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District Storage Paper

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Smart Networks for Energy Transition

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1 EXECUTIVE SUMMARY

District energy storage systems (DESS) are identified as a critical enabling technology for achieving deep decarbonisation, enhancing grid stability, and improving energy resilience at the local level. Scaling their deployment from pilot projects to industrial use requires a concerted, multi-faceted strategy that addresses financial, regulatory, technical, and societal challenges simultaneously. The promise of a decentralised, renewable energy future hinges on this DESS critical component. If DESS are to be adopted on a large scale, then a joined-up approach needs to be applied across policy, finance, technology and society.

1.1 Key findings and recommendations:

The path to widespread DESS adoption is well-defined, yet fraught with substantial financial, social and regulatory obstacles. Our observations reveal that the initial cost of infrastructure development acts as a major brake on investor confidence, closely followed by the uncertainty in legal and regulatory landscapes that govern DESS operation. Furthermore, the power grids must evolve to handle a vastly increased quantity of decentralised energy resources. To overcome these, a coordinated action and a shift in mindset are required, as follows:

1. Unlock Investment: To de-risk the large adoption of DESS, the financial aspects (CAPEX, OPEX, and ultimately LCOE) must immediately be lowered or/and optimised. Reducing the Levelized Cost of Energy (LCOE) is essential for improving project bankability and long-term profitability. This can be achieved through targeted subsidies, grants, and special tax incentives that direct cashflow and reduce the initial capital burden for developers.

2. Govern with Clarity: Governments must actively pave the road by implementing flexible, forward-looking regulations. These rules must incentivise sustainable goals while remaining agile enough to incorporate future technological innovations quickly.

3. Design for Storage: The future must be "storage-ready" by design. Municipalities, construction companies, and urban developers must collaborate from the very first planning stages to integrate DESS and smart-grid infrastructure as core elements, not afterthoughts.

4. Measure What Matters: Success cannot be measured by technology alone. This paper recommends establishing a robust monitoring framework using multi-criteria decision-making (MCDM) to balance social, economic, and environmental impact indicators. This framework must be developed with community input to ensure the metrics are meaningful to all stakeholders.

1.2 Strategic role of district storage in the energy transition

District storage is essential for achieving deep decarbonisation targets. As we transition to a system where most of our electricity comes from intermittent sources like wind and solar, the energy system's need for flexibility skyrockets.

DESS steps in as the essential buffer. It stores the daytime sun and the night-time wind, ensuring that when a local business needs power or when a neighbourhood faces peak demand, the supply is reliably met. This flexibility not only prevents the curtailment of clean energy but also helps stabilise the public grid against fluctuations. Moreover, by coupling electricity storage with thermal networks (district heating), DESS unlocks significant efficiencies and helps decarbonise the heat sector, which is far more complex than just decarbonising electricity. DESS fundamentally moves the energy system from a passive, top-down structure to an active, resilient, and localised network.

1.3 Summary of use cases and implementation potential

The implementation potential is vast, covering every spatial context, urban, rural, and industrial. The core challenge is ensuring that enough participants join the system to make the investment viable.

The primary use cases are defined by the scale and the needs of the participating users:

1. **Residential Sharing:** Small to medium-scale systems shared among local households, offering immediate value through shared infrastructure and potentially lower energy bills.

2. **Industrial Load Management:** Larger installations serving local industry, designed to participate actively in flexibility and ancillary service markets to generate revenue while smoothing local peak loads.

3. **District Heating Integration**: Using thermal storage to leverage the low operational costs and high efficiency of modern district heating networks, making the entire local energy system more efficient and reducing reliance on fossil fuels.

The success of all these cases relies on stakeholder engagement. Municipalities hold the key by defining planning boundaries large enough to host viable systems, while continuous education, hosting conferences and sharing success stories, drives the societal acceptance needed for widespread, long-term adoption. By focusing on coordinated action across demonstration, funding, and market design, DESS can move from being a specialized solution to a mainstream asset for a sustainable energy future.

2 INTRODUCTION

In the quest for a sustainable future, the European Union (EU) seeks to bring about an energy transition, with the objective to achieve climate neutrality by 2050. This ambitious goal is at the heart of the European Green Deal. It requires a paradigm shift from fossil fuels to renewable energy sources and calls for innovative solutions to address challenges such as energy intermittency and grid stability. Among these solutions, district energy storage systems (DESS) are emerging as key enablers to increase energy flexibility and facilitate decarbonisation.

2.1 Definition of district energy storage system (DESS)

A DESS is a shared energy storage solution designed to serve multiple users or applications within a defined local geographic area (such as an urban district or industrial park). The energy needs of the users, their consumption patterns, and the requirements of the local grid will determine the appropriate scale, the capacity, and the technology of energy storage systems. Instead of each user relying on an individual storage unit, a DESS provides a collective, optimised approach. This sharing model enhances efficiency and flexibility both at the district and system grid level, delivering technical, social, environmental and economic benefits to all involved stakeholders.

2.2 Importance of district storage for flexibility and decarbonization and role of grid system operators

Compared to individual storage solutions , DESS facilitates more efficient energy management by aggregating resources and addressing energy demand and supply imbalances across a broader network. Their capacity to integrate multiple energy vectors, such as electricity, heating, cooling, and mobility, further enhances their strategic value, aligning with the broader goals of sector coupling and system decarbonisation. The deployment of DESS is increasingly recognised as a cornerstone of the European energy transition. Their ability to bridge the gap between local energy generation and consumption, enhance energy independence, and support the integration of renewable energy sources underscores their importance.

District storage is also a key component of the energy district, where assets such as renewable generation, storage, demand-side flexibility, and electric mobility interact to optimise the local system behind certain nodes. Within these energy districts, DESS enhance flexibility by coordinating with other components and local initiatives such as citizen energy communities, enabling collective self-consumption and efficient energy sharing. In addition, these districts increasingly act as *local flexibility nodes*, helping to ease local congestion and support grid stability.

The grid system operators (GSOs) are responsible for the stability and reliability of energy transmission and distribution networks. Their responsibilities also include balancing supply and demand in real-time, optimising grid performance and managing voltage variation. Consequently, GSOs should facilitate the deployment, safe integration and market participation of DESS to enhance system flexibility and resilience. New actors, such as aggregators, should complement this role by pooling distributed energy resources, including DESS, into manageable portfolios that can participate in energy markets and provide ancillary services to the grid.

2.3 Objectives and scope of the paper

This paper examines the strategic role of DESS in supporting the green energy transition, focusing on their current and potential contributions to achieving grid flexibility, decarbonisation, and energy system resilience. Furthermore, this study evaluates the technological and regulatory frameworks that influence the deployment of DESS and highlights key use cases that demonstrate their application and adoption in diverse settings. Through an analysis of best practices, innovative technologies, legislative gaps and business impacts, the report seeks to provide comprehensive insights and actionable recommendations to support policy development, foster stakeholder engagement, and align technological advancements with local and European market rules.

The scope of this analysis encompasses district-level energy storage applications, with particular attention to shared, multi-user systems that exemplify the collaborative potential of DESS. The report reviews a wide array of storage technologies, including batteries, hydrogen, power-to-gas, and thermal solutions, and explores their integration with sector coupling strategies. By incorporating insights from European and national projects, and other local initiatives the paper contextualises the findings within the broader European energy transition framework.

2.4 Methodology and approach

This research adopts a mixed-methods approach, combining qualitative and quantitative analyses to provide a holistic understanding of DESS. Case studies and best practices from living labs and smart city projects are analysed to identify the key factors driving successful implementations. Additionally, benefit assessment is conducted to evaluate the implications of DESS deployment. The paper also considers the social and environmental impacts of these systems, emphasising their role in promoting equity and inclusivity within energy communities.

Comparative analyses of legislative frameworks are undertaken to identify regulatory gaps and formulate recommendations for policy development.

Stakeholder engagement is central to this methodology. Facilitating meetings and focus groups within energy communities, industrial partners, and regulatory bodies provides a platform to discuss challenges, barriers, and enablers for DESS deployment. The integration of stakeholder feedback ensures that the findings and recommendations are grounded in practical realities and aligned with the needs of diverse actors.

3 USE CASES OF DISTRICT STORAGE: UNLOCKING POTENTIAL

3.1 Key user group and benefits of district storage

The adoption of district storage systems presents a transformative opportunity for many stakeholders, reducing costs, enhancing efficiency, and optimizing resource use. These storage solutions enable the accumulation and redistribution of thermal or electrical energy. DESS ensures that surplus energy produced during off-peak periods is available for later use. They also ensure that the energy, especially in the form of heat from human activities or industrial processes is recovered. By doing so, they significantly reduce energy waste, lower energy dependency from whatever energy source. This results in cost savings, sustainability benefits, and a more resilient energy infrastructure from a systems-level perspective.

A well-designed district storage system can achieve substantial energy savings by balancing supply and demand. Studies indicate that district thermal energy storage, for instance, can enhance system efficiency by around 20%, leading to 20-30% cost savings on heating and cooling expenses[1][2]. Similarly, district electricity storage can help stabilise grid operations, mitigate peak demand charges, and reduce transmission and distribution congestions and losses, contributing up to 15% savings on electricity costs[3].

District storage can be considered part of energy districts as defined in Solution Booklet for Positive Energy District[4]. Although energy districts mainly focus on urban areas or groups of connected buildings, they require the integration of different interconnected systems and infrastructure which includes all components related to production, conversion, delivery, storage and use of energy.

These storage systems in a district area can maintain the balance of supply and demand if they have a sufficient storage capacity (both electricity storage and, through sector coupling, renewable heat and gas) to balance periods of high variable renewable energy generation and periods of high demand but low generation. Energy storage provides the basis for flexibility within the energy system. Storage supports the integration and optimisation of intermittent renewable energy into the system by storing excess renewable energy during periods of peak production to align with periods of peak demand. Storage has the potential to reduce energy consumption, emissions and costs, while increasing overall system efficiency.

Given these advantages, multiple sectors and user groups stand to benefit from district storage implementation. The present sub-chapter identifies these potential users and how they can leverage district storage systems for improved efficiency, cost reduction, and sustainability to their benefit. Identifying potential users of district storage is central to developing use cases and business models. The main potential user groups identified are the following:

3.1.1 Municipalities and Local Governments

Local governments and municipalities play a crucial role in energy management and urban planning. By integrating district storage into their energy strategy, they can enhance energy efficiency in public buildings, street lighting, and public transport systems. Municipalities are often owners of a significant share of a city's building stock, and the distribution of heat especially to those parts of public activities or managed by the municipality is an opportunity. Social housing projects can benefit from heat and electricity acquisition mitigating energy poverty, while improving energy efficiency using heat from near urban industrial processes. The integration of district storage and use would align with the sustainability goals that many municipalities have, in agreement with other European cities (e.g. under the Covenant of Mayors). It would help them tackle these ambitious carbon reduction targets and facilitate integrating district storage to enable greater

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[1] Reynolds, J., Ahmad, M. W., & Rezgui, Y. (2018). *District heating energy generation optimisation considering thermal storage.* In 2018 IEEE International Conference on Smart Energy Grid Engineering (SEGE) (pp. 330–335). IEEE. https://doi.org/10.1109/SEGE.2018.8499509

[2] Powell, K. M., Kim, J. S., Cole, W. J., Kapoor, K., Mojica, J. L., Hedengren, J. D., & Edgar, T. F. (2016). *Thermal energy storage to minimize cost and improve efficiency of a polygeneration district energy system in a real-time electricity market.* Energy. https://doi.org/10.1016/j.energy.2016.07.009

[3] Powell et al. (2016)

[4] Vandevyvere, H., Ahlers, D., Alpagut, B., Cerna, V., Cimini, V., Haxhija, S., ... Padilla, M. (2020). *Positive Energy Districts solution booklet.* https://cris.vtt.fi/en/publications/positive-energy-districts-solution-booklet

renewable energy use.

3.1.2 Commercial and Industrial Facilities' operators

Businesses with significant energy demands, such as manufacturing plants, data centres, and large commercial buildings, can greatly benefit from district storage. This is especially pertinent for energy-intensive industries. They can lower peak demand charges as businesses can store electricity or heat during off-peak hours when rates are low and use it during peak hours, avoiding high demand charges.

Additionally, they would improve process efficiency: Manufacturing facilities can use thermal storage to optimise production processes, ensuring consistent heating and cooling without excess energy consumption.

For business continuity in critical processes, backup power increases resilience, especially important for data centres. District storage enhances operational continuity by mitigating the impact of power outages and ensuring a more predictable supply, which can support mitigation action facilitation and event preparation.

3.1.3 Residential Neighbourhoods and Housing Complexes

Apartment buildings, residential complexes, and neighbourhoods can use district storage systems in residential settings allowing for the centralized collection, storage, and redistribution of energy. This can include:

- Thermal energy storage (TES): Storing excess heat from industrial sources, combined heat and power (CHP) plants, or renewable energy sources like solar thermal panels.
- Electricity storage: Storing surplus electricity from solar panels, wind power, or off-peak grid electricity in battery banks.

When industries or municipalities with high-heat processes are located nearby, residential districts can recover waste heat to supplement their heating needs, reducing reliance on conventional energy sources and lowering emissions. One of the most direct benefits of using district storage in residential neighbourhoods is a significant reduction in heating costs. Instead of heat being released into the atmosphere, this heat can be captured, stored, and distributed to nearby homes for: space heating e.g. radiant floor heating systems, and water heating.

A particular type of stakeholder would be a renewable energy community (REC), in which, besides heat consumption, electricity can also be stored in collective assets such as batteries. In this sense the community can store excess solar energy generated during the day and use it in the evening when demand is higher. It can shift heating and cooling demand from peak hours to off-peak periods, reducing strain on the grid. Moreover, it can avoid peak electricity pricing, saving residents the corresponding energy costs.

3.1.4 Hospitals and Healthcare Facilities' operators

Hospitals and healthcare facilities require an uninterrupted energy supply to ensure the proper functioning of critical medical equipment, climate control, and daily operations. District storage plays a crucial role in enhancing reliability by providing backup power, ensuring that life-saving equipment remains operational during power outages. Additionally, large hospitals consume vast amounts of energy for heating, cooling, and lighting, and district thermal storage can significantly reduce these costs by optimising energy use and reducing waste. Furthermore, many healthcare institutions aim to meet strict energy efficiency regulations and sustainability goals. By integrating district storage, hospitals can improve compliance with green energy mandates while lowering their overall environmental impact.

3.1.5 University and Educational Campuses

Universities and large educational institutions function as self-contained communities with substantial energy demands. District storage helps lower operational costs by storing surplus energy from solar panels or combined heat and power (CHP) plants, reducing overall expenses. It also enhances energy reliability, ensuring that campuses experience fewer disruptions in power supply, which is crucial for maintaining education and research activities. Additionally, many universities are significant energy consumers, considering their demanding residential complexes, laboratories and sport activities. Another particularity of universities is that they have high different amplitudes of consumption from during the day to evening hours. Moreover, their facilities are at the forefront of sustainability efforts, and district storage aligns with their carbon neutrality objectives by enabling more efficient energy use and greater integration of renewable resources.

3.1.6 Real Estate Developers

Real estate developers can leverage heating and cooling individual or shared assets in a condominium, apartment block or neighbourhoods, such as large heat pumps or chillers. This could reduce the upfront costs of heating or cooling systems in new buildings, offering a more efficient and potentially cheaper alternative to individual heating/cooling systems. Such optimisation would come from shared maintenance costs and reduction in idle time of asset operation.

3.1.7 Electricity System Operators

System operators can benefit from district storage for flexibility purposes and other grid services. This can be achieved by exploring thermal load capacity or electric loads for voltage regulation and congestion management. It may also be used for load balancing using excess electricity for heat generation, particularly from renewable sources during periods of low demand on the grid.

3.1.8 EV users

Storage can play a role in mitigating mobility poverty, making available energy stored during more economical hours (for e.g. during the day with high PV generation) for deferred use at night or during high electricity cost hours. Large-shared assets may also be used in apartment building blocks or other building complexes where there is limitation in terms of simultaneity factor of EV charging. Electricity storage may provide higher availability and support to improve the capacity in charging more vehicles at the same time.

The table below illustrates the key user group and benefit of DESS

Table 1 - Key user group and benefit of DESS

Key User	Short Description	Potential Role in DESS	Benefits from DESS
Municipalities & Local Governments	Public authorities managing city infrastructure, buildings and services.	Integrate DESS into urban energy planning; deploy storage for public buildings; coordinate heat networks; promote renewable integration.	Lower public sector energy costs; improved energy efficiency; reduced energy poverty (e.g., social housing); recovery of urban waste heat; alignment with climate targets and CoM commitments; improved resilience.
Commercial & Industrial Facility Operators	High-energy-demand businesses (manufacturing plants, data centers, large commercial buildings).	Use DESS for peak shaving, thermal buffers, backup power, and process heat management.	Lower peak demand charges; improved process efficiency; stable thermal conditions; enhanced business continuity; reduced operational costs and emissions.
Residential Neighbourhoods & Housing Complexes	Apartment blocks, residential districts, and energy communities.	Use collective thermal or electrical storage; integrate waste-heat recovery; manage collective batteries for RECs.	Lower heating and electricity bills; use of industrial/municipal waste heat; reduced emissions; improved comfort; ability to shift demand; avoidance of peak pricing; enhanced self-consumption.
Hospitals & Healthcare Facility Operators	Critical-infrastructure facilities with high heating, cooling, and power needs.	Integrate DESS for emergency backup, mission-critical reliability, and thermal optimization.	Increased energy security; uninterrupted operation of life-saving equipment; lower heating/cooling costs; easier compliance with sustainability and efficiency regulations.
Universities & Educational Campuses	Large campuses with residential, research, and recreational facilities.	Deploy DESS for campus microgrids; store surplus CHP/PV energy; manage varying daily load profiles.	Lower operational costs; improved energy reliability; enhanced sustainability performance; higher renewable penetration; reduced disruptions during peak periods.
Real Estate Developers	Developers of residential or mixed-use buildings and new urban districts.	Integrate shared DESS assets (e.g., thermal storage, large heat pumps) in new designs; optimize heating/cooling	Reduced upfront HVAC costs; higher building value; shared maintenance; lower energy use through demand aggregation; improved sustainability credentials.

		centralization.	
Electricity System Operators	Entities responsible for grid stability, balancing, and congestion management.	Use DESS for flexibility services, load shifting, voltage regulation, and sector coupling (power-to-heat).	Less congestion; improved voltage stability; better integration of variable renewables; reduction of curtailment; enhanced system efficiency.
EV Users & Mobility Stakeholders	Individual EV drivers, fleets, and charging-infrastructure operators.	Use DESS to support EV charging hubs, mitigate simultaneity issues, enable smart charging.	Lower charging costs (charging energy stored at low-price hours); improved charging availability; mitigation of mobility poverty; enhanced grid-friendly charging.

3.2 Use case, best practices and insights from European project

Across Europe, a growing number of projects illustrate the diversity of DESS applications. A list of European projects is presented in the report "Advancing District Heating & Cooling Solutions and Uptake in European Cities[5]". They develop different solutions for district areas, regarding district heating and cooling systems. Some of the projects presented are not only focused on heat energy storage solutions, but also on electrical energy storage solutions.

- READY, Resource Efficient cities implementing ADvanced smart citY solutions – This is a demonstration of flexible combined grid balancing/energy storage solutions for buildings and RES systems including combined heat pumps for heating and cooling, electrical vehicles charging, new PVT systems and 2nd life reuse of EV batteries in buildings. A new residential battery pack of 120 kW has been developed. Smart-building-energy-hub consisting of "site controller" and "cloud" part. The system collects data and optimises the use of the battery system[6].

- RESTORE – The Restore project (Finishing at the end of 2025) provides a clear breakthrough thermal energy storage technology for the decarbonisation of the district heating sector, enabling the use of renewable energy sources, especially solar heat, and waste excess heat collected in summer for heating purposes in winter, in a very competitive way. This project presents an innovative thermos-chemical energy storage (TCES). This technology has high energy density, low energy losses and low cost. The Restore concept is based on two key innovation technologies, namely thermochemical energy storage and a reversible organic Rankine cycle. With this combination, a wide variety of renewable and waste excess heat sources, also at different temperature levels, as well as renewable electricity are possible as energy sources for the Restore solution[7].

  - Entering low or medium temperature heat supplied the DHC (District Heating and Cooling network) network to cover the actual existing demand or elevated to high temperature heat by the reversible organic Rankine cycle unit to be store by the thermochemical energy storage unit later use. In periods where the energy demand in DHC network is higher than the actual available energy sources, the storage energy can be discharged from the thermochemical energy storage and heat and electricity can be supplied to the DHC network.

  - The solution of modelling and optimizing for the presented TCES has being tested and validated in laboratory. The Technical University of Vienna has developed a lab-scale demonstration of thermochemical energy storage, which later will be scaled up to industrial proportions. It has been virtually tested in six different cities in four European countries: Brønderslev (Denmark), Gmünder and Holzkirchen (Germani), Ružomberok (Slovakia) and Brescia and Milan (Italy).

- SMILE – The objective of the project is to demonstrate, under real operating conditions, a set of both technological and non-technological solutions for distribution grids to enable demand response schemes, smart grid functionalities, storage and energy system integration. Special attention has been paid to the development of

[5] European Commission. (2023). Advancing district heating & cooling solutions and uptake in European cities: Overview of support activities and projects of the European Commission on district heating & cooling (Publication No. MJ-04-23-164-EN-N). Publications Office of the European Union. https://op.europa.eu/publication/manifestation_identifier/PUB_MJ0423164ENN

[6] READY Project. (s.d.). *Resource efficient cities implementing advanced smart city solutions (READY)*. http://www.smartcity-ready.eu/ smartcity-ready.eu

[7] RESTORE Project. (s.d.). *RESTORE – Renewable Energy based seasonal Storage Technology for district heating & cooling*. https://www.restore-dhc.eu/ www.restore-dhc.eu

enabling technological solutions, in particular BESS (Battery Energy Storage System) for grid support and residential applications, energy management system and predictive algorithms. Nine technologies are demonstrated and further developed on the three pilot islands. They vary from the integration of battery technology, power to heat, power to fuel, pumped hydro, electric vehicles, electricity stored on board of boats to an aggregator approach to demand side management to predictive algorithms[8].

  - There are three pilots' islands: Madeira (Portugal), Orkney Islands (UK), and Samsø (Denmark).

- MUSE GRIDS – Multi-energy SustainablE Grids. The objective is the maximisation of local energy independence by optimised management of production via users' centred control strategies, smart city functionalities, storage and energy system integration. Multi-energy demand side management is demonstrated with EV, electro-thermal storage, batteries, thermal storage. The interconnection of the existing networks is achieved integrating flexible technologies (EVs, electro-thermal storage, large thermal storage, batteries) and managing them via proper multi-energy demand side management (DSM) driven by end-user habits. It has been implemented in two loosely connected regions[9].

  - The first one is a hilltop town in Italy, Osimo. It has just one point of connection with the national grid/TSO; it configures itself as a municipal microgrid. The demo will demonstrate that the interaction among several energy networks together with energy storage systems, will contribute to the decarbonisation of the municipal microgrids.

  - The second is a rural neighbourhood in Belgium, Oud Heverlee. The objective is to demonstrate the synergy of a neighbourhood strategy for flexibility and grid balancing. They want to make this neighbourhood an efficient local energy community, future-proofed with EVs and heat pumps and with efficient communication and order of operation in case of blackout.

- SPARCS – Sustainable energy Positive & zero cARbon CommunitieS. The objective of the project is to demonstrate and validate technical and socioeconomic feasibility of innovative solutions for planning, deploying and implementing smart energy systems. The project's overall objective is to achieve citizens' inclusive carbon-free urban communities by integrating technologies for energy positivity in buildings and districts, citizen engagement, city planning and governance, flexible grid management and energy storage and; e-mobility as an energy system element[10].

  - The project has two lighthouse cities: Espoo in Finland and Leipzig in Germany. These cities aim to prove that the urban energy transformation of a city into a carbon neutral urban community is socially and economically viable. In addition, the project also has five fellow cities: Reykjavik in Iceland, Maia in Portugal, Lviv in Ukraine, Kifissia in Greece and Kladno in the Czech Republic. They demonstrate that this transformation model can be transferred to other cities without problems.

- MAKING-CITY - It is a 72-month Horizon 2020 project launched in December 2018. It aims to address and demonstrate the urban energy system transformation towards smart and low-carbon cities, based on the Positive Energy District (PED) concept. The PED operational models developed in MAKING-CITY will help European and other cities around the world to adopt a long-term City Vision 2050 for energy transition and sustainable urbanisation whilst turning citizens into actors of this transformation.

  - The PED concept will be tested and validated in two Lighthouse cities: Groningen (Netherlands) and Oulu (Finland). It will be then replicated in 6 Follower cities: Bassano del Grappa (Italy), Kadiköy (Turkey), León (Spain), Lublin (Poland), Trenčín (Slovakia), and Vidin (Bulgaria). The technologies selected to be implemented in the project are mature or already on the market. The PED concept appears as a step beyond the current European building regulations by bringing major structural, societal, economic and technological changes in the cities (https://makingcity.eu/)

- +CityxChange – Within the project, the cities of Trondheim, Limerick, Alba Iulia, Písek, Sestao, Smolyan and Võru

[8] SMILE Project. (s.d.). *Smart Islands Energy System (SMILE)*. https://www.h2020smile.eu/ h2020smile.eu+1
[9] MUSE GRIDS Project. (s.d.). *Multi Utilities Smart Energy GRIDS (MUSE GRIDS)*. https://www.muse-grids.eu/ CORDIS+1
[10] SPARCS Project. (s.d.). *Sustainable energy Positive & zero cARbon CommunitieS (SPARCS)*. https://www.sparcs.info/ smart-cities-marketplace.ec.europa.eu+1

will experiment how to become leading cities integrating smart positive energy solutions. Through the use of digital services, the quality of life for and together with the citizens shall be improved, more energy produced than consumed, and experiences with cities across Europe exchanged to learn faster together. creates solutions for positive energy blocks leading to positive energy districts and cities through: Decision support tools which enable informed decisions to be made by all stakeholders in the community; An approach to creating a positive energy block through energy reduction and efficiency measures, local renewables, local storage, flexibility and peer-to-peer energy trading; Top-down community engagement driven by the local authority and bottom-up citizen engagement to inform, educate and drive behavioural change.

- Platone – The project aimed at defining new approaches to increase the observability of renewable energy resources and of the less predictable loads while exploiting their flexibility. Because flexibility means customer involvement, Platone put the grid users at the centre, investigated their needs and expectations, and used the underlying blockchain to unlock the potential of higher dynamics of response. The project developed a blockchain-based market platform which allows the support of wide geographical area flexibility requests from TSOs and local flexibility requests from DSOs. These are matched with offers from aggregators, resolving conflicts according to pre-defined rules of dispatching priorities. All the market operations are registered and certified within the blockchain service layer, ensuring a transparency, security and trustworthiness among all the market participants. The platforms were tested at three large pilots in Europe and analysed in cooperation with a large research initiative in Canada.

- INTERACT – Integration of Innovative Technologies of Positive Energy Districts into a Holistic Architecture

- FlexCHESS - (Horizon Europe project) focuses on developing interoperable hybrid energy storage systems, including DESS, that integrate thermal, electrical, and innovative flexibility assets to enhance the resilience and efficiency of energy communities.

- The PEDvolution project (Horizon Europe) aims to accelerate the energy transition in the EU by equipping positive energy districts (PEDs) with seven interoperable solutions (tools, methodologies, services and products) accommodating the planning, design and operation of ever-evolving PEDs. Pilots in Germany, Slovenia, and Switzerland will validate how PEDvolution enhances grid flexibility, sector coupling (especially integrating renewables, heating, and digital systems), and community engagement at a neighbourhood scale. As part of the PED development process within PEDvolution, every building of the German pilot will become part of the PED, supporting the energy generation and storage facility. Additionally, surplus energy identified in the local environment, will be channelled to heating and electricity storage facilitates, further improving overall performance and reducing the need for investments. Another use case is the shared community electricity which reduced the risk and upfront cost for users as they can share ownership and make use of the capacity according to their need. The operation would benefit from local generation and charging from the grid during economic hours and discharging during higher cost hours.

    - Regarding mobility, existing apartment building blocks may take advantage of electricity storage to enable multiple EV charging sessions simultaneously. Many existing buildings have limitations in terms of power connection of the existing cables, switchgear and overall connection to the secondary substation, and storage is a way to increase capacity locally without refurbishment costs.

    - Large heat pumps could be applied to complementary uses of heat in neighbourhoods. Distinct applications could improve operational time of heat pumps such as showers, radiant floor, indoor heating, that due to their times of use could target specific hours of the day of the operation of the heat pump. This would allow the thermodynamic cycle to occur and still reduce the idle time of the asset.

4 TECHNOLOGY OVERVIEW AND SELECTION CRITERIA

This chapter provides an overview of prevalent storage technologies suitable for district applications, evaluating their maturity, applications, cost-effectiveness, and operational characteristics. Also, the selection of these hybrid technologies is guided by key criteria such as scalability, integration potential with existing district systems, environmental impact, flexibility services offered, and overall contribution to reducing energy costs and emissions.

4.1 Thermal energy storage (TES) for district applications

Thermal energy storage (TES) plays a crucial role in district heating and cooling networks, allowing for load shifting, energy efficiency improvements, and decoupling energy generation from consumption. TES technologies are categorised into sensible heat storage (SHS), latent heat storage (LHS), and thermochemical storage (TCS), each with different operating temperatures, applications, and suitability for district-scale implementations.

4.1.1 Sensible Heat Storage (SHS)

The most common configurations of SHS systems include water tanks and underground thermal energy storage (UTES) systems. **Water tanks**, which can be installed either aboveground or underground, represent the simplest form of SHS and are frequently used due to their high efficiency, low cost, and ease of integration into existing infrastructure. On the other hand, **UTES** systems use subsurface infrastructure and comes in two primary forms: **borehole thermal energy storage (BTES)** systems, which consist of arrays of vertical boreholes filled with heat exchangers that inject or extract heat from the ground, and **aquifer thermal energy storage (ATES)**, which uses natural groundwater reservoirs to store thermal energy by circulating warm or cold water through wells.

The performance of SHS systems can vary depending on their design and application. In terms of **power capacity**, SHS systems range from small-scale installations of around **100 kW to** large-scale systems exceeding **several hundred megawatts**. **The storage duration** is flexible, accommodating both **short-term (hourly)** balancing and **long-term seasonal** storage. The operational temperature range depends on the system type: water tanks typically operate between 5°C and 95°C, ATES systems between 5°C and 80°C (depends on geological conditions), and BTES systems between 30°C and 90°C. Hot water tanks provide a near-instantaneous response time, making them ideal for rapid load balancing, while underground systems react more slowly due to the slower thermal diffusion in the ground.

A key advantage of SHS systems is their compatibility with renewable energy sources and industrial processes. They are effective in storing thermal energy harvested from **solar thermal systems**, such as flat-plate, evacuated tube, and concentrated collectors, as well as from **industrial waste heat recovery**. Furthermore, SHS systems can be used with **combined heat and power (CHP) plants** in district heating networks to store surplus heat from cogeneration units.

From a technological perspective, SHS is a well-established and proven solution. Water tank systems, in particular, are **widely implemented** in urban and district-scale heating and cooling networks due to their reliability and cost-effectiveness. Although ATES and BTES systems are also mature technologies, their successful deployment is **dependent on** the favourable **geological conditions**.

Water tanks have a capital cost typically ranging from **5 to 50 €/kWh** of thermal capacity, and **low operational costs**. While ATES and BTES systems require **higher initial investment**, the cost per unit of **stored energy is relatively low**. Round-trip efficiencies for SHS systems are generally range from **70% to 90%**, depending on system configuration and losses during charge and discharge cycles.

The application of SHS in district energy systems is particularly notable. **Water tanks** are frequently employed **for short-term storage** to manage daily variations in heating or cooling demand. Meanwhile, **UTES** systems provide an effective solution for **seasonal energy management**, enabling the storage of excess thermal energy collected solution for seasonal energy storage. This capability can significantly reduce primary energy consumption and improve

4.1.2 Latent Heat Storage (LHS) – Phase Change Materials (PCMs)

One of the most common approaches for LHS and phase change materials (PCMs) is the use **of PCM-enhanced water storage tanks**, where the PCM material is integrated into traditional hot or cold-water tanks to increase their energy storage capacity without the need for additional volume. PCMs are also used in **building materials**, such as wallboards and ceiling tiles, to provide passive thermal regulation in buildings. Another increasingly popular method is the deployment of

encapsulated PCM modules within *heating and cooling networks*.

LHS systems are typically designed for **short to medium-term storage**, with durations ranging from a few **minutes to several hours**. The power capacity of these systems depends largely on the specific application and integration within the overall system, but they can reach **up to 10 MW** in larger-scale applications. The operation temperature range of PCMs varies according to the material: **Low-temperature** PCMs (**5-40°C**) in cooling applications, such as air conditioning and refrigerated storage; **Medium-temperature** PCMs (**40-120°C**) for hot water storage and space heating applications; and **High-temperature** PCMs (**120-300°C**) for industrial heat recovery. One of the standout features of LHS systems is their **very rapid response time**.

LHS technologies are well-suited for integration with renewable energy sources, especially **solar thermal systems** that often produce fluctuating energy depending on sunlight availability, and **low-temperature industrial waste heat recovery**, capturing and reusing thermal energy that would otherwise be lost.

LHS is in **commercialisation phase**, with numerous PCM products already available on the market. However, the application of LHS at the district energy network scale is still in the **early stages of development**. Most existing implementations are focused on **building-level** applications rather than large-scale district storage solutions.

The cost-effectiveness for LHS systems depends heavily on the type of PCM used. The cost of materials ranges from approximately **20-200 €/kWh** of thermal storage, depending on properties of the PCM type. Despite these material costs, PCMs often achieve **higher energy density** and efficiency compared to LHS systems.

4.1.3 High-Temperature Thermal Storage (Molten Salt Systems)

The most established configuration of high-temperature thermal energy storage is the **two-tank molten salt** system. Beyond this, molten salt is also used in **direct heating systems** and **steam production units**, where it serves as a working fluid or intermediary for powering turbines or process heat systems. Additionally, **concrete-based sensible heat storage systems** are gaining traction in similar high-temperature applications, particularly for industrial heat recovery.

These systems can deliver between **10 MW and 500 MW** of thermal power, depending on system size and integration. Storage duration typically ranges from **a few hours to several days** and the temperature range is between **250-600 ºC**. The response time is generally **moderate**, limited by the rate of heat exchange and the thermal inertia of the storage materials and systems involved.

Molten salt storage integrates particularly well with concentrated solar power (CSP) technologies. These systems are also being explored for high-temperature industrial waste heat recovery, particularly in energy-intensive sectors such as steelmaking, glass manufacturing, and cement production.

Despite their technological maturity and widely used in CSP applications, molten salt storage is **rarely used in district heating networks**. A major limiting factor is their dependence on a high-temperature heat source and the proximity of an industrial facility capable of supplying or using heat at the required temperature. Their application is typically restricted to cases where a **high-temperature industrial partner**, like industrial and utility-scale renewable applications, is more than conventional urban district heating.

In terms of economics, molten salt systems involve relatively high initial capital costs, generally in the range of **30–80 €/kWh** of storage capacity. However, once installed, they tend to exhibit low operational costs and very high thermal efficiencies, often approaching 95% when integrated directly into a CSP plant or closed-loop industrial process.

4.2 Electrochemical energy storage for District Applications

Electrical energy storage (EES) plays a vital role in district energy systems, enabling grid flexibility, renewable integration, peak demand management, and energy arbitrage. The following sections categorize lithium-ion, sodium-ion, and flow batteries, highlighting their common systems, performance metrics, renewable energy integration, maturity, and cost-effectiveness. Lead-acid and nickel-based battery technologies (e.g. NiCd, NiMH) are still valid solutions for niche applications.

4.2.1 Lithium-Ion Battery Energy Storage Systems (Li-BESS)

Lithium-ion batteries are the most widely deployed energy storage technology, known for their high energy density and fast response times. Common configurations include containerized battery banks deployed for district-level microgrids, building-integrated systems for self-consumption and peak shaving, utility-scale installations coupled with district-oriented renewable energy plants, and large-scale installations paired with renewable generation assets such as solar photovoltaic (PV) or wind farms.

Their modularity allows them to be tailored to diverse scales, **from a few kilowatts to several megawatts**. Lithium-ion systems typically offer short-term storage durations, from a few **minutes up to 6 hours**. Their **response times** are extremely fast, often within **milliseconds**, making them particularly well-suited for grid frequency regulation and other fast-response services. The cycle life of Li-ion BESS systems depends on battery chemistry, ranging from 4,000 to over 10,000 charge-discharge cycles, and their round-trip efficiency typically falls between 85% and 95%.

Li-BESS are ideal for daily load shifting, particularly with **solar PV and wind**, by storing excess generation during periods of low demand and dispatching it when demand increases, or generation decreases. In **hybrid renewable-storage microgrids**, lithium-ion batteries play a key role in improving energy autonomy and system reliability, especially in districts seeking to decarbonise and localise their energy supply.

Lithium-ion storage is a mass production phase, driven by strong demand across the electric vehicle, consumer electronics, and stationary energy markets. Ongoing innovation continues to improve energy density, reduce costs, and enhance safety and lifecycle performance. Today, Li-BESS remains the market-dominant solution for stationary storage, with widespread use across residential, commercial, and utility applications.

Current lithium-ion battery systems are priced at around 130 **€/kWh**, with costs projected to drop below 100 **€**/kWh by 2025. While **low** operational costs, the reliance on critical raw materials such as lithium, cobalt, and nickel raises concerns around long-term sustainability and supply chain vulnerability. Nevertheless, the **high performance** and reliability of Li-BESS justify their continued use, particularly for short-duration storage needs**.**

Within district energy systems, lithium-ion batteries are increasingly used to provide peak shaving, enhance the self-consumption of local renewable energy, and ensure backup power for critical infrastructure. Their **fast response** capabilities make them ideal for grid balancing, grid congestion management services and post fault restoration.

4.2.2 Sodium-Ion Battery Energy Storage Systems (Na-BESS)

Sodium-ion batteries are an emerging alternative to lithium-ion, offering lower-cost materials and enhanced sustainability. Na-BESS systems are being developed for various use cases, including stationary storage for district energy networks, building-integrated units for residential complexes, and utility-scale battery farms. Their scalability and flexibility make them well-suited to decentralised energy infrastructure and community-level energy systems.

Sodium-ion batteries deliver power capacities comparable to lithium-ion systems, scalable from kilowatt-level microgrids to megawatt-scale district networks. They are used for short to medium-term storage durations, typically ranging from a few minutes to six hours. Their response time is nearly instantaneous, measured in **milliseconds**. However, they currently have a shorter cycle life**,** between 2,000 and 5,000 cycles**,** compared to their lithium-based counterparts, and lower round-trip efficiency, averaging between 85% and 90%.

Na-BESS integrates well with renewable energy systems, particularly solar PV and wind, and is an excellent choice for off-grid applications and decentralised energy projects.

Technologically, sodium-ion batteries are in the early commercialisation phase, with mass production expected to scale rapidly by 2027. Several pilot projects are already testing their integration within district heating and cooling networks, signalling growing confidence in the technology's viability for urban energy infrastructure.

Sodium-ion systems are expected to be approximately 30% cheaper than lithium-ion, with projected costs around 100 **€/kWh**. The use of widely available materials not only reduces costs but also mitigates supply chain risks associated with critical minerals like lithium and cobalt. However, lower energy density currently limits sodium-ion batteries in applications requiring compact, high-power solutions, such as electric vehicles or space-constrained environments.

For district storage applications**,** Na-BESS presents a viable, cost-sensitive alternative **to lithium-ion**. It is particularly well-suited for projects focused on renewable integration, grid support, and backup power, especially where lower energy density is not a critical limitation.

4.2.3 Solid-state batteries.

Solid-state batteries are still a relatively low TRL technology. Despite the announcements, they face **challenges in scalability and cost**. The complexity of manufacturing and the need for advanced materials make mass production expensive and technologically demanding. On the other hand, solid-state batteries offer several potential advantages. They have a much **higher energy density** compared to traditional lithium-ion batteries, allowing them to store more energy in a smaller space, making them particularly attractive for **electric vehicles** and **large-scale grid storage** systems, where space is an issue. Moreover, they are **safer**, as they reduce the risk of fires associated with liquid electrolytes, and they offer a **longer lifespan**, withstanding more charge-discharge cycles before degrading.

4.2.4 Flow Batteries

Flow batteries use liquid electrolytes stored in external tanks, offering scalability and long-duration energy storage. The most widely studied and implemented types are vanadium redox flow batteries (VRFBs), commonly used in utility-scale and large district applications, and zinc-bromine flow batteries, which are gaining traction in commercial and industrial buildings. Emerging hybrid flow battery configurations are also being developed for district-level microgrids, combining cost-effective materials with modular designs.

Flow batteries offer power capacities scalable from kW-sized installations to multi-MW systems. They typically provide storage durations of 4 to 12 hours, addressing the needs of long-duration discharge applications. While their response time is slower than lithium-ion, from seconds to minutes**,** they compensate with an exceptionally long cycle life, often exceeding 20,000 charge-discharge cycles. This makes them one of the most durable storage technologies available. However, their round-trip efficiency, generally between 65% and 85%, is lower than that of lithium-ion systems.

Flow batteries are highly compatible with renewable energy integration, especially in systems with significant variability such as solar and wind power. Their long-duration storage capability makes them ideal for off-grid communities, district microgrids, and grid stabilisation where multi-hour energy balancing is essential.

While **commercial deployment is advancing**, flow batteries are **not yet as widely adopted** as lithium-based systems, partly due to their **higher initial capital cost**, currently around **350 €/kWh**. Additionally, the **cost of the liquid electrolytes** can be high, which can affect the overall economic feasibility for smaller installations. Nonetheless, their **extended operational lifespan,** relatively **easy maintenance** and **minimal degradation** over thousands of cycles translate into **lower total cost of ownership** over time. Moreover, the ability to **scale energy capacity independently** of power output makes them economically attractive for large-scale applications. A key limitation, however, is their **lower power density**, which restricts their use in **fast-response scenarios**.

In the context of district energy storage, flow batteries are particularly well-suited for use cases requiring 6–12 hours of continuous discharge, such as overnight energy supply from solar generation or daily load levelling. Their long lifespan and robust cycling performance make them a compelling choice for districts with high storage demand.

4.2.5 Supercapacitors:

Supercapacitors are a special class of electrochemical energy storage devices known for their ability to **charge and discharge rapidly**, making them ideal for applications that require **quick bursts of power**. They also offer exceptional **durability**, withstanding a **large number of charge-discharge cycles** without significant degradation. Their **high-power density** means they can deliver energy quickly and reliably. The main limitation of supercapacitors is their relatively **low energy density**, which means they cannot store as much energy as traditional batteries. As a result, they are often used **together with other energy storage systems**, especially in standalone solutions where quick power delivery is essential Solid-state batteries.

4.3 Mechanical energy storage for district applications

Mechanical energy storage systems store energy through kinetic or gravitational potential, making them robust and scalable solutions for large-scale storage and grid balancing. These technologies include pumped hydro storage (PHS), compressed air energy storage (CAES), and gravity energy storage, each with distinct applications, response times, and scalability in district energy systems.

4.3.1 Pumped Hydro Storage (PHS)

PHS is the most widely deployed large-scale energy storage solution, using water reservoirs at different elevations to store and release energy. There are two primary types of PHS systems: **open-loop and closed-loop**. Open-loop PHS relies on natural water bodies such as rivers and lakes for storage, while closed-loop PHS uses two artificially created reservoirs in a self-contained system, offering greater control over the process.

These systems typically have a power capacity ranging from **100 MW to 1 GW** and can provide storage durations spanning from **6 to 20 hours**, with the potential to extend to several days in some cases. The **response time** of PHS is measured in **minutes**, depending on the ramp-up rate of turbines. Additionally, the cycle life of PHS systems is impressively long, ranging from **40 to 60 years**, which is the longest among energy storage technologies. The round-trip **efficiency** is typically between **70% and 85%.**

PHS systems are crucial in integrating renewable energy sources, such as **wind and solar,** into the grid. They enable the storage of excess energy generated during periods of high renewable output, which can later be used to meet peak demand. Moreover, PHS plays a critical role in **base-load balancing** for **district-level** energy systems, ensuring a consistent and reliable power supply.

PHS accounts for more than **90% of the world's energy storage capacity**. However, its potential for further expansion is constrained by **geographical factors**, as it requires significant elevation differences and access to adequate water resources.

PHS remains a cost-effective solution with a low cost per kilowatt-hour stored, approximately **50 €/kWh**. The **initial capital costs** for PHS installations are **high**, typically ranging from 1,000 to 2,500 €/kW, due to the substantial land use and civil engineering requirements. However, the technology's **low operational costs** and long lifespan make it a highly viable and cost-efficient long-term energy storage option.

PHS is particularly well-suited for **large-scale energy districts** connected to national grids, where it can provide stable and reliable energy storage. However, it is **less ideal for urban district energy systems** unless natural elevation differences and water resources are available in proximity.

4.3.2 Compressed Air Energy Storage (CAES)

CAES stores energy by compressing air in underground caverns or high-pressure tanks, which is later expanded to drive turbines and generate electricity. CAES systems are typically categorised into three types: diabatic, adiabatic, and isothermal. **Diabatic CAES** uses natural gas combustion to reheat the air during expansion, while **adiabatic CAES** stores and reuses the heat generated during compression, improving efficiency. **Isothermal CAES** employs thermal management techniques to maintain temperature balance during compression and expansion, further enhancing efficiency.

The power capacity of CAES systems ranges from **50 MW to 300 MW**, and they typically offer storage durations of **8 to 24 hours**. The **response time** of these systems varies from **minutes to hours**, depending on the specific design. CAES systems generally have a cycle **life of 30 to 40 years**, which is competitive within the energy storage industry. However, the round-trip **efficiency** of CAES is lower compared to other energy storage technologies, ranging from **40% to 70%.**

CAES is particularly beneficial for integrating renewable energy sources into the grid. It is well-suited for **storing surplus wind and solar power**, helping to balance long-duration grid requirements. CAES systems are **ideal for energy districts** that experience excess renewable generation and have **variable loads**, providing a solution for grid stability during periods of high renewable output and low demand.

CAES technology is **commercially available**, with a few large-scale installations in operation worldwide. However, it is **site-dependent**, requiring suitable underground formations, such as salt caverns, for efficient energy storage. This restricts its deployment to regions with appropriate geological conditions.

In terms of cost-effectiveness, CAES has mid-range capital costs, generally between **500 and 1,500 €/kW** installed, making it less expensive than pumped hydro storage. The lower round-trip **efficiency** of CAES impacts its overall economics around **40%-70%,** though it remains competitive in terms of the levelised cost of storage, with an estimated cost of around **100 €/MWh**. This is lower than the cost of lithium-ion storage, particularly for long-duration energy storage.

CAES is most suitable for **industrial districts** with significant energy needs and access to suitable underground storage formations. However, its application in **urban districts is less feasible** due to space and geological constraints, limiting its use to areas where underground storage can be effectively implemented.

4.3.3 Gravity Energy Storage

Gravity storage lifts heavy weights using excess energy and lowers them to generate electricity, offering a scaleable alternative to PHS. There are two common types of gravity energy storage systems: solid mass lifting systems and underground gravity storage. **Solid mass lifting systems** use steel or concrete blocks that are lifted by electric motors, while **underground gravity storage** uses deep mine shafts or tunnels to store energy by lifting and lowering large masses.

These systems typically have a power capacity of **up to 100 MW**, depending on the mass and height of the system. The storage duration of gravity energy systems generally ranges from several hours, typically between **4 and 10 hours**. These systems are capable of **fast discharge**, with response times ranging from **seconds to minutes**. The cycle life of gravity energy storage systems exceeds **30 years**, and they are known for their high round-trip **efficiency**, which ranges between **75% and 90%**.

It is particularly effective for **storing excess energy generated by solar and wind power**, which can then be released when needed to meet demand. The system works **best in energy districts** that rely on intermittent renewable energy sources, offering a reliable solution for balancing supply and demand.

As an emerging technology, gravity energy storage is still in the **early stages** of commercial deployment, with several pilot projects currently in development.

The projected cost of gravity energy storage is between **100 and 200 €/kWh**, but it is expected to decrease as the technology scales and becomes more widely deployed. Despite the high initial infrastructure investment required, the **long lifespan** of **over 30 years** makes gravity energy storage a promising option for large-scale energy applications.

Gravity energy storage offers a viable solution for districts that do not have suitable sites for traditional PHS or compressed air energy storage (CAES). It is particularly **well-suited for industrial or semi-urban energy districts** with high peak loads, where the ability to store and release energy quickly is essential.

4.3.4 Flywheel

Flywheels nowadays are effectively employed in all kinds of applications requiring short-term power management, pulsed power and very high frequency charge/discharge cycles. Flywheels usually provide load responses of around few minutes. For this reason, there is a limited number of applications where flywheels are ideally suited, and this explain the relatively low number of investments received. This kept its maturity levels not so high, as well as costs not so low.

The main limitation in scalability is due to the need of mitigating the considerable safety issues that flywheels pose. In fact, most of the infrastructure volume and cost is currently devoted to bunkering any single flywheel unit, with the additional inconvenience of maintaining a specific safety distance to avoid domino effects.

Flywheel energy storage may have a limited applicability within DESS, although specific power applications may justify their implementation.

4.4 Chemical energy storage for district applications

Chemical energy storage (CES) converts excess renewable electricity into chemical fuels, allowing for long-term storage and flexible energy conversion. This approach supports seasonal storage, decarbonisation of energy grids, and industrial applications. Key technologies include hydrogen energy storage and power-to-gas (P2G) systems, both of which enable large-scale energy storage and sector coupling.

4.4.1 Hydrogen Energy Storage

Hydrogen energy storage systems produce hydrogen through electrolysis during periods of excess electricity supply, typically sourced from renewable energy such as solar or wind. The key components of these systems include various types of electrolyzers commonly alkaline electrolyzers, proton exchange membrane (PEM) electrolyzers, and solid oxide electrolysis cells (SOECs) which use electricity to split water into hydrogen and oxygen. The hydrogen produced is then compressed and stored using methods suited to the application's needs, including high-pressure gaseous tanks, cryogenic liquid storage, or solid-state storage materials like metal hydrides. Stored hydrogen serves as an energy carrier for multiple applications, including fuel cells for electricity generation, hydrogen combustion turbines, industrial heating, and blending with natural gas. This flexible cycle enables efficient long-term energy storage and utilization, enhancing grid stability and supporting a sustainable, low-carbon energy infrastructure.

Power capacity is **highly scalable**, from small kilowatt-scale units to systems **exceeding 100 MW** depending on the configuration. These systems are particularly well suited for **long-term storage**, with durations ranging from **several days to multiple months**, making them ideal for seasonal energy balancing. The **response time** varies from **minutes to hours** depending on the system design and operational mode. **Cycle life** ranges significantly, from **10,000 to 80,000 hours**, depending on the electrolyser technology in use. The round-trip **efficiency** for electricity-to-electricity applications is relatively low, typically **between 30% and 50%**, but can approach **90%** when hydrogen is used **directly for heating or in transport** applications.

Hydrogen energy storage offers significant potential for enhancing the integration of renewable energy sources by converting **excess wind and solar power into hydrogen**, thereby avoiding energy curtailment and improving grid flexibility. In addition, hydrogen can be **blended into existing gas grids**, contributing to the gradual **decarbonisation of heating systems** and industrial energy usage.

Hydrogen energy storage is moving from demonstration projects towards commercial-scale deployment. The development of green hydrogen initiatives worldwide is being driven by supportive policy frameworks and decreasing electrolyser costs, which are critical to enhancing the economic viability of hydrogen systems.

The **initial investment** for electrolysis infrastructure remains **high**, ranging from approximately 500 to 1,500 €/kW, though these costs are expected to decline due to economies of scale and technological advancements. Current **hydrogen production** costs are around **4 to 7 €/kg**, with projections suggesting a reduction to below 2 €/kg by 2030. Storage costs are influenced by the method of hydrogen containment, with gaseous storage being the most **cost-efficient at approximately 10 to 20 €/kg.**

Hydrogen energy storage offers significant value for **district-level applications** by providing long-duration and seasonal storage capabilities that align well with the variability of renewable energy generation. It serves as a clean and versatile fuel source for industrial processes, district heating systems, and hydrogen-powered transportation, supporting decarbonization across multiple sectors. Furthermore, establishing decentralized hydrogen hubs within urban energy districts enhances local energy resilience and autonomy, facilitating more effective integration of renewable energy into the urban energy landscape and enabling flexible, sustainable energy management tailored to community needs.

4.4.2 Power-to-Gas (P2G) Systems

P2G converts excess electricity into hydrogen or synthetic natural gas (SNG), offering seasonal storage and grid decarbonisation potential. The most common configurations of P2G systems include **electrolysis-based hydrogen production**, where electricity is used to split water into hydrogen and oxygen, and **methanation reactors**, which convert hydrogen into synthetic methane (CH_4) by combining it with carbon dioxide captured either from the atmosphere or industrial sources. These gases can then be **injected into the natural gas grid** and later reconverted for use in power plants, heating systems, or the transport sector.

P2G systems are **modular and scalable**, with power capacities typically ranging from **1 MW to 100 MW** depending on the installation size and intended application. These systems are designed for **long-term storage**, with durations extending from **weeks to months** through the storage of hydrogen or SNG in underground caverns, pipeline networks, or existing gas grids. **Response times** range from minutes to **hours**. The **cycle life** of electrolysis units is generally between **15 and 30 years**. In terms of **efficiency**, the round-trip efficiency for electricity-to-electricity applications is relatively low, at around **30% to 40%**, but can reach approximately **70%** when the produced gas is used directly for **heating or in transportation**.

P2G systems play a key role in enhancing renewable energy integration by converting **surplus wind and solar power** into storable chemical fuels, thus enabling long-term and large-scale energy management. By injecting hydrogen or SNG **directly into natural gas infrastructure**, P2G contributes to reducing the reliance on fossil gas and facilitates a gradual transition towards cleaner energy systems.

The maturity of P2G technology is advancing, with increasing commercial deployment observed particularly in Germany, Denmark, and the Netherlands. While electrolysis-based hydrogen production is already commercially available and expanding, the methanation process for generating SNG remains in the early stages of commercial implementation but shows strong potential with continued development.

P2G systems require significant capital investment, with installation costs ranging from approximately **600 to 2,000 €/kW**, although these costs are declining with technological advancements and larger-scale deployment. The current cost of synthetic methane is estimated at **8 to 15 €/MWh**, making it increasingly competitive with fossil natural gas in regions with carbon pricing mechanisms. Although infrastructure investments are substantial, P2G reduces **long-term dependency** on imported fossil fuels and enhances national energy security.

For district-level energy storage, P2G systems offer effective solutions for decarbonising **district heating networks and gas grids**, particularly through the provision of renewable-based synthetic fuels for CHP plants. Furthermore, they enable seasonal storage of renewable energy, helping to manage fluctuations in energy demand and contributing to the stability and resilience of regional energy systems.

4.5 Selection criteria for district energy storage technologies

The selection of an appropriate district energy storage technology depends on various factors, including power capacity, storage duration, location, efficiency, scalability, cost effectiveness, and integration with renewable energy sources. The following table provides a comparative analysis of different thermal, electrical, mechanical, and chemical storage technologies, outlining their key selection criteria to aid decision-making for district-level energy storage implementation.

Table 2: Selection Criteria for District Energy Storage Technologies

Technology	Power Capacity	Storage Duration	Response Time	Round-Trip Efficiency (%)	Maturity	Cost-Effectiveness	Best Suited Applications	TRL	MRL
Sensible Heat Storage (SHS) (Water Tanks, UTES)	100 kW – 500 MW	Hours – Seasonal	Immediate – Moderate	70–90%	Highly mature	Low (5–50 €/kWh, but site-dependent for UTES)	District heating & cooling, seasonal energy balancing	9	7-9
Latent Heat Storage (LHS) (PCM)	Up to 10 MW	Minutes – Hours	Very Fast	75–95%	Emerging, commercialized in niche applications	Material-dependent (~20–200 €/kWh)	Building-integrated TES, low-temp heating & cooling	7-8	6-8
High-Temperature Thermal Storage (Molten Salt, Concrete)	10 MW – 500 MW	Hours – Days	Moderate	~95%	Mature for CSP, rare in districts	Moderate (~30–80 €/kWh)	Industrial districts with high-temperature heat sources	8-9	7-8
Lithium-Ion Batteries (Li-BESS)	10 kW – 10 MW	Minutes – 6 Hours	Milliseconds	85–95%	Mass production	Declining (~130 €/kWh, expected <100 €/kWh by 2025)	Grid balancing, peak shaving, fast-response applications, post fault restoration and grid congestion management	9	9
Sodium-Ion Batteries (Na-	100 kW – 5 MW	Minutes – 6	Milliseconds	85–90%	Early commerci	Projected ~100 €/kWh,	Cost-sensitive district	6-7	5-6

BESS)		Hours			alization	lower than Li-ion	storage, microgrids		
Flow Batteries (VRFBs, Zn-Br, Hybrid)	500 kW – 50 MW	4–12 Hours	Seconds – Minutes	65–85%	Growing commercial adoption	Higher CAPEX (~350 €/kWh), long lifespan reduces LCOE	Long-duration grid stabilization, industrial storage	7-8	6-8
Supercapacitors		Seconds – Minutes	Microseconds	95-99%	Mature, early commercial stage	Low for energy; high for power	Power quality, bridging power, short-term backup	9	9
Pumped Hydro Storage (PHS)	100 MW – 1 GW	6–20 Hours	Minutes	70–85%	Highly mature	Low (~50 €/kWh), but high CAPEX (~1,000–2,500 €/kW installed)	Large-scale energy districts, grid balancing	9	9
Compressed Air Energy Storage (CAES)	50 MW – 300 MW	8–24 Hours	Minutes – Hours	40–70%	Commercial but site-limited	Mid-range (~100 €/kWh), lower efficiency	Industrial districts with geological suitability	7-9	7-9
Gravity Energy Storage	Up to 100 MW	4–10 Hours	Seconds – Minutes	75–90%	Emerging, early commercial stage	Projected (~100–200 €/kWh), high CAPEX	Districts lacking natural elevation for PHS	6-8	5-7
Flywheels	1 - 20 MW	Seconds – 30 min	Milliseconds	85–95%	Commercial but limited applications	220 – 1000 €/kW; 1000 - 5000 €/kWh	Frequency regulation, UPS, high-cycling	9	8-9
Hydrogen Storage (H2 Electrolysis & Fuel Cells)	kW – 100 MW	Days – Months	Minutes – Hours	30–50% (electricity-to-electricity), ~90% (direct use)	Emerging, growing adoption	High CAPEX (~500–1,500 €/kW), costs declining	Seasonal renewable storage, hydrogen hubs, industrial heating	6-8	6-8
Power-to-Gas (P2G)	1 MW – 100 MW	Weeks – Months	Minutes – Hours	30–40% (electricity-to-electricity), ~70% (for heating/transport)	Early commercial stage	High CAPEX (~600–2,000 €/kW), competitive with carbon pricing	Decarbonizing district heating & gas grids, fuel production	6-8	6-8

The choice of district energy storage technology depends on technical, economic, and regulatory factors, as well as specific district energy needs.

- For short-term flexibility and fast response, lithium-Ion and sodium-ion batteries offer high efficiency and rapid discharge, making them ideal for peak shaving and frequency regulation.
- For long-duration storage, flow batteries and mechanical storage (PHS, CAES, gravity energy storage) provide

scalability, but site constraints may limit deployment.

- For district heating and cooling, sensible and latent heat storage (TES) offer high efficiency and cost effectiveness, particularly for urban energy districts.
- For seasonal energy storage and decarbonisation, hydrogen storage and P2G systems enable renewable energy integration, but high costs remain a barrier.

Future advancements in hybrid storage solutions and sector coupling (e.g., combining TES with electrochemical storage or integrating hydrogen in district heating networks) will further enhance efficiency, reduce costs, and support decarbonisation of district energy systems.

4.6 Integration of artificial intelligence (AI) and machine learning

The integration of artificial intelligence (AI) and machine learning (ML) is revolutionising the way energy storage systems operate. These technologies analyse vast amounts of data, including consumption patterns, weather forecasts, and energy production trends, to enhance efficiency and reliability. By **predicting energy demand and supply in real time**, AI helps optimise storage and distribution strategies.

Furthermore, AI can **identify inefficiencies** within storage systems, **manage multiple storage units** simultaneously, and **provide predictive maintenance** by **detecting early signs of battery wear and tear**. This not only reduces operational costs but also improves grid stability and energy reliability. Optimising the interaction between energy production, storage, and consumption allows energy systems to operate at peak performance while minimising cost.

It is also expected that AI will reduce the development cycle of new technologies and materials required for energy storage systems. By enabling faster data analysis, simulation, and optimisation, AI can accelerate R&D processes, allowing innovative materials or system designs to reach the market sooner. This helps to close the current price gap between emerging and mature solutions. In addition, AI will help reduce current inefficiencies and technical issues within existing systems by continuously learning from operational data, proposing improvements, and ensuring that performance is consistently optimised unlocking new potential business models and system integrations.

AI will also enable better hybrid usage of storage solutions by enabling the stacking of different storage technologies, such as batteries, thermal storage, or mechanical storage, to fine-tune the full energy system according to local needs. Ultimately, this will unlock new opportunities for advanced storage technologies, business models, and system integrations that were previously too difficult or costly to implement.

5 LEGISLATIVE AND REGULATORY FRAMEWORK

5.1 Overview of European energy storage legislation

European energy storage legislation is rooted in several key sources, including Directive (EU) 2019/944[11], Regulation (EU) 2019/943[12], its amending Regulation (EU) 2024/1747[13] and Directive (EU) 2024/1711[14], and the Commission Recommendation (2023/C 103/01)[15]. These frameworks collectively include the rules, principles, and incentives necessary for integrating energy storage into the EU's energy market and achieving climate neutrality.

The Regulation (EU) 2024/1747 and Directive (EU) 2024/1711 are key to electricity market reform (also known "Electricity Market Design"). The aim is to stimulate the transition to clean energy while ensuring energy security and affordable prices for consumers, promoting the development of renewable energy and enhancing industrial competitiveness. These two pieces of legislation give energy storage a central role, introducing it among the resources that must have non-discriminatory access to the markets for energy, capacity, ancillary and flexibility services, demand response and encouraging national regulators to remove any regulatory barriers to its development. In addition, it identifies energy storage as a possible solution for flexible connection agreements as a permanent solution where grid development is not the most efficient solution.

Regulation (EU) 2022/869[16] of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009[17], (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013[18] https://eur-lex.europa.eu/eli/reg/2022/869/oj/eng Supports the development of energy infrastructure, including storage systems for heating and cooling.

GSOs, aggregators and regulators are the stakeholders involved in these activities. Concerning the distribution and transmission system operators, the new directive keeps strict limits on their ability toown, develop, manage and operate energy storage facilities, requiring them to without follow an open, transparent and non-discriminatory tendering procedure. The new directive does not weaken the rules set by the previous Directive 2019/944 (Art. 54), granting an

[11] European Commission. (2019a). *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast)* (OJ L 158, 14.6.2019, pp. 125–199). https://eur-lex.europa.eu/eli/dir/2019/944/oj

[12] European Commission. (2019b). *Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity* (OJ L 158, 14.6.2019, pp. 54–124). https://eur-lex.europa.eu/eli/reg/2019/943/oj

[13] European Commission. (2024a). *Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024 amending Regulations (EU) 2019/942 and (EU) 2019/943 as regards improving the Union's electricity market design* (OJ L 2024/1747). https://eur-lex.europa.eu/eli/reg/2024/1747/oj

[14] European Commission. (2024b). *Directive (EU) 2024/1711 of the European Parliament and of the Council of 13 June 2024 amending Directives (EU) 2018/2001 and (EU) 2019/944 as regards improving the Union's electricity market design* (OJ L 2024/1711). https://eur-lex.europa.eu/eli/dir/2024/1711/oj

[15] European Commission. (2023). *Commission recommendation of 14 March 2023 on energy storage – Underpinning a decarbonised and secure EU energy system (2023/C 103/01).* https://eur-lex.europa.eu/eli/reg/2023/103/oj

[16] European Commission. (2022). *Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013* (OJ L 152, 3.6.2022, pp. 45–102). https://eur-lex.europa.eu/eli/reg/2022/869/oj

[17] European Commission. (2009). *Regulation (EC) No 715/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the natural gas transmission networks, and repealing Regulation (EC) No 1775/2005* (OJ L 211, 14.8.2009, pp. 36–54). https://eur-lex.europa.eu/eli/reg/2009/715/oj

[18] European Commission. (2013). *Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013 on guidelines for trans-European energy infrastructure, and repealing Decision No 1364/2006/EC, and amending Regulations (EC) No 713/2009, (EC) No 714/2009 and (EC) No 715/2009* (OJ L 115, 25.4.2013, pp. 39–75). https://eur-lex.europa.eu/eli/reg/2013/347/oj

exemption only for some European countries and for a limited period of time (3 years). The aforementioned rule, which may appear to hinder the development of energy storage, aims to prevent distortions of competition, avoid risks of discrimination and ensure equal access to energy storage services for all market players.

EU Member States have taken different approaches to regulating energy storage. In France, Finland, Germany, Italy, Spain, Belgium and Slovenia, regulations have been enacted to prevent GSOs from owning and operating storage, with the aim of promoting a fair and competitive market. Conversely, in Poland, DSOs and TSOs are allowed to own and operate storage and recover costs through grid tariffs. In Germany, conflicting regulations allow storage to be financed through tariffs by TSOs, but impose restrictions that discourage private operators from engaging in energy markets, leading to significant distortions. Meanwhile, Finland, Spain and France have made progress in implementing market-based procurement frameworks, although regulations still need to be improved to fully incorporate all DERs. This diverse regulatory landscape highlights the tension between regulatory frameworks and the drive for innovation across Member States.[19]

Directive (EU) 2019/944 defines energy storage in Article 2(59) as the deferral of electricity use to a later moment through various technologies, including mechanical, thermal, and electrical systems. Energy storage facilities, as described in the directive, are integral to providing flexibility and stability to the electricity system. Regulation (EU) 2019/943 complements this by ensuring market-based principles for storage integration, while its amendment, Regulation (EU) 2024/1747, enhances support for non-fossil flexibility solutions, including storage.

The Commission Recommendation (2023/C 103/01) emphasises the dual role of energy storage as both a consumer and generator of electricity. It advocates for regulatory frameworks that address barriers such as double taxation and permitting delays, while promoting visibility and predictability of revenues to facilitate investment in storage infrastructure. These provisions collectively highlight the critical role of energy storage in achieving grid flexibility, renewable energy integration, and overall energy system resilience.

The legislative framework addresses several challenges. Directive (EU) 2019/944, particularly in Articles 32 and 36, emphasises the need for non-discriminatory market access and operational independence of energy storage systems. Regulation (EU) 2019/943, supported by its amendment, ensures fair participation of storage in balancing and re-dispatching markets. However, as noted in the Commission Recommendation, administrative inefficiencies and fragmented implementation often hinder progress at the Member State level.

Several Member States have introduced a legislative definition of energy storage, providing clarity and fostering the deployment of storage systems. Specific national targets for installed storage capacity, supported by financing and regulatory programmes, are proving effective in driving investments. For instance, tendering processes for energy storage projects, either standalone or integrated with renewable energy installations, have been implemented in a limited number of Member States, showcasing best practices that could be expanded across the EU[20].

The EU has established storage requirements for 2030 and 2050[21] as part of the climate goals. The energy capacity required by 2030 is more than 100 GW, while by 2050 it is estimated around 80-720 GW. Although all the services it can offer, energy storage needs are underestimated. For example, energy storage is needed to:

- Avoid critical grid stability situations;
- Replace the need for irregular RES backup systems;
- Minimise curtailments with energy displacement and reduction of the number and power of grid lines;
- Consider thermal storage as a flexible change of consumption or seasonal hours;
- Handle external weather events and ensure appropriate time resolutions;
- Maximise switching power flows from existing grid infrastructure and decrease grid congestion at certain times by

[19] European Commission. (n.d.). *Electricity market design*. Energy – Markets and consumers. https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/electricity-market-design_en
[20] Hoogland, O., Fluri, V., Kost, C., Klobasa, M., Kühnbach, M., Khanra, M., ... Cerny, O. (2023). *Study on energy storage — EnTec*. Publications Office of the European Union.
[21] EASE. (2022). *Energy storage targets 2030 and 2050*. https://ease-storage.eu/publication/energy-storage-targets-2030-and-2050/

managing the nominal power of the grid.

Flexibility and storage needs should be updated considering that storage needs should be based on updated climate targets; address systems based on a technology-neutral approach; and ensure Europe's energy independence. The flexibility needs for 2030 are more than 456 GW:

- 67 GW batteries in an EC study;
- 65 GW PHS in EC impact assessments;
- 55 GW power-to-X-to-power replacing gas turbines;
- 40 GW electrolyser with hydrogen storage systems;
- V1G and P2H is including qualitatively.

In addition, the flexibility needs for 2050 are 811 GW, of which 600 GW are in storage:

- 65 GW PHS in EC impact assessments;
- 200 GW in long duration energy storage technologies;
- 120 GW of V2G in a European EV deployment;
- 50 GW of batteries;
- 165 GW in P2X technologies.

Consequently, a massive increase in storage of 146 GW/year is needed, 200 GW in 2030 and 600 GW in 2050.

The estimated the need for 200 GW by 2030 and 600 GW by 2050 of storage, and financial requirements are estimated at between €100 and 300bn for 2050.

The financing mechanisms for energy storage include market-based approaches like capacity payments, as detailed in Regulation (EU) 2024/1747, as well as EU funding programmes such as Horizon Europe and REPowerEU. Implementation is ongoing and aligned with the EU's 2030 and 2050 climate goals. Member States are required to update their National Energy and Climate Plans (NECPs) to include specific storage objectives and measures, as highlighted in the Commission Recommendation.

Financeability considerations are typically based on technology readiness, levelised cost of storage, and revenue streams.

Several key factors influence the investment environment for energy storage:

- Reducing Dependence on Russian Fossil Fuels: The EU is prioritising energy independence, increasing the need for storage solutions to support renewable energy.
- Economic Challenges: Rising interest rates, inflation, and supply chain disruptions create financial hurdles. To maintain momentum in the energy transition, it is crucial to establish a supportive financing environment for clean technologies.
- The Green Deal: This initiative aims to secure access to essential technologies, products, and solutions needed for a successful transition to a net-zero economy while attracting investments in innovative clean energy technologies.
- Net Zero Industry Act (NZIA): A proposed framework designed to strengthen Europe's manufacturing capacity for net-zero technology products by addressing scaling barriers and boosting industrial growth.
- TRL technologies typically require public or venture capital instruments, while commercial-stage technologies tend to be "bankable" and are more likely to have access to debt. Storage project with a long-term capacity market contract in place would face low market risk. SMEs and larger companies are the most supported category of beneficiaries of the mapped financial support schemes.

Rules for the internal market for electricity and amending Directive 2012/27/EU https://eur-lex.europa.eu/eli/dir/2019/944/oj/eng "Household customers should be allowed to participate voluntarily in community energy initiatives as well as to leave them, without losing access to the network operated by the community energy initiative or losing their rights as consumers." System operators should not own, develop, manage or operate energy storage facilities." Energy storage systems should be treated equitably and allowed to provide services like demand response and ancillary grid services.

5.2 Legislative references for energy communities and district storage

Energy communities are essential components of the EU's strategy for decentralised energy systems, as defined in Directive (EU) 2019/944 and reinforced by Regulation (EU) 2019/943 and its amendment. These legislative instruments, alongside the Commission Recommendation (2023/C 103/01), outline the roles, obligations, and opportunities for energy communities in achieving sustainability and grid efficiency. While the legislative framework does not explicitly mention the concept of "district storage," this paper introduces the term to describe energy storage systems integrated into community-level energy grids. The concept draws parallels to provisions for "energy communities" and recognises the limited representation of "thermal districts" within the legislative framework.

Citizen energy communities are defined as legal entities that can engage in activities such as energy generation, distribution, storage, and aggregation. Articles 2 and 15 of Directive (EU) 2019/944 empower energy communities to own and operate energy storage facilities, promoting their active participation in renewable energy integration and flexibility markets. Regulation (EU) 2019/943 emphasises non-discriminatory market access for energy communities, while Regulation (EU) 2024/1747 provides additional support mechanisms for renewable energy-based solutions.

The Commission Recommendation (2023/C 103/01) identifies energy communities as pivotal for fostering renewable self-consumption and local energy sharing. It highlights the need for streamlined regulatory frameworks to reduce administrative and technical barriers, particularly for low-income households. The recommendation further underscores the importance of enabling storage systems to enhance flexibility and renewable integration within community energy grids.

Despite progress under the Clean Energy Package, significant barriers remain for District Energy Storage Systems (DESS) in accessing balancing markets and participating in ancillary service provision. Specific challenges include the lack of locational information provided to market participants, limited regulatory frameworks for DSO procurement of flexibility, and insufficient support for revenue stacking by storage operators. Member States vary significantly in their approaches, with some advancing market-based procurement frameworks, while others still face inefficiencies and restrictions, particularly for small-scale storage assets.

Although the concept of district storage is not explicitly defined in the analysed legislative framework, it complements the principles outlined for energy communities. District storage can address critical issues such as lowering energy costs, enhancing participation in flexibility service markets and consequently, in some cases, reduce investments in network reinforcements, even though the network remains an enabling factor for the installation of BESS. By allowing local actors to store and manage renewable energy, district storage systems align with the broader objectives of community empowerment and decentralised energy management.

Energy communities provide services including the storage of renewable energy for local consumption, ancillary services to support grid stability, and participation in demand response and flexibility markets. These systems also enable energy sharing within communities, optimising resource use and reducing overall costs. Articles 36 and 40 of Directive (EU) 2019/944 emphasise the role of DSOs in facilitating the integration of community-based storage systems while restricting their direct ownership to ensure market independence.

The financing of energy communities and storage initiatives is supported through mechanisms such as competitive bidding processes and capacity mechanisms, as detailed in Regulation (EU) 2024/1747. The Commission Recommendation highlights the importance of addressing financing gaps and providing investment predictability to ensure equitable deployment of energy storage across diverse socioeconomic contexts.

The implementation of these measures requires Member States to establish enabling regulatory frameworks, as mandated by Directive (EU) 2019/944. These frameworks must also be reflected in updates to NECPs, ensuring alignment with the EU's 2030 and 2050 climate targets. Simplified permitting processes and incentives for community participation are essential to overcoming existing barriers and fostering widespread adoption of decentralised energy solutions.

In conclusion, while the concept of district storage is not explicitly addressed in the legislative framework, its introduction complements the principles of energy communities and decentralised energy systems. By leveraging provisions for energy citizens and renewable self-consumption, district storage systems can enhance local energy solutions, promote renewable integration, and support the EU's overarching climate objectives.

Recommendations for initiating and engaging local energy communities in alignment with justice principles – evidence from seven European citizen engagement processes (https://open-research-europe.ec.europa.eu/articles/3-175) "Regulations regarding the energy market, and energy communities in particular, differ strongly across EU member states (Caramizaru & Uihlein, 2020). The regulatory framework can be of influence on the opportunities LECs have to financially exploit from renewable energy generation. In the Dutch context, where there is no formal definition of an energy community; local initiatives can make use of subsidies aimed at fostering a decentralised and renewable energy system[22] (Caramizaru & Uihlein, 2020). Meanwhile Spanish legislation officially recognises the concept of local energy communities and the regulatory framework allows for sharing energy among peers[23] (Frieden *et al.*, 2019). The possibilities a regulatory framework offers can also be a determinant of what motivates people to be part of a local energy initiative[24][25] (Bauwens, 2016; Oteman *et al.*, 2014). On the other hand regulatory barriers can be obstructive to the formation of energy communities as argued by Brummer (2018)[26][27]. An overview of the regulatory frameworks in the respective pilot countries can be found in Deliverable 2.2[28] "Regulatory Impact Analysis for CECs and Flexibility Services" (downloadable here) and Deliverable D2.6[29] "Policy recommendations for CECs and Flexibility uptake" (downloadable here) of the Lightness project."

Europe's local energy community landscape: It's complicated, say researchers[30] **(**https://cordis.europa.eu/article/id/436171-europe-s-local-energy-community-landscape-it-s-complicated-say-researchers**)**. "An EU-funded report outlines how current regulations and policies affect the operation of local energy communities (LECs) in Europe, highlighting the need for a holistic approach."

A roadmap for a policy and legal framework for energy communities (https://build-up.ec.europa.eu/en/resources-and-tools/publications/roadmap-policy-and-legal-framework-energy-communities). "This Roadmap outlines essential Building Blocks and steps to establish robust frameworks for energy communities, including: Clearly defining and recognising energy communities. Enhancing access to information and raising awareness. Facilitating access to finance and support schemes. Establishing minimum regulatory conditions. Implementing a framework to monitor emerging initiatives and persistent obstacles[31]."

District heating is instead defined in several legislative frameworks. Directive (EU) 2018/2001[32] of the European Parliament

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22 Caramizaru, A., & Uihlein, A. (2020). *Energy communities: An overview of energy and social innovation.* European Commission Joint Research Centre. https://publications.jrc.ec.europa.eu/repository/handle/JRC121193

23 Frieden, D., Tuerk, A., Roberts, J., et al. (2019). *Collective self-consumption and energy communities: Overview of emerging regulatory approaches in Europe* (COMPILE project, Working Paper)

24 Bauwens, T. (2016). Explaining the diversity of motivations behind community renewable energy. *Energy Policy, 93*, 278–290. https://doi.org/10.1016/j.enpol.2016.03.017

25 Oteman, M., Wiering, M., & Helderman, J.-K. (2014). The institutional space of community for renewable energy: A comparative case study of the Netherlands, Germany and Denmark. *Energy, Sustainability and Society, 4*(11). https://doi.org/10.1186/2192-0567-4-11

26 Brummer, V. (2018). Community energy – benefits and barriers: A comparative literature review of community energy in the UK, Germany and the USA. *Renewable and Sustainable Energy Reviews, 94*, 187–196. https://doi.org/10.1016/j.rser.2018.06.013

27 Falduto, E., Pavan, A., et al. (2023). *Recommendations for initiating and engaging local energy communities in alignment with justice principles – evidence from seven European citizen engagement processes.* Open Research Europe, 3, 175. https://open-research-europe.ec.europa.eu/articles/3-175

28 Lightness Project. (2023). *Deliverable 2.2: Regulatory impact analysis*

29 Lightness Project. (2023). *Deliverable 2.6: Policy recommendations for CECs.*

30 European Commission. (2022). *Europe's local energy community landscape: It's complicated, say researchers.* CORDIS. https://cordis.europa.eu/article/id/436171-europe-s-local-energy-community-landscape-it-s-complicated-say-researchers

31 European Commission. (2022). *A roadmap for a policy and legal framework for energy communities.* BUILD UP. https://build-up.ec.europa.eu/en/resources-and-tools/publications/roadmap-policy-and-legal-framework-energy-communities

32 European Commission. (2018). *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.* OJ L 328, 18.12.2018, pp. 82–209. https://eur-lex.europa.eu/legalcontent/EN/TXT/?uri=CELEX%3A02018L2001-20231120

and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02018L2001-20231120) Promotes thermal energy storage to improve the efficiency and flexibility of district heating and cooling systems by mean of a better integration of renewable energy.

Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AJOL_2023_231_R_0001&qid=1695186598766. "Member States shall ensure that, for district heating, district cooling and domestic hot water, final customers are provided with competitively priced meters that accurately reflect their actual energy consumption[33]."

Framing the possibilities: EU legislative framework for District Heating (https://smart-cities-marketplace.ec.europa.eu/insights/solutions/framing-possibilities-eu-legislative-framework-district-heating). "District heating and cooling is affected by numerous laws and policies, at EU, national and local levels. The legislative framework covers a wide range of areas, such as market regulation and customer protection, energy and environment, emissions and building standards. As EU member states offer a contrasted picture with different regulatory and policy environments, this article does not go into detail on specific national laws but rather focuses on the most important parts of EU legislation relevant for the district heating and cooling sector. **District heating will have a key role in the decarbonisation ambition of the EU. At the same time, the DHC systems are governed by numerous laws and policies, affecting developments in the field. This article helps you navigate the regulations, to assist you in contributing to the net-zero emission goal[34].**"

A comprehensive European approach to energy storage was undertaken by the European Parliament through the resolution of 10 July 2020 (2019/2189(INI)). (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020IP0198) "53. Considers thermal storage (such as large-scale boilers) and district heating in densely populated areas to be a very efficient tool for energy storage providing the necessary flexibility to integrate a greater share of intermittent renewables and waste heat from industrial processes and the tertiary sector; calls on the Commission and the Member States to support and develop highly energy-efficient district heating networks; moreover, calls on the Commission to take heat infrastructure and thermal storage into account when developing the Ten-Year Network Development Plans for both the European Network of Transmission System Operators for Electricity (ENTSO-E) and the European Network of Transmission System Operators for Gas (ENTSO-G). 56. Welcomes the fact that district heating and cooling networks will be eligible for funding under the revised CEF Regulation, and calls for their inclusion as potential PCIs under the TEN-E Regulation[35];"

[33] European Commission. (2023). *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955.* OJ L 231, 18.9.2023, pp. 1–33. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AJOL_2023_231_R_0001&qid=1695186598766
[34] European Commission. (2022). *Framing the possibilities: EU legislative framework for District Heating.* Smart Cities Marketplace. https://smart-cities-marketplace.ec.europa.eu/insights/solutions/framing-possibilities-eu-legislative-framework-district-heating
[35] European Parliament. *(2020). Resolution of 10 July 2020 on a comprehensive European approach to energy storage (2019/2189(INI)).* https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020IP0198

6 BARRIERS AND ENABLERS FOR DESS ADOPTION

Identifying regulatory or policy barriers for the deployment of DESS and labelling them is rather difficult because regulation is the foundation upon which all markets function and by which all markets are restricted. It affects participants in several ways. Furthermore, existing energy grids are highly complex and attempts to categorise them might exclude relations between specific market actors. Tangible examples are the liberalisation and competition within markets, sharing and ownership of energy, connection to larger energy grids and the integration of green energy mentioned by Wouters[36]. These categories do not include interactions between actors who may influence further effects of certain regulations, for example[37].

Therefore, the focus of this paper is based on regulatory barriers regarding the creation and integration of DESS and their operation within the local grids. Accordingly, market structure and social challenges will be highlighted.

Furthermore, R&I needs beyond technology will be analysed.

6.1 Gaps and challenges in the current framework

The implementation of EU provisions related to energy storage, aggregators, and energy communities, as analysed in the report by Sina, Stephan, et al. (2024), reveals significant disparities in progress among European Member States[38]. The report evaluates the transposition and execution of provisions from Directive (EU) 2019/944, Regulation (EU) 2019/943, Directive (EU) 2018/2001, and Regulation (EU) 2022/2577[39] across six countries: Austria, Bulgaria, France, Germany, Poland, and Spain.

Energy storage, frequently discussed in connection with grid flexibility and renewable integration, is addressed in Articles 32 and 19 of Directive (EU) 2019/944. However, the report of Sina, Stephan, et al. (2024) highlights delays in transposing these provisions in several Member States, alongside a lack of clear regulations and incentives for integrating storage systems into distribution networks. The observations made in the Commission Recommendation (2023/C 103/01) are still valid. Administrative inefficiencies and fragmented implementation often hinder progress at the Member State level. Poor coordination between administrative levels further hampers permitting processes for storage projects, reflecting a gap between legislative goals and practical implementation.

Aggregators, described in Article 17 of Directive (EU) 2019/944, play a crucial role in supporting demand response and consumer participation. Despite recent efforts by Bulgaria and Poland to transpose these provisions, the Sina et al. (2024) report notes that practical frameworks for aggregators remain underdeveloped. Vague regulations and insufficient technical and legal frameworks limit their ability to participate in demand response schemes. Secondary legislation in some Member States, such as Bulgaria, often fails to align with the directive's objectives, creating additional barriers.

Key issues such as double taxation, surcharges, and discriminatory grid tariffs continue to hinder the economic viability of energy storage projects. These barriers affect multiple use cases, from arbitrage to ancillary services, reducing the competitiveness of storage solutions. Recent advancements in some Member States include the adoption of cost-reflective and non-discriminatory grid tariffs, aligning with the Clean Energy Package requirements.

Energy communities, emphasised in Articles 15 and 21 of Directive (EU) 2018/2001, are identified as vital for promoting local renewable energy generation and consumption. While Austria and Spain have made strides in supporting energy communities, the Sina et al. (2024) report highlights challenges such as complex regulatory frameworks and administrative barriers that discourage participation. Limited provisions for ensuring non-discriminatory grid access and supporting low-income households further exacerbate these issues.

[36] Wouters, C. (2015). Towards a regulatory framework for microgrids—The Singapore experience. *Sustainable Cities and Society, 15*, 22–32. https://doi.org/10.1016/j.scs.2014.10.007

[37] Norouzi, F., Hoppe, T., Elizondo, L. R., & Bauer, P. (2022). A review of socio-technical barriers to Smart Microgrid development. *Renewable and Sustainable Energy Reviews, 167*, 112674. https://doi.org/10.1016/j.rser.2022.112674

[38] Sina, S., Dengler, F., Faber, R., Kocher, D., Pumberger, M., de la Vega, R., & Niewitała-Rej, M. (2024). *Analysis of the implementation of EU provisions for the clean energy transition in selected Member States*. Ecologic Institute, Berlin.

[39] Council of the European Union. (2022, December 22). *Regulation (EU) 2022/2577 of the Council laying down a framework to accelerate the deployment of renewable energy* (OJ L 335, 36–61). https://eur-lex.europa.eu/eli/reg/2022/2577/oj

Moreover, smaller-scale storage assets are often overlooked in national and distribution-level resource adequacy assessments, despite their potential to provide significant contributions. Addressing this gap requires greater consideration of distributed and small-scale storage solutions in network development plans.

Overall, the Sina et al. (2024) report underscores recurring themes of delayed transposition, fragmented implementation, and insufficient monitoring mechanisms across all areas. These gaps hinder the realisation of the EU's legislative goals, highlighting the need for streamlined processes, enhanced administrative coordination, and targeted support mechanisms. The Commission Recommendation (2023/C 103/01) provides additional guidance for addressing these challenges by emphasising the removal of barriers and the need for investment predictability.

Additionally, the economics of energy storage reflects the investment's risk profile. In this regard, it should be understood the risks associated with each technology and the use cases.

Unlike energy storage, the new design of the electricity market, composed by the recent Directive (EU) 2024/1711 and Regulation (EU) 2024/1747, does not specifically strengthen the role of district storage, but does so generally for all renewable energy-based resources.

In summary, while the legislative frameworks established by Directive (EU) 2019/944, Regulation (EU) 2019/943, and their related provisions offer a solid foundation for energy storage, aggregators, and energy communities, their effective implementation remains uneven. Addressing these challenges is crucial for achieving the EU's energy and climate objectives and ensuring equitable participation across Member States.

6.2 Market structure

A local energy grid, on which a DESS can operate within, has several levels that can be linked to different actors and their specific role. On the first level there are the flex- / pro- / and consumers that generate mostly electricity and consume this energy in form of electricity for powering, heating or transportation. DESS function as aggregators that store energy fed in by actors on the first level. Furthermore, DESS are the link between level one and level three (DSO) and can also supply energy to a larger energy grid or store energy from the distribution grid in favourable times. On level three there is the public grid operated by the DSO and established electricity markets to trade energy[40].

As a local aggregator, DESS can be seen as an off-grid electricity market for all participants. It benefits actors on level one as communal energy storage that was produced locally and system operators face less congestion and high loads on their grid because DESS function as a buffer and there is only one point of connection[41].

6.2.1 Barrier 1: Application of current regulation

Consumers´ interaction with suppliers and aggregators (DESS) need to be reconsidered, as contractual arrangements and financial adjustments are not clearly defined for a functioning local energy market that is integrated within the public grid[42].

Current legislation and regulations handle consumers' rights in public energy markets, e.g. the wholesale market. Nevertheless, it is unclear whether these same laws apply to local energy markets with integrated DESS as aggregator[43]. The main difference being that energy markets such as retail or wholesale markets are connected to the distribution grid and therefore no one is restricted from participation in general. However, a local energy market with a DESS as aggregator has major restrictions for participants that are not close enough to be integrated into the communal energy storage system.

6.2.2 Barrier 2: Contracting

Moreover, consumers might need several contracts for the operation of a local energy market. First, consumers would still be obligated to be included within the public grid and need an electricity supplier to maintain security of supply and to be

[40] Norouzi et al. (2022)

[41] Mengelkamp, E., Notheisen, B., Beer, C., Dauer, D., & Weinhardt, C. (2018). A blockchain-based smart grid. *Computer Science Research & Development, 33*, 207–214. http://dx.doi.org/10.1007/s00450-017-0360-9

[42] Norouzi et al. (2022)

[43] Zame, K. K., Brehm, C. A., Nitica, A. T., Richard, C. L., & Schweitzer, G. D. (2018). Smart grid and energy storage: Policy recommendations. *Renewable and Sustainable Energy Reviews, 82*, 1646–1654.

able to maintain a status as residential building. This is the case in Germany where, for example, all residential buildings are required to feature basic infrastructure such as electricity connection. Additionally, contracting with the operator of the DESS would be necessary to be able to participate within the local energy market. Both of these arrangements might possibly interfere with each other, depending on the terms and tariffs. Careful coordination and a regulatory foundation are needed to fine-tune and align the necessary contracts[44].

6.2.3 Barrier 3: Investment security

The current market for DESS centred local energy grids is characterised by regulatory uncertainty regarding the establishment and operation that stems from the high dependency from policymakers, and unclear existing legislature. Long payback periods and perceived risks in combination with unclear regulation are not a desirable environment for investors[45].

Despite the ongoing decline of battery prices, financing and installing DESS and large-scale batteries in general, is still a CAPEX (capital expenditures) intensive business with comparably long payback periods of up to 10 years, depending on the business case and operation modes. Investors run CBA (cost-benefits-analysis) and despite the already existing lack of sufficiently clear regulation that favours investments in energy markets, payback periods this long inherently incur a political risk because policymakers' sentiment might change over time.

6.2.4 Barrier 4: Investment competitiveness

CBA of investors is only a monetary assessment that doesn’t include additional values of the investment such as increased resilience of the public grid[46]. In order to further incentivise Investors and increase bankability, regulation should take added values of DESS into account.

This is especially important as investments in DESS and local energy markets are in competition with other assets within the field of energy transition and renewable energies. Investments in DESS-centred investments need to be competitive to standalone BESS, BESS Co-Location (BESS + PV/Wind), PV and Wind. Regulatory changes and security in favour of DESS, analogue to PV and Wind, can be a real booster for the deployment of these local systems.

6.3 Social and stakeholder challenges

Stakeholder challenges involve the same problems that almost all new technologies have to face. Nouri described this as three stages: participation, performance and persistence.

As participation in a DESS system unveils slight inconveniences for involved parties because they might need to shift their daily load patterns (e.g. starting the dish washer or the washing machine around noon instead of in the evening), the standard adoption curve for new, convenience enhancing technology cannot be applied[47]. Therefore adoption is likely to take longer.

Performance and persistence are dependent on the individual DESS setup. The more people are incentivised monetarily and the more convenient it is to be part of a DESS system, the better the performance and the persistence of participants will be.

6.3.1 Barrier 1: Community Engagement and Public acceptance

Establishing DESS at a European wide scale is not a single person's or company's preference because these systems are highly complex and include several activities such as generation, storage and local distribution of electricity. Every DESS installed is a communal action and, therefore, is required to be accepted publicly. As it was seen since the introduction of renewable energy generation, the lack of public acceptance has the potential to slow down the implementation of

[44] Brown, M. A., Zhou, S., & Ahmadi, M. (2018). Smart grid governance: An international review. *Wiley Interdisciplinary Reviews: Energy and Environment, 7*(5). https://doi.org/10.1002/wene.290

[45] Cambini, C., Meletiou, A., Bompard, E., & Masera, M. (2016). Market and regulatory factors influencing smart-grid investment. *Utilities Policy, 40*, 36–47. http://dx.doi.org/10.1016/ j.jup.2016.03.003.

[46] Stadler, M., Cardoso, G., Mashayekh, S., et al. (2016). Value streams in microgrids: A literature review. *Applied Energy, 162*, 980–989. http://dx.doi.org/10.1016/j.apenergy.2015.10.081

[47] Nouri, A., Khadem, S., Mutule, A., ... Carroll, P. (2022). Identification of gaps and barriers in Regulations, Standards, and Network Codes to Energy Citizen Participation in the Energy Transition. *Energies, 15*, 856. https://doi.org/10.3390/en15030856

technologies[48][49].

Wolsink describes social acceptance on different levels in society[50]. The first level of acceptance involves regulators, policymakers and the public population as a whole. These entities make the first step and are the foundation of social acceptance. This is followed by market acceptance of producers, distributors and financial actors that level the playing field for mass adoption. Lastly, community acceptance is described by end users, local authorities and residents in the proximity of the physical systems.

6.3.2 Barrier 2: Ownership and Involvement

As community energy initiatives may vary in organisational structure, opportunities for contributors to DESS to also own party of it also varies. Different legal forms might be beneficial for private small stake owners or the exact opposite[51].

As every installed DESS must be financially beneficial for all stakeholders involved, the splitting of ownership is a delicate topic. Usually, these systems need a financial partner like a bank to fund the installation. This goes hand in hand with some financial risks that must be compensated, or else actors might be scared away[52].

Furthermore, taxation and liability is a topic to consider when talking about partial ownership. First, proper taxation is not an easy task for private shareholders, which might hinder the involvement of private households. Second, as shareholders of a registered company, participants usually are liable for the actions, which means they have to put a lot of trust in the operator right from the start.

6.3.3 Barrier 3: Cybersecurity and Privacy

The architectural and technical network of a locally acting DESS requires the use of smart meters and other advanced components. Regular (offline) metering is not sufficient for tracking the multiple pathways of electricity in this environment. However, the use of advanced components, especially ones that are connected to the internet, bears the risk of exposure to cybercrime like denial-of-service attacks, viruses or data breaches[53].

Contributor's data needs to be protected from malicious purposes and kept confident to authorised entities. Furthermore, data integrity must be ensured by the operator of a DESS so data cannot be manipulated in real time or retroactively to avoid harm to the participants.

Therefore, it is evident that robust cybersecurity measures must be continuously upgraded and restrict unauthorised use of data to ensure that private households or companies are safe to contribute to a DESS[54].

6.4 R&I needs beyond technology

The installation of DESS environments is a complex task because the electricity grid is highly regulated and secured by policy makers as critical infrastructure. There are several topics apart from technological advancements that need further investigation and research for the safe deployment of DESS such as taxation, operational markets for DESS (business case) and licence for the operator.

6.4.1 Grid Fees and Taxation:

A storage system, including DESS, can lead to several actions that generate fees for the usage of the electricity grid. In

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[48] von Wirth, T., Gislason, L., & Seidl, R. (2018). Distributed energy systems on a neighbourhood scale: Reviewing drivers of and barriers to social acceptance. *Renewable and Sustainable Energy Reviews, 82*, 2618–2628. http://dx.doi.org/10.1016/j.rser.2017. 09.086.

[49] Norouzi et al. (2022)

[50] Wolsink, M. (2012). Social acceptance of distributed generation in smart grids: Renewable as common pool resources. *Renewable and Sustainable Energy Reviews, 16*, 822–835. http://dx.doi.org/10.1016/j.rser.2011.09.006.

[51] Norouzi et al. (2022)

[52] Gancheva, M., O'Brien, S., Crook, N., & Monteiro, C. (2018). Models of local energy ownership and the role of local energy communities in energy transition in Europe. 2018, http://dx.doi.org/10.2863/603673, https://cor.europa.eu/en/ engage/studies/Documents/local-energy-ownership.pdf.

[53] Budka, K. C., Deshpande, J. G., & Thottan, M. (2014). Smart grid applications 2014, p. 111–47. http://dx.doi.org/10.1007/978-1-4471-6302-2{_}5

[54] Norouzi et al. (2022)

some cases, every amount of energy fed into the grid as well as every amount of electricity drawn from the grid incurs grid fees. On top of that, traded and transferred energy trigger a taxation event e.g. value added tax (VAT) and more. The precise measurement and declaration of energy amounts is not an easy task and comes under the operator's responsibility. Additionally, several taxes and fees put a burden on business cases and disincentivise operators.

To tackle the problem of high fees and taxation the policy makers in Germany, for example, provided for some exceptions in the tax code and energy laws for storage operators. Every storage facility built before August 2029 will be exempt from grid fees[55].

However, these exceptions are for a limited time only and further research is necessary to determine what implications storage as DESS have on the public electricity grid and how grid fees should apply or not for a sustainable integration.

6.4.2 Operational Markets for DESS:

Usually, storage systems can operate in different markets according to their technological capabilities of storing or providing energy. A BESS, for example, can activate within milliseconds and therefore it can not only operate in wholesale markets but also in reserve markets like frequency containment reserve (FCR) and automatic frequency restoration reserve (aFRR) where response time goes down to some seconds. More inert systems may not be able to operate in these markets.

The European Commission acknowledges that the energy transition needs a change from regular consumers in the energy market to prosumers and new policies and structures as electricity markets are necessary to boost the interest of participants[56]. Prosumers generate electricity, e.g. with rooftop PV on residential buildings, and feed the generated electricity into the distribution grid. On the large scale the conclusion is that this further increases the demand for grids that are capable of managing this energy.

DESS are optimal to make the transition from consumers to flexsumers, as participants have the capabilities to store generated energy and even draw from the grid if necessary. This can help manage the load of the electricity grid and a market for flexibility can help regulate and financially incentivise storage operators to participate in transactions that help stabilise and secure the distribution electricity grid. This naturally needs to be complemented by the appropriate regulatory incentives that enable the network operator to choose between a market-based solution versus traditional network investment.

Besides a flexibility market, further R&I is needed to investigate peer-to-peer (P2P) market options as well. Several DESS participants may transact with each other or even several DESS clusters may have transactions. It needs to be investigated how these P2P markets may be beneficial for the electricity grid and participation can be incentivised financially and how to include them in the wholesale markets or not[57].

6.4.3 Licencing of Operators:

Conventional power systems and energy grids consisted of large units that generate electricity for transmission through the grid to consumers like residential housing and commercial or industrial sites[58]. These large generators are operated by licensed energy suppliers that need certification and are responsible for certain quality standards. With the number of prosumers and potentially flexsumers rising, and energy generation being more and more decentralised, grid operators need to manage bi-directional power flow, maintaining and ensuring high quality of service standards. Therefore, renewable generation and storage facilities already need certain certification for components, e.g. transformers, inverters, …, used to ensure connected facilities are included into the existing grid.

Besides the necessary certification for components, it needs to be investigated how operators of these facilities need to be licenced as energy supply companies. Official energy supply companies have high standards according to structure and operations, and further investigation is necessary to determine whether these high standards should be applied to all energy generating companies or not. On the one hand, this poses many challenges and long processes before a company

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[55] Gährs, S., & Knoefel, J. (2020). Stakeholder demands and regulatory framework for community energy storage with a focus on Germany. *Energy Policy, 144*, 111678. https://doi.org/10.1016/j.enpol.2020.111678.
[56] Nouri et al. (2022)
[57] Maldet, M., Revheim, F. H., Schwabeneder, D., et al. (2022). Trends in local electricity market design: Regulatory barriers and the role of grid tariffs. *Journal of Cleaner Production, 358*, 131805. https://doi.org/10.1016/j.jclepro.2022.131805. (https://www.sciencedirect.com/science/article/pii/S0959652622014159)
[58] Maldet et al. (2022)

can become an operator of such facilities and clearly disincentivises participation. On the other hand, it might be beneficial for the stability and quality of energy grids.

7 BUSINESS AND GOVERNANCE MODELS[59,60,61,62,63,64,65]

In the conventional energy market, existing business models were designed within a centralised energy system framework and are not suited for decentralised, local contexts. To establish energy districts and their storage counterparts, new concepts and business models integrating traditional and emerging players are essential. These new models must foster innovative and fair cooperation mechanisms, creating value in novel ways to attract investment. Their success will largely depend on their ability to generate and capture value while ensuring its fair distribution among all stakeholders.

A tailored combination of business models must be developed for each stakeholder, with a clear value proposition aligned with their specific needs and expectations. A fundamental step in this process is the identification and mapping of stakeholders, their individual interests, and their interactions, forming the complex ecosystem of the energy district. This mapping process is crucial in both energy districts and storage districts, as the design and objectives of power system operations vary depending on stakeholders' roles, interests, and operational levels.

Experience from energy community pilots shows that citizen engagement should be at the heart of effective participation in all energy and sustainability initiatives. While technology offers innovative solutions, it must serve citizens' interests and remain aligned with their goals. A successful approach requires integrating top-down (e.g., legislation, municipal budgeting) and bottom-up (e.g., citizen proposals, crowdfunding) strategies to ensure broad and meaningful involvement. Essential best practices include defining and fostering an inclusive community, maintaining a clear purpose to enhance credibility, and ensuring continuous engagement through transparent communication. Open processes, including open-source and open-data approaches, can enhance trust, but they must balance transparency with data protection and avoid overwhelming participants. Ultimately, co-creation and co-production among all stakeholders, including industry and private companies, are crucial for successful project implementation. Engaging vulnerable groups is particularly challenging and requires time, trust-building and careful messaging to overcome historical neglect and to foster long-term engagement.

7.1 Role of municipalities and local authorities

District energy business models often involve the public sector in various capacities, such as policymakers, planners, regulators, consumers, or even direct project owners[66]. Public participation, including the involvement of local enterprises and citizens as shareholders, can enhance acceptance and facilitate adoption.

Different use cases for heat districts are reported worldwide. Different roles taken by the public sector are reported, which categorise the business models into three main types: wholly public, hybrid public-private and wholly private models. The wholly public model is the most common worldwide, where the public sector fully owns and operates district energy systems. Case studies, including Vancouver and London, show how municipalities can use public funding to develop sustainable district heating.

The hybrid public-private model is an approach where both public and private stakeholders share investment and responsibility. Under the hybrid approach, the local authority has a wider range of options such as the public and private joint venture, the concession contract, and the community owned not-for-profit or cooperative. It allows for private sector

[59] European Commission; Tzoumpas, A., Pinnarelli, A., ... Krušvar, V. (2024). Consumer and citizen engagement working group – Annual activity report 2023 – November 2024. Publications Office of the European Union.
[60] Huntjens, P., & Kemp, R. (2022). The importance of a natural social contract and Co-Evolutionary Governance for Sustainability Transitions. *Sustainability, 14*(5) https://doi.org/10.3390/su14052976.
[61] Huntjens, P., Rinscheid, A., Kemp, R., et al. (2023). The Transformation Flower Approach for leveraging change towards multiple value creation and institutional change. https://www.preprints.org/manuscript/202307.1539.
Collaborative business models:
[62] Janssen, K. L., & Van Diepen, R. (2021). Shared values as connecting factor for upscaling circular initiatives: A circular festival crewmember T-shirts concept. *ISPIM Conference Proceedings.*
[63] Hina, M., Chauhan, C., Kaur, P., Dhir, A., & Kraus, S. (2021). Barriers and drivers of circular economy business models. *Journal of Cleaner Production.* https://doi.org/10.1016/j.jclepro.2021.130049
[64] Corvellec, H., Stowell, A. F., & Johansson, N. (2022). Critiques of the circular economy. *Journal of Industrial Ecology, 26*(2), 421–432. https://doi.org/10.1111/jiec.13187
[65] Rizos, V., Bryhn, J., Alessi, M., Righetti, E., Fujiwara, N., & Stroia, C. (2021). Circular economy business models.
[66] UNEP. (2016). *Business models for district energy: A continuum from public to private.* In *District Energy* in *Cities (pp. 84–101).* United Nations. https://www.un-ilibrary.org/content/books/9789210601849c007

expertise and capital to be brought in, while maintaining some level of public sector oversight. Within the concession contract model the public authority typically develops a feasibility study of the district energy project and then tenders it to the private sector (usually an energy service company, or ESCO) as a concession that runs for a specified term. **Examples (see table below)** from cities such as Dubai and Cyberjaya show how hybrid models attract investment while ensuring long-term sustainability or the case of London's Olympic Park where a 40-year concession contract was awarded to the energy service company Cofely, with the resulting concession agreement to finance, design, build and operate the heating and cooling network and associated energy centres.

Finally, the wholly private model is typically pursued in markets where a high return on investment is expected, minimising the need for public sector intervention. Private companies fully finance and operate district energy systems, often with indirect support from the public sector (e.g. through incentives or regulatory support). Case studies, such as the Port Louis Seawater Air Conditioning project, highlight successful implementation of privately owned district energy systems.

Table 3 - Examples of hybrid models

City	Business Model	Main Technology	Stakeholders Involved
Vancouver (Canada)	Wholly Public	Waste heat recovery from sewage	City of Vancouver, SEFC NEU (municipal energy utility)
London (UK) - Bunhill Heat & Power	Wholly Public	Combined heat and power (CHP) with waste heat recovery from subway	Islington Council, Local Housing Associations
Bergen (Norway) - BKK Var me	Wholly Public	Waste incineration-based district heating	BKK Var me (public utility), BIR Afvallsenergi (waste management company), Local Government
Brest (France)	Wholly Public	Waste-to-energy, seawater heat pumps, biomass boilers	Brest Métropole, SAS Dalkia Nord Finistère (operator), Sotraval (subsidiary of Brest Métropole)
Dubai (UAE) - Empower	Hybrid Public-Private	District cooling using recycled water and thermal storage	DEWA (public utility), TECOM Investments (private real estate developer), Empower (SPV)
Toronto (Canada) - Enwave Energy Corporation	Hybrid Public-Private	Deep-water cooling system integrated with city drinking water system	Enwave (private operator), Toronto City Council (initial owner), BPC Penco (private investor)
Anshan (China)	Hybrid Public-Private (Split-asset model)	Surplus heat from steel production for district heating	Angang Steel (private heat supplier), Qianfeng (municipal district heating company), FUAN (private investor)
London (UK) - Olympic Park	Private Concession Contract	Combined Cooling, Heat, and Power (CCHP)	Olympic Development Authority (ODA), Stratford City Development, Cofely (private ESCO)
Cyberjaya (Malaysia) - Pendinginan Megajana	Hybrid Public-Private (Concession Contract)	District cooling with ice storage	Pendinginan Megajana (private operator), Cyberview Sdn Bhd (public authority), Malaysian Ministry of Finance
Copenhagen (Denmark) - Høje Taarstrup	Cooperative Model	District heating with multiple private and municipal heat	Høje Taarstrup Fjernvarme (cooperative), Municipal transmission company, Private

Fjernvarme		suppliers	power stations
Aberdeen (UK)	Not-for-Profit	CHP-based district heating	Aberdeen City Council, Local community cooperative
Port Louis (Mauritius) - SWAC	Private	Seawater Air Conditioning (SWAC) using deep-sea cold water	Sotravic Ltd. (private operator), Government of Mauritius, African Development Bank

To accommodate the diverse needs of different sub-projects and local contexts[67], a customised financing mix and tailored investment models should be derived from an integrated approach. In each participating city, local and no-local stakeholders, along with new market entrants, are expected to share investments and financial risks, contributing collectively to the energy transition towards a low-carbon future while addressing sustainability and socioeconomic adaptation.

In line with this vision, the ETIP-SNET WG1 paper on energy communities[68] highlights that energy communities should operate in a local market, where electricity grid tariffs serve as a key driver for development. To ensure that the creation of such local markets does not disrupt existing assets while establishing a fair grid tariff structure, the authors propose a LINK-based decentralised architecture[69], inspired by the fractal structure of smart grids. This approach calls for a market redesign that focuses on the local market and harmonises with the power grid structure, ensuring both technical and economic efficiency.

The results of the work of Lombardi (2017) suggest that a sharing battery operation can lead to additional profit if the battery management prioritizes certain users[70]. The resulting business model, which is based on the sharing economy approach, helps BESS operators as well as BESS potential investors on the possibility to make the BESS an economically attractive solution.

According to the results of the work of Zhang (2023) the sharing economy provides new opportunities for the commercial applications of energy storage and improvement of resource use efficiency[71]. The authors use the concept of distributed energy storage, and cloud aggregated energy storage system to operate them. Through the complementation of users' demand profiles and unified coordination of multiple distributed sourced energy storage systems, aggregators and storage operators can aggregate the distributed energy storage and create a chain on both sides of supply and demand, respectively, thus improving the use efficiency of energy storage systems.

7.2 Industrial symbiosis

Several real-world applications already demonstrate how energy storage can be effectively integrated within the broader framework of industrial symbiosis and district energy systems see Branca et alii (2021)[72]. For instance, in the **iron and steel sector**, thermal energy storage systems have been developed using **blast furnace (BF) and steel slags**. These byproducts, originally treated as waste, are repurposed due to their high thermal inertia and specific heat capacity, enabling their use as **heat storage materials**. Such integration allows industries to decouple heat supply and demand, while promoting cross-sectoral collaboration—for example, supplying preheated air or steam to nearby ceramic or cement industries. A notable

[67] Cimini, V., Giglio, F., & Carbonari, G. (2019). Report on bankability. *CityxChange*. https://cityxchange.eu/knowledge-base/report-on-bankability-of-the-demonstrated-innovations/
[68] Ilo, A., Rossi, J., Gallego Amores, S., et al. (2024). Energy community embedment increasing grid flexibility and flourishing electricity markets. *European Commission*. https://doi.org/10.2833/299800
[69] Ilo, A., Bruckner, H., Olofsgard, M., et al. (2023). Viable fully integrated energy community based on the holistic LINK approach. *Energies, 16*(6), 2935. https://www.mdpi.com/1996-1073/16/6/2935
[70] Lombardi, P., & Schwabe, F. (2017). Sharing economy as a new business model for energy storage. *Applied Energy, 188*, 485–496. https://doi.org/10.1016/j.apenergy.2016.12.016
[71] Zhang, S., Li, Y., Du, E., et al. (2023). A review and outlook on cloud energy storage: An aggregated and shared utilizing method of energy storage system. *Renewable and Sustainable Energy Reviews*, *185*, 113606. https://doi.org/10.1016/j.rser.2023.113606
[72] Branca, T. A., Fornai, B., Colla, V., et al. (2021). Industrial symbiosis and energy efficiency in European process industry: A review. *Sustainability, 13*, 9159. https://doi.org/10.3390/su13169159

large-scale example of thermal energy exchange can be found in the **Kalundborg Symbiosis** in Denmark. In this industrial ecosystem, **waste heat from a power plant** is reused by various partners, including an oil refinery, a pharmaceutical plant, and a municipal district heating network. Although not originally conceived as an energy storage system, the **buffering effect** created by thermal infrastructure and flexible demand-response processes mirrors many principles of heat storage. In **Puerto Rico**, the **AES coal-fired power plant in Guayama** exemplifies the integration of surplus thermal energy through symbiotic exchange. The plant provides **recovered steam and heat** to an adjacent oil refinery and pharmaceutical companies, reducing fuel consumption and supporting stable thermal supply. While the system does not include explicit long-term storage devices, it constitutes a **temporal storage solution** by redirecting otherwise-wasted energy flows. Finally, in **South Korea's Ulsan Industrial Complex**, several companies share **waste heat and water**, forming a robust IS network with potential for **embedded thermal energy storage**. The reuse of process heat across sectors creates an implicit energy storage effect, improving energy efficiency and supporting peak load management. Another interesting example for P2X was the **REFHYNE** project in Germany, funded by the European Commission, where Shell's refinery used renewable electricity to produce green hydrogen via electrolysis which was used within the refinery but also for additional industrial processes and blended into the gas grid.[73]

7.3 Shared value and circular business models

The transition to decentralised and local power systems requires a shift in traditional business models, with shared ownership and cooperative structures emerging as fundamental pillars. In energy districts, value creation is inherently collaborative, necessitating dynamic and diverse partnerships that effectively link supply and demand[74]. Unlike conventional models that prioritise financial returns, energy district frameworks must also incorporate non-monetary values such as participation, shared purpose, and energy autonomy[75]. Some of these value outcomes can be quantitatively assessed, while others remain subjective, shaped by stakeholders' perceptions. Consequently, the business models adopted in these districts must deliver comprehensive economic, technical, societal, and environmental benefits, catering to the varied priorities of all involved actors.

To ensure the required flow of information, materials, and energy, an ecosystem based on shared values is indispensable. Circular economy principles can support this ecosystem by fostering sustainable interactions among stakeholders. Janssen and Van Diepen (2021) highlight that circular initiatives yield significant impact when shared values underpin collaborative business models, serving as a connecting factor for scaling such initiatives[76]. Similarly, Kramer (2016) argues that shared value results from policies and practices that simultaneously enhance competitive advantage and strengthen the communities in which businesses operate[77]. Companies can generate shared value by reimagining products and markets, redefining productivity along the value chain, and reinforcing local clusters. These strategies align with circular economy objectives, which emphasise stakeholder collaboration in the creation, capture, delivery, and redistribution of value. Ultimately, shared value acts as the foundation for collaborative business models, benefiting companies through increased competitiveness while also fostering community well-being.

A practical application of the circular economy in energy systems can be found in Gai's (2021) work, which offers a methodology for integrating multi-resource systems[78]. This approach accounts for diverse material and energy flows across global patterns, enabling decision-makers to assess the economic and performance of proposed circular economy solutions. Such methodologies provide valuable insights into enhancing the sustainability contributions of both industrial and urban systems.

When applied to energy districts, circular economy principles facilitate the development of a symbiotic ecosystem that maximises energy cascading and optimises conversion technologies across industrial, commercial, and residential sectors.

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[73] REFHYNE. (n.d.). *About.* https://www.refhyne.eu/

[74] Barnes, J., Hansen, P., Kamin, T., et al. (2024). Creating valuable outcomes: An exploration of value creation pathways in the business models of energy communities. *Energy Research & Social Science, 108*, 103398. https://doi.org/10.1016/j.erss.2023.103398

[75] Sirviö, K., Motta, S., Rauma, K., & Evens, C. (2024). Multi-level functional analysis of developing prosumers and energy communities with value creation framework. *Applied Energy, 368*, 123496. https://doi.org/10.1016/j.apenergy.2024.123496

[76] Janssen, K. L., & Van Diepen, R. (2021). Shared values as connecting factor for upscaling circular initiatives: A circular festival crewmember T-shirts concept. *ISPIM Conference Proceedings*.

[77] Kramer, M. R., & Pfitzer, M. W. (2016). The ecosystem of shared value. *Harvard Business Review.* 94(10), 80–89. https://phasocal.org/wp-content/uploads/2018/04/HBR-article-collective-impact-Oct-16.pdf

[78] Gai, L., Varbanov, P. S., Fan, Y. V., et al. (2021). Trade-offs between the recovery, exergy demand and economy in the recycling of multiple resources. *Resources, Conservation and Recycling, 167*, 105428. https://doi.org/10.1016/j.resconrec.2021.105428

A reimagined approach to products, services, and markets fosters innovation in the design, production, and distribution of energy-related goods and services, addressing broader societal concerns. By redefining productivity within the energy value chain at the district level, these principles contribute to reducing waste, minimising energy consumption, and improving resource efficiency. Furthermore, strengthening local clusters is crucial for fostering collaboration and cooperation among interconnected businesses, suppliers, customers, and other relevant stakeholders, including local authorities, renewable energy source (RES) operators, prosumers, TSOs, DSOs, and aggregators.

In conclusion, the integration of circular economy principles in DESS is imperative for achieving a more sustainable, efficient, and resilient energy landscape. By embedding shared values into business models, stakeholders can drive collaboration, optimise resource use, and create lasting economic and social benefits. The circular economy provides a strategic pathway to enhance the adaptability and self-sufficiency of energy districts. However, the analysis of these collaborative business models is a R&I area that needs to be addressed.

8 PROMOTING DISTRICT STORAGE DEPLOYMENT

This chapter outlines key legislative, financial, social, environmental, and technical strategies to accelerate the deployment of district-level energy storage. This deployment aims to foster a just, inclusive, and sustainable energy transition through stakeholder engagement, market integration, and circular economy practises. DESS is defined as a shared energy storage solution designed for multiple users or applications within specific geographic areas, enhancing efficiency, flexibility, and value creation. Addressing the gaps outlined in the chapter 6 requires enabling cooperative models to promote collaboration among diverse stakeholders, fostering financial incentives and market design to ensure that shared storage systems like DESS are viable and profitable, and creating clear ownership and access frameworks by addressing operational roles and access rights.

DESS exemplifies the shift towards cooperative and efficient energy solutions, aligning with both the ENTSO-E RDI Implementation Report[79] and the challenges highlighted in the Sina report[80]. By embedding shared value as a central tenet, the following recommendations underscore the importance of stakeholder collaboration and innovative market mechanisms to transform Europe's energy landscape. The success of these initiatives will depend on regulatory alignment, effective stakeholder engagement, and the provision of incentives.

8.1 Legislative and regulatory recommendations

District storage systems require a clear regulatory framework that defines their role within the energy ecosystem. National and regional policies should recognise district storage as a distinct infrastructure class, enabling fair market access and establishing rights for third-party ownership and community co-investment. Regulations must support dual-use functionality both as generators and consumers of electricity by updating grid codes. Additionally, permitting processes should be simplified to reduce project lead times and administrative burden, particularly for small-scale and community-driven installations.

In particular, the Renewable Energy Directives REDII and REDIII provide a robust legislative foundation for district storage deployment. They recognise the role of energy storage in supporting renewable integration, mandate simplified permitting for small-scale and community-led projects (e.g. FlexCHESS, MASTERPIECE) and ensure fair grid access. By legally empowering renewable energy communities (RECs) to generate, store, and share energy, these directives facilitate co-ownership and citizen participation. REDIII further strengthens this framework by explicitly identifying storage as a key enabler of system flexibility and energy security, encouraging EU to include storage strategies in their national energy plans.

In this context, the regulatory sandboxes[81] are tools for testing new solutions and reducing the regulatory barriers.

In the energy industry, regulatory sandboxes help new businesses overcome entry barriers, fostering innovation and driving economic growth. At the same time, they ensure consumer protection by detecting and addressing potential risks.

- Grid Flexibility: Aggregation services, control power & business model for storage
- Flexibility market: Implicit DR, explicit DR, storage in all forms (also EVs), flexibility, optimal balance, avoid valuable RES curtailments
- Demand response: peak electricity demand, reduced costs, increased grid reliability.
- Energy communities: Support for energy storage as part of REC and CEC (including e-Cars as distributed storage capacity).
- District energy storage systems: Extra remuneration of capital cost, provides for a period of 12 years, 75 MW of

[79] ENTSO-E. (2021). *RDI implementation report 2021–2025.* https://eepublicdownloads.azureedge.net/clean-documents/RDC%20documents/I_entso-e_rdi_implementation_report_update_2112_05.pdf

[80] Sina, S., Dengler, F., Faber, R., Kocher, D., Pumberger, M., de la Vega, R., & Niewitała-Rej, M. (2024). *Analysis of the implementation of EU provisions for the clean energy transition in selected Member States*. Ecologic Institute, Berlin.

[81] Publications Office of the European Union. (2023). *Regulatory sandboxes: Policy report drafted by WG5's regulatory sandboxes task force.* https://op.europa.eu/en/publication-detail/-/publication/d74556a2-4ba0-11ee-9220-01aa75ed71a1/language-en.

storage facilities have been installed, including different kinds of batteries.

In competitive markets, regulatory constraints can arise when innovations rely on rules or infrastructure from the regulated sector, such as market design regulations or grid codes. Business models for district energy storage, which are significantly influenced by how system usage fees are structured.

Energy storage plays a key role in integrating renewable energy into the grid, enhancing grid stability, and lowering costs. However, regulations for energy storage are still developing, and it's important to test new business models and pricing strategies to support the growth of these technologies.

It is also mentioned in (https://op.europa.eu/en/publication-detail/-/publication/d74556a2-4ba0-11ee-9220-01aa75ed71a1/language-en) that new regulatory frameworks need to be tested to support the creation, operation, and grid integration of energy communities[82]. This includes enabling self-consumption and peer-to-peer energy trading within renewable energy communities (REC) and citizen energy communities (CEC). Additionally, policies should encourage the use of energy storage, including electric vehicles as decentralised storage solutions.

Further regulatory experimentation can drive innovation and accelerate the energy transition, particularly in areas such as expanding the role of storage technologies beyond batteries in providing ancillary services to the grid.

8.2 Financial mechanisms to support deployment

The financial viability of district storage can be greatly improved through targeted support mechanisms. Public-private partnerships (PPPs) can mobilise investment in underserved areas, while direct grants and capital subsidies lower the entry barriers for municipalities and communities. Stable revenue streams should be guaranteed through instruments like contracts-for-difference (CfD), availability-based payments, or dynamic flexibility remuneration schemes. Time-of-use tariffs and tailored incentives for self-consumption can further promote efficient energy behaviour. Tax incentives such as VAT exemptions or accelerated depreciation also provide strong fiscal levers. Moreover, to further encourage adoption, reward-based mechanisms (e.g. defined in FlexCHESS EU project by RDIUP) could be introduced alongside traditional financial tools. These could include incentives for households or energy communities that contribute flexibility, participate in peer-to-peer energy sharing, or achieve energy savings through storage use. Such rewards could take the form of monetary bonuses, energy credits, or reduced tariffs, creating a direct and visible benefit for active engagement in local energy systems. Operational modes like self-consumption and providing flexibilty to the system can further be promoted by integrating DESS (or Storages in general) into the CO2-certificate trade. With increasing prices for CO2-certificates this can further drive investment decisions towards the deployment of DESS. In contrast to Stand-Alone-BESS district storages need a way to monetize from energy sharing to encourage private participation. Different business cases will attract different actors and multiple revenue streams are crucial for an extensive rollout of distric storages as private investors/participants have a different (mostly lower) return expectation as institutional investors and therefore can opt for a less financially rewarding but more stable operation of the system.

Among others, the following European funding programmes play a crucial role in de-risking DESS innovation and deployment:

- **Horizon Europe and Digital Europe** can fund R&I in advanced storage materials, hybrid integration, and digitalisation
- **LIFE Clean Energy Transition** continues to support the delivery of EU policies in the field of sustainable energy, in particular, the European Green Deal, the Energy Union (2030 energy and climate targets) and the European Union's 2050 long-term decarbonisation strategy[83].
- **Innovation Fund** focuses on highly innovative clean technologies and big flagship projects with European added value that can bring significant emission and greenhouse gas reductions[84].
- **European Regional Development Fund** is designed to strengthen economic, social and territorial cohesion in the

[82] European Commission (2023)
[83] CINEA. (n.d.). *LIFE Clean Energy Transition.* https://cinea.ec.europa.eu/programmes/life/clean-energy-transition_en cinea.ec.europa.eu
[84] CINEA. (n.d.). *Innovation Fund.* https://cinea.ec.europa.eu/programmes/innovation-fund_en cinea.ec.europa.eu

European Union. It aims to do this by correcting imbalances between regions enabling investments in a smarter, greener, more connected and more social Europe that is closer to its citizens[85].

- **Recovery and Resilience Facility for clean energy** is a temporary instrument, launched in 2021, to help the EU emerge stronger and more resilient from the coronavirus pandemic and increase the resilience of the national economies[86].

- **European Investment Bank** helps finance energy projects by providing companies with loans and other financial instruments. Together with the European Commission, the EIB launched the European Investment Advisory Hub as part of the Investment Plan for Europe. The hub acts as a single access point that provides advice and expertise on administration and project development across the EU[87].

8.3 Engaging energy communities and stakeholder networks

Community engagement is pivotal to the successful integration of district storage. Empowering local stakeholders through co-ownership and participatory governance models fosters long-term social acceptance and equitable benefit sharing. Energy communities and civil society groups should be involved from the planning phase onward, using digital tools and platforms to facilitate transparency, coordination, and shared decision-making (e.g. transparent and fair voting mechanism). Training programmes and capacity-building initiatives can ensure communities are well equipped to manage and operate storage infrastructure effectively. To further boost private or communal engagement in district storages it is strictly necessary, that the legislative framework as well as a strong financial incentive are prepared by policy makers. Despite the ongoing trend of falling storage prices, it is still highly capital intensive and investments need to be protected in order to encourage engagement. As with stand-alone BESS the operation should be outsourced to a specialized marketer.

8.4 Integrating coordinated flexibility into future energy systems

The focus is on harnessing flexibility from DERs and storage systems, proposing a coordinated methodology to integrate these resources into larger energy networks. DESS serves as a cornerstone for aggregating flexibility resources, offering solutions for peak shaving, grid balancing, grid congestion management, voltage regulation and renewable energy variability management.

To enhance the deployment of energy storage systems, policy actions should include targeted support for long-duration energy storage (LDES) technologies. These measures could involve specific funding programmes or incentive schemes, justified by the growing need for seasonal and weekly flexibility. Additionally, harmonising market access across Member States and ensuring non-discriminatory practices in network planning are critical steps to level the playing field for energy storage operators.

This action aligns with the call for financial incentives and market designs that reward shared energy services. The development of standardised approaches to measure and value flexibility enables stakeholders to collaborate effectively, ensuring that benefits are distributed equitably. The Sina report highlights the need for addressing market barriers and promoting shared value, a principle deeply embedded in this action framework.

Addressing issues like double taxation and discriminatory grid tariffs is also critical for improving the economic viability of energy storage projects. Member States should work towards cost-reflective and non-discriminatory tariff structures, which are essential to unlocking the full potential of DESS and other storage solutions.

8.5 Adoption of circular economy and resource efficiency principles

District storage systems should embrace circular economy and resource efficiency principles to maximise sustainability. This means promoting modular and upgradeable system design, reuse of existing infrastructure, and integration of second-

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[85] European Commission. (n.d.). *European Regional Development Fund.* https://ec.europa.eu/regional_policy/funding/erdf_en
[86] European Commission. (n.d.). *Recovery and Resilience Facility — Clean energy.* https://energy.ec.europa.eu/topics/funding-and-financing/recovery-and-resilience-facility-clean-energy_en
[87] European Investment Bank. (n.d.). *Sustainable energy and natural resources.* https://www.eib.org/en/projects/topics/energy-natural-resources/energy/index

life batteries where feasible. Beyond the storage technology itself, local supply chains and maintenance models should prioritise low-carbon materials, repairability, scalable and long-term asset value retention. Digital tools such as battery passports can enhance transparency and traceability of materials, supporting responsible sourcing and sustainable end-of-life management. Together, these measures reduce environmental impact, strengthen the overall sustainability of district-level energy infrastructure and help towards the adoption of the solution.

8.6 Market structures and cross-sector integration with local energy markets

For district storage to reach its full potential, it must be well integrated into local and national energy markets. This requires the development of local energy markets and peer-to-peer (P2P) trading schemes that allow communities to monetise their flexibility. Coordination between GSOs should facilitate district storage participation in balancing and local grid services provision. Real-time pricing and demand-response incentives should be deployed, supported by standardised contracts to ensure clarity and accessibility for all stakeholders, including SMEs and prosumers. These new energy markets can headstart the implementation of DESS once they allow the monetization of behind-the-meter applications. In this case DESS participants would benefit from not using the public energy grid but generating, using and distributing their own energy.

The market mechanisms should be developed to facilitate the integration of energy systems by allowing DESS to act as a key enabler for energy trading, demand response, and renewable energy storage. Market platforms should be created to leverage DESS, aggregate distributed energy resources (DERs) and enhance market participation.

The implementation of shared storage solutions like DESS necessitates regulatory frameworks addressing ownership, operational responsibility, and equitable access. These considerations align with the Sina report's emphasis on enabling frameworks for energy storage that clarify access rights and responsibilities. The success of such measures relies heavily on fostering collaboration among TSOs, DSOs, energy aggregators, and local communities to ensure shared value creation.

8.7 Strategies for data management and energy sharing

Effective and secure data management underpins the future of district storage. Open, interoperable platforms should be promoted to ensure seamless data exchange and integration across systems while complying with the Common European Energy Data Space. Communities must retain sovereignty over their energy data, with mechanisms for monetisation and value-sharing. Blockchain and distributed ledger technologies (DLT) offer transparent and secure frameworks for energy sharing and transaction validation. Ensuring compliance with privacy regulations such as GDPR is essential to maintain trust and safeguard citizen rights in digital energy ecosystems.

The aim should focus on creating innovative models and tools for multi-sector system operation and planning to support multi-sector energy system operations, focusing on cross-sector integration and energy storage. Through innovative modelling tools, this recommendation addresses the need for coordinated planning of renewable energy sources, flexible storage options, and demand response systems. DESS is integral to this action, as its shared infrastructure model optimises the energy balance across sectors, reducing redundancy in individual systems. By pooling resources, it improves the financial viability of investments in renewable integration. Furthermore, such planning tools can assess DESS's capacity to deliver stability, flexibility, and resilience to urban districts and industrial parks.

9 STRATEGIC PATHWAYS FOR EU INDUSTRY COMPETITIVENESS

District energy storage systems represent a strategic opportunity for the European Union to strengthen its industrial competitiveness while accelerating the clean energy transition. DESS can support further renewable energy integration, local flexibility, and sector coupling at district level. It can attract new strategic stakeholders, build bridges between the public and private infrastructure and unlock new value chains and market opportunities and these multiple storage technologies such as thermal, electrical, mechanical, and chemical solutions. The European Union is trying to position itself as a global leader in the energy transition, and so these integrated solutions will enhance its energy security, support decarbonisation goals, and create sustainable economic growth.

9.1 Opportunities for industry leadership in DESS deployment

The deployment of DESS offers multiple strategic opportunities for European industry leadership:

- **Manufacturing and Technology Leadership**: Reinforcing and scaling up the development and production of innovative systems and solutions, such as advanced flow batteries, thermal storage technologies, and hydrogen storage, can reduce reliance on non-European countries, reduce imports and make Europe less dependent on foreign countries for critical energy infrastructure. It can reinforce or create knowledge hubs and prove strong industrial competitiveness.

- **Hybrid and Multi-Tech Systems**: Developing integrated solutions that combine thermal, electrical, and chemical storage (for example, pairing short-duration Li-ion batteries with long-duration redox flow batteries, or coupling heat pumps with batteries and hydrogen electrolysers) can position the EU industry at the forefront of sector coupling innovation. These hybrid systems enhance knowledge creation, support industrial diversification, offer new more efficient systems that are adjusted for local constraints and so support new industrial activities and employment.

- **Digital Leadership**: Expanding capabilities in Energy Management Systems (EMS), AI-driven optimisation, and blockchain-based energy trading platforms will generate competitive advantages in the emerging smart district storage market. These solutions are at the core of the current digitalisation of the energy ecosystem. The European Commission has prioritised AI leadership as a strategic goal, and deploying AI within DESS will drive innovation while improving energy system resilience, reliability, and flexibility.

- **Export Opportunities**: By developing expertise in integrated DESS solutions, EU companies can offer products and services that can be exported to non-European countries, helping them with their energy transition and reinforcing their energy resilience. This can enhance Europe's position as a global leader in sustainable energy technologies.

- **Strengthening Existing European Companies or Enabling New Market Players**: The deployment of DESS can create opportunities for large European energy, technology, and construction companies to expand their services. It can also enable the entry of innovative startups and SMEs specialising in storage technologies, digital platforms, and integrated solutions. This diversification can help with a more competitive and resilient European energy industry ecosystem.

9.2 Building a collaborative ecosystem across sectors

To fully realise the benefits of DESS, different sectors and players across the value chain need to work closely together. This creates opportunities to strengthen bridges and facilitate the development of a symbiotic ecosystem fostering collaboration and cooperation among relevant stakeholders. Some of the strategic priorities are:

- **Facilitating Public-Private Partnerships (PPPs)** to bring in investment, share risks, enable larger projects and roll out pilot projects that can be scaled up quickly.

- **Bringing together technology providers, software companies, energy companies,** municipal utilities **and industries** to create complete integrated solutions that include both the physical storage systems and the digital tools needed to manage and control them efficiently.

- **Connecting industry and communities**, reinforcing symbiosis especially where industries can provide surplus heat or energy to nearby homes, businesses, or community facilities. This helps reduce waste and supports local energy needs in a more sustainable way and creating mutually beneficial opportunities.

- **Engaging municipalities with real estate developers, and local communities** to include DESS in city planning, sustainable energy districts, and new housing or renovation projects so that innovative solutions can be implemented that fit local needs and benefit people directly.

- **Improving interoperability between technologies and players**, fostering common standards and interoperable platforms making sure different types of storage systems, digital tools, and energy networks can work well together. This reduces costs, speeds up deployment, and makes it easier for new companies to enter the market.

- **Connect research, companies, and communities**, by supporting innovation hubs and living labs where new technologies can be tested in real conditions and improved quickly, with input from local people and businesses.

- **Creating Shared Value Clusters:** Building strong local and regional clusters around DESS involving technology suppliers, prosumers, DSOs, TSOs, aggregators, and local authorities, establishes the framework for cooperative business models based on shared purpose and community resilience and embrace circular economy principles

9.3 Creating value through innovation and stakeholder engagement[88,89,90,91,92]

To fully benefit from DESS for European industry and society and create long lasting value, it is important to focus on:

- **Creating New Solutions**: From core chemistries and mechanical designs to digital control systems, operational excellence practises, and integration with other local energy solutions. These advances will make DESS more efficient, cost-effective, and adaptable to different district needs.

- **Creating New Business Models**: Developing new ways for people, companies, and communities to work together, such as shared ownership structures, cooperatives, capacity or flexibility-as-a-service offerings (where storage provides services to the grid in exchange for economic compensation established on the basis of a competitive market), and peer-to-peer energy trading platforms. These business models will open up new income streams, support market growth, increase public acceptance, and enable project or bank financing for these innovative structures.

- **Creating Jobs and a Skilled Workforce**: Developing and operating DESS at scale can create a wide variety of jobs and enhance local knowledge ensuring the people have the right skills needed for the energy transition. This will further strengthen local economies and the European Union.

- **Embedding Circular Economy Principles**: It is important to approach the design and operation of DESS with a circular economy mindset to make sure all solutions are sustainable on the long terms. From using second-life batteries or introducing battery passports to track materials and usage, to improving recycling systems or core components and reduce waste of energy. These actions will make DESS more sustainable, reduce waste, and use resources more efficiently.

- **Valuing Non-Monetary Outcomes and Participation**: Making sure local communities and stakeholders are included in planning, design and ownership while also benefiting from these DESS projects is vital. This builds trust, fairness, and long-term community support for energy transition initiatives. Some impacts are quantifiable (e.g., avoided emissions, job creation, revenue streams), while others are subjective and perception-based, yet equally crucial for community buy-in and long-term success.

[88] CINEA. (n.d.). *LIFE Clean Energy Transition.* https://cinea.ec.europa.eu/programmes/life/clean-energy-transition_en cinea.ec.europa.eu

[89] CINEA. (n.d.). *Innovation Fund.* https://cinea.ec.europa.eu/programmes/innovation-fund_en cinea.ec.europa.eu

[90] European Commission. (n.d.). *European Regional Development Fund.* https://ec.europa.eu/regional_policy/funding/erdf_en

[91] European Commission. (n.d.). *Recovery and Resilience Facility — Clean energy.* https://energy.ec.europa.eu/topics/funding-and-financing/recovery-and-resilience-facility-clean-energy_en

[92] European Investment Bank. (n.d.). *Sustainable energy and natural resources.* https://www.eib.org/en/projects/topics/energy-natural-resources/energy/index

- **Modelling and Scaling Collaborative Business Models:** As these innovative business approaches evolve, further research and innovation (R&I) is essential to develop modelling tools that capture the complexity of multi-actor circular business ecosystems, support policy alignment, and guide replication across European regions.

10 FUTURE DIRECTIONS AND IMPLEMENTATION ROADMAP

10.1 Actions for scaling up use cases at industrial levels

District storage can take different forms, ranging from residential systems shared by several households to industrial-scale installations serving local businesses or larger corporate users. A roadmap for scaling use cases must consider and understand the barriers that exist for the deployment of these systems. Tackling legal, financial, operational or regulatory barriers is the foundation on which additional use cases can be built upon and replicated across regions.

As initial costs for deployment and infrastructure development are a major barrier to large-scale adoption of DESS, it is important to reduce the threshold for investors and developers. Subsidies, grants or tax incentives in the form of special depreciation rates are tools often used for lowering the initial investment or for directing investors' cashflow.

From a technical perspective, it is necessary that the existing power grids can handle DESS in large quantities. The integration of renewable, fluctuating and decentralised energy sources comes with many challenges for grid operators. Sophisticated and interconnected grid balancing mechanisms to ensure reliability and stability for the public grid need to be installed to handle additional systems like district storage.

As discussed previously, regulatory and legislative uncertainty regarding the installation and operation of DESS is a major obstacle for the extensive adoption of district storage solutions. Governments must pave the road for investors and participants alike. Implementing regulations that promote environmental and operational goals in the mind of the lawmakers is helpful to create incentives for local businesses to join DESS and implement energy efficient solutions. Additionally, regulatory bodies must adopt flexible frameworks that allow the fast scaling of new technologies and innovative use cases.

Scaling up the deployment of district storage will require coordinated action across demonstration, funding, digitalisation, and market integration. Demonstration projects should be expanded and replicated across regions and sectors to prove technical reliability and commercial value. Cross-industry collaboration will be key to accelerate learning and standardisation, while municipalities and professional networks can help increase awareness of DESS viability.

To strengthen the ecosystem, targeted lobbying and funding efforts should align regulation, incentives, and stakeholder engagement. Large industrial players, municipalities, and SMEs could be brought together to co-develop viable business models. Access to diverse funding sources will be essential to scale projects, alongside support for local manufacturing capacities that boost regional value creation.

Digitalisation and workforce development remain critical enablers. New digital tools that bridge technologies and industries can optimise storage operation and market participation, while training programmes should ensure a skilled workforce capable of deploying and maintaining district storage systems. Finally, sustainable business models and fair market access must be established to enable DESS participation in flexibility and ancillary service markets.

10.2 Framework for monitoring and measuring impact

As DESS are implemented, there will be a growing need to develop and apply tools and indicators capable of assessing their performance. These assessment tools should not be limited to technological indicators alone. Instead, they should ideally cover multiple thematic areas to capture how DESS solutions may influence and transform urban, rural, and industrial territories, along with their associated sub-systems. It is important to recognise that employing an extensive list of criteria is not always desirable or feasible. Excessive comprehensiveness may lead to the creation of long lists of indicators that are difficult, or even impossible, to measure effectively[93].

The framework for monitoring and evaluating the impact of DESS implementation should integrate several key paradigms,

[93] Corvellec, H., Stowell, A. F., & Johansson, N. (2022). Critiques of the circular economy. *Journal of Industrial Ecology, 26*(2), 421–432. https://doi.org/10.1111/jiec.13187

such as the circular economy, industrial symbiosis, process and system integration[94], and smart cities[95]. Selecting an appropriate set of indicators requires navigating the complex interplay of social, environmental, and economic factors within local contexts, particularly in light of ongoing challenges such as urbanisation, reindustrialisation, resource scarcity, and climate change. While existing methodologies tend to prioritise environmental dimensions, there is a clear need for more balanced approaches that equally address social and economic aspects.

The integration of community perspectives and expert judgments is crucial, although it may make the whole adoption process longer. The stakeholder engagement is a central element in the development and implementation of assessment tools. Participatory approaches enhance transparency and ensure that tools and indicators are meaningful to all involved stakeholders. Furthermore, such approaches promote collaboration among the various actors engaged in the development and operationalisation of DESS solutions, generating opportunities for learning, creativity, synergy, and innovation. In the context of different geographical areas, urban, rural, and industrial, stakeholder participation is particularly relevant. Service provision in these contexts increasingly follows a collaborative, bottom-up model rather than a traditional top-down mechanism dominated by central or local authorities and DSOs. As services are co-created and co-delivered by multiple stakeholders, involving them in the assessment process becomes a vital step towards mainstreaming participatory practices in DESS planning. Participation may take diverse forms, including interviews, questionnaire surveys, focus groups, community workshops, and design exercises. The emphasis should be on combining bottom-up community input with top-down expert knowledge to achieve comprehensive and credible sustainability assessments.

Given the multidimensional nature of the challenge and the numerous interdependent factors involved, it is recommended to apply tools and techniques from the field of multi-criteria decision-making (MCDM)[96]. These methods help structure complex problems, integrate expert opinions, and determine the relative importance or ranking of different options or criteria, particularly under uncertainty or when dealing with ill-defined issues[97]. Through such approaches, the most relevant indicators can be identified across social, economic, environmental, technological, and governance dimensions.

To establish a robust framework for monitoring and measuring the impacts of DESS implementation, research and innovation (R&I) efforts must adopt a multidisciplinary approach and focus on indicators that are both measurable and meaningful. Existing urban sustainability assessment tools, such as Leadership in Energy and Environmental Design (LEED, USA), Building Research Establishment Environmental Assessment Method (BREEAM, UK), Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan), German Sustainable Building Council (DGNB, Germany), and the Pearl Rating System (Estidama, UAE), can serve as initial reference points for further development. Circular economy indicators[98][99], as well as those related to industrial symbiosis and Industry 5.0[100], and social impact should also be integrated.

Among the analytical tools available for monitoring sustainability performance are Energy/Exergy and Material Flow Analysis (MFA), Bills of Materials, Life Cycle Inventory (LCI), and Life Cycle Assessment (LCA). Economic indicators may include local GDP, the share of public and private investments in relevant industries or services, development and operational costs of DESS projects, the number of new relevant businesses established annually, the degree of innovation among industrial stakeholders, relevant tax revenues, and measures of circularity such as product circularity, value capture potential, recycled content, reuse indices, and energy cost savings. Social indicators could encompass trends in local employment rates, labour market dynamics, demographic structure (age distribution, population growth), and quality of housing and livelihoods, particularly regarding energy affordability and access to sustainable mobility infrastructure. Finally, governance indicators may include the effectiveness of legal and regulatory frameworks, the degree of stakeholder participation and transparency, the efficiency of public and social services, and the overall performance of integrated

94 Gai, L., Varbanov, P. S., Fan, Y. V., et al. (2021). Trade-offs between the recovery, exergy demand and economy in the recycling of multiple resources. *Resources, Conservation and Recycling, 167*, 105428. https://doi.org/10.1016/j.resconrec.2021.105428
95 Sharifi, A. (2019). A critical review of smart city assessment tools. *Journal of Cleaner Production, 233*, 1269–1283. https://doi.org/10.1016/j.jclepro.2019.06.172
96 Taherdoost, H., & Madanchian, M. (2023). Multi-criteria decision making methods. *Encyclopedia, 3*(1), 77–87. https://doi.org/10.3390/encyclopedia3010006
97 Renthlei, E., & George, A. (2025). Holistic neighbourhood sustainability assessment. *Local Environment, 30*(5), 622–641. https://doi.org/10.1080/13549839.2024.2413080
98 Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production, 207*, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014
99 ISO. (2024). *ISO 59020: Circular economy—Measuring circularity performance.* https://www.iso.org/standard/80650.html
100 Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., & Roman, L. (2019). Mapping industrial symbiosis in Europe. *Resources, Conservation and Recycling, 141*, 76–98. https://doi.org/10.1016/j.resconrec.2018.09.016

urban and district management systems

10.3 Drivers to ensure participation and societal acceptance

An implementation and strategic roadmap should focus on those drivers that have the leverage to promote the deployment and use of district storage initiatives.

The implementation of new technology or use cases has always been and will always be disruptive and is carried by a few that have the possibilities to promote the deployment.

Municipalities are a cornerstone for future use cases of shared energy storage and can encourage the adoption of DESS. This is especially true for industrial areas where there is a reduced number of participants to get involved. In this context, local authorities can incentivise industrial players to participate by granting tax benefits, thereby creating a framework that promotes district storage use cases.

Another driver for participation and social acceptance is the free dissemination of knowledge about district storage and its benefits for local business or residents. In this respect, talks and other small events on the topic could be organised by municipalities, business owners already involved, and third parties. They could include training materials and more importantly they should demonstrate the added value of the solutions put forward.

Construction companies and urban developers also have an important role in promoting district storage. When shared storage and smart-grid infrastructure are included already in the design of new districts or industrial areas, future costs and delays can be avoided. Early coordination between developers, utilities, and municipalities ensures that energy flexibility and storage are treated as core design elements rather than later add-ons. This proactive approach not only enhances the long-term value and resilience of built environments but also helps demonstrate the economic and environmental benefits of integrated district solutions to investors and residents alike.

11 CONCLUSIONS

11.1 Summary of key insights and recommendations

District energy storage systems are essential to achieve a flexible, low-carbon, and resilient European energy system. They allow energy to be stored and shared efficiently at local level, linking electricity, heating, cooling, and mobility. Their deployment can reduce system costs, avoid renewable curtailment, optimize energy flows and support grid stability.

The main conclusions from this research are:

- **Integration of technologies:** Combining thermal, electrical, and chemical storage increases flexibility and makes better use of local renewable resources.
- **Regulatory clarity:** DESS need a clear legal definition, simplified permitting, and recognition as a specific infrastructure type in EU and national frameworks.
- **Finance and market access:** Stable rules for revenue stacking, support schemes, and tax or depreciation incentives are needed to attract investment.
- **Digital management:** AI-based control systems and secure, interoperable data platforms are critical for system optimisation and monitoring.
- **Community participation and system operators:** Ownership and governance models must ensure transparency and fair distribution of benefits, while also guaranteeing citizen engagement and a stable, functional electricity grid network.
- **Circular economy:** The planning process should implement material recovery and reuse, modular and eco-design principles, and end-of-life equipment management to minimise environmental impact. By adopting circular economy principles, value can be created through collaborative business models that enable a fair exchange of information and energy.

DESS deployment should be guided by coherent policies that link technology, regulation, and finance, with a strong focus on operational viability and measurable performance.

11.2 Strategic role of district storage in achieving EU goals

District storage directly contributes to the objectives of the Green Deal, REPowerEU, and the Net-Zero Industry Act. It provides the flexibility needed to integrate large shares of renewable energy and stabilise the system at local scale.

Key contributions include:

- **Balancing renewable generation:** DESS absorb surplus electricity and heat and release them when needed, reducing curtailment and reliance on fossil backup systems.
- **Decarbonising heating and cooling:** Integration of thermal storage and waste-heat recovery reduces emissions from one of the most energy-intensive sectors.
- **Improving energy security:** Local storage cuts exposure to imported fuels and strengthens regional self-sufficiency.
- **Boosting industrial competitiveness:** The deployment of DESS can enable European industry to take the lead in selected storage technologies, as well as in their hybridisation and digital control systems, creating opportunities to strengthen competitive manufacturing capacity.
- **Empowering municipalities and citizens:** Shared storage makes local energy management possible and supports new forms of cooperation between users and operators.

District storage is therefore a key operational tool for meeting EU climate and energy targets while maintaining grid stability and social inclusion.

11.3 Final call to action for stakeholders

Progress depends on coordinated action from all parties involved in the energy transition.

- **Policy makers:** Set out consistent regulatory frameworks for DESS, ensure fair market participation, and include district storage in national energy and climate plans.
- **Grid System Operators (GSOs):** Facilitate safe and efficient integration of district storage into the grid, enable participation in ancillary services (e.g., aFRR, mFRR), and support the development of local flexibility markets. GSOs should coordinate more with aggregators to maximize the system-wide benefits of DESS.
- **Industry and investors:** Focus on modular, hybrid, and scalable storage technologies, and develop business models based on real performance and shared benefits.
- **Municipalities and planners:** Integrate DESS into urban and industrial development plans and promote “storage-ready” infrastructures.
- **Research and innovation actors:** Develop practical tools for impact assessment, digital control, and interoperability, supporting replication across regions.
- **Communities and citizens:** Participate in collective storage and energy-sharing schemes to strengthen local resilience and reduce energy costs.

District storage is ready for large-scale implementation. The technologies exist, the use cases are proven, and the regulatory framework is advancing. The next step is action, turning pilot projects into standard infrastructure across European districts.

12 APPENCIDES

Glossary of Key Terms and Concepts

Spreadsheet with Legislative References

Spreadsheet with Use Cases and Implementation Examples

13 REFERENCES

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