TECH FOR NET ZERO

The First Principles Playbook:

How new Energy Storage Technologies can unlock low-cost and resilient Energy for Germany

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Executive Summary

Germany's energy transition should prioritize affordability and security for all users. As the country moves to phase out fossil fuels and build a clean energy system, success should be judged by one decisive question: How much does energy actually cost the people and businesses who use it? High electricity prices threaten Germany's industrial competitiveness and erode public support for climate policy. To keep the transition both fair and future-proof, Germany needs a clear shift in how it invests – guided by five core principles: price, reliability, efficiency, long-term viability, and energy independence.

Investment should focus on technologies that deliver lasting value and reduce geopolitical risk. This means investing only in technologies that deliver low-cost electricity, perform reliably over time, minimize waste from unnecessary energy conversions, and remain economically viable and relevant for decades. Crucially, Germany should also reduce its exposure to geopolitical risks by cutting its dependence on imported fossil fuels and uncertain hydrogen supplies – many of which would come from unstable or adversarial regions.

Renewables combined with long-duration storage offer the best path to secure, affordable power. Direct electrification – using renewable sources like wind and solar – already provides the most cost effective available and can be deployed domestically at massive scale. However, these sources are variable, producing power only when the sun shines or the wind blows. Long-duration energy storage (LDES) addresses this challenge by storing excess energy for use when generation dips. McKinsey and the LDES Council estimate that by 2040 LDES will store up to 10% of all energy consumed leading to cost savings of up to 540bn USD.[1][2] This enables reliable, around-the-clock electricity without relying on fossil gas turbines, which introduce both financial volatility and strategic vulnerability due to fuel price fluctuations and supply dependencies.

Building new gas-fired power plants entails high costs and strategic risks. Continued investment in a new generation of gas turbines risks locking Germany into expensive, inefficient, and politically vulnerable energy systems. Even if labeled "hydrogen-ready," these turbines are unlikely to operate sustainably in the medium term due to high projected costs and limited hydrogen availability. As a result, they are likely to become stranded assets well before the end of their technical lifespans—leaving consumers to bear the financial burden.

[1] McKinsey (2021)
[2] LDES Council (2025)

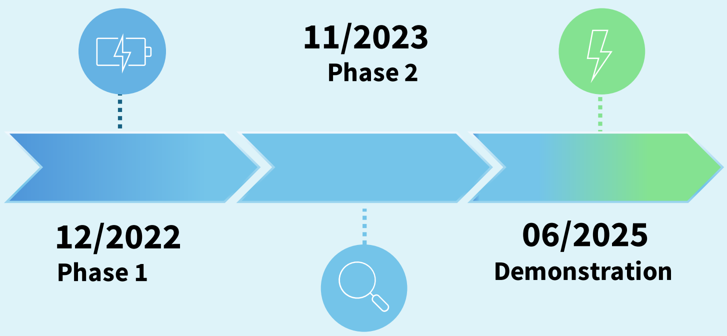
Long-duration energy storage technologies are cost-effective and can be built using domestic resources. Innovations such as reversible solid oxide cells, iron-air batteries, and redox flow batteries – with ultra-thin or no membranes – offer lifespans of 20 to 40 years and low long-term operating costs. Rapid progress during the recent LDES Challenge by SPRIND showed how quickly these technologies can advance. Within just 18 months, several teams managed to advance the technical readiness level (TRL) while reducing system costs by 20% and more – demonstrating that European innovation can help drive a secure, affordable energy future.

BOX: SPRIND Long-Duration Energy Storage (LDES) Challenge

The Long-Duration Energy Storage (LDES) Challenge, launched by SPRIND in December 2022, supports the development of resilient, scalable, and low-cost energy storage technologies that can stabilize the electricity grid and reduce energy costs for both industry and households. The goal is to make the German and European energy system more robust, affordable, and independent by enabling the flexible integration of renewable sources at all times and under all conditions. Through fast-track public funding, the challenge has been catalytic in turning ambitious ideas into real, deployable solutions.

Challenge Structure

- Phase 1 (Dec 2022 – Dec 2023):
  More than 40 qualified teams applied to receive up to €1 million each to develop their initial concepts. Progress was assessed after one year based on feasibility, innovation, and potential for scale.
- Phase 2 (Dec 2023 – May 2025):
  Four finalists were selected in November 2023. Each team received up to €3 million in additional funding and individualized coaching to further develop and demonstrate their technologies. Final demonstrations took place in June 2025.



Finalist Startups and Core Technologies

1. Reverion

   Technology: A compact, high-efficiency system combining gas storage with reversible solid oxide fuel cells.

   Use Case: Converts excess renewable electricity into gas for storage and reconverts it to power during demand peaks. It supports grid stability by providing dispatchable electricity and participating in energy price arbitrage.

2. HalioGen Power

   Technology: Advanced redox-flow battery using ultra-thin ceramic membranes for ion exchange without short-circuits.

   Use Case: Modular and scalable battery ideal for medium- to long-duration storage. Offers improved safety, durability, and cost efficiency over traditional flow battery systems.

3. Ore Energy

   Technology: Iron-air battery using iron, air, and water as abundant, low-cost materials to enable multi-day storage.

   Use Case: Provides up to 100 hours of discharge capacity, making it suitable for bridging multi-day gaps in renewable energy supply during low wind and solar periods.

4. Unbound Potential

   Technology: Membrane-less flow battery using immiscible water-based electrolytes and drastically simplified manufacturing

   Use Case: Enables hyper-scaling of build-out stationary storage, 30% below the projected Li-ion costs, while guaranteeing non-flammability and independence from the supply of critical minerals.

1. Introduction: Defining the First Principles of the Energy Transition

Germany's energy transition needs to balance competitiveness, resilience, and decarbonization. The country faces the urgent task of reducing energy prices to avoid economic decline, while ensuring a reliable energy supply and simultaneously lowering greenhouse gas emissions. Affordability protects consumers and industrial competitiveness, while resilience ensures the system can withstand disruptions and external shocks. In parallel, decarbonization is essential to meet climate targets, limit global warming, and fulfill constitutional obligations. Pursuing these goals simultaneously requires clear guiding principles.

The primary yardstick for measuring success is the cost of energy delivered to end users. Energy prices directly influence industrial competitiveness, household budgets, and public acceptance of the energy transition. According to the German Energy Agency (dena), high electricity costs can lead to energy poverty and growing skepticism towards climate policies.[3] A transition that raises costs without clear benefits risks political backlash and delays in implementation. Investments should focus on technologies that reduce costs and reliance on imports while strengthening efficiency and ensuring lasting economic and geopolitical stability.

Several constraints and risks shape investment decisions. Stranded assets – investments that become obsolete before their expected lifetime – pose a significant financial threat to consumers and the economy. For example, gas turbines built today are likely to become redundant as energy storage technologies mature and prices fall. Technology lock-in, where early choices prevent adoption of superior solutions, should be avoided to maintain flexibility.[4] Political and supply chain risks, especially reliance on imported fossil fuels from geopolitically unstable or adversarial regions, further jeopardize energy security.[5]

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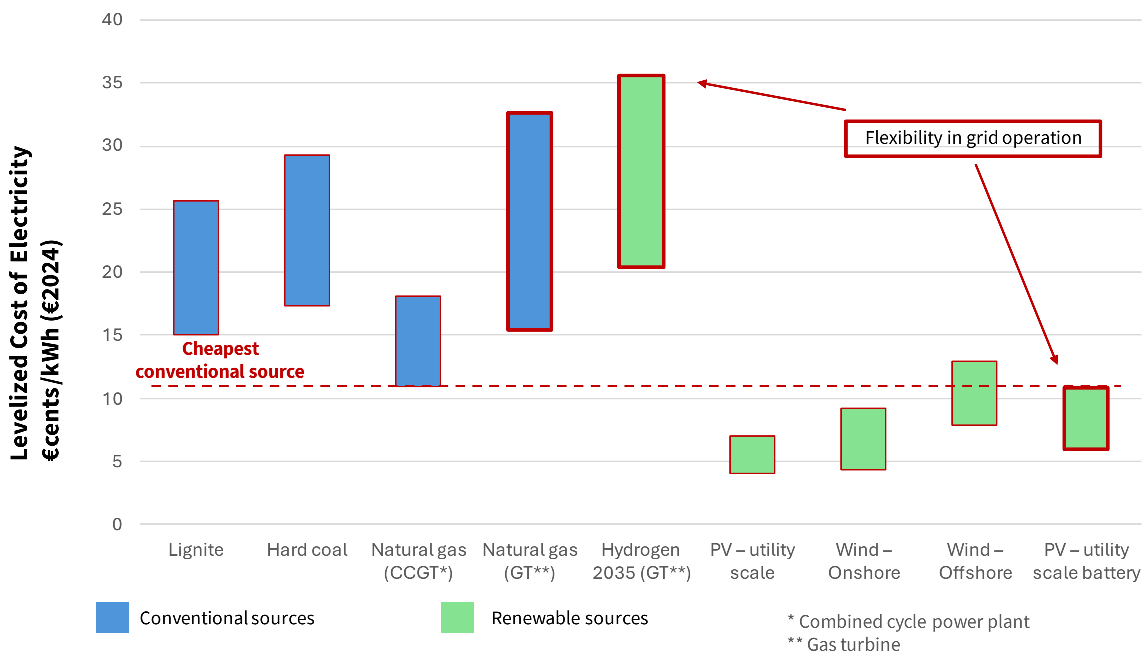
[3] dena (2023)
[4] Agora Energiewende (2024)
[5] PIK (2024)

2. First Principle: Industrial Competitiveness

The cost of energy should guide transition decisions because keeping energy costs manageable is crucial for maintaining the competitiveness of industries during the energy transition. Since energy expenses make up a significant portion of production costs in many sectors, decisions about which technologies or policies to implement must carefully consider their impact on energy prices. Choosing options that minimize cost increases helps protect businesses from losing competitiveness, thereby avoiding job losses and the associated impact on the public budget. To illustrate this, the graph below compares the costs of generating energy and stabilizing the energy grid, with a focus on gas turbines versus energy storage solutions.

Figure 1: Levelized Cost of Electricity - Renewable Energy Technologies, Germany

Levelized Cost of Electricity (LCOE) of renewable energy technologies and conventional power plants at locations in Germany in 2024. Specific investments are considered using a minimum and maximum value for each technology.



Note: To ensure stable grid operation, only three of the energy sources presented – natural gas turbines, hydrogen turbines, and photovoltaic systems paired with large-scale batteries – are capable of providing flexible power.

Source: Fraunhofer ISE, Levelized Cost of Electricity- Renewable Energy Technologies 08/2024

2.1. Direct Use of Renewables is Most Cost-Efficient

The cheapest electricity comes directly from wind and solar, without energy conversion losses. According to the Frauenhofer Institute, onshore and offshore wind plus solar PV now represent the lowest levelized cost of electricity (LCOE) for new power plants in Germany.[6] These sources produce electricity at costs consistently below fossil alternatives. Unlike other carriers, renewables deliver energy with no intermediate conversion, resulting in an effective 90% or greater efficiency from generation to consumption.

Offshore wind is a critical but underutilized resource. The Federal Maritime and Hydrographic Agency estimates Germany's offshore wind potential at over 70 GW by 2040, yet current plans cover only a fraction of this.[7] Deploying hybrid multi-source systems – combining wind, solar, and storage – as showcased by recent clean energy innovation Challenges, can reach grid efficiencies of 90–95%, enhancing system reliability while minimizing costs.[8]

2.2. Effect of Hydrogen and Fossil Gas on System Costs

Fossil gas may contribute to higher system costs, partly due to its exposure to price volatility and geopolitical uncertainties, as illustrated by recent disruptions in European energy markets. In contrast, some regions are already experiencing periods of surplus renewable electricity, which presents potential opportunities for cost-effective, long-duration storage through flexible, molecule-based systems. Moreover, renewable gases could support efforts to enhance energy security and reduce reliance on external energy sources. Under certain conditions, locally produced hydrogen may contribute to lower overall system costs by facilitating more consistent utilization of renewable generation and potentially reducing the need for redispatch.

Time-shifting renewables over long durations with molecules can be a cost-effective way to provide electricity. Given the energy intensity of producing hydrogen, its role is limited to hard-to-electrify sectors rather than bulk power supply. While in principle hydrogen or synthetic methane can be cost-effective power sources, it requires the power-to-gas and the gas-to-power technologies deployed to be highly efficient and flexible enough, for example reversible solid oxide fuel cells. In the meantime, green hydrogen production using state-of-the-art electrolyzers and current renewable energy costs is not expected to become cost-effective for reliable, dispatchable power supply until at least 2040.[9]

[6] Fraunhofer Institute for Solar Energy Systems ISE (2024)
[7] Federal Maritime and Hydrographic Agency (BSH) (2023)
[8] SPRIND Innovation Challenge (2025)
[9] McKinsey (2024)

3. Avoiding Stranded Assets: Investment Must Target Long-Lived Infrastructure

3.1. New Gas-fired power plants are likely to become stranded

New gas turbines face high financial risks with no clear commercial viability. The German government plans to procure 10 to 20 GW of new gas turbines. There is no viable business case when turbines are only used as occasional backup, undermining returns. As a result, private investors will find it difficult to finance these projects, meaning billions in public money will be needed – diverting much-needed capital from the energy transition.

Expensive gas turbines will raise electricity costs and threaten European industrial competitiveness (and climate goals). As renewable energy sources are increasingly price setting in electricity markets, fossil power generation is driven out of the electricity mix. Building new turbines, which currently have lead times of six years, will most certainly lead to cost overruns.[10] These high costs need to be compensated by declining plant operating hours, leading to high peak prices and CO2 emissions. As a result, procuring gas turbines risks locking Europe into costly infrastructure that undermines Germany's industrial strength and jeopardizes the climate transition.

3.2. Renewable Energy and LDES are Long-Life Assets

In contrast, renewable generation and long-duration energy storage technologies typically have lifespans of 20 to 40 years, providing durable infrastructure that supports cost stability. Offshore wind turbines, solar PV installations, pumped hydro, and advanced flow batteries are designed for multi-decade use, ensuring long-term returns on investment and reducing exposure to fuel price volatility.

Participants in the recent SPRIND LDES Challenge proposed modular battery systems with projected lifetimes of 30–40 years and low operational expenditures, further proving their economic promise and suitability for grid-scale deployment.[11] These investments help future-proof Germany's energy system by locking in low marginal costs and reducing dependence on imported fuels.

[10] S & P Global (2025)
[11] SPRIND Innovation Challenge (2025)

4. Optimize the Energy Grid

4.1 Efficiency: Avoiding energy losses through conversion

Minimizing energy conversion steps is essential to reducing system costs and improving efficiency. The round-trip efficiency from renewable electricity to hydrogen and back to electricity with conventional technologies is only about 20–30%, reflecting substantial conversion losses at each stage.[12] In contrast, Long-Duration Energy Storage (LDES) technologies – particularly electrochemical systems – offer 75–90% round-trip efficiency, enabling a far greater proportion of generated electricity to be utilized. This efficiency gap translates directly into lower system-level costs, as fewer generation assets are needed to meet demand. By maximizing usable output from renewable generation, LDES reduces the capital intensity of the energy transition and supports more streamlined, cost-effective grid expansion.

4.2 Electrification: Prioritizing direct use of renewable electricity

Direct electrification of end-uses – such as heating, mobility, and industrial processes – is the most effective means of maximizing the value of renewable electricity. Technologies like heat pumps, electric vehicles, and electric arc furnaces deliver high efficiency and low marginal cost compared to conversion-based alternatives. Avoiding intermediate carriers reduces infrastructure complexity and lifecycle losses. In this context, LDES serves as a critical enabler of direct electrification by providing time-shifting flexibility and ensuring that renewable electricity is available on demand. This supports stable operations for electrified end-use sectors, reduces reliance on fossil backup systems, and enhances the economic case for clean electrification across the energy system.

4.3 Security: Enhancing resilience and price stability through LDES

Long-Duration Energy Storage technologies are crucial for enhancing energy system resilience and mitigating exposure to market volatility. By storing surplus renewable electricity for dispatch during periods of low generation or high demand, LDES reduces dependence on imported fossil fuels and mitigates the need for short-term balancing through volatile spot markets. This function stabilizes wholesale electricity prices and enhances predictability for investors and consumers. In a grid dominated by variable renewables, LDES provides the dispatchable capacity needed to maintain reliability without reintroducing carbon-intensive generation. Its integration enables a more flexible, self-sufficient electricity system, reducing both operational risks and the long-term cost of securing supply.

[12] IRENA (2023)

4.4 Autonomy: Building strategic independence with local, scalable technologies

LDES systems developed under the SPRIND challenge are designed with material circularity and supply chain sovereignty in mind. Participating technologies avoid reliance on critical raw materials (CRMs) such as lithium, cobalt, and rare earth elements, opting instead for chemistries based on iron, zinc, sulfur, and other abundant elements available within Europe. This approach enables secure, large-scale deployment without exposing the region to geopolitical risks or long-term supply constraints.[13] As LDES technologies are highly scalable and industrially flexible, they support domestic value chains, stimulate regional economic development, and align with the EU's goals of strategic autonomy. In this way, LDES provides not only technical performance but also systemic resilience, making it a cornerstone of Europe's energy independence strategy.

5. Innovation and Scaling: Accelerate Cost Reductions through Competition

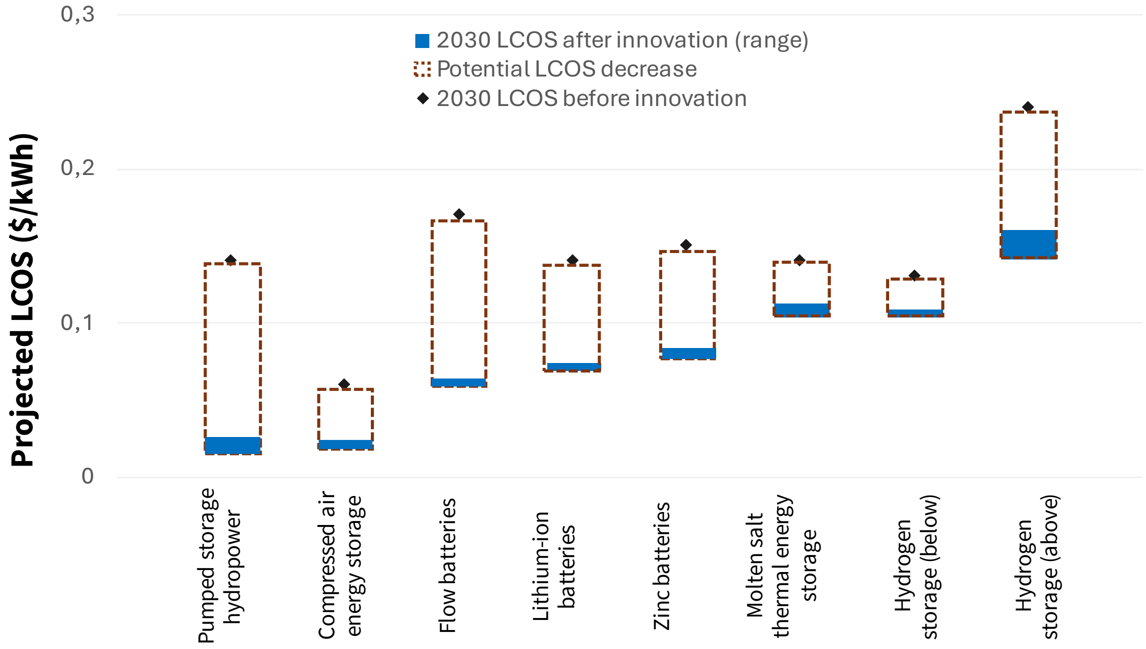
5.1 Precedent: Leveraging innovation cycles to drive down costs

The rapid cost declines achieved in solar photovoltaics and lithium-ion batteries over the past two decades offer a clear model for LDES development. Strategic early-stage demand-side support – such as Germany's EEG feed-in tariffs and China's scale-focused industrial policy – created predictable demand and revenue, which in turn enabled global manufacturing scale-up and 80–90% cost reductions.[14] These dynamics were not incidental but policy-driven and highly replicable. If similarly structured instruments are applied to LDES, such as long-term offtake mechanisms or scale-anchored funding programs, comparable innovation curves can be achieved. As seen in recent LDES Challenge results, several teams have reduced projected capital expenditure by 20–40% within a matter of months – driven by iterative prototyping and aggressive design-to-cost approaches. These signals confirm that LDES technologies are entering a phase of accelerated learning and cost reductions, contingent on stable policy support and credible market formation.

[13] SPRIND Innovation Challenge (2025)
[14] BNEF (2023)

Figure 2: Cost savings potential in LDES

The figure shows the projected range of levelized cost of storage (LCOS) reductions through innovation for each LDES technology.



Note: For long duration energy storage, the range of impact on the 2030 LCOS after implementing the top 10% of LCOS-reducing innovations. Above and below ground hydrogen storage are shown separately. LCOS: levelized cost of storage.

Source: U.S. Department of Energy (2024)

5.2 Scale-up: Driving system impact through targeted deployment

Realizing the system-level benefits of LDES requires a rapid transition from laboratory validation to large-scale demonstration and deployment. Multi-gigawatt-scale pilot programs are essential to de-risk project delivery, validate performance under real-world grid conditions, and accelerate cost discovery at commercial scale. Public capital – particularly through instruments like the European Innovation Fund, national climate investment banks, and green public procurement – can play a catalytic role by anchoring early markets and mobilizing private sector investment. Targeted support should focus on non-lithium LDES technologies, such as reversible solid oxide cells, iron-air batteries, and redox flow technology, which are well-suited for grid-scale applications and do not rely on critical raw materials. The recent LDES Challenge has demonstrated Europe's capacity for high-velocity innovation under time constraints, offering a scalable blueprint for national and EU-level deployment strategies.[15] With strategic investment and deployment, LDES can

[15] European Innovation Fund (2024)

replicate the success of past clean tech transitions and emerge as a foundational pillar of Europe's energy system.[16]

6. Policy Recommendations: A new energy strategy putting competitiveness first

Realizing the full potential of Long-Duration Energy Storage (LDES) requires a policy framework grounded in first principles. The guiding benchmark should be the cost of energy delivered to end users – not just upfront asset costs – to direct investments that support long-term competitiveness, resilience, and affordability. Germany should align all new energy infrastructure investment with this principle, prioritizing renewables and LDES while phasing out support for new gas turbine projects. This approach would accelerate decarbonization and reduce vulnerability to fuel price volatility and foreign energy dependence.

To operationalize this strategic shift, the policy architecture must correct three core market failures: (1) the absence of bankable revenue models for LDES; (2) disproportionately high entry barriers for innovative firms; and (3) regulatory frameworks that undervalue the system benefits of storage technologies. The following recommendations address these challenges across three domains: **demand-side instruments**, **supply-side enablement**, and **market design reform**.

6.1 Demand-Side Instruments: Creating Bankable Revenues and Long-Term Market Signals

LDES technologies provide system-wide value—including grid stability, balancing, and avoided infrastructure costs—that is not captured by current energy-only market structures. Establishing robust demand-side incentives is essential to unlocking private investment and accelerating deployment.

- **Long-Term Availability or Capacity Payments:**
  Introduce technology-neutral contracts that remunerate availability, not just dispatch. This would reflect the full system value of LDES—including curtailment avoidance, frequency regulation, and seasonal flexibility—and reduce investor reliance on volatile arbitrage markets.
- **Bonus Mechanism for Ultra-Long-Duration (>72 Hours):**
  Award additional remuneration or evaluation points in tenders for storage systems that can sustain discharge beyond 72 hours, addressing prolonged renewable droughts and enhancing resilience to multi-day grid stress events.

[16] SPRIND LDES Challenge (2023)

- **Cost-Efficiency Ceiling for CAPEX (EUR 75/kWh):**
Implement a price cap to ensure public procurement remains aligned with economic feasibility. This threshold reflects developer input and promotes fiscal discipline without discouraging innovation.
- **National LDES Deployment Roadmap:**
Establish and regularly update a strategic roadmap for LDES scale-up to 2040. The roadmap should specify capacity targets, deployment zones, and integration pathways to provide clear signals to market participants and grid planners.
- **Creation of a German or European LDES Alliance:**
Support the establishment of an industrial alliance bringing together governments, manufacturers, research institutions, and financiers. The Alliance would coordinate R&D, de-risk investment, and facilitate the development of skilled labor and sovereign supply chains.

6.2 Supply-Side Enablement: Reducing Entry Barriers and Mobilizing Innovation Capital

Germany's tendering and financing frameworks must be recalibrated to support first-of-a-kind projects and attract new entrants to the market. Targeted reforms can improve bankability, enhance competition, and stimulate the emergence of a globally competitive LDES sector.

- **Prioritization of Non-Lithium, CRM-Free Technologies:**
Focus public support on technologies that do not rely on critical raw materials (CRMs) or lithium, thereby strengthening strategic autonomy and aligning with industrial policy goals on raw material sovereignty.
- **Reduction or Elimination of Guarantee Requirements for Startups:**
Lower financial security requirements by up to 90%—or remove them entirely where feasible—to level the playing field for early-stage firms. This would unlock greater innovation potential and diversify the solution space.
- **Support for Medium-TRL Technologies (TRL 6–8):**
Allocate a portion of public tenders to demonstration-scale projects within the TRL 6–8 range to bridge the commercialization gap and enable scaling of nascent technologies.
- **Limited or No Penalty Clauses:**
Refrain from applying punitive contractual penalties in early-stage tenders. Instead, introduce milestone-based performance reviews and risk-sharing mechanisms tailored to FOAK project realities.

- **Accelerated Implementation Timelines:**
  Shorten the maximum implementation horizon from six years to three years to align with urgent grid flexibility needs and reduce temporal uncertainty for developers and lenders.
- **Upfront CAPEX Disbursement in Three Tranches:**
  Reform disbursement models to allow capital provision in three larger tranches tied to key project milestones. This would significantly improve liquidity and financing feasibility for capital-intensive storage projects.

6.3 Market Design and Regulatory Reform: Mainstreaming LDES in Grid Operations

To fully integrate LDES into the energy system, its multifunctional role must be recognized within Germany's regulatory, planning, and market frameworks.

- **Regulatory Classification of LDES as a Distinct Asset Class:**
  Establish a formal definition for LDES that reflects its grid-stabilizing, capacity, and balancing services. This would facilitate tailored ownership models (e.g., by TSOs, DSOs, and public-private consortia), streamline permitting, and ensure inclusion in grid expansion planning.
- **Elimination of Double Grid Fees:**
  Remove duplicate transmission and distribution charges for storage projects that both charge and discharge to the grid, thereby avoiding artificial cost burdens that undermine economic viability.
- **Inclusion in Integrated System Planning:**
  Mandate the inclusion of LDES in national and regional grid planning scenarios to capture their value as infrastructure deferral tools and ensure optimal siting within the transmission and distribution network.

These policy recommendations are designed to function in concert with Germany's broader energy transition and industrial competitiveness goals. They reflect international best practices and are grounded in consultations with project developers, financiers, and technology providers.

7. Conclusion: Building a resilient, cost-efficient green energy system

Germany should plan its energy system from first principles, not legacy structures. In an era of rapid change, the only path to resilience is one built on efficiency, scalability, and independence. The new energy system should deliver clean power at the lowest cost to households, businesses, and the climate – while ending reliance on geopolitical adversaries like Russia.

Cost-effective renewables plus LDES is a proven path forward. Offshore wind, solar PV, and grid-scale storage – especially innovations such as reversible solid oxide cells, iron-air batteries, and redox flow batteries – can now deliver 24/7 renewable power without expensive detours. Hydrogen, as replacement of fossil gas, should only be used where strictly necessary. Circular energy routes add cost, waste electricity, and risk lock-in.

The window to act is closing, but Germany still has a first-mover advantage. With €500 billion in financial leeway, world-class engineering talent, and a functioning policy ecosystem, Germany is positioned to lead the next phase of the energy transition – if it commits to storage and system efficiency as its industrial backbone.

Challenge learnings show that rapid acceleration is not just necessary – it's possible. Over 30 startup teams demonstrated that LDES technologies can halve capital costs and reach commercial scale within 3–5 years – if governments provide demand certainty and infrastructure support. A new energy paradigm is not theoretical – it's in reach.

Germany's energy choices will define Europe's future. By prioritizing cost, efficiency, and resilience, Germany can build an energy system that competitively powers its industries, supports its climate goals, and protects its sovereignty. But it must choose – decisively – between outdated infrastructure and forward-looking solutions.

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TECH FOR NET ZERO

Tech for Net Zero is a network of leading climate tech start-ups, scale-ups and investors in Germany and the DACH region. The aim of the network is to accelerate the scaling of breakthrough climate technologies by improving access to finance, stimulating market demand and supporting a conducive regulatory environment. Climate tech is about much more than just meeting climate targets - the faster progress is made, the better the security, energy resilience, economic development and sustainability of our industrial base.

Given the diversity of technical solutions, available talent and financial resources, we are convinced that achieving growth and climate targets is above all a question of speed, focus and consistent implementation. In order to develop Europe into a leading climate tech hub, we need determined support and joint efforts. Tech for Net Zero is a reliable partner for founders, investors and political decision-makers. Together, we are working on solutions to promote and establish a strong and sustainable climate tech ecosystem in Germany and Europe.

You can find more information on our website: https://techfornetzero.org/

Publishing details

Publisher

Tech for Net Zero

Commissioned by

Bundesagentur für Sprunginnovationen SPRIND GmbH

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Status

07/2025