IRENA coalition FOR ACTION

KEY ENABLERS FOR THE ENERGY TRANSITION

THE "STORAGE+" PARADIGM FOR SYSTEM INTEGRATION



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About the Coalition

The IRENA Coalition for Action brings together leading renewable energy players from around the world with the common goal of advancing the uptake of renewable energy. The Coalition facilitates global dialogues between public and private sectors to develop actions to increase the share of renewables in the global energy mix and accelerate the energy transition.

About this publication

Produced by the IRENA Coalition for Action's Task Force on Enabling High Shares of Variable Renewable Energy (VRE) through Grid Stability and Energy System Advances, led by Kangqiao Huang (CATL), this report presents case studies, innovative applications and policy recommendations on the role of energy storage, particularly battery energy storage systems (BESS), in enabling broader energy system transformation. It explores how storage can support grid flexibility and stability, AI infrastructure, transport electrification and industrial decarbonisation, highlighting technological innovation, safety standards, market mechanisms and regulatory frameworks.

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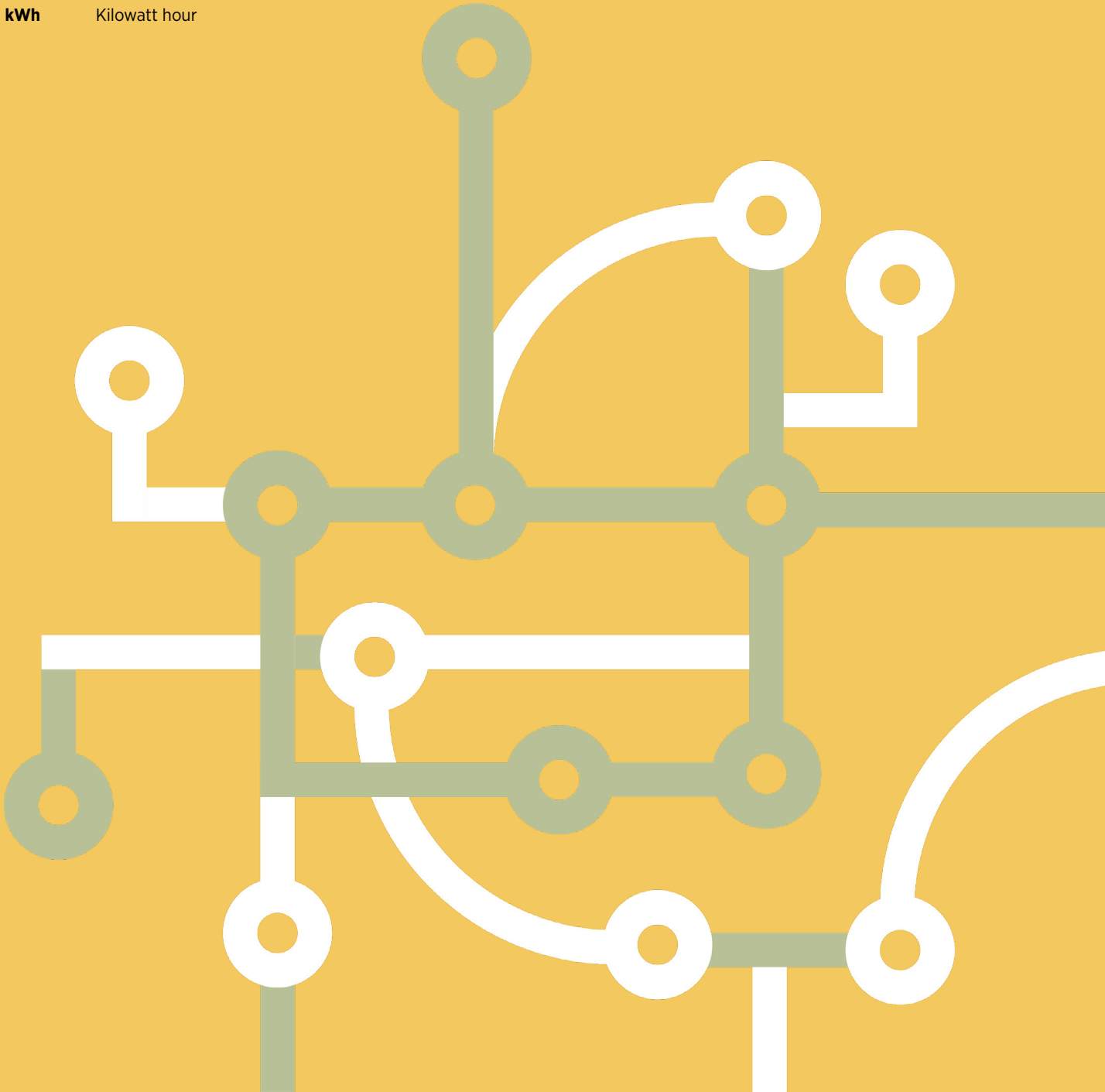
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ABBREVIATIONS

AI	Artificial intelligence
BESS	Battery energy storage systems
CAISO	California Independent System Operator
CO_2	Carbon dioxide
COP	Conference of the Parties
EV	Electric vehicle
GPU	Graphics processing unit
GW	Gigawatt
GWh	Gigawatt hour
INR	Indian rupee
IRENA	International Renewable Energy Agency
IT	Information technology
kW	Kilowatt
kWh	Kilowatt hour
LFP	Lithium iron phosphate
MW	Megawatt
MWh	Megawatt hour
PV	Photovoltaic
TW	Terawatt
TWh	Terawatt hour
USD	United States dollar
V2G	Vehicle-to-grid
VPP	Virtual power plant
VRE	Variable renewable energy





EXECUTIVE SUMMARY

The global energy landscape is being reshaped by three interlinked aspects of the energy trilemma: energy security, energy equity (accessibility and affordability) and environmental sustainability.

Since 2020, geopolitical uncertainty and tensions have fundamentally affected global energy security, with two fossil fuel crises in under five years severely impacting markets. Although these crises were centred in Europe and the Middle East, they have had worldwide repercussions, resulting in increasingly volatile fossil fuel prices. They disrupted global energy markets (oil and gas) and commodity markets (wheat and fertilisers among others), leading to high inflationary pressures. These pressures have amplified existing inequalities, impacting energy equity for millions across the globe.

In parallel, the energy landscape is facing unprecedented growth in global electricity demand and changing power system needs, driven by four key trends explored in this report: grid transformation, the rapid growth of data centres, transport electrification and industrial decarbonisation. At the same time, accelerated climate change, due to fossil fuel use, is increasing the frequency and severity of climate-related impacts and adding to existing economic, social and geopolitical vulnerabilities. The urgency of accelerating the transition towards highly efficient 100% renewables-based energy systems and economies cannot be emphasised more.

Unlike fossil and uranium fuels, renewable energy resources are widely distributed and locally available, enabling countries to reduce dependence on imported fuels, strengthen resilience against geopolitical and price shocks, and improve long-term energy security (IRENA, 2019a, 2024). In 2025, a global record of 692 gigawatts (GW) of new renewable electricity capacity was added, a 15.5% year-on-year increase, bringing the total global renewable capacity to 5155 GW. Additionally, more than 90% of the utility-scale renewable energy projects commissioned in 2025 delivered power below the cost of the cheapest new fossil fuel plant built in their market (IRENA, 2026a, 2026b).

These capacity additions have driven unprecedented deployment of renewables and have helped to avoid an estimated USD 480 billion in fossil fuel costs and around 8.4 gigatonnes (Gt) of carbon dioxide emissions, confirming their role not only as the cheapest source of new power but as a pillar of energy security, economic stability and resilience. While renewables are by far the dominant share of new power capacity additions, their growing role in the power sector has not yet translated

into a dominant share of global generation and final energy consumption. As renewable electricity has become the lowest-cost source of new power generation in most regions, renewables-based electrification also offers the most cost-effective pathway to affordable and secure energy services (IRENA, 2026b).

At the same time, rapid renewable energy expansion remains indispensable for achieving the objectives of the Paris Agreement and the commitment at the 2023 United Nations Climate Change Conference (COP28) to triple renewable capacity and double energy efficiency by 2030 while transitioning away from fossil fuels (UNFCCC, 2023).

The next phase of the energy transition is no longer about deploying renewable capacity alone but about building renewable power systems capable of delivering reliable electricity 24/7. These trends are creating two interlinked system needs. First, growing shares of variable renewable energy require new sources of flexibility and system stability, functions that traditionally were provided by conventional synchronous generators. Second, electrification is driving unprecedented growth in electricity demand, requiring renewable energy systems that can reliably supply power around the clock. These developments increasingly shift the focus to addressing system integration requirements, closing policy and regulatory gaps, and speeding implementation of enabling policies and frameworks. This report explores the broader "Storage+" paradigm, exploring various storage solutions and applications, with a particular focus on how battery energy storage systems (BESS) can be integrated with renewable generation, grid technologies and emerging energy-intensive sectors to deliver broader system benefits. To fully reap the benefits of a renewables-based system, today's centralised legacy energy systems must be transformed towards more flexible, decentralised and digitalised ones. Energy storage is a critical enabler of renewables-based energy systems, providing flexibility and helping to integrate variable renewable generation into reliable power supply.

Energy storage improves system flexibility and stability – reducing dependence on volatile imported fossil fuels – and enables renewable electricity to meet rapidly growing demand across the economy. Energy storage encompasses a diverse portfolio of technologies, including pumped hydropower, batteries, thermal energy storage, compressed air energy storage, hydrogen and other emerging solutions. Each offers distinct technical characteristics and is suited to different scenarios. Building a resilient and cost-effective renewables-based energy system will therefore require a combination of technologies. Within this broader portfolio, this report focuses on BESS and their role in addressing the four energy transition trends identified above.

BESS has experienced particularly rapid deployment in recent years, accounting for over 90% of new storage capacity added in 2025 (IEA, 2026b). BESS costs have fallen by 93% since 2010 and by 30% in 2025 alone, and the technology has never been more affordable and accessible, with advanced equipment increasingly present across Europe, Asia and the Americas (IRENA, 2026c). In addition, BESS combines unprecedented cost reduction with the modularity, fast deployment and locational flexibility needed to address two major challenges: supporting grid operations, and enabling renewables to meet growing demand (IRENA, 2026c).

- **Supporting grid operations:** As conventional synchronous generators (fossil fuel-powered generators) are decommissioned, replaced or displaced, grids need alternatives to set voltage and frequency, absorb supply-demand imbalances and hold reserves. Under the International Renewable Energy Agency's 1.5°C Scenario, global daily flexibility will need to triple from the 2019 level of 1550 terawatt hours (TWh) to 4 225 TWh by 2030, and grow ten fold to

15 100 TWh by 2050 (IRENA, 2026d). While multiple technologies contribute to this task, battery storage systems with grid-forming inverters are particularly well suited. Grid-forming systems independently establish and maintain the electrical conditions that the grid requires, responding to disturbances in milliseconds and being deployable at any scale and location in the network. For microgrid and off-grid systems, BESS can also strengthen resilience by balancing local generation and demand and supporting continuity of supply.

- **Enabling renewables to meet growing demand:** Electrification is driving the fastest sustained growth in electricity demand in decades. Between 2024 and 2030, global electricity demand is expected to increase by roughly 1 100 TWh/year, which is 50% more than the annual average increase of 730 TWh over the previous decade (2013 to 2023).

Beyond grid transformation, this report examines three major sources of growing and changing electricity demand – data centres, transport electrification and industrial decarbonisation – as they are among the important drivers of growing electricity demand (IEA, 2026b). Together, these trends are increasing both electricity demand and the need for system flexibility and integration. Battery storage can help address these needs in several ways:

- **Data centres:** Electricity consumption from data centres is projected to double to 945 TWh by 2030, growing four times faster than all other sectors combined (IEA, 2025a). Yet, fossil fuels still dominate supply in key markets, with fossil gas providing over 40% of the electricity supply for data centres in the United States (IEA, 2025a). Battery storage enables the shift to a renewable power supply while buffering the sharp load fluctuations of artificial intelligence workloads, protecting grid infrastructure.

- **Transport electrification:** Electricity covers barely 1% of global transport energy needs today, but its contribution is projected to more than quadruple by 2030, reaching 780 TWh (IEA, 2025b). Battery storage supports the bi-directional charging infrastructure that this transition requires – from fast-charging stations for electric vehicles to fleet depots and battery swapping facilities. Battery storage is therefore an enabler of transport decarbonisation, while also allowing transport sector assets to provide flexibility to the power system.

- **Industrial decarbonisation:** Electricity accounts for roughly 23% of industrial final energy consumption, with substantial growth expected as manufacturing electrifies (IEA, 2026b). Storage supports the 24/7 reliable supply of renewable electricity, enabling manufacturers to meet clean energy standards without compromising production.

Scaling energy storage, and BESS in particular, at the pace that the transition requires calls for co-ordinated policy action across four areas:

- **Planning and regulatory frameworks:** Energy storage should be recognised as a distinct asset class in national energy plans and grid development strategies, taking into account evolving demand patterns from data centres, transport electrification, and industrial decarbonisation, and supported by dedicated capacity targets and deployment timelines supported by enabling policies. Regulatory frameworks should clarify storage's eligibility to participate across generation, transmission and distribution segments.

- **Standards and interoperability:** Harmonised technical standards for battery safety, performance testing and grid interconnection are needed to reduce market fragmentation, support cross-border supply chains, and enhance data security, while at the same time building public confidence in renewable energy and storage technologies.

- **Market design and revenue certainty:** Market frameworks should enable storage to earn revenue from its full range of contributions, including energy arbitrage, capacity provision and ancillary services. Clear and bankable revenue streams are a precondition for attracting private capital at scale.

- **International co-operation:** Co-operation on supply chain development and reliability, workforce training, knowledge exchange and regulatory alignment is essential to ensure that all countries can access the benefits of energy storage and contribute to a resilient global value chain.

Keeping within reach the target of limiting global temperature rise to 1.5 degrees Celsius (°C), and delivering on the COP28 commitment to transition away from fossil fuels, requires renewables to be the dominant and system-defining sources of energy – and to rapidly replace conventional generation. The pathway towards fully renewables-based energy systems is technically and economically viable, particularly when variable generation can deliver dispatchable supply across every scale and sector.

Energy storage is one of the key technologies enabling this flexibility and supporting security of supply. Within the broader storage portfolio, BESS, with its proven scalability, rapidly falling costs, and capacity to deliver both energy and grid services, is well positioned to make this pathway operational, resilient and affordable. At the same time, broader socio-economic benefits – including stimulated downstream economic activities, employment creation, improved energy affordability and greater resilience to energy price volatility – will be generated along with wider deployment of battery storage. Taken together, these benefits reinforce the role of battery storage as one of the key enablers of the transition towards secure, affordable and sustainable renewables-based energy systems.



1. INTRODUCTION

Energy storage has evolved from a supporting technology into a key enabler of the energy transition. It helps compensate for the variability of renewable generation while enabling more flexible demand management. This expanded role is captured by the concept of "Storage+": a paradigm in which storage integrated with variable renewables and grid-forming technologies becomes an active enabler of energy transformation.

All forms of energy storage (such as pumped hydropower, thermal storage and hydrogen-based solutions) play important roles in the energy system. Battery energy storage systems (BESS) have experienced particularly rapid deployment, supported by declining costs (predominantly of lithium iron phosphate, or LFP, batteries), modularity and scalability across a wide range of applications. LFP has become the dominant cathode chemistry in grid-scale battery storage, accounting for roughly 90% of new global deployments in 2025-2026.

This report covers the broader "Storage+" paradigm and focuses on BESS as the primary technology for short- to medium-duration flexibility while, recognising the continued importance of other storage technologies, particularly for longer-duration applications. BESS supports system reliability and stability by adding flexibility across time and sectors. It provides key stabilising mechanisms and flexibility through cross-sector coupling, allowing the energy system to dynamically balance supply and demand across the power, transport and industrial sectors. In this context, storage enhances grid resilience, delivering flexibility while appropriately configured BESS can help maintain critical electricity supply during wider grid disruptions.

Energy storage can deliver a wide range of benefits, including avoided or deferred grid investment, reduced curtailment, improved system efficiency, climate resilience and energy access. Beyond deployment, the broader battery value chain – including end-of-life management, second-life applications and recycling – has important implications for resource efficiency, environmental sustainability and the circular economy. Given this broad scope, it would not be possible to cover the full range of topics in a single report. Accordingly, this report concentrates on the role of BESS within the "Storage+" paradigm, rather than providing a comprehensive review of battery manufacturing, recycling or circular economy policies.

This report examines how BESS, including systems equipped with grid-forming inverters where relevant, can support renewables-based power systems by improving flexibility, facilitating the integration of high shares of variable renewable energy (VRE) and providing selected system services. Grid transformation provides the foundation for the three end uses examined in this report: 1) artificial intelligence (AI) data centre expansion, 2) transport electrification and 3) industry decarbonisation.

Realising these system benefits at scale requires not only technological innovation but also co-ordinated system planning, enabling regulation, appropriate market design and investment frameworks. Against this backdrop, the report presents policy recommendations for governments, regulators, system operators, utilities and development institutions, reflecting their respective roles in planning, regulating, financing and operating future electricity systems.

While the speed of the global energy transition varies across regions and economies because of differences in their economic, financial and social circumstances, the transformation is expected to lead to vastly increased electrification across all major end-use sectors. Achieving this shift will result in electricity systems increasingly powered by renewable energy, alongside extensive investment in storage, grids and other enabling infrastructure. The pace of this transformation will influence progress in energy security, strengthening system resilience and advancing climate mitigation.



2. FROM CAPACITY EXPANSION TO SYSTEMIC INTEGRATION: STORAGE+

The global energy transition is at a critical juncture. Global electricity consumption in the period 2024-2030 is projected to grow by roughly 1 100 terawatt hours (TWh) per year, 50% more than the average of around 730 TWh/year over the previous decade (2013 to 2023) (IEA, 2026b). Power generation must accelerate at an unprecedented scale to meet burgeoning electricity demand, which is expanding rapidly due to digitalisation and the electrification of end-use sectors, placing increasing pressure on power networks. Electricity currently accounts for around 23% of global final energy consumption (IRENA, 2026e), illustrating substantial potential for further electrification across sectors. As electrification accelerates, sufficient generation capacity, grid infrastructure and system flexibility become increasingly important to support the transition towards a more electricity-based energy system.

Beyond meeting rising energy demand, the energy transition provides a strategic response to global energy uncertainty. It can address disruptions to energy supply by reducing dependence on imported fossil fuels and building structural resilience through domestic distributed energy systems. Recent geopolitical tensions and conflicts have highlighted the price volatility and import dependencies associated with fossil fuels. Economies with diversified and rapidly expanding renewable energy deployment have generally demonstrated greater resilience to external energy shocks. Renewables helped avoid an estimated USD 480 billion in global fossil fuel costs in 2025, underscoring that greater resilience translates into greater economic stability (IRENA, 2026b).

Reducing greenhouse gas emissions from the energy sector remains an urgent global priority for achieving climate mitigation targets under the Paris Agreement. Meeting rising electricity demand, strengthening energy security and reducing greenhouse gas emissions must be pursued together through an integrated energy system approach. Within this context, renewable energy, particularly variable renewables such as solar and wind, has become the preferred source on the supply side for both distributed and utility-scale applications – driven by its declining costs, rapid scalability and deployment – and plays a central role in achieving global climate goals.

The convergence is already translating into unprecedented expansion of renewable energy deployment. Wind and solar technologies generated around 17.3% of global electricity in 2025 (Ember, 2026). A total of 692 gigawatts (GW) of renewable power capacity was added globally that year, representing a 15.5% year-on-year increase and bringing the total installed renewable capacity

to around 5 155 GW, or 49.4% of global electricity capacity (IRENA, 2026a). This reflects a structural shift from incremental growth to large-scale system transformation.

Looking ahead, long-term transition pathways further illustrate the scale of this transformation. According to the International Renewable Energy Agency's *World Energy Transitions Outlook 2026* (IRENA, 2026f), renewable energy is expected to become the dominant source in the power system under the 1.5°C Scenario, increasing from 30% in 2023 to around 67% by 2030 and exceeding 90% by 2050. Installed renewable capacity would expand from 3.8 terawatts (TW) in 2023 to over 38 TW by 2050. While actual development pathways may vary, the scenario highlights the scale of renewable deployment and system transformation required to meet climate and energy security objectives. Under the 1.5°C Scenario, the share of electricity in global total final energy consumption (TFEC) would rise from around 23% today to approximately 35% by 2035 and over 50% by 2050.

However, expanding renewable energy capacity does not automatically ensure a stable and resilient power system. As the share of variable renewable energy rises, power systems face a growing flexibility gap: a structural mismatch between the need for balancing the supply and demand, frequency regulation, voltage support, and reserve services, and the declining capability of retiring fossil fuel assets to provide them. In the US state of California, for instance, the independent system operator CAISO curtailed 3.4 million megawatt hours (MWh) of utility-scale wind and solar power in 2024, a 29% increase year-on-year, largely due to insufficient system flexibility and transmission constraints (US EIA, 2025). The so-called duck curve for solar photovoltaics (PV) – where high daytime solar generation reduces net load, followed by a steep increase in the evening as solar output declines– becomes more pronounced, while net load swings widen and system inertia declines. These issues are not marginal; they are central to maintaining power system reliability.

Additionally, the energy transition differs across regions and economies, as access to energy-related investment and the deployment of infrastructure remain concentrated in some major emerging economies (IEA, 2026b). Crucially, 85% of global renewable energy investment benefited less than 50% of the world's population as of 2024 (IRENA, 2024). These disparities are further compounded by rapid demand growth from data centres (including AI applications), accelerating transport electrification and industrial decarbonisation. These trends are reshaping electricity demand patterns and increasing system complexity, requiring electricity systems to be more flexible, reliable, affordable, secure and adaptable to rapidly changing conditions.

Against the evolving energy landscape, energy storage has evolved from a supporting technology into a key enabler of the energy transition. In this context, the "Storage+" paradigm has emerged as an integrating framework connecting multiple sectors of the global economy. It extends beyond conventional roles in the power system related to power generation, grids, and loads, demonstrating diverse innovative applications. These applications include, but are not limited to, the use of energy storage to support data centres (including for AI), microgrid and off-grid configurations, bi-directional energy flows between the power grid and electric mobility (including electric vehicles, vessels and aircraft), and the decarbonisation of high-emission, energy-intensive industrial settings, such as renewable industrial parks and smart mining operations.

Importantly, these diverse applications are not limited to wealthy or well-connected regions. Their modular and decentralised nature makes them inherently suited to bridging the very investment and access gaps highlighted earlier. In other words, the technical flexibility of "Storage+" is not an end in itself; it can also support a just energy transition.

"Storage+", together with smart grids and variable renewables, is an active, cross-sectoral enabler that provides the flexibility needed for resilient modern energy systems. Its applications are increasingly diverse and geographically widespread. "Storage+" can provide the resilience needed for large-scale utility grids, while simultaneously supporting industrial hubs, transport corridors, distribution networks and remote microgrids.

Since 2010, utility-scale as well as distributed solar PV and energy storage have experienced significant cost reductions. The levelised cost of energy (LCOE) from utility-scale solar PV has fallen by around 90%, while the costs of utility-scale battery storage have declined by 93% (IRENA, 2025). Meanwhile, the costs of LFP batteries have declined by around 80% per kilowatt hour (kWh) over the past decade, driven by continued technological innovation, economies of scale, and advances in research and development (IEA, 2024a). These cost reductions have greatly improved the commercial competitiveness of batteries.

While "storage" refers to the physical infrastructure and technologies that provide temporal flexibility to the energy system, "Storage+" represents the integrated systemic paradigm where storage, integrated with renewable sources and demand response, enables cross-sectoral flexibility to support decarbonisation, digitalisation and grid resilience. Therefore, "Storage+" is viewed as an architecture, an ecosystem and a comprehensive solution rather than as a single product category. It is the key approach required to redesign existing grids and markets – and build new ones – to accommodate higher shares of VRE while maintaining power system reliability and supporting climate objectives.

"Storage+" encompasses mechanical, thermal, electrochemical and chemical storage pathways suited to different applications and time scales. Pumped storage hydropower, thermal storage, hydrogen-based storage and other storage technologies can be important for longer-duration, including seasonal, needs. Battery storage has grown rapidly for short- to medium-duration applications (typically up to 8–10 hours), supported by its fast-response modular deployment and high round-trip efficiency. Technological advances are also expanding the potential of battery storage for longer-duration applications, although the appropriate technology depends on system requirements and local conditions.

High shares of VRE, particularly wind and solar power, introduce new operational requirements for power systems, including enhanced flexibility, improved co-ordination and adaptive system management. These requirements entail a transition towards a more modular but inherently more complex power structure. At its core, the primary challenge of the contemporary power sector is the widening structural gap between the escalating demand for system flexibility and the lack of the ability of legacy infrastructure to provide it. Increasing decentralisation requires further system changes. Therefore, grid transformation is not merely a consequence of the energy transition, but an essential enabler for renewables-based energy systems to provide stable, reliable and resilient energy supply.

The future power system will evolve into a sophisticated "system of systems" that relies on robust co-operation between transmission and distribution networks connecting diverse energy sectors, with grid operators serving as core enablers and facilitators of integrated system operation (ENTSO-E, 2022). Aligning with this view, the term "grid" in this report is conceptualised as a structurally layered system. This structural complexity spans multiple voltage levels and physical configurations, from high-voltage backbones and cross-border interconnects to distribution networks and microgrids.

Recognising this shift from a centralised to a more decentralised architecture is noteworthy, as power systems are moving away from traditional supply-side models towards more dynamic approaches that co-ordinate variable generation with demand. The growing contributions of VRE and distributed resources require greater operational flexibility, supported by energy storage, demand response, advanced forecasting and digitalisation. Flexibility is therefore becoming a core requirement for maintaining reliable and efficient power systems. Flexibility means shifting the focus from static load-following to dynamic, digitalised balancing of supply and demand in order to compensate for ageing, inflexible assets.

Energy storage is becoming an important operational asset in the shift towards renewable energy and flexibility. Globally, this necessitates an evolution in regulatory asset classification. Across major transitioning markets, traditional electricity legislation often forces renewable energy storage into legacy binary categories of either "supply" or "demand" – a structural mismatch that introduces market-entry barriers, double taxation of electricity flows, and compliance ambiguities via potential double counting of renewable energy. To resolve these challenges, modern regulators are considering frameworks that recognise storage as a distinct asset class in its own right, ensuring clear regulatory accountability for bi-directional energy flows.

Storage can strengthen system integrity by adding flexibility across time and sectors. It supports system stability and the balancing of supply and demand, while enabling greater integration across the power, transport and industrial sectors. Storage can also strengthen grid resilience and, when combined with appropriate control and islanding capabilities, support local energy systems in maintaining critical operations during wider system disruptions.

Achieving a stable grid involves more than technical capacity. Attaining power system stability in systems with high shares of renewable energy requires regulatory frameworks that explicitly value stability services such as frequency and voltage control. As VRE penetration increases, traditional capacity-based planning becomes insufficient to manage temporal mismatches between supply and demand. Therefore, regulatory design must evolve to incentivise both flexibility and system stability across multiple dimensions of the power system.

When conventional fossil fuel power plants retire, the fundamental requirements for frequency regulation, voltage control, reactive power compensation, oscillation control, system inertia and black-start capability do not simply vanish from the system architecture. Instead, these services require a regulatory environment where they can be transformed and re-integrated within a widely digitalised and modular architecture. One primary challenge lies in designing and facilitating the enabling frameworks necessary to manage this systemic shift, ensuring that the grid remains resilient, and thereby enabling reliable, affordable and equitable access to renewable electricity services.

The "Storage+" approach reflects a shift from the traditional view of energy storage as mere hardware towards becoming a strategic tool. By re-imagining storage and flexibility not as a stand-alone product but as a foundational architecture for a high-renewable energy future, this framework integrates fragmented energy ecosystems into a cohesive, systemic whole. This report examines how this approach can support the transition towards renewables-based energy systems and economies.

Chapter 3 investigates the "Why" behind this systemic shift and explores four emerging trends that are reshaping global energy demand and grid architecture: grid transformation, AI and digital infrastructure, transport electrification and industrial decarbonisation. The chapter first explains how integrated storage solutions deliver dynamic power supply-demand balance and satisfy the grid's structural operational needs, laying a solid foundation for stable grid operation. Building on this, the chapter further explores innovative "Storage+" applications across three emerging end-use sectors: 1) AI infrastructure expansion, 2) transport electrification and 3) industrial decarbonisation.

Chapter 4 shifts from the drivers of change to the mechanics of implementation, focusing on the "How". It details the specific roles, technical requirements, and "Storage+" application scenarios and bridges strategic logic with operational practice, pairing enabling conditions of both policy and technical frameworks with best practice case studies. The objective is to demonstrate how renewables and energy storage systems in combination deliver maximum system value in diverse environments.

Chapter 5 translates these cross-sector discussions into a comprehensive set of policy recommendations, covering guidance across four key dimensions: planning and regulatory frameworks, standards and interoperability, market design and revenue certainty, and international co-operation. These recommendations are designed to create enabling environments required to institutionalise the flexibility paradigm provided by storage, renewables and demand response. The recommendations further support climate mitigation goals and a just energy transition for all.

3. ENERGY TRANSITION TRENDS AND THEIR APPLICATIONS IN THREE END-USE SECTORS

The global energy transition is being shaped by technological progress, changing market dynamics and enabling policy environments. On the supply and delivery side, grid transformation provides the foundation for the energy transition by creating electricity systems that are more flexible, resilient and capable of integrating higher shares of renewable energy. Building on this foundation, three major end-use sectors – AI infrastructure expansion, transport electrification and industrial decarbonisation – are reshaping electricity demand and creating new requirements for system flexibility.

These three end-use sectors represent major structural shifts in energy consumption and electrification. They are creating rapidly growing demand for flexible electricity systems and illustrating how the role of "Storage+" is evolving beyond traditional energy shifting.

AI infrastructure expansion is reshaping demand profiles and system operation; transport electrification is linking mobility and power systems; and industrial decarbonisation is driving demand for flexible low-carbon energy solutions. Together, these sectors demonstrate that the role of "Storage+" extends beyond balancing renewable electricity. Storage is increasingly becoming an enabling infrastructure that connects power systems with emerging electricity-intensive sectors, creating new opportunities for cross-sector integration and system flexibility.

3.1 Grid transformation

As the global energy transformation accelerates, centralised energy grids, which have served as the backbone of electricity infrastructure for decades (Aoun *et al.*, 2024), are facing increasing pressure due to surging demand for system flexibility. While the centralised grid model was historically effective, the current energy landscape is transitioning towards a modular, decentralised architecture, in which VRE and flexibility are system-defining. By shifting towards a multi-directional architecture, decentralisation helps integrate diverse renewable energy assets while addressing the inherent limitations of localised legacy infrastructure.

According to IRENA (2026f), renewable energy is projected to account for around 92% of global electricity generation by 2050, while representing an installed capacity share of around 93%. This profound shift towards renewables signals an opportunity to transform the inherited architecture of centralised generation. Systems and markets should increasingly be designed around flexibility

rather than relying on inflexible baseload operation, which is becoming more of a burden than an asset for stability.

A flexibility-centred power system requires additional sources of flexibility and stability services. Energy storage, demand response and dispatchable renewable generation can provide flexibility across different time scales. Grid-forming technologies can support inertia and voltage control as the contributions from conventional synchronous generation decline. Grid-forming technologies and decentralisation can contribute to power system resilience. One application of grid-forming technology is grid-forming storage, which refers to battery storage equipped with inverter controls that establish voltage and frequency references and support stable operation in low-inertia systems (Chen, X. *et al.*, 2025). Decentralised architectures can also improve resilience by enabling local resources to respond more flexibly to system conditions. These approaches can operate alongside other flexibility options, with the appropriate combination shaped by local power system conditions.

GRID-FORMING STORAGE AND MAIN GRID STABILITY

Modern renewable generation and energy storage systems connect to the grid through power electronic inverters and are therefore classified as inverter-based resources. Grid-forming inverters allow these resources to establish voltage and frequency references and support stable grid operation (Bahrani *et al.*, 2024). Inverter-based resources equipped with grid-forming controls can operate as grid-forming assets.

Energy storage supports this transformation by storing excess generation for peak demand hours while delivering key stability services. As power systems integrate higher shares of variable renewables, maintaining system stability becomes critical to the energy transformation (IEA, 2024b). Equipped with grid-forming inverters, battery storage actively establishes grid voltage and frequency. This capability provides essential synthetic inertia in grids with limited synchronous generators.

Grid-forming storage can support selected stability functions that historically have been associated with synchronous generators. In particular, it can contribute to three key system services: synthetic inertia, frequency and voltage support, and black-start capabilities (Chen, Y. *et al.*, 2025).

- **Synthetic inertia:** As inverter-based resources replace synchronous generators, power systems have less inertia from the kinetic energy stored in rotating masses (ENTSO-E, 2020). This can reduce inherent inertial response and make frequency change faster after disturbances, increasing the rate of change of frequency concerns (Hashimoto *et al.*, 2023). Grid-forming storage can emulate part of this inertial response by injecting or absorbing active power rapidly (Hashimoto *et al.*, 2023). Grid-forming resources are designed to support voltage and frequency during disturbances, which can improve frequency stability in low-inertia systems (Kikusato *et al.*, 2023).

- **Frequency and voltage support:** Grid-forming storage can contribute to frequency and voltage support by operating with voltage-source behaviour. Grid-forming inverters establish their own voltage reference and adjust power output according to frequency and voltage deviations (Zhang *et al.*, 2021). This capability is relevant in weak-grid or inverter-dominated areas, where effective voltage-source behaviour can improve grid strength and small-signal stability (Wang *et al.*, 2024).

- **Black-start capabilities:** Black start refers to the restoration of an electrical power system following a total or partial shutdown. The renewable energy transformation requires system operators to reconsider how this service can be provided without fossil fuel black-start units (Pan *et al.*, 2025). Grid-forming storage can contribute to restoration because grid-forming inverter control can establish voltage and frequency references in de-energised network sections. This allows selected feeders, microgrids or critical loads to be energised in stages (Jain *et al.*, 2020).

One early attempt to codify this shift is Germany's 2026 regulatory framework (Bundesnetzagentur, 2025), which introduced explicit remuneration for synthetic inertia provided by energy storage systems and synchronous condensers, recognising it as a distinct system function. Spain has also adopted a Royal Decree to strengthen power system resilience through enhanced system monitoring, voltage control, energy storage deployment and electrification (MITECO, 2025). Furthermore, flexibility encompasses a broader range of mechanisms, where demand-side flexibility enables industrial and commercial loads to adjust their electricity consumption in response to grid conditions and to support system balancing. These mechanisms strengthen system-wide flexibility and help renewables-based power systems balance supply and demand in real time through co-ordinated storage, responsive demand and digital grid control.

RESILIENCE IN MICROGRID AND OFF-GRID SYSTEMS

Microgrids provide one architecture through which distributed generation, energy storage and controllable loads can be co-ordinated in remote communities or commercial/industrial operations (IEA, 2024c). By enabling these resources to operate in a co-ordinated manner, microgrids can enhance the resilience of decentralised power systems (Muhtadi *et al.*, 2021). When connected to the main grid, microgrids can support local flexibility and manage distributed resources. During grid disturbances, they can operate in an islanded mode to maintain electricity supply to selected critical loads, subject to the availability of local generation, storage and appropriate control systems.

Storage plays a key role in enhancing resilience in decentralised architectures (IEA, 2024a). Grid-forming storage with flexible renewables (*i.e.* biomass, hydro, geothermal) and sector coupling (*i.e.* heat pumps, electric vehicles) can contribute to power system stability. IRENA (2026d) highlights that energy storage and other flexible and distributed sources are playing an increasingly important role in providing system services, including balancing supply and demand and grid-stability services such as frequency and voltage support. In this context, technologies at the grid interface are becoming integral to the operation of modern power systems.

In remote and weak-grid areas, microgrids and off-grid energy systems can provide reliable electricity where conventional grid expansion is technically or economically challenging. Solar PV paired with battery storage can supply essential power around the clock to households, schools, and health centres, as well as support agricultural activities and telecommunication services. This is particularly relevant in many countries in Sub-Saharan Africa, where access to electricity remains limited or grid supply is unreliable, as well as in island states and conflict-affected areas. By reducing reliance on imported fossil fuels, these hybrid systems can lower energy costs and improve system reliability, while reducing exposure to price volatility, import disruptions and grid failures.

In grid-connected distributed settings, smart scheduling and behind-the-meter storage can aggregate local assets into distributed flexibility resources, helping to reduce peak demand and improve VRE

integration (IRENA, 2019b). These resources can also complement microgrid operation by providing additional flexibility during normal grid conditions and supporting local resilience during external disturbances. Storage can transform localised nodes into active and resilient energy clusters capable of maintaining independent operation during external disturbances.

3.2 AI infrastructure expansion

As AI adoption accelerates across sectors, the resulting growth in computing demand is placing increasing pressure on energy infrastructure. Industry stakeholders increasingly recognise that electricity availability is becoming a critical constraint on AI expansion. According to the International Energy Agency (IEA, 2025a), global electricity consumption from AI data centres reached around 415 TWh in 2024 and is projected to double to around 945 TWh by 2030.

In the United States and other key markets, a main bottleneck is grid interconnection and power availability for AI data centres. Lawrence Berkeley National Laboratory (LBNL, 2025) shows that the time required for power projects to reach commercial operation has increased significantly. Median interconnection timelines have risen from less than two years for projects built in 2000-2007 to over four years for projects built between 2018 and 2024. These infrastructure constraints are becoming a global phenomenon: from Northern Europe to South-East Asia, hyperscale data centre clusters requiring gigawatt-level electricity supplies are frequently outpacing local grid infrastructure. Consequently, the pace of AI advancement is increasingly influenced by grid access, power availability and the speed of grid modernisation – as well as by the strategic deployment of energy storage.

The rapid deployment of AI and VRE is accelerating the transformation of legacy infrastructure, creating new technical requirements that legacy power systems are no longer able to meet. Three technical challenges are particularly apparent:

- **Large load transients:** Certain AI data centre loads can be characterised by rapid and large-scale power transients, (Ginzburg-Ganz *et al.*, 2026). Large-scale AI training workloads operate through graphics processing units (GPUs) with tightly synchronised computational cycles, during which GPU power consumption can swing from peak to idle within milliseconds (Jensen *et al.*, 2026). These high-frequency power spikes generate substantial load transients that legacy infrastructure was not designed to accommodate, leading to significant voltage instability and potential equipment stress.

- **Need for continuous power supply:** AI training workloads generally require continuous, around-the-clock power supply, which is increasingly secured by a diversified energy portfolio that includes wind, solar and storage rather than legacy baseload generation. The integration of VRE with dispatchable renewable generation can help meet growing electricity demand and improve supply continuity. Within this framework, storage bridges the gap between VRE generation and the constant power demand of AI compute loads, thus allowing modern clean energy systems to achieve the exceptional reliability and regulation capacity expected by advanced digital infrastructures.

- **High rack power density:** The step-change increase in the rack power density of information technology (IT) – shifting from the kilowatt-scale power requirements of traditional IT racks to the substantially higher demands of GPU-intensive AI systems – redefines data centre architecture. This density leap places extensive strain on localised power distribution. The

concentration of high electrical loads within individual racks places greater demands on local power distribution infrastructure, often times exceeding the capacity of existing on-site systems. Managing these concentrated electrical loads involves re-imagining back-up power architectures, where integrated storage serves as the stabilising component for high-density operations.

BESS, combined with flexible renewable energy and demand response, emerges as a critical enabling technology with a lower cost and rapid deployment compared to alternative energy sources. By deploying behind-the-meter generation and storage, AI data centres are evolving from passive consumers into self-sufficient "energy islands" or pro-active microgrids. In this context, storage can serve as a high-speed buffer that helps align variable renewable generation with continuous electricity demand, while demand response and grid-interactive operation can allow AI data centres to shift loads, reduce peak stress and potentially provide flexibility services to the public grid.

However, this deep integration introduces operational vulnerabilities, particularly regarding cybersecurity. The transition to "Storage+" in AI infrastructure increases exposure to the attack surface for malware and co-ordinated cyberattacks targeting power management. Addressing these risks entails the systemic deployment of zero-trust communication protocols, robust encryption and decentralised edge computing nodes capable of autonomous island operations.

Furthermore, the rapid upscaling of AI infrastructure highlights a growing challenge in global resource allocation, where rapid AI expansion must be balanced against broader sustainability and equity principles. As highlighted by Aczel *et al.* (2026), the concentrated energy and water demand of hyperscale AI data centres risks a resource crowding-out effect on local communities and agriculture. To prevent this digital expansion from encroaching on regional capacities, modern policy frameworks can integrate circular economy principles, such as repurposing waste heat for district heating and adopting water-free cooling technologies. Such approaches aim to minimise the localised ecological footprint while requiring load entities to bear the cost of grid upgrades to safeguard multi-sectoral resource equity.

3.3 Transport electrification

Electric mobility has evolved from a niche market into a rapidly expanding segment of global transport. Global sales of electric cars, including passenger and commercial vehicles, surpassed 20 million units in 2025, accounting for roughly one-quarter of all new vehicle sales worldwide. Reflecting this continued market expansion, the global stock of electric vehicles (EVs) is projected to reach around 510 million by 2035, supported by improved affordability and increasingly stringent emissions and fuel economy requirements (IEA, 2026a).

The transition is now scaling across the maritime and aviation sectors. Although battery-electric aviation remains at an early stage, a nine-seat electric aircraft with a flight range of around 450 kilometres has completed successful test flights, and a 4-tonne civil electric aircraft was successfully tested in 2024 (IEA, 2025d). In the maritime sector, battery-electric ferries have entered commercial operation, with vessels capable of carrying around 200 passengers and 30 vehicles over distances approaching 38 kilometres on a single charge (CINEA, 2024).

As transport electrification accelerates, EV batteries are creating a growing pool of distributed BESS resources. These resources can interact more flexibly with the power system through smart charging,

where appropriate charging infrastructure, interoperability standards, market arrangements and bi-directional capabilities are in place. "Storage+" can facilitate this interaction by co-ordinating stationary storage, renewable generation, smart charging and, where applicable, vehicle-to-grid (V2G) solutions. By shifting charging to periods of lower demand or abundant renewable generation, these integrated solutions can reduce peak load pressures, increase the use of renewable electricity and provide additional system flexibility. Transport electrification therefore represents both a growing source of electricity demand and, under appropriate enabling conditions, a potential flexibility resource.

V2G configurations operate as a foundational decentralised pathway for unlocking the storage potential of transport batteries, enabling bi-directional power flows between vehicles and the grid while supporting renewable energy integration, grid stability and broader system flexibility (Shariff *et al.*, 2019; Mojumder *et al.*, 2022). This decentralised model is typically implemented through two primary approaches: aggregators, which consolidate large numbers of EV batteries into virtual power plants (VPPs) to provide co-ordinated and dispatchable flexibility while enhancing grid resilience (Roy *et al.*, 2024), and smart metering solutions, which empower individual owners to optimise charging and discharging behaviours based on real-time price signals and grid conditions.

Beyond these decentralised operational models, centralised battery storage applications are also emerging as complementary storage resources in applications such as fleet depots and battery swapping stations. By consolidating charging demand within managed facilities or separating batteries from vehicles, these applications enable centralised battery management, improve charging co-ordination and enhance renewable energy integration in transport operations. Together, these approaches transform transport batteries from passive electricity consumers into flexible energy assets, strengthening the integration between mobility and the power system.

- **Depot-based energy management for electric fleets:** In North America, electric fleet depots are increasingly adopting centralised charging infrastructure and energy management approaches to support large-scale fleet electrification. By co-ordinating charging demand across multiple vehicles, these systems improve operational efficiency, facilitate renewable energy integration and create opportunities for future integration with stationary storage and smart energy management solutions (NACFE, 2024).

- **Battery-as-a-service and swapping infrastructure for electric fleets:** In Japan, battery-as-a-service models supported by battery swapping infrastructure are being explored for commercial EV fleets (Hampel, 2025). By separating battery ownership from vehicle operation, this model enables centralised battery management, allowing batteries to be independently scheduled, maintained and optimised while reducing operational constraints associated with fleet electrification (WEF, 2025).

While both decentralised V2G and centralised battery storage applications present notable value, the practical transition from localised deployment to system-level integration remains constrained by infrastructure, technical and battery management challenges. The cost of bi-directional charging infrastructure, interoperability requirements and communication complexity continue to hinder broader system integration. Realising this potential, however, requires widespread deployment of V2G compatible vehicles and chargers, multiparty interoperable communication protocols, as well as supportive testing regimes, regulatory frameworks, and financial incentives (IEA, 2026a).

Integrated BESS solutions act as an essential enabler for the large-scale grid deployment of transport-integrated storage systems. Within V2G systems, battery-powered vehicles operate as integrated "load" or "source-load" units, allowing existing transport batteries to serve as distributed storage assets and thereby potentially reducing the need for dedicated stationary storage investments. Intelligent storage dispatch resolves the spatial-temporal mismatch of renewable electricity generation and transport energy demand and mitigates the grid impact of uncoordinated charging (Owens, Miller and Gençer, 2022). Consequently, integrated storage – whether on-vehicle or in swapping stations – acts as the cornerstone that stabilises the grid, optimises battery utilisation and improves the overall economics of transport-integrated storage.

Building on these operational improvements, a mature circular economy provides systematic solutions to the long-term sustainability of transport-integrated storage systems. Closed-loop recycling and second-life re-use further cut the upfront capital expenditure required for transport-integrated storage infrastructure. These approaches also help preserve residual asset value to offset the potential cell degradation costs associated with V2G cycling. The systematic integration of battery recycling, second-life applications and alternative chemistries such as sodium-ion technologies within circular loops will bridge fragmented cross-industry standards and form consistent evaluation criteria for all battery stakeholders. The closed-loop tracking and maintenance mechanisms inherent to circular systems also standardise full-lifecycle battery monitoring and degradation control, resolving the long-standing challenge of fragmented battery asset management.

3.4 Industrial decarbonisation

Decarbonising energy-intensive industrial sectors – in particular, hard-to-abate industries such as steel, aluminium, mining, paper and pulp, and chemical production – is an important challenge to overcome for the energy transition. Although the electrification of less-energy-intensive industries can also contribute to emission reductions and provide flexibility to the energy system, hard-to-abate industries require particular attention due to their higher energy intensity, scale and technological challenges. These hard-to-abate industries are responsible for a large share of global greenhouse gas emissions: in 2022, the industrial sector directly emitted 9.0 gigatonnes of carbon dioxide (CO_2), or around one-quarter of the total CO_2 emissions from the energy system (IEA, 2024a). The scale and intensity of these operations create conditions in which conventional grid-based solutions are often insufficient, giving rise to structural and operational constraints.

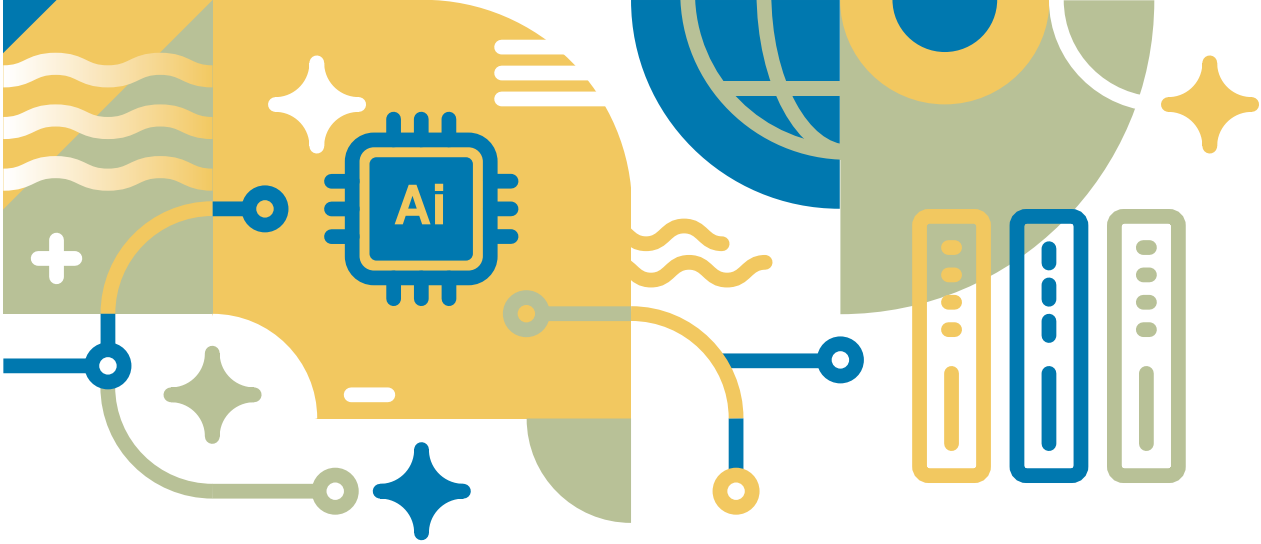
These constraints arise from both the characteristics of existing power systems and the technical demands of heavy industry. Existing legacy grids remain carbon intensive – limiting the potential for industrial decarbonisation – and often lack sufficient physical capacity to supply the high and continuous power demand required by heavy industrial processes. Heavy equipment frequently requires megawatt-scale start-up power, generating transient load spikes that legacy or remote grids cannot reliably accommodate. Sudden voltage sags can result in key production losses, such as molten materials solidifying in furnaces.

Integrating energy storage with co-located wind and solar generation addresses these challenges by buffering instantaneous shocks, smoothing output and creating a reliable, firm generation for 24/7 operations (Li *et al.*, 2017). In regions with inadequate infrastructure, the combination of storage and renewables – particularly storage systems with long-duration discharge capability, grid-forming functionality and flexible deployment characteristics – is already proving to be an economic solution.

- **Industrial self-generation in grid-constrained regions:** In Pakistan, unreliable grid supply and rising electricity prices are accelerating industrial investment in renewable energy integrated with battery storage. Typical commercial and industrial solar-plus-storage projects achieve payback periods of four to six years (Isaad and Shah, 2025), while some leading industrial deployments have reportedly reduced investment payback to less than two years under favourable market conditions (Jilani, 2025).

- **Renewable-powered remote industrial operations:** In Chile, mining companies are increasingly deploying solar-plus-storage systems to replace diesel generation in remote operations. Reported projects have achieved around 40% reductions in energy costs while improving energy security and operational reliability, demonstrating the commercial competitiveness of storage-enabled industrial decarbonisation (Hirpara, 2026).

These cases demonstrate that the driving force for industrial decarbonisation is no longer primarily regulatory – it is increasingly commercial. As "Storage+" achieves record-low costs, it has become a compelling business case for enterprises. By bypassing grid bottlenecks, renewables with integrated storage are emerging as a competitive solution for industrial decarbonisation schemes in many contexts.



4. INNOVATIVE APPLICATIONS OF "STORAGE+"

4.1 Building the foundation: Grid-forming resilience, smart microgrids and virtual power plants

THE ROLE OF ENERGY STORAGE

Energy storage can support flexibility and resilience across different power system configurations, from large-interconnected grids to microgrids and off-grid systems. Its specific role depends on system conditions and local needs. Across these configurations, three functions are particularly relevant:

- **Stabiliser of frequency and voltage (virtual inertia):** As thermal generation retires, grids lose the innate physical resilience once provided by synchronous generators. Storage serves as the primary mechanism through which grid-forming services such as synthetic inertia, voltage support and frequency regulation are maintained and remunerated. In main grids, storage provides the large-scale synthetic inertia required to prevent wide-area blackouts. These services have become the structural precondition for grid stability. Within microgrids and off-grid systems, grid-forming storage underpins stable autonomous operation by establishing primary voltage and frequency references independently of any legacy centralised network. This allows industrial sites, remote communities and island systems to function autonomously off the main grid, while maintaining the seamless option to reconnect and trade energy when grid conditions are favourable.

- **Enabler of system flexibility:** Storage supports flexibility on both the supply and demand sides, across centralised and distributed systems. Storage can act as a flexible resource within virtual power plants (VPPs), while digital aggregation platforms co-ordinate distributed assets such as batteries, rooftop PV, electric vehicle charging and flexible loads. By aggregating decentralised assets, storage transforms passive consumption into active demand-side flexibility, allowing the main grid to balance VRE influxes without the need for new infrastructure. Within microgrid and off-grid configurations, storage acts as a strategic reserve to mitigate peak demand and smooth internal load fluctuations, thereby minimising energy costs and enhancing the overall economic viability of renewable integration.

- **Core asset for system resilience:** Beyond daily balancing, storage supports system resilience by contributing to black-start restoration. Equipped with grid-forming capability, storage can facilitate the restoration of critical loads as part of a co-ordinated system restoration process after major outages. In microgrids, storage can also support islanded operation, helping to maintain critical services and localised energy security during external disruptions.

ENABLING CONDITIONS FOR "STORAGE+"

POLICY AND REGULATORY ENVIRONMENTS

As the penetration of VRE increases within power systems, leveraging utility-scale storage to mitigate this source of variability and maintain grid stability requires formal policy recognition of the systemic value of flexibility. Four enabling regulatory policies should be considered:

First, national planning frameworks should institutionalise the value of energy storage through flexible regulation. Regulatory frameworks should also recognise storage as a distinct asset class, with appropriate grid tariff and taxation. Additionally, frameworks should assess large-scale grid flexibility demands to establish dedicated operational pathways for diverse storage technologies, particularly grid-forming assets capable of autonomous stabilisation.

Second, market designs and regulations should enable grid-forming BESS participation in ancillary services markets, ensuring that the stabilisation value provided to the main grid translates into quantifiable revenue streams. In markets with existing ancillary frameworks, policy adaptations could grant comprehensive access to storage assets. In emerging or legacy markets, regulatory authorities could introduce specialised trading commodities that define uniform technical standards and transparent pricing mechanisms for storage-driven voltage support, frequency regulation and system stabilisation.

Several markets are beginning to recognise synthetic inertia and grid-forming capabilities as valuable system services, increasingly supporting them through explicit remuneration and dedicated incentive frameworks

- In Germany, the Federal Network Agency (Bundesnetzagentur, 2025) introduced a dedicated procurement framework for inertia as a stand-alone system service through decision BK6-23-010. Since January 2026, German transmission system operators have procured *Momentanreserve* (instantaneous reserve) through a technology-neutral mechanism open to both synchronous and inverter-based assets, including grid-forming BESS.

- In the United Kingdom, the National Energy System Operator (NESO) has procured stability services through the Stability Pathfinder 2 programme awarding long-term contracts in 2022. Under this framework, grid-forming BESS and synchronous condensers are eligible to provide short-circuit level, inertia and system strength services traditionally supplied by thermal generation.

- In Australia's National Electricity Market, grid-forming capabilities are incentivised indirectly through system strength obligations, network support contracts and avoided remediation costs. Projects capable of self-remediating their impact on weak grids can reduce connection-related costs, making grid-forming BESS commercially attractive while supporting higher renewable penetration and grid resilience.

In other markets, grid-forming BESS integration is driven by commercial considerations, without the need for dedicated subsidies.

Third, energy market designs, policies and regulations should enable long-term risk-hedging arrangements for storage projects– including long-term power purchase agreements, tolling agreements and contracts for difference – stabilising long-term revenue expectations to catalyse large-scale capital investment. Concurrently, technical compliance frameworks should unify base-level grid access performance requirements, mandating that all utility-scale storage installations possess autonomous grid stabilisation and post-fault emergency power restoration capabilities.

As a supplementary layer to main grid resilience, administrative authorities can optimise and simplify the interconnection and regulatory approval processes for microgrid projects that demonstrate proven emergency back-up and autonomous island operational capabilities. Lowering the administrative barriers could lead to enhanced localised risk mitigation and to more rapid power restoration post-disaster.

Fourth, through international co-operation, the current gap in broad stakeholder awareness regarding the systemic value and technical capabilities of storage can be addressed. This can be accomplished through targeted capacity building initiatives that communicate the comprehensive value proposition of storage assets to policy makers and project developers. Collaborative frameworks can foster cross-disciplinary professional training and joint technical research and development, facilitating the cross-border and cross-sectoral exchange of grid modernisation practices to strengthen systemic flexibility and grid transformation capabilities.

TECHNICAL REQUIREMENTS

To achieve grid flexibility and reliability through energy storage, power systems require autonomous voltage and frequency stabilisation capabilities, ensuring stable power delivery across main grid, microgrid and isolated off-grid regions. This capability is realised primarily through grid-forming control technology and supplemented by black-start functionalities. Concurrently, systems can deploy digitalised co-ordinated scheduling platforms to orchestrate and integrate distributed solar PV, charging infrastructure, and flexible industrial loads, aggregating them into unified, flexible resource complexes that collaborate with power grids to maintain dynamic supply-demand balancing.

CASE STUDIES

MAIN GRID LEVEL

Case **01**

Remuneration and incentivisation of grid-forming services at the utility scale in Spain

Lower system inertia increases operational complexity and system costs, as smaller disturbances can trigger faster frequency deviations and more frequent activation of ancillary services. As a result, synthetic inertia and grid-forming capabilities are increasingly being recognised as valuable system services.

In Spain, inertia is not yet remunerated as a stand-alone operational service. However, recent storage support schemes recognise grid-forming capability at the investment stage by allowing higher eligible thresholds for capital expenditure and granting additional evaluation scores for BESS with grid-forming functionality. These measures provide indirect incentives for advanced stability-support capabilities even in the absence of dedicated operational remuneration. Spain's support schemes are administered by the Institute for Energy Diversification and Saving (Instituto para la Diversificación y Ahorro de la Energía, IDAE) under the Strategic Project for Economic Recovery and Transformation (PERTE) and the European Regional Development Fund (FEDER).

A concrete illustration is the El Matorral hybrid solar plant in Gran Canaria, which combines 8.25 megawatts (MW) of solar PV with a 4.2 MW lithium-ion BESS. The projec received approximately USD 6.3 million (EUR 5.6 million) in IDAE funding under Spain's Recovery, Transformation and Resilience Plan, is designed to provide grid-forming and stability-support services to enhance the reliability of the Canary Islands' isolated electricity system. It demonstrates how incentives at the investment stage can support the deployment of grid-forming BESS even in the absence of dedicated operational remuneration (Endesa, 2025).

Case study contributed by: Enel Green Power.

Case **02**

Pumped storage hydropower supporting grid flexibility in Croatia (RHE Velebit)

Hydropower remains the largest source of renewable electricity worldwide, and pumped storage potentials globally are huge. In Croatia, the Velebit Reversible Hydropower Plant (RHE Velebit) is one of the country's most important energy storage facilities and a notable example of successful long-duration non-battery energy storage. Commissioned in 1984 near Obrovac, the pumped storage facility has a generating capacity of 276 MW and a pumping capacity of 240 MW. The plant operates between the upper reservoir Štikada and the lower reservoir Razovac on the Zrmanja River.

RHE Velebit functions as a large-scale "water battery". During periods of low electricity demand or high renewable generation, excess electricity is used to pump water to the upper reservoir. When demand rises, the stored water is released through reversible turbines to generate electricity. This allows the plant to store surplus renewable energy and provide electricity when it is most needed, while also supporting grid stability through frequency regulation and balancing services.

The project demonstrates significant economic benefits. By shifting electricity from low-demand to high-demand periods and reducing renewable energy curtailment, RHE Velebit improves the efficiency and flexibility of the Croatian power system. Its continued operation for more than 40 years highlights the long lifespan and durability of pumped storage hydropower compared to many alternative storage technologies.

Beyond energy storage, the reservoirs support water supply for parts of northern Dalmatia and provide opportunities for recreation, including fishing and cycling. Environmentally, the plant facilitates greater integration of renewable energy sources, helping to reduce reliance on fossil fuel-based balancing generation and supporting Croatia's long-term decarbonisation objectives.

Case study contributed by: Climate Action Network (CAN).

Case **03**



Increasing the penetration of renewable energy sources through grid-forming BESS in China

The Gertse project in northwest China combines a 30 MW solar PV plant with a grid-forming energy storage system (6 MW / 24 MWh). Built at an altitude of around 4 600 metres, where the grid is significantly weak, the project is the first grid-forming energy storage facility designed for this application, using BESS to support renewable energy integration.

Prior to the addition of the grid-forming BESS, the facility's main challenge was the weakness of the grid. Before the BESS was installed, the output of the solar PV plant was limited to only 1.5 MW to avoid oscillations and power quality degradation. The commissioning of the BESS helped to stabilise both voltage and frequency, providing synthetic inertia and voltage support. The storage system raised the PV output to 12 MW, showing how grid-forming BESS can unlock more renewable generation in a constrained network.

Notably, the power conversion system (PCS) units demonstrated fault ride-through capability, staying connected and delivering three times the rated apparent current within 10 metres. This is key for maintaining stability in weak grids with a large share of integrated solar PV or wind. Due mainly to the high altitude of the site, the Gertse project has recorded instances of more than 30 major grid disturbances over a 10-day period. However, the system maintains stable operation, demonstrating the value of grid-forming BESS for enabling higher renewable penetration in weak-grid systems in harsh, high-altitude conditions.

Case 04 Business demand turned into grid-friendly assets through market mechanisms: Enel X in South Australia, Australia

Enel provides an example of how business demand can participate in electricity markets as a remunerated flexibility resource. Through its demand response platform Enel X, the company aggregates the flexible load of commercial and industrial clients – manufacturing facilities, water utilities, refrigeration systems, and heating, ventilation and air conditioning (HVAC) – and bids that flexibility into wholesale electricity and ancillary services markets. Businesses participate by temporarily reducing consumption or switching to back-up power during grid stress events and are compensated for availability as well as delivered load reductions. This mechanism allows businesses to participate in electricity markets and receive compensation for providing flexibility without changing their electricity retail structure.

In Australia, Enel X provides around 30% of the total frequency reserves and contributed to reducing ancillary services prices following its entry into the market. At the system level, aggregated demand response can help defer grid investment, reduce renewable integration costs and strengthen resilience during stress events.

The benefits extend to different actors. Businesses can generate additional revenue by providing demand-side flexibility, while grid operators gain access to fast-response resources that can help balance the system. Consumers may benefit from reduced price volatility, while demand response can support the integration of higher shares of variable renewables. With 9 GW of flexible capacity managed across 18 countries, Enel X provides an example of how aggregated demand response can operate in markets where regulations allow aggregators to participate on behalf of commercial and industrial consumers.

Case study contributed by: Enel X (World Business Council for Sustainable Development).

Case 05 Battery storage enables high penetration of renewable energy in California, United States (International Solar Energy Society)

In May 2023, the US state of California published its clean energy transition plan (State of California, 2023) for meeting the state's goal of 100% clean electricity by the year 2045, set by a landmark policy decision in 2018 known as SB 100 (California Energy Commission, 2025).

Rapid solar expansion, however, worsens California's duck curve, creating sharper net load swings and higher curtailment of renewable energy. In 2024, the state's grid operator CAISO curtailed 3.4 million MWh of utility-scale wind and solar generation, a 29% increase compared with the previous year, largely due to lack of flexibility and other transmission constraints (US EIA, 2025). These developments demonstrate that renewable energy deployment alone is insufficient to ensure system reliability. As power systems become increasingly renewables-based, storage, demand response and grid-forming technologies are needed to incentivise flexibility resources.

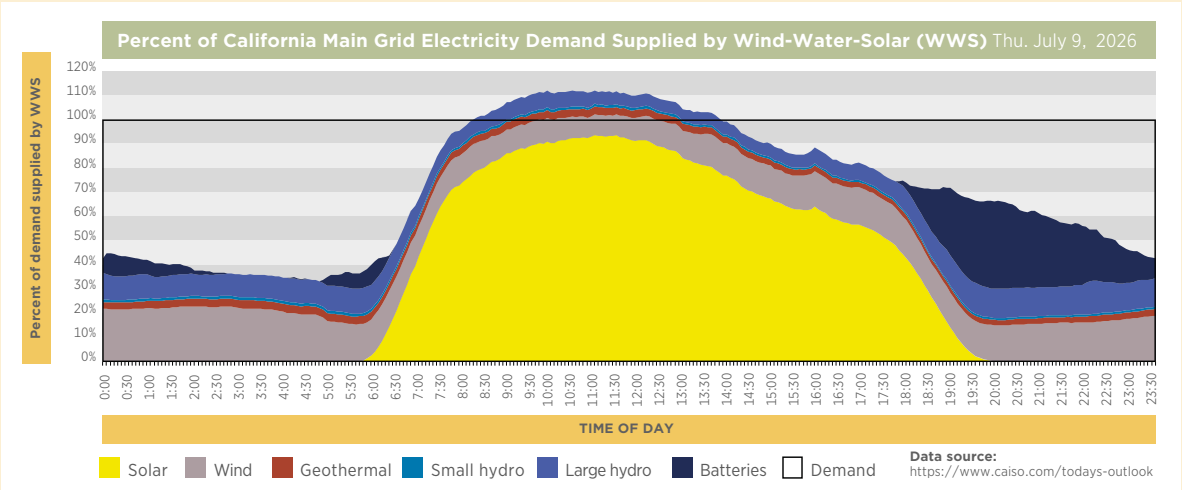
Key to achieving the SB 100 target will be to add 145 000 MW of clean energy resources to the grid. The plan's implementation is supported by strategies to greatly improve energy efficiency, expand the use of electric vehicles, and upgrade and strengthen transmission and distribution grids. New generation capacity will come entirely from renewables (solar, onshore and offshore wind, and very small amounts

of biomass and geothermal) coupled with battery and long-duration energy storage. Batteries are a key enabler for achieving a 100% clean electricity system, allowing for firm PV power to be delivered to the grid 24/7.

California has already made significant progress towards the SB 100 target. The state has more than 55 500 MW of installed solar capacity, including utility-scale and rooftop solar (SEIA, 2026). In May 2026, solar produced a reported 51% of California's electricity (McCarthy, 2026). This expansion has been supported by battery storage installed across the state, enabling greater integration of solar generation into the electricity system. CAISO operates around 80% of California's wholesale electricity flow and provides real-time and day-ahead information on generation across its network. As of June 2026, CAISO reported 17 023 MW of installed battery storage in its system (CAISO, 2026).

Battery storage can supply stored solar electricity after sunset and reduce the need for fossil fuel generation during these periods. Thus, solar power generation in California has already outproduced generation supplied by natural gas for every month in 2026 (McCarthy, 2026).

Professor Mark Jacobson of Stanford University, who developed a 100% renewables scenario* for California that relies almost entirely on wind, water, and solar resources with battery storage, posted in mid-2026** that, based on CAISO forecast data, these technologies had exceeded 100% of electricity demand on 86% of all days that year as of 9 July, averaging 5.6 hours/day. Battery storage is playing a significant role in these extraordinary statistics for a large grid system, as shown in the graphic below for 9 July 2026.



* The scenario was developed for the 2024 IRENA Coalition for Action report titled 100% renewable energy scenarios: Supporting ambitious policy targets (IRENA, 2024).

** https://www.linkedin.com/feed/update/urn:li:activity:7481389647693127680

Case **06**

Distributed storage and virtual power plants in South Australia, Australia

In Australia, over 44% of detached homes have rooftop solar, with penetration exceeding 50% in Queensland and South Australia (IEA PVPS, 2025). This presents unique challenges including reverse power flows in the distribution network and negative daytime demand.

In this highly distributed system, small behind-the-meter batteries and virtual power plants are emerging alongside grid-scale storage as a key component of the energy mix. Naturally complementary to distributed solar, household batteries store daytime energy at the source, reducing stress on the grid, and can be deployed rapidly at scale without the delays associated with connecting grid-scale infrastructure.

In 2020, the Australian Energy Market Operator (AEMO) ran trials that included 7 000 batteries at eight different virtual power plants that demonstrated that the VPPs could reliably provide energy arbitrage and frequency control ancillary services in real market conditions (AEMO, 2021). The trials also pioneered advanced integration of VPPs with the distribution network to dynamically optimise dispatch capacity within the technical limits of the network (SA Power Networks, 2021).

In mid-2025, the Australian government moved to accelerate uptake of behind-the-meter batteries, introducing subsidies for small batteries with VPP capability as a requirement. In the following six months, Australia added 160 000 new behind-the-meter batteries with aggregated capacity of almost 3.6 gigawatt hours (GWh), achieving growth rates exceeding 400 MWh/month (CEEW, 2026).

Australia aims to add a further 40 GWh of behind-the-meter batteries by 2030, offering a compelling vision for the role that small-scale distributed storage can play in shaping the energy transition.

Case study contributed by: World Wind Energy Association.

Case **07**

Grid-forming storage solution in the Peruvian Amazon, Peru

The Peruvian Amazon rainforest presents a complex energy landscape. Remote communities across this vast region have long grappled with weak grid infrastructure and chronic power instability, where frequent outages severely disrupt daily life and constrain economic development. The dense jungle terrain makes grid expansion technically challenging and cost-prohibitive, leaving residents with inadequate or unreliable electricity access. This energy deficit limits educational opportunities, compromises healthcare delivery, and stifles local business activities, perpetuating poverty in a region already marginalised by geography.

Environmental challenges in the region are just as significant. The tropical climate of the Amazon involves persistent humidity, heavy rain, and extreme temperatures, all of which demand high-performance energy infrastructure. Meanwhile, the region's ecological sensitivity precludes reliance on diesel generation – the conventional off-grid fallback – which requires costly, logistically complex fuel transport along river systems while posing significant environmental risks to one of the planet's most biodiverse ecosystems.

In response to these challenges, grid-forming BESS systems with varying system capacities have been deployed across three remote Amazon sites: San Lorenzo (2.5 MW/5 MWh), Caballococha (7.5 MW/15 MWh) and El Estrecho (2.5 MW/5 MWh). The systems combine black-start capability and grid-forming functions with smart dispatch to support the integration of solar generation and storage. By reducing reliance on diesel-based power supply, the project helps lower the environmental and logistical pressures associated with fuel transport in the rainforest. The project now supports more reliable renewable electricity access for around 200 000 residents, with potential benefits for education, health care and local economic activity.

Case **08**

Red Sea microgrid powered by solar PV and supported by grid-forming BESS in Saudi Arabia

The Red Sea Project is a large off-grid renewable energy development along Saudi Arabia's Red Sea coast that supplies electricity to a tourism development and associated infrastructure (Huawei, 2026). Its energy system combines 400 MW of distributed solar PV with a 1.3 GWh grid-forming BESS. Biodiesel generators are retained for emergency back-up.

Because the project is electrically isolated from the Saudi national grid, the microgrid is designed with grid-forming capabilities to maintain stable islanded operation. The BESS provides fast-frequency and voltage support, while solar PV supplies daytime loads and charges the batteries for use after sunset. The system also supports black start, transformer energisation and fault ride-through. Its black-start process co-ordinates more than 400 power conversion system (PCS) units to reduce circulating currents and accelerate system restoration.

The project's electrical network includes a 110 kV underground ring with five sub-stations and three smaller islanded grids serving resort areas, the airport and utility loads including desalination and wastewater treatment. The system has operated stably since October 2023, and the wider integrated utilities project reached full commercial operation in September 2026 (ACWA Power, 2026).

Case study contributed by: Huawei.

4.2 "Storage+" with AI: Data centres equipped with storage

THE ROLE OF ENERGY STORAGE

In AI data centre applications, energy storage may contribute to back-up power provision and load management, particularly where electricity demand is large, continuous and sensitive to interruptions. However, energy storage should be assessed not only at the facility level but also in relation to wider grid conditions and public electricity supply. High-quality power supply provided by storage serves four key functions:

- **Protection from grid disturbances:** Energy storage shields sensitive AI training clusters from frequency and voltage fluctuations, reducing the risk of momentary interruptions and allowing back-up generators sufficient time to start during extended outages.
- **Buffering load transients:** Storage acts as a high-speed buffer for extreme load transients generated by synchronised GPU operations, preventing the "compute-crash" scenarios discussed in section 3.2.
- **Peak demand reduction:** Through active peak shaving, storage can smooth abrupt demand spikes and make AI data centre load profiles more predictable for grid operators.
- **Faster access to power:** When combined with on-site generation, storage can help data centres start operations earlier while awaiting grid connection. The 24/7 renewable commitment: Storage can strengthen 24/7 renewable electricity strategies by improving the temporal matching between variable renewable generation and continuous AI data centre demand.

ENABLING CONDITIONS FOR "STORAGE+" WITH AI

POLICY AND REGULATORY ENVIRONMENTS

AI data centres have growing and diverse power demand. Certain AI training workloads will generate extreme load fluctuations that can compromise grid stability or trigger system collapse. Unleashing the full potential of BESS in AI data centres requires that:

- **National top-level energy planning explicitly defines the development targets for flexible grid-regulation resources,** in alignment with the long-term, high-growth power demands of the AI industry.
- **Policy frameworks incentivise large-scale BESS deployment, encouraging data centre parks to adopt behind-the-meter or other developer-procured capacity models.** Such measures lower the capital expenditure of self-built storage for enterprises through subsidies and market-based revenue mechanisms, fostering a more favourable investment and construction environment for project developers.

- **Policy frameworks streamline the permitting and grid-interconnection procedures for energy storage projects.** For example, regulatory bodies can establish fast-track approval channels for storage projects and introduce flexible grid-interconnection protocols specifically tailored for data centres. Priority grid access could be also provided to data centres that offer flexibility and other grid supporting services.

TECHNICAL REQUIREMENTS

Driven by a surge in rack power density and severe load fluctuations induced by GPUs, AI data centres feature massive and highly volatile power loads. This imposes stringent requirements on power stability and continuous, reliable operation, requiring BESS to deliver corresponding baseline capabilities. On one hand, storage systems need to interface seamlessly with the high-power distribution architectures of data centres. Systems can ensure uninterruptible emergency power supply during grid outages through technical topologies such as high-voltage direct current (HVDC) direct-coupled back-up configurations. On the other hand, storage systems need to leverage unified, intelligent energy orchestration platforms to dynamically smooth the severe, rapid power load fluctuations caused by computing equipment, thereby guaranteeing the stable and secure operation of the entire data centre.

CASE STUDIES

Case **09**

31 MW / 62 MWh data centre co-located BESS supporting grid in Hillsoboro, Oregon, United States

Data centre buildout in the local grid is expected to increase peak power demand by 20% per year. The local utility faces significant challenges in connecting new loads to the grid, resulting in considerable delays for data centre projects, where time-to-power is critical for business operations. In addition to connection times of several years, the traditional approach of strengthening the grid would have involved excessive grid investment costs and disputes around cost sharing. By investing in a co-located 31 MW / 62 MWh BESS the data centre operator was able to connect to the grid several years faster than it could have been able with the traditional grid buildout approach and also saved significant costs in grid upgrade and expansion. The BESS helps balance the data centre's electricity demand through energy arbitrage, charging during periods of low prices and oversupply, and discharging when demand and prices are high. It also offers ancillary services to the local grid operator.

As a result, a win-win solution was created: The data centre operator was able to connect to the grid years earlier than it would otherwise have been able to, while BESS offers it backup power, and the arbitrage and ancillary services bring additional revenues for the data centre. The grid operator was able to avoid high investment costs and lengthy construction and connection times, while also receiving grid balancing and stabilising services.

Case **10**

Data centre co-located BESS supporting a grid with a high share of wind power in Dublin, Ireland

Microsoft's data centre in Dublin, Ireland, operates in a grid characterised by a high share of wind power, causing fluctuations in the electricity supply-demand balance, market prices, and grid frequency. As the share of wind power has grown, the amount of traditional rotating turbine generation has decreased, further increasing the frequency control challenge.

Microsoft started exploring the opportunity to upgrade its backup batteries (usually designed for short-term emergency needs to ensure power supply and quality) to also provide services to the local grid operator. The data centre's co-located BESS supports the grid in terms of both balancing and frequency control. It arbitrages between high- and low-price periods, thus helping balance supply and demand partly caused by fluctuating wind power generation. It also provides ancillary services for frequency control, helping the grid operator keep the grid stable. As peak power is largely provided by fossil fuel-based generation, the arbitrage function also partly replaces this generation, reducing fossil fuel use and thereby CO_2 emissions.

4.3 "Storage+" with transport: The evolution of mobile energy assets

THE ROLE OF ENERGY STORAGE

Transport electrification positions batteries as an expanding network of mobile energy storage assets across the transport sector, demonstrating rapid market maturity in road transport while scaling through advanced pilot applications in the maritime and aviation sectors. As the deployment of these mobile storage assets expands, their role is evolving beyond transport application towards more co-ordinated and system-level energy participation. Transport batteries can increasingly be managed individually or as aggregated fleet, integrated into wider energy systems to provide flexibility services, with bidirectional charging emerging. By absorbing renewable electricity surplus during generation peaks and, in some cases, discharging during periods of high demand, these mobile assets provide system-level flexibility and generate revenue through grid services, reducing the net lifetime cost of electrification for fleet operators and individual users.

ENABLING CONDITIONS FOR "STORAGE+" WITH TRANSPORT

POLICY AND REGULATORY ENVIRONMENTS

As a mobile, distributed storage and regulation resource, transport energy storage operates across regions characterised by diverse grid load profiles, VRE infrastructure, distinct electricity market rules and heterogenous vehicle operational models. These factors necessitate a co-ordinated development framework that harmonises policy standards with technological evolution.

With "Storage+", electric vehicles transition beyond traditional transport tools to serve as distributed mobile storage resources with dispatchable, bidirectional power flow and significant grid flexibility capabilities. Meanwhile, the transition from individual vehicle-to-grid pilots to large-scale deployment drives market penetration and stakeholder cultivation. Unleashing the full potential of storage in transport electrification requires that:

- **Policy frameworks accelerate standards interoperability and enhance V2G grid-connection compliance and standards systems.** Regulatory bodies can unify technical standards for V2G interaction and interconnection safety, grant electric vehicles full market access rights to ancillary services markets, and establish robust safety management and metering compliance rules for reverse power flow.

- **Policies institutionalise streamlined processes, simplifying approvals for V2G charging stations and lowering market entry barriers.** Concurrently, targeted incentive frameworks can support demand-side aggregators in exploring commercial V2G paradigms, leveraging demonstration project incentives to facilitate the strategic upgrade from single-vehicle V2G to co-ordinated, utility-scale vehicle fleets.

- **Market-based revenue mechanisms for bi-directional charging and discharging are enhanced, enabling electric vehicles to capture value by providing grid services.** Regulatory frameworks can implement tiered, time-of-use, and scenario-specific pricing and settlement architectures. These mechanisms allow electric vehicles to generate economic returns through active provision of grid flexibility, thereby reducing total cost of ownership and lowering storage participation barriers for users.

TECHNICAL REQUIREMENTS

To transform automotive batteries into revenue-generating, mobile assets for grid flexibility, technical frameworks must drive the continuous upgrading of battery cells, while maximising the multi-scenario adaptability of BESS and expanding the foundational infrastructure. The transport industry will need to scale up the deployment of bidirectional charging infrastructure, complemented by the development of multi-scenario adaptable battery application systems and battery swapping paradigms. By establishing flexible, high-efficiency energy interaction networks between vehicles and grids, technical architectures empower large-scale EV fleets with the operational capacity for synchronised provision of grid flexibility and optimised peak shaving and valley filling.

CASE STUDIES

Case 11 "Vessel-Shore-Cloud" integrated solution in maritime electrification applications in Asia, China and Viet Nam

To address key barriers to maritime electrification – including high upfront investment costs, limited charging infrastructure and operational complexity – an integrated "Vessel–Shore–Cloud" solution was introduced in China in 2025, combining electric propulsion systems, shore-based energy infrastructure and cloud-based energy management to co-ordinate energy scheduling across vessels and ports. The solution was first deployed by CATL and has since been applied across a range of electrified maritime applications, including battery-swapping cargo vessels and ferries, hybrid PV–battery offshore support vessels and high-frequency ferry services.

By 2025, the solution had supported the deployment of nearly 900 electric vessels in China, with pilot projects expanding into overseas markets. A subsequent application includes the BESS for the world's first 3 000-tonne-class all-electric inland container ship, scheduled to operate in Viet Nam. These deployments demonstrate how integrated storage ecosystems can improve operational efficiency while lowering barriers to the large-scale adoption of electric shipping.

Case 12 BESS integration for high-power electric bus charging infrastructure in India

A pre-feasibility study conducted in 2022 evaluated the integration of a BESS into high-power electric bus charging stations in the cities of Surat and Rajkot in Gujarat, India, where municipal authorities are scaling public e-bus fleets and associated charging infrastructure. The system design addresses operational challenges arising from high peak charging loads, limited distribution capacity and weak commercial frameworks for behind-the-meter battery storage participation in grid service markets.

The modelled configuration comprises a lithium-ion LFP liquid-cooled BESS (3 088 kW / 4 751 kWh), supporting twelve 180 kW direct current (DC) fast chargers and an on-site renewable energy capacity of 325 kW (expandable to 650 kW). The system is designed to manage a peak charging demand of around 3 003 kW, with load concentration during daytime and nighttime charging windows creating significant stress on local distribution infrastructure. From a financial perspective, high upfront capital expenditure for BESS deployment, combined with relatively low EV tariffs and demand charges in Gujarat, limits immediate cost competitiveness under a business-as-usual scenario.

To improve system feasibility, the study proposes a multi-value-stack approach, where the BESS provides peak shaving, reduction of sanctioned load requirements, renewable self-consumption, back-up power and power quality support. Under optimised configurations, including higher renewable penetration or the use of second-life batteries, the system demonstrates improved economic viability through reduced grid dependency and enhanced use of on-site renewable energy. The case illustrates how storage can enable scalable electrified public transport systems while mitigating grid stress in high-density urban charging environments.

Case **13**

Solar-powered charging station for electrified bus rapid transit in India

The Indian city of Ahmedabad operates around 200 electric buses for its bus rapid transit system, with an annual power consumption exceeding 18 GWh. Reliant on overnight charging at two central depots, the fleet requires mid-day return trips to fulfil the 200-kilometre daily operational requirement, resulting in around 4 000 non-revenue mileage and around 600 non-productive fleet hours per day. Frequent unoptimised fast charging further raises concerns regarding battery degradation and charger-port wear. Financially, these inefficiencies translate into estimated losses of around USD 0.58 (INR 55) per kilometre in non-revenue mileage, amounting to around USD 0.84 million (INR 80 million) annually.

To address operational inefficiencies and financial losses inherent in depot-centric e-bus charging models, the Ahmedabad Municipal Corporation (AMC), with support from the CapaCITIES II project, piloted an on-route solar-powered charging station for the city's bus rapid transit fleet. The charging infrastructure is installed at the Regional Transport Office Junction and includes a 240-kW or 240 kW, same for 180-kW and 120 kW supported by robotic panel cleaning. The system enables mid-route "opportunity charging" for around 40 to 45 buses, reducing reliance on full depot returns while partially offsetting charging demand through on-site solar generation. Estimated impacts include the elimination of around 4 000 kilometres per day, a reduction of around 400 MWh and 170 MWh per year.

Positioned as a storage-ready transitional solution, the pilot preserves technical upgrade pathways for future system integration. A subsequent "Storage+" layer could integrate stationary or second-life BESS to buffer intermittent solar output, reduce grid peak demand, provide back-up power and enable participation in smart-metred building-to-grid grid service frameworks. This phased development approach enables incremental enhancement of grid-interactive capabilities while supporting scalable urban public transport electrification in emerging market contexts.

4.4 "Storage+" with industry: Integrated storage systems for industrial decarbonisation

THE ROLE OF ENERGY STORAGE

In industrial settings, the critical role of energy storage systems can be understood through three key contributions, which require a combination of short-duration and long-duration storage technologies to displace fossil-based back-up:

- **Integration of continuous operations:** Storage enables the inherent variability of renewable energy, thereby enabling its integration into industrial processes that demand a continuous, high-quality power supply and rigid load characteristics.

- **Maximising local resource value:** Storage enables industrial sites to maximise self-consumption of co-located renewable generation, greatly reducing and eliminating dependence on diesel generators or a high-emission grid.

- **Verified green credentials:** Beyond engineering, storage builds the traceability and verified credentials increasingly demanded by global supply chains under emissions disclosure and management.

ENABLING CONDITIONS FOR "STORAGE+" WITH INDUSTRY

POLICY AND REGULATORY ENVIRONMENTS

Fiscal incentives are needed to accelerate the deployment of industrial energy storage and drive deep decarbonisation. Unleashing the full potential of storage in industrial decarbonisation requires that:

- **Fiscal frameworks introduce a range of economic incentives to mitigate the initial capital expenditure pressures of deploying storage systems**. Targeted construction and operational subsidies can lower investment barriers, while regulatory updates can optimise transaction rules for storage participating in grid flexibility services, clearly defining and securing revenue streams for flexibility provision. Such approaches can substantially improve the economic returns of localised clean energy consumption.

- **Regulatory bodies establish fast-track grid-interconnection channels for industrial park projects that meet specified storage-to-capacity ratios,** streamlining permitting and technical compliance procedures to accelerate project commissioning.

- **Regulatory frameworks diversify project monetisation streams by institutionalising robust mechanisms for industrial storage participation in spot electricity markets, capacity leasing, and ancillary services,** thereby mitigating the industry-wide bottleneck of extended investment payback periods.

Further enabling measures could include:

- **Regulatory authorities establish a green electricity accounting framework tailored for localised storage-consumption models** to guide industrial parks to reduce procurement reliance on carbon-intensive electricity.

- **Policy frameworks officially recognise and issue Green Electricity Certificates (GECs) for local, storage-backed, self-generated renewable energy,** ensuring that enterprises' efforts in carbon reduction and renewable penetration receive certified regulatory compliance endorsement.

- **Targeted incentives and risk-sharing mechanisms for energy storage solutions in industrial applications.** Such solutions could help reduce the perceived and operational risk and can help build confidence among industry and technology providers, and support the wider deployment of such solutions.

TECHNICAL REQUIREMENTS

Technical implementations must rely on grid-forming energy storage capabilities. The objective is to engineer an industrial energy system that achieves deep decarbonisation rather than relying on compliance through carbon offsets. By deploying integrated "Storage+" architectures, technical systems deliver dual-mode switching capacities that support both off-grid islanded operations and flexible grid-connected interactions, enabling industrial parks to maintain autonomous, stable power supplies independent of the main grid or to execute seamless synchronised parallel operations. The system should use coordinated control platforms to balance electricity generation and demand in real time, while tracking renewable electricity use. Together, these capabilities would help maintain grid stability and provide reliable records of renewable electricity consumption. Additionally, the electrification of industrial heat, supported by technologies such as heat pumps and thermal energy storage, offers significant decarbonisation potential, although these applications fall outside the scope of this report.

CASE STUDY

Case **14**

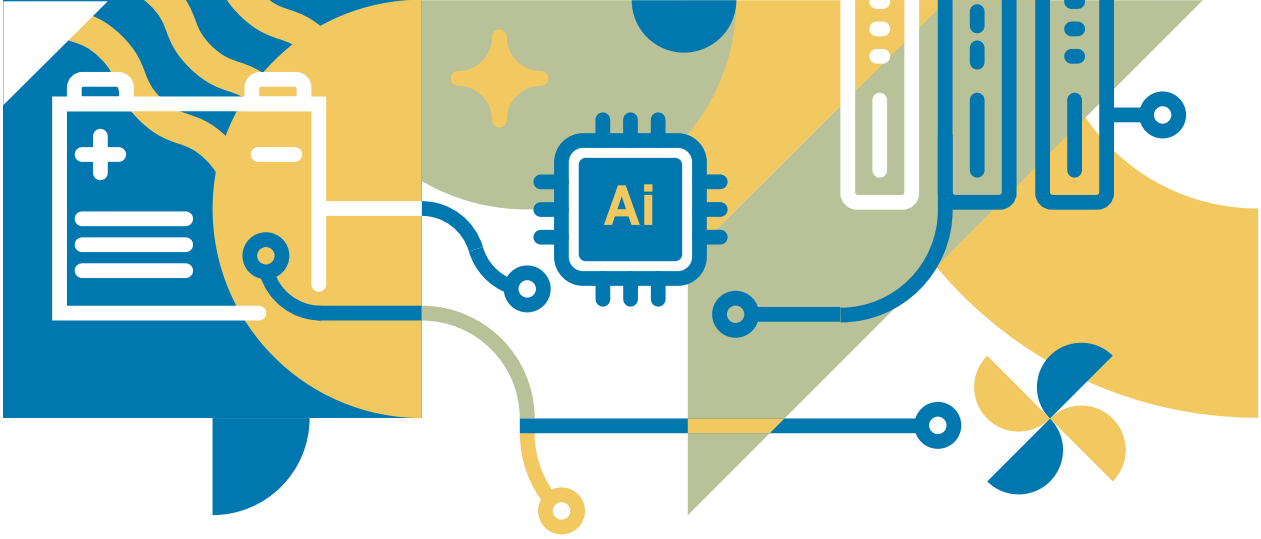
Renewable power direct connection in industrial parks: Grid-connected and off-grid systems in China

Industrial parks represent a core application scenario for renewable power direct connection, particularly in energy-intensive industries such as battery manufacturing, chemicals, steel and electronics. These parks typically exhibit stable but high electricity demand profiles, combined with urgent decarbonisation pressures and increasing requirements for carbon compliance in export-oriented production.

The Yancheng industrial park in Jiangsu Province, China addresses the challenge of integrating large-scale renewable electricity into high-load manufacturing while ensuring continuous and reliable power supply. This is achieved through an on-grid renewable direct connection model, where dedicated transmission lines link on-site renewable generation to industrial load centres. BESS is deployed to enhance renewable consumption and system flexibility, while smart energy management platforms co-ordinate renewable output with production demand. As a result, the park achieves over 80% renewable electricity supply, reduces carbon emissions by around 80%, and lowers electricity costs by more than 20%, while also enabling full carbon traceability for export-oriented products.

The Dongying industrial park in Shandong Province, China faces a more stringent challenge, namely the establishment of a fully renewable-powered industrial system without reliance on the public grid. This is realised through off-grid renewable direct connection architecture, combining wind and solar generation with large-scale grid-forming and long-duration energy storage systems. Advanced battery management and dispatching capabilities ensure stable operation under highly variable renewable supply conditions, enabling continuous power delivery to high-load industrial activities. The system achieves 100% renewable electricity supply and near-zero operational carbon emissions, demonstrating the feasibility of large-scale off-grid industrial energy systems.

Together, these cases illustrate two representative configurations of renewable power direct connection in industrial contexts: on-grid high-renewable industrial parks and fully off-grid renewable industrial systems, both enabled by integrated renewable generation, energy storage and intelligent energy management.



5. POLICY RECOMMENDATIONS

The preceding chapters have established that energy storage is a critical enabler of renewable-centred power systems. This report has highlighted how the broader Storage+ paradigm, with BESS as the most prominent technology, can accelerate renewable energy deployment and enhance system flexibility, provided that co-ordinated policy action is taken across four key areas:

Planning and regulatory frameworks: Energy storage lacks an independent institutional status in most national energy planning frameworks. Permitting pathways remain unclear, deployment targets are absent, and regulatory incentives tend to favour conventional grid expansion over flexibility solutions, placing storage at a disadvantage in infrastructure planning.

Standards and interoperability: Battery storage technologies are advancing faster than the technical rules governing them. Performance requirements for grid-forming inverters, bi-directional charging protocols, and methods for measuring and verifying renewable electricity differ across jurisdictions, preventing cross-market scale and the cost reductions that come with it.

Market design and revenue certainty: The core value that storage provides to the power system lies in flexibility, stability and availability. Yet many electricity markets have not established or fully developed procurement or pricing mechanisms for these services. Where markets do exist, rules restricting the combination of multiple revenue streams limit the income that storage projects can earn. As storage deployment scales, early revenue sources such as ancillary services payments are compressing rapidly, reinforcing the need for diversified and predictable income structures. Additionally, the lack of harmonised approaches to carbon accounting can make it more difficult to consistently quantify, compare and monetise the emission savings enabled by energy storage across different markets and applications.

International co-operation: Scaling energy storage will require stronger international co-operation and permanent knowledge exchange across national and regional planning and regulatory bodies, technical standards and market design. Regulatory and technical expertise remains concentrated in a relatively small number of mature markets, while many developing economies face capacity constraints alongside higher financing costs. Sharing experience, methodologies and regulatory approaches can help accelerate the development of national planning and enabling frameworks, support greater interoperability and alignment, and avoid unnecessary fragmentation. This is

particularly important as electricity markets and power systems become increasingly interconnected, requiring greater cross-border co-ordination on technical requirements, market rules and accounting and safety standards.

5.1 Planning and regulatory frameworks

Energy storage should be recognised as an independent infrastructure category in national energy planning, with a clear institutional status, predictable short permitting pathways, and a level playing field with conventional grid expansion, which will have to be replaced by smart and flexible grids designed for high shares of VRE.

- **Flexibility needs assessments:** Regulators should conduct periodic, qualified and quantified assessments of the flexibility requirements of power systems across multiple time horizons. These assessments have to provide the analytical foundation for setting storage deployment targets, informing deployment targets, designing market mechanisms and prioritising investment.

- **Grid-connection reform:** National regulatory authorities should review and reform connection-queue regimes and, where appropriate, move from first-come-first-served to a project readiness and grid-support capabilities approach. Such an approach prioritises projects with demonstrated construction readiness and/or advanced technical capabilities (grid-forming inverters and power system dampening, among others), and helps reducing the grid connection queue congestion caused by speculative or not sufficiently developed projects.Authorities should also identify acceleration areas or special economic development zones (SEZs) where permits and approvals are streamlined.

- **Elimination of double charges:** Regulatory authorities should ensure that storage systems are not subject to double network charges or double energy taxation arising from their classification as both consumer and generator. Storage should be treated as a single, distinct asset class for the purposes of network charging and taxation.

- **Flexibility procurement:** Regulatory frameworks should require grid operators to evaluate flexibility services and physical grid expansion on comparable economic terms. The tendency of regulatory frameworks to favour capital expenditure on network assets over operational expenditure on flexibility procurement should be addressed in order to ensure a level playing field across alternative solutions.

5.2 Standards and interoperability: Harmonising global frameworks for "Storage+"

Cross-border interoperability at key technical interfaces is a precondition for the global scale-up and continued cost reduction of energy storage. Unified accounting standards are equally essential to translate the environmental benefits of storage into verifiable economic value.

- Grid-forming inverter standards: International standards bodies and national regulatory authorities should align core performance and safety requirements for grid-forming inverters – covering frequency response, voltage support and black-start capability – so that grid codes and procurement specifications across jurisdictions can reference a common or similar technical baseline.

- Bi-directional charging protocols: Transport and energy regulators should adopt or promote unified, non-proprietary standards for vehicle-to-grid and battery-to-grid applications, building on ISO 15118-20. These protocols should cover charging infrastructure, battery swapping stations and modular storage facilities.

- Data security standards: Governments and standards bodies should pursue technical dialogue to develop shared data-protection and privacy requirements for digitalised energy systems. Common technical standards in this domain would build mutual confidence across jurisdictions and reduce friction in cross-border deployment of digitally connected storage and grid infrastructure.

5.3 Market design and revenue certainty: Unlocking the multi-service value of "Storage+"

Market frameworks should establish procurement and pricing mechanisms for the full range of system services that storage provides and offer investors long-term revenue predictability.

- **Market-based procurement for ancillary services:** Regulators should establish competitive, technology-neutral procurement mechanisms for the full range of system services that storage can provide, including fast frequency response, frequency regulation, spinning and non-spinning reserves, peak regulation, reactive power and black-start services. These markets should be accessible to aggregated distributed energy resources, including virtual power plants, electric vehicle fleets and residential battery storage. However, as storage deployment scales and ancillary services markets mature, revenues from these services alone may become insufficient or less predictable, justifying the need for diversified and longer-term revenue mechanisms.

- **Long-term revenue instruments:** Policy makers and regulators should establish enabling market and regulatory frameworks for technology-neutral long-term revenue mechanisms – such as competitive auctions, capacity markets, contracts for difference and revenue-floor agreements – to complement shorter-term market revenues and provide predictable investment signals that reflect storage's contribution to system flexibility and adequacy. For co-located renewable-plus-storage projects, regulators should streamline power purchase agreement structures and define metering and settlement rules for combined assets, including tariff arrangements for behind-the-meter self-consumption.

- **Carbon pricing and emission accounting:** Governments should ensure that carbon pricing and emission accounting frameworks recognise the emission reductions that energy storage can achieve, including through the integration of higher shares of VRE and the replacement of fossil fuel generation. Harmonisation of methodologies for measuring and verifying the emission impacts would support their consistent valuation across markets.

5.4 International co-operation: Catalysing the global "Storage+" transition through multi-sectoral synergies

Governments, multilateral organisations, development banks and industry should co-operate to address financing gaps and institutional capacity gaps simultaneously, facilitate the exchange of knowledge and experience, and support greater alignment of regulatory, technical and market approaches across jurisdictions.

- **Institutional knowledge transfer:** International organisations and experienced national agencies should support structured programmes sharing the regulatory, market design and grid code expertise required for storage integration. The objective is to build local institutional capacity, enabling countries to take ownership and to independently design flexibility-oriented planning frameworks, incentives, revenue mechanisms and technical regulations tailored to their power system needs.

- **Cross-border co-ordination:** As electricity markets become increasingly interconnected, greater co-ordination is needed among governments, regulators and system operators on grid codes, market rules and technical requirements. This can enable storage and other flexibility resources to operate across markets and to support interconnected power systems.

- **Technology co-operation and supply chain governance:** Governments, industry and international organisations should strengthen co-operation on harmonised technical standards for battery recycling, second-life performance specifications and material traceability across value chains. Technology licencing and joint manufacturing arrangements can broaden the geographic base of battery production capacity and value creation.

- **Financing and de-risking:** Multilateral development banks and international financial institutions should provide de-risking instruments such as concessional financing, guarantees and insurance products tailored to storage projects in developing countries, reducing the cost of capital to levels that support commercially viable deployment.

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