. Hemmati, R.; Saboori, H. Emergence of Hybrid Energy Storage Systems in Renewable Energy and Transport Applications—A Review. *Renew. Sustain. Energy Rev.* **2016**, *65*, 11–23. [CrossRef]
88. Liu, T.; Yang, Z.; Duan, Y. Short- and Long-Duration Cooperative Energy Storage System: Optimizing Sizing and Comparing Rule-Based Strategies. *Energy* **2023**, *281*, 128273. [CrossRef]
89. Wang, Z.; Du, B.; Li, Y.; Xie, C.; Wang, H.; Huang, Y.; Meng, P. Multi-Time Scale Scheduling Optimization of Integrated Energy Systems Considering Seasonal Hydrogen Utilization and Multiple Demand Responses. *Int. J. Hydrogen Energy* **2024**, *67*, 728–749. [CrossRef]
90. Available online: https://www.susi-partners.com/wp-content/uploads/2024/08/Decarbonising-Electricity-Grids-with-Investments-in-LDES_SUSI-Partners.pdf (accessed on 18 August 2025).
91. London, J. Compensation Mechanisms for Long-Duration Energy Storage. Available online: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-32978.pdf (accessed on 22 May 2025).
92. Sepulveda, N.A.; Jenkins, J.D.; Edington, A.; Mallapragada, D.S.; Lester, R.K. The Design Space for Long-Duration Energy Storage in Decarbonized Power Systems. *Nat. Energy* **2021**, *6*, 506–516. [CrossRef]
93. Guerra, O.J.; Zhang, J.; Eichman, J.; Denholm, P.; Kurtz, J.; Hodge, B.-M. The Value of Seasonal Energy Storage Technologies for the Integration of Wind and Solar Power. *Energy Environ. Sci.* **2020**, *13*, 1909–1922. [CrossRef]
94. Lilliestam, J.; Patt, A.; Bersalli, G. The Effect of Carbon Pricing on Technological Change for Full Energy Decarbonization: A Review of Empirical Ex-post Evidence. *WIREs Clim. Change* **2021**, *12*, e681. [CrossRef]
95. Bird, L.; Lew, D.; Milligan, M.; Carlini, E.M.; Estanqueiro, A.; Flynn, D.; Gomez-Lazaro, E.; Holttinen, H.; Menemenlis, N.; Orths, A.; et al. Wind and Solar Energy Curtailment: A Review of International Experience. *Renew. Sustain. Energy Rev.* **2016**, *65*, 577–586. [CrossRef]
96. ENTSO-E RDI Roadmap 2024–2034. Available online: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/RDC%20publications/entso-e_RDI_roadmap_2024-2034_240710.pdf (accessed on 18 August 2025).
97. *Richtlinie (EU) 2019/944 des Europäischen Parlaments und des Rates vom 5. Juni 2019 mit Gemeinsamen Vorschriften für den Elektrizitätsbinnenmarkt und zur Änderung der Richtlinie 2012/27/EU (Neufassung) (Text von Bedeutung für den EWR.)*; European Comission: Brussel, Belgium, 2019; Volume 158.
98. *Commission Recommendation of 14 March 2023 on Energy Storage—Underpinning a Decarbonised and Secure EU Energy System 2023/C 103/01*; European Union: Maastricht, The Netherlands, 2023.
99. Available online: https://energystoragecoalition.eu/wp-content/uploads/2024/01/NECP-2023.pdf (accessed on 14 August 2025).
100. European Energy Storage Inventory | JRC SES. Available online: https://ses.jrc.ec.europa.eu/storage-inventory (accessed on 14 August 2025).
101. Twitchell, J.; Dave, P.; Boff, D.; Powell, D.; Bhatnagar, D. Targeted Financial Incentives for Long-Duration Energy Storage. In Proceedings of the 2025 IEEE Electrical Energy Storage Applications and Technologies Conference (EESAT), Charlotte, NC, USA, 20–21 January 2025; IEEE: Charlotte, NC, USA, 2025; pp. 1–6.