UNIVERSITY OF CAMBRIDGE
INSTITUTE FOR SUSTAINABILITY LEADERSHIP

Corporate Leaders Network

The New Power Couple

Decarbonising economies via renewable electricity and storage innovations

ACHIEVING ZERO

The University of Cambridge Institute for Sustainability Leadership

The University of Cambridge Institute for Sustainability Leadership partners with business and governments to develop leadership and solutions for a sustainable economy. We aim to achieve net zero, protect and restore nature, and build inclusive and resilient societies. For over three decades we have built the leadership capacity and capabilities of individuals and organisations, and created industry-leading collaborations, to catalyse change and accelerate the path to a sustainable economy. Our interdisciplinary research engagement builds the evidence base for practical action.

The Corporate Leaders Network for climate action

The Corporate Leaders Network (CLN) is convened by CISL and brings together business groups representing more than 450 businesses across the globe. These groups bring the voice of business to their governments to raise national levels of climate ambition and action, in line with achieving the targets of the Paris Agreement and in support of the aims of the UN High-level Climate Champions. CLN's model of change is underpinned by the 'ambition loop' whereby bold government policies and private sector leadership reinforce each other, and together take climate action to the next level.

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Foreword

Beverley Cornaby

Director, Policy and Systems Change Collaborations, CISL

The need to decarbonise the power sector across the globe has never been more urgent. Concentrations of carbon dioxide in the atmosphere are at the highest in at least 2 million years, and we've already reached 1.1 degrees Celsius of warming, creating unprecedented social and environmental challenges.[1] However, it is still possible to keep global temperature rise below 1.5 degrees and avoid the most catastrophic consequences of climate change.

For more than three decades, CISL has worked with businesses and governments to drive greater understanding of the impact of climate change on our economies and to support the key role the business sector can play in identifying and delivering solutions to global warming and increasing greenhouse gas emissions. I don't perceive any lack of ambition or willingness from the individuals and organisations we work with when addressing climate change. 8,600 influential leaders and business stakeholders completed our education programmes in 2021-2022. We have more than 450 businesses represented within our business groups in the UK, the EU and internationally. It is clear that businesses and the communities they service support climate action, demonstrated by over 8,000 companies taking part in the Race to Zero Campaign. Perhaps what is missing is the actions underpinning the ambition: the 'how' that needs to follow the 'what' and the 'why'.

We are ramping up our efforts to enable and incentivise businesses and policymakers to take tangible climate action. At COP27 in 2022, we relaunched the Corporate Leaders Network for climate action (CLN): an international cohort of business groups working together to share best practice, enable collaboration and increase ambition on climate. Multilateralism has always been central to climate action, but the geopolitical and economic challenges presented by events such as the war in Ukraine and COVID-19 render it more important than ever. The CLN will support the transition to a climate neutral economy through the 'ambition loop' model of change, whereby businesses action and advocacy spur ambitious national level government policy and accelerates efforts across the economy. It will provide a robust and action-oriented forum for international business co-operation on climate.

This briefing, *The New Power Couple: Decarbonising economies via renewable electricity and storage innovations*, is the first publication from the CLN. We have gathered ideas, lessons, innovations and insights from across the globe to provide real-world solutions to climate problems and build the capacity of CLN members to call for ambitious climate action. The briefing enables our members to learn from each other, sharing lessons from geographies including South Africa, Japan, Chile and the EU. It supports them in understanding steps that businesses could take to increase national ambition and align with international processes, including the agreed outcomes from meetings such as the G7 and international negotiation processes such as the United Nations Framework Convention on Climate Change.

We have an ambitious agenda for the CLN, and we welcome business networks from all regions of the world to join us and help shape our future activity. Our evidence-based thought leadership will always be developed in consultation with CLN members, connecting with CISL's key themes of people, nature and climate. It will focus on a range of topics calibrated to provide tangible, realistic measures to help businesses tackle the climate crisis.

If businesses bring the will, we'll help discern the way.

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Abbreviations

AI	Artificial intelligence
BESS	Battery energy storage system
BTM	Behind-the-meter
CAES	Compressed air energy storage
CB	Carnot battery
CISL	Cambridge Institute for Sustainability Leadership
CLN	Corporate Leaders Network
CO_2	Carbon dioxide
ES	Electricity storage
ESO	Energy Superhub Oxford
ESS	Electricity storage solution
EU	European Union
EV	Electric vehicle
FES	Flywheel energy storage
FOM	Front-of-the-meter
GES	Gravity energy storage
GHG	Greenhouse gas
GWh	Gigawatt-hour
HESS	Hybrid energy storage solutions
IRENA	International Renewable Energy Agency
KWh	Kilowatt-hour
LAES	Liquid air energy storage
LCOS	Levelized cost of storage
Li-ion	Lithium-ion
MWh	Megawatt-hour
NDC	Nationally determined contribution
PPA	Power purchase agreements
PHES	Pumped hydro energy storage
PTES	Pumped thermal energy storage
PV	Photovoltaic
R&D	Research and development
RE	Renewable electricity
SC	Supercapacitor
SMES	Superconducting magnetic energy storage
TWh	Terawatt-hour
VRE	Variable renewable electricity

Executive summary

Electricity storage solutions (ESSs) are a crucial component of the renewable power transition.

Investment and innovation are both growing rapidly: by 2030, energy storage installations around the world are projected to reach fifteen times the amount of storage that was online at the end of 2021.[2] However, the energy sector still faces a range of challenges, and the suitability of different types of storage depends on the geographical, political and economic circumstances of individual countries and regions. This business briefing explores these challenges in detail, and identifies five key recommendations for businesses and policymakers.

1. **ESSs should be tailored to the country context**. While 197 nations are united in the mission to mitigate climate change, they are each at different stages of the energy transition. Decision-makers can look at several indicators to identify whether and which type of energy storage is appropriate, including increasing ramping requirements for conventional power plants, high or spiking electricity production costs, high levels of renewable energy curtailment, regular local and/or regional power disruptions, and the presence of significant targets for renewable energy deployment or power sector decarbonisation.
2. **Electricity storage (ES) requires regulatory certainty**. Clear regulations, long-term grid planning, a level playing field with other resources, and a long-term direction of travel are all essential for establishing a conducive regulatory landscape.
3. **The storage sector requires an enabling financial environment for investment**. Cost, as well as *perceived* cost, can present significant barriers to investment in new technologies. Grants, subsidies, tax incentives and low-interest loans may help to reduce the risks associated with investing in new technology and encourage businesses to take a long-term view.
4. **Supply-side policies should be supplemented with demand-side management**. Government intervention, as well as distributed solutions deployed by businesses, can significantly enhance demand-side management. If end-users can actively participate in managing and balancing the grid then this will ease the burden on infrastructure and on grid operators, enabling the flexibility which is essential for achieving high levels of renewable electricity (RE) generation.
5. **Decision-makers must leverage cross-border synergies through international cooperation**. This can create regional 'power pools', allowing access to a greater variety of renewable resources, potentially reducing the need for ESSs and curtailment, while also enabling the deployment of a broader range of ESS options to meet extant storage needs.

To illustrate and explore these policy recommendations, the briefing **contains real-world examples and case studies provided by businesses** in the energy storage sector. It considers a range of technologies, including storage hydropower, liquid air energy storage (LAES), and Carnot batteries (CBs).

Fundamentally, the briefing examines how businesses and policymakers can utilise electricity storage (ES) technologies as a central component of a larger energy transition toolkit. In acting on these recommendations, both businesses and policymakers have instrumental roles: the former by investing and innovating and the latter by serving as a convening force and ensuring an enabling environment for investment and progress. Policymakers and businesses must continue to work in tandem to harness the potential of the ES sector, and the central role it can play in achieving net zero targets.

Introduction

To keep global heating below 1.5 degrees Celsius and prevent the most severe consequences of climate change, we must decarbonise the power sector. This means exchanging electricity generation from fossil fuels such as coal, oil and gas for low carbon and renewable technologies.

Businesses play a crucial role in facilitating decarbonised power as part of the transition to a net zero economy. Governments worldwide have committed to the Paris Agreement, supported by nationally determined contributions (NDCs) which outline each country's domestic mitigation plan. And while governments are faced with concurrent environmental, social and geopolitical challenges, businesses have the opportunity to take targeted action and lead the charge in the energy transition.

Action by businesses will spur more ambitious, relevant and enabling government policy and reduce the cost of low carbon technologies. This will, in turn, inspire more businesses to take action to support the energy transition. This 'ambition loop' of change will not only benefit the climate but also give businesses the advantage of identifying the early risks and opportunities and allow them to shape the dialogue on what regulations and policies are required to establish zero carbon and renewable energy technologies in a consistent and supportive business environment.

RE technologies will be central to the energy transition. The installation of RE technologies, such as wind and solar, is accelerating rapidly, adding new generation capacity alongside more established renewable technologies, such as hydropower. This trend is witnessed in every continent, and major economy, and recent estimates suggest that nearly 90 per cent of electricity generation could come from renewables by 2050.

The world is already moving towards a low carbon future in power generation. However, some questions remain: How quickly can this transition be delivered? Using which technologies? And who will benefit from the first mover advantage?

ES will be a key component of the transition to a fossil-free power sector. Storage is one of the most significant challenges in establishing reliable, predominantly renewable-based power systems. Intermittent sources such as solar and wind – which only generate electricity when the sun is shining, or the wind is blowing – need to be supplemented by storage and other generation technologies to guarantee supply. Otherwise, gaps in supply will lead to blackouts or brownouts, which will affect not only providers and consumers but also confidence in the ability of the power sector to successfully transition to a low carbon future.

This briefing examines a range of options specifically for RE storage, including the opportunities and challenges associated with each type of technology.

The appropriate combination of renewable power sources and storage depends heavily on the context and requirements of those generating and consuming the electricity. Wind, solar and hydropower are subject to seasonal variation and are influenced by geographical factors and local weather conditions. The same applies to storage: pumped hydro energy storage (PHES), for example, is suitable for predominantly hilly geographies with abundant freshwater resources (or, with the latest technological advances, access to seawater), whereas gravity energy storage (GES) requires access to large swathes of land. Many technologies, such as lithium-ion (li-ion) batteries, are expensive and require significant upfront investment and ongoing maintenance.

The efficacy of some of these storage solutions is affected by the maturity of the interlinked transmission and distribution networks, which may need to be changed or upgraded before they can be connected to renewable power supplies.

Regulatory clarity and stability are central to a successful energy transition.

In many countries, the politicisation of climate change has created a changeable regulatory environment, where laws and policies – and the willingness and ability of the administrations to pass and enforce them – shift according to the political cycle. Businesses and start-ups earnestly seeking to support the transition to renewable futures are competing on an uneven playing field with fossil fuels, which benefit from entrenched regulation and large market share. Regulatory certainty and a clear direction of travel will, in turn, create an enabling environment for investment in renewable technologies, thereby further accelerating the resources and options available in the decarbonisation of the economy.

Once the balance of RE sources and storage technologies is achieved, the next step is to move beyond the power sector and into the broader economy. If the power grid is fuelled with renewable energy and more energy uses across the economy are electrified, we can power vehicles and industrial operations and heat buildings without further contributing to climate change, incrementally transitioning all sectors of the economy to a low carbon future.

This briefing will examine the electricity storage landscape to outline the opportunities and challenges for businesses and policymakers, as summarised in table 1 below.

Table 1: Electricity Storage (ES) Landscape

Important Stakeholders in the power sector	Motivators for deployment of ES technologies	Challenges facing deployment of ES technologies	Trends and scope for innovation in ES technologies	Enabling policies that business should advocate for
• End-user (household, industrial and commercial) • Policy-makers/ministries • Regulators • Transmission Operators • Distribution operators • Generation companies (public, private, public-private, independent) • Retail trading organisations • Businesses • R&D organisations	• Integration of variable renewable electricity such as solar and wind power • First movers' advantage in developing technologies that will see a growth in demand • Participation in wholesale electricity capacity and ancillary markets • Creating stability in the business environment by ensuring uninterrupted electricity • Desire for self-sufficiency at household, local and national levels.	• Cost- upfront outlay required • Cost – uncertainty about how to ascertain short-term, mid-term and long-term cost and value of each ES • Cost- misconception of high cost pertaining to some technologies which have significantly come down • Outdated regulatory framework • Fragmented policy framework	• Growth in tried and tested technologies (pumped hydro storage, stationary batteries et al) • Growth in new technologies (hydrogen storage, gravity energy storage, thermal/Carnot batteries) • Development of hybrid storage solutions • Development of distributed storage solutions • Circular use of materials (such as reusing material from EVs)	• Tailoring storage solutions to systemic context • Providing regulatory certainty • Enabling environment for investment • Supplementing supply-side policies with demand-side responses • Leveraging cross-border synergies through international cooperation

Section 1

The international context

Economy-wide electrification and a parallel acceleration in RE generation are both important to meet internationally mandated decarbonisation goals. ESSs are essential for increasing renewable penetration and must be tailored to suit the contextual needs of a country.

1.1 The importance of electrification and energy security

Electrification is important for decarbonisation because it enables the phasing out of fossil fuels in many sectors of the economy, such as transportation, industry and buildings. This substitution will reduce greenhouse gas (GHG) emissions because electricity can be generated from renewable and low carbon sources, such as wind, solar, and hydropower.

When electricity is generated from these sources, it produces little or no carbon emissions. In contrast, the combustion of fossil fuels, such as coal, oil and natural gas, releases large amounts of carbon dioxide (CO_2) and other GHGs into the atmosphere. These emissions are the leading cause of anthropogenic climate change. By decarbonising the power supply and electrifying sectors that traditionally rely on fossil fuels, we can reduce our dependence on these sources and reduce emissions, which remains a crucial strategy to meet the world's climate goals.

195 countries worldwide have committed to the Paris Agreement, which seeks to limit global warming to 1.5 degrees Celsius.[3] Effective implementation of net zero targets is crucial to achieving the Paris Agreement goals: to stay below 1.5 degrees, carbon emissions must decrease to net zero by 2050, and other GHG emissions must reach zero by 2070.[4] However, the current policies do not deliver on these targets. While 33 countries[5] and a growing number of cities and businesses have made pledges to achieve net zero emissions, only 20 per cent[6] meet the minimum criteria for robustness set out by the UN Race to Zero Campaign.[7] Broadly, regulation and specificity[8] around net zero requirements is lacking, leading to a lack of credibility and consistency. According to analysis by the UN,[9] countries' NDCs, taken in aggregate, are still not sufficient to avoid catastrophic global warming.

In addition to wrestling with complex decarbonisation requirements, many countries have been contending with compromised energy supply: energy security has been hugely affected by geopolitical conflicts such as Russia's war in Ukraine and the COVID-19 pandemic; they have also had to endure disruptions in supply chains due to climate-related disasters (such as flooding and heat waves) and political actions (such as sanctions against Russia et al.), all of which have contributed to inflationary pressures and cost-of-living crises. This simultaneous occurrence of several catastrophic events has prompted significant business and policy development in relation to energy security and electricity supply. While it has been used as a justification for further investment in fossil fuels by countries such as the UK and Norway,[10] it is also being used as an opportunity to restructure and reform power sectors and electricity generation to safeguard both energy security and climate change commitments (such as the Inflation Reduction Act in the USA and the British Energy Security Strategy). These conditions present opportunities for incorporating novel elements, such as storage technologies, into the wider power sector to improve its adaptability and resilience.

1.2 The acceleration in installed renewable electricity (RE) generation capacity

Ever-growing decarbonisation commitments and obligations are transforming the world's energy system at an unprecedented rate. From January to September 2022, 77 gigawatts (GW) of new renewable auction capacity was awarded globally, mostly in solar photovoltaics (PVs) and wind. This is a 70 per cent increase from the same period in 2021,[11] indicating that many countries are ramping up the installation of low carbon electricity generation from renewable sources. By the end of 2022, global renewable generation capacity amounted to 3,372 GW, growing the stock of renewable power by a record 295 GW or by 9.6 per cent. An impressive 83 per cent of all power capacity added last year was produced by renewables.[12]

However, global trends and averages hide significant national-level variation. Substantial differences persist between different countries regarding the composition of the energy system (i.e. the share of electricity in total energy supply and demand) and the power mix (i.e. the share of renewables in the electricity sector). For example, in 2019, RE accounted for 28 per cent of Chile's total energy supply,[13] compared to 18 per cent in Japan,[14] 13 per cent in the UK,[15] 8 per cent in Australia,[16] and 7 per cent in South Africa.[17]

For the power sector, these figures vary even more. In 2021, 18 per cent of South Africa's installed electricity generation capacity was renewables, with the vast majority being solar generation. This is compared to 54 per cent in Chile, with hydropower being the largest source, followed by solar.

There is also variation in terms of where most of the new renewable electricity capacity is being installed: three-quarters of the new renewable electricity auction capacity in the first nine months of 2022 was accounted for by China and Europe.[18]

While the energy and RE landscape vary among these jurisdictions, the key trend among all contexts remains that the share of renewables is increasing at an accelerating pace. However, further progress is still needed if the countries are to decarbonise in line with international goals and carbon budgets within the stipulated timeframe.

Section 2

The importance of storage solutions

As RE underpins decarbonisation efforts, the annual rate of addition of capacity is expected to increase five-fold from 2020 to 2050, resulting in a 90 per cent fossil-free electricity supply under net zero scenarios by 2050, up from 29 per cent in 2020.[19]

As RE underpins decarbonisation efforts, the annual rate of addition of capacity is expected to increase five-fold from 2020 to 2050, resulting in a 90 per cent fossil-free electricity supply under net zero scenarios by 2050, up from 29 per cent in 2020.[19] In many countries, the potential of dispatchable renewables – such as hydropower, geothermal or bioenergy – is limited and their cost is higher. The renewable energy transition is thus often driven by wind power and solar PVs. Wind and PVs have characteristic features that are increasingly relevant with growing penetration because their generation patterns are both temporally and spatially variable: the generation of these sources varies across time, and good locations for wind and solar installations do not necessarily coincide with the historical grid layout.[20] They are not 'dispatchable', meaning that they cannot be powered on or dialled up, per the grid and end-user requirements. Therefore, the successful integration of variable renewable electricity (VRE) into the grid and the wider power and energy ecosystem means that effective ESSs are a key component for the renewable power transition.

Just how much storage capacity is required at increasing levels of RE penetration has received much attention in recent years. While the studies use a variety of models to assess the requirement and cost–benefit of ESSs, the consensus seems to be that storage requirements are reasonably low in the early stages of RE penetration but rapidly escalate as RE penetration reaches higher levels (>70–90 per cent, according to various estimates). Underestimating those needs could jeopardise the health, flexibility and functioning of the grid and subsequently adversely affect many businesses and sectors of the economy.

Ruhnau and Qvist (2022) formulated a system cost optimisation model based on a German 100 per cent renewable case study using 35 years of hourly time series data.[21] Their time series analysis supports the hypothesis that when considering storage losses and charging limitations, the period defining storage requirements extends to 12 weeks. For this longer period, the cost-optimal storage needs to be large enough to supply 36 terawatt-hours (TWh) of electricity, which is about three times larger than the energy deficit of the scarcest two weeks. A similar study estimates that in a 100 per cent RE penetration scenario, the UK will need 43 TWh of storage with 15 per cent curtailment (reducing electricity generation to match the difference in supply and demand).[22]

While most literature stresses that ESSs are elemental to increasing RE penetration, the returns can start to diminish as penetration approaches high levels. Therefore, a comprehensive understanding of the physics and economics of the future energy system is mandatory to build and operate an optimal ESS system.[23]

Other crucial motivations for storage solutions

Aside from the need to balance supply and demand and energy arbitrage for VRE, other motivators have been spurring the demand for ESSs.

- **First mover advantage as cost and performance improve:** Despite the current uncertainty in policy and regulation surrounding ESSs and the high cost of research and development (R&D) surrounding new technologies (as well as the lack of guaranteed returns or availability of other risk-mitigation mechanisms), many businesses realise that these solutions will gain traction as the transition to RE ramps up globally. Companies that have developed appropriate solutions will have a significant advantage and financial upside. Increased investment, adoption rates and technological advancements in the ES market have been driving down the price for many technologies (although not necessarily enough to make them commercially viable).

  Much of this cost improvement has been related to li-ion batteries, driven by expanding electric vehicle (EV) markets and related manufacturing economies of scale. Given the technology readiness levels, li-ion batteries are being deployed widely for grid-scale solutions, especially in the EMEA region (i.e. Europe, the Middle East and Africa),[24] and in mega economies such as India and China. This is happening regardless of whether they are the most appropriate solution in that context, and companies that invested in the technology are reaping the benefits.

While cost and performance for li-ion batteries have improved significantly in recent years, focus has also been increasing on other technologies (detailed in the next section), and it is hoped that further developments will drive down their cost enough to make them commercially viable. This presents an opportunity for businesses to invest in ES technologies for the stability of their own operations and to gain entry into untapped markets.

- **Grid modernisation:** ES technologies have grown concomitantly with grid restructuring, reform and update attempts, including the transition to smart grids.
- **Participation in wholesale electricity markets:** ESSs can help to balance the grid and improve power quality regardless of the generation source. Many jurisdictions are revamping their wholesale energy storage market structure to allow ES technologies to provide capacity and ancillary services.[25] As this can be a significant source of revenue for any ES project, it is an important financial incentive.
- **Creating stability in the business environment:** An efficient, secure and uninterrupted power supply is crucial for a healthy business environment in all sectors, particularly the industrial and manufacturing sectors.

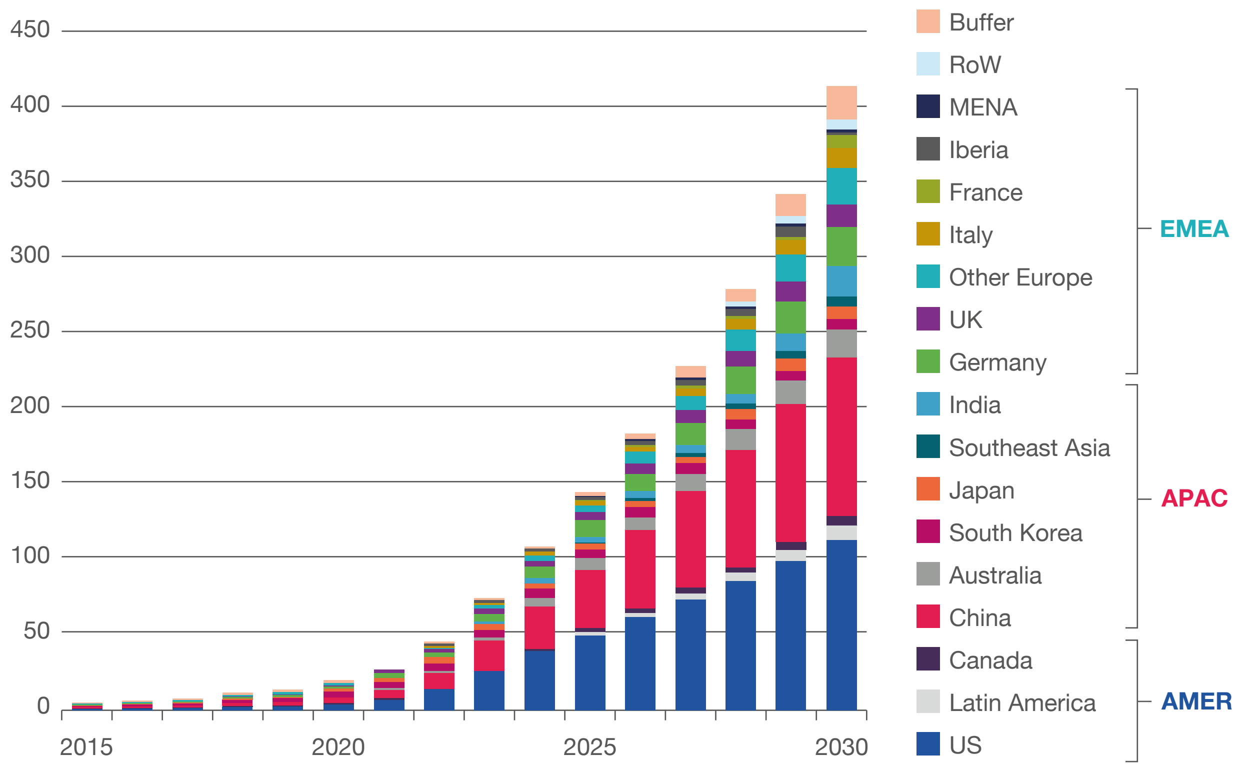
  Therefore, as countries move to decarbonise, they want to avoid the adverse impacts of decarbonisation on overall productivity. Governments and businesses have a similar incentive to invest in grid-scale and distributed solutions to ensure that they remain competitive and that electricity remains affordable.
- **Desire for self-sufficiency:** Motivations for installing storage systems are not purely financial. In Germany, ecological motives, independence from utilities, systemic resilience and technical advancement are all potentially important factors. Similarly, self-sufficiency is a strong driver in Italy, the UK, Japan and Australia, which depend on VRE, fossil fuels and/or imports, and recent policy developments and discourses reflect that. This desire for self-sufficiency also extends to the individual and household level, which is spurring a growth in decentralised, distributed and behind-the-meter (BTM) solutions.[26]

According to the latest forecast by BloombergNEF,[27] energy storage installations around the world are projected to reach a cumulative 411 GW (or 1,194 GW-hours) by the end of 2030; that is 15 times the 27 GW/56 GWh of storage that was online at the end of 2021 (Figure 1).

Governments around the world are adopting various policy approaches as the energy sector evolves towards a new era where renewable power sources are combined with ESSs. The primary focus of these policies is on achieving net zero emissions by 2050. The policies range from wide-ranging exercises like setting targets at a national level (such as the Inflation Reduction Act in the USA, and REPowerEU in the EU) and adding new statutes to the legal framework (e.g. Japan amending its energy legislation to introduce a feed-in-premium scheme), to more targeted interventions like regulatory reforms and provision of financial incentives (e.g. subsidies, tax credits or government investment).

Despite significant developments in global and national policy landscapes, the legal and regulatory framework is not keeping pace with technological developments. Additionally, policies and regulations remain fragmented and are generally not calibrated to support emerging technologies. Together, these circumstances mean ES technologies are not able to achieve their potential as a tool for decarbonisation.

Figure 1: Global cumulative energy storage installation, 2015–30 (source: [BNEF 2022])



Note: "MENA" refers to the Middle East and North Africa; "RoW" refers to the rest of the world. "Buffer" represents markets and use cases that BNEF is unable to forecast due to lack of visibility

Section 3

Overview of electricity storage technologies and trends

Different types of ESSs are available, each with relative advantages and disadvantages. A few of these different technologies have gained traction in recent years, both for grid-scale applications and in distributed ESSs. Businesses can and already are capitalising on the opportunities and must take action to mitigate for the challenges.

ES is broadly defined as any technology that allows taking up electrical energy at one point in time and releasing energy again at a later point in time. This can take the form of converting power-to-power, power-to-gas and/or power-to-heat.

The main ES technologies can be classified into five main groups based on the type of technology they use:

- **Electrochemical:** This method converts electrical energy into chemical form via batteries. Examples include secondary state batteries (e.g. li-ion, sodium–sulphur) and flow batteries (e.g. vanadium redox and zinc–bromine).
- **Chemical:** This method converts electricity into the molecular bonds of chemical substances. Examples include hydrogen production, solar fuels and synthetic gases.
- **Mechanical:** This method converts electrical energy into kinetic energy. Examples include PHES, GES, compressed air energy storage (CAES) and flywheel energy storage (FES).
- **Electrical:** In this method, electrical energy is contained in electrical fields. Examples include supercapacitors (SC) and superconducting magnetic energy storage (SMES).
- **Thermal:** This method stores electrical energy as heat energy by heating or cooling substances to extreme temperatures. Examples include LAES and CBs.

(See Annex for detailed definitions of these technologies.)

Table 2 below provides a qualitative comparison of the different types of ESSs listed above, with specific examples of the technologies falling into each category.[28] As this table shows, the different storage solutions are available at various scales and differ significantly in round-trip efficiency and energy- and power-related costs. They also differ in stages of technological readiness level and commercialisation.

Given that ESSs can vary widely in cost and duration of storage, some of them have more use cases in grid-scale applications. In contrast, others may have more decentralised or distributed applications. The diagram in Figure 2 provides an overview of the ES ecosystem, how various technologies can be deployed at different points of the grid and power sector, and which ones are more appropriate for bulk storage and/or long-term storage.[29]

Figure 2: Energy storage ecosystem (source: NREL, 2021)

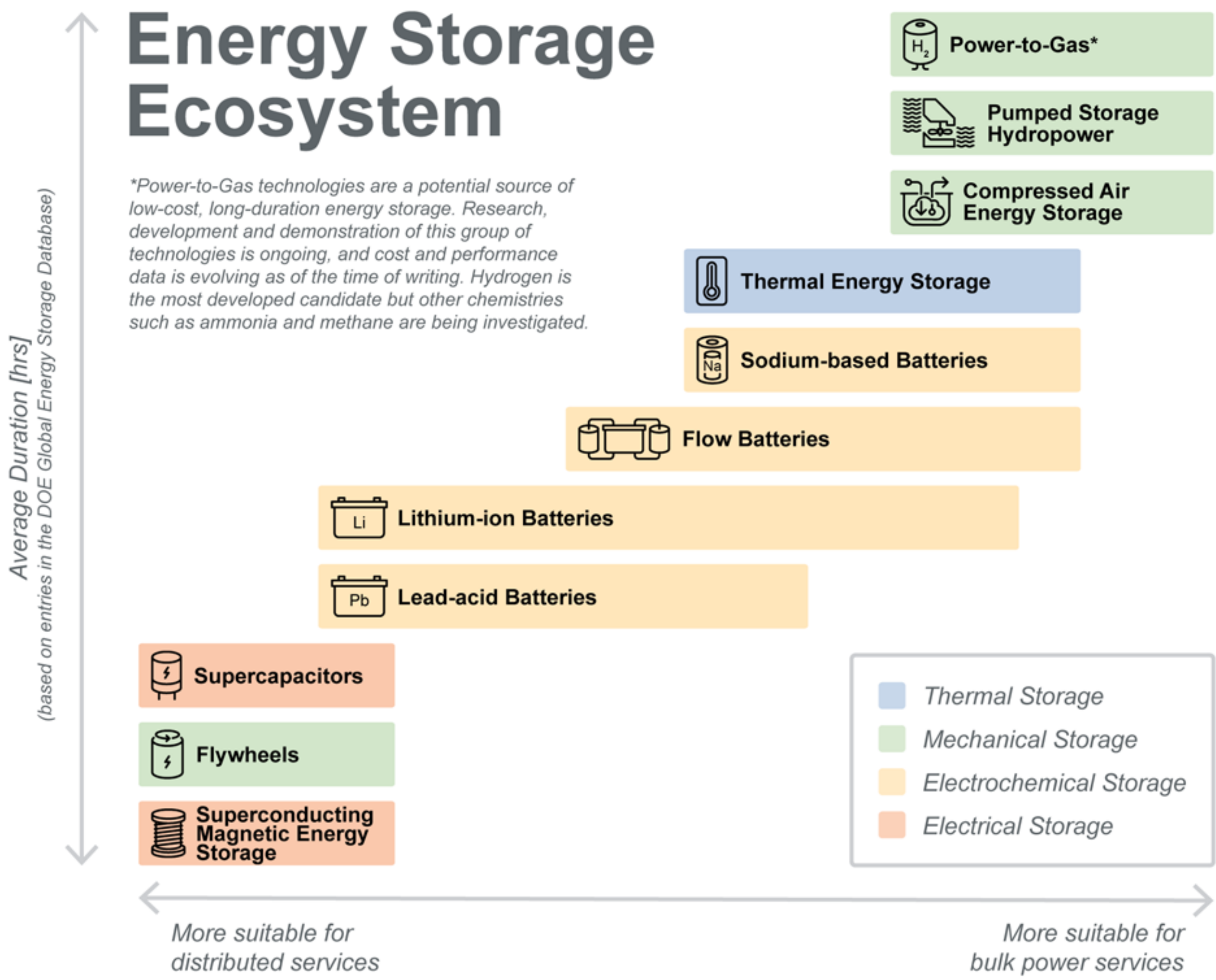


Table 2: Qualitative comparison of energy storage technologies

Category	Technology	Development stage for utility-scale grid applications	Cost range	Typical duration of discharge at max power capacity	Reaction time	Round-trip efficiency (of storing and releasing electricity)	Lifetime	Pros	Cons
Electrochemical batteries	Lithium-ion (Li-ion)	Widely commercialised	1,408–1,947 ($/kW), 352–487 ($/kWh)†	Minutes to a few hours	Subsecond to seconds	86–88%	10 years	Long history of R&D Low maintenance cost	Limited number of discharge cycles Waste management Battery degradation cost
	Flow (vanadium redox and zinc–bromine)	Initial commercialisation	1,995–2,438 ($/kW), 499–609 ($/kWh)†	Several hours	Subsecond to seconds	65–70%	15 years	Decouple power and energy storage Ability to support continuous operation under maximum load Total discharge is possible without any risk of damage	Limited number of discharge cycles Waste management Battery degradation cost
	Lead–acid	Widely commercialised	1,520–1,792 ($/kW), 380–448 ($/kWh)†	Minutes to a few hours	Seconds	79-85%	12 years		Limited number of discharge cycles Waste management Battery degradation cost
	Sodium–sulphur	Initial commercialisation	2,394–5,170 ($/kW), 599–1, 293 ($/kWh)††	Several hours	Subsecond	77–83%	15 years	High power and energy density High cycle life Low-cost potential Insensitivity to ambient conditions	High production cost Safety issues Stringent operation and maintenance requirements Need to be operated above 300°C

Mechanical	Pumped hydro energy storage (PHES)	Widely commercialised	1,504–2,422 ($/kW), 150–242 ($/kWh)[†††]	Several hours to days	Several seconds to minutes (depends on technology choice)	80+%*	40 years	Minimal environmental impact Long lifetime Long-term storage at high capacities	Geographical constraints Drought and overflow can both affect generation capacity
	Compressed air energy storage (CAES)	Initial commercialisation	973–1,259 ($/kW), 97–126 ($/kWh)[†††]	Several hours to days	Several minutes	52%**	30 years	Energy storage capacity is high Cost/kWh is low Long lifetime Less need for power electronic converters	Necessity for fuel and underground cavities High investment cost Geographical constraints Low efficiency
	Flywheel Energy Storage	Widely commercialised	1,080–2,880 ($/kW), 4,320–11,520 ($/kWh)[††]	Seconds to a few minutes	Subsecond	86–96%	20 years	Fast response Overall costs are low High in terms of charge–discharge cycles	Limited discharge time High standing losses Maintenance is required
	Gravity Energy Storage	R&D stage	Insufficient data	Several hours	Several minutes	Insufficient data	Insufficient data	Long-term and large-scale uses Minimal environmental impact Flexible location	High cost of construction May not be suitable for urban area
Chemical	Hydrogen production and fuel cells	Pilot stage	2,793–3,488 ($/kW), 279–349 ($/kWh)[††††]	Several hours to months	Subsecond	35%	30 years	Potential to be 100% zero carbon Long-term storage	Low efficiency Issues with safety of hydrogen storage High component costs

Thermal	Carnot batteries (CBs)	Initial commercialisation	1,700–1,800 ($/kW), 20–60 ($/kWh)	Several hours	Several minutes	90+%	30 years	No geographical constraints Can use cheap, abundant, sustainable, non-toxic storage materials Can use existing technologies – eg from concentrated solar power industry Modular Integrates with other systems	Materials can sometimes be critical or face shortages
Electrical	Supercapacitors (SC)	R&D stage	930 ($/kW), 74,480 ($/kWh)[††]	Seconds to a few minutes	Subsecond	92%	10–15 years	High power and energy density compared with normal capacitors Highest round-trip efficiency up to 96% Speed charging ability and faster response time Environmentally friendly	The self-discharge rate is high and low energy density compared with batteries Cannot be used in AC and high-level frequency circuits
	Superconducting magnetic energy storage (SMES)	Initial commercialisation	200–300 ($/kW), 1,000–10,000 ($/kWh)	Seconds	Subsecond	~97%	20 years	Power capability is high No environmental impacts Faster response time Capable of part and deep discharges	Lower energy density Raw materials, operation and manufacturing processes are expensive

Adapted from USAID NREL (2021) p. 3–4, with information from Kumar and Palanisamy (2020) p. 6 and Mitali, Dhinakaran and Mohamed (2022)

3.1 Utility-scale battery storage solutions

Utility-scale batteries (grid-scale or front-of-the-meter, FOM, batteries) are stationary electrochemical batteries that can be connected to distribution/transmission networks or power-generation assets. Utility-scale storage capacity ranges from several megawatt-hours (MWh) to hundreds. They have the advantage of location and sizing flexibility and, therefore, can be deployed where they are most needed, and can be scaled relatively easily. Global investment in battery energy storage reached almost US$ 10 billion in 2021. It is led by grid-scale deployment, which represented more than 70 per cent of total spending in 2021, and by li-ion batteries, which took more than 90% of total deployment in 2020 and 2021.[30]

Another advantage propelling this solution is the long history of R&D behind the different kinds of commercial batteries that are available (see Table 2 above). Businesses and governments, therefore, face less risk where commercial viability and return on investment are concerned.

According to the International Renewable Energy Agency innovation landscape brief, "Utility-scale battery storage systems will play an important role in facilitating the next stage of the energy transition by enabling greater shares of variable renewable energy (VRE)".[31] They can provide a range of benefits to various stakeholders within the power sector.

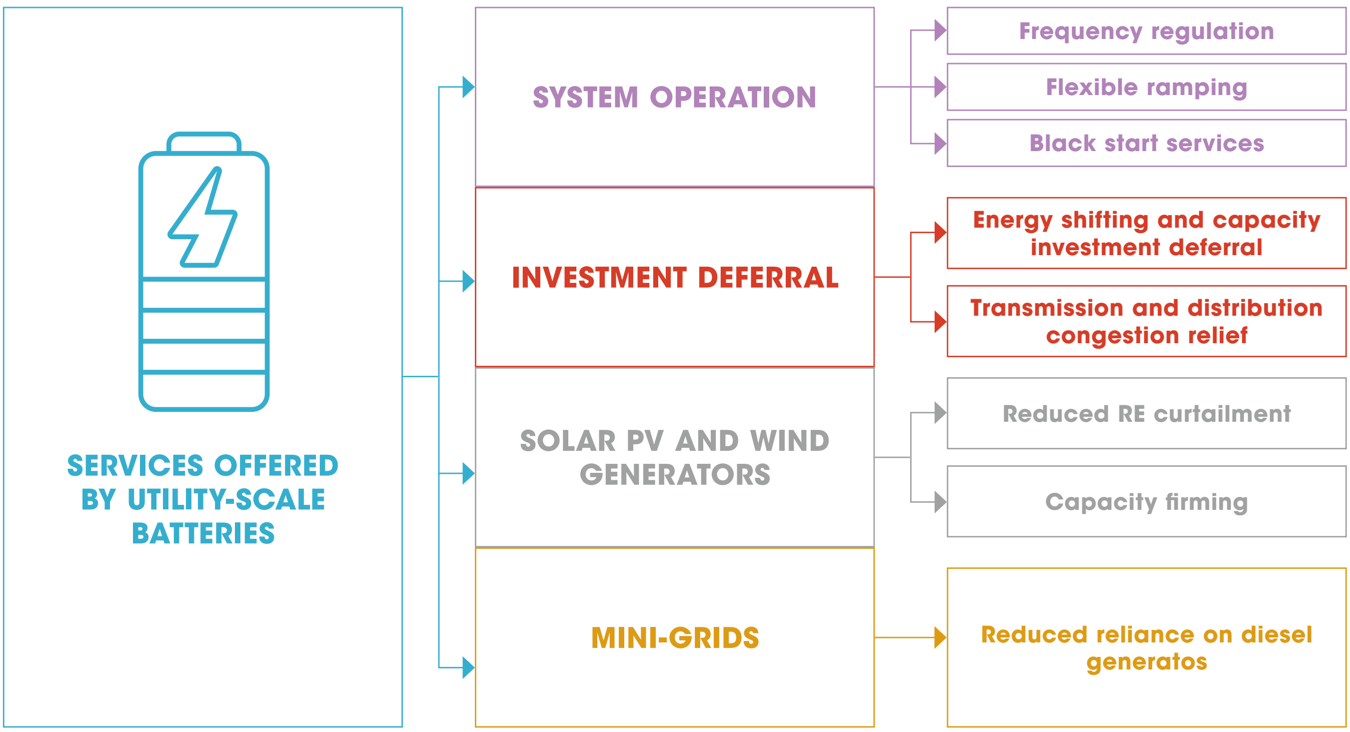
"For system operators, battery storage systems can provide grid services such as frequency response, regulation reserves and ramp rate control. It can also defer investments in peak generation and grid reinforcements. Utility-scale battery storage systems can enable greater penetration of variable renewable energy into the grid by storing the excess generation and firming the renewable energy output. Further, particularly when paired with renewable generators, batteries help to provide reliable and cheaper electricity in isolated grids and to off-grid communities, which otherwise rely on expensive imported diesel for electric generation."

Figure 3 demonstrates the services that grid-scale battery solutions can provide.[32]

Many countries are looking to utility-scale battery energy storage systems (BESS), and flagship projects have been inaugurated in recent years.

- In March 2023, South Africa's Department of Mineral Resources and Energy formally invited interested parties to register prospective bids under the Battery Energy Storage Capacity Bid Window of the Independent Power Producers Procurement Programme (Battery Energy Storage IPPPP) to install 513 MW/2,052 MW-hour battery storage spread across five sites.[33]

Figure 3: Services offered by utility-scale battery storage systems (source IRENA, 2019)



3.2 Pumped hydro energy storage (PHES)

PHES is a mechanical storage system that uses water to store and generate electricity. The system works by pumping water from a lower reservoir to a higher one when excess electricity is available, usually during times of low demand or high renewable energy production (or a combination of both). When there is a shortage of electricity or during times of high demand, the water is released from the higher reservoir, and it flows back down to the lower reservoir through turbines, generating electricity. The same water can be pumped up and released numerous times, meaning that PHES plants do not need to be linked to a continuous water supply.

PHES is still the most widely deployed grid-scale storage technology today. Total installed capacity stood at around 160 GW in 2021. Global capability was about 8,500 GWh in 2020, accounting for over 90 per cent of total global electricity storage.[34] Increasingly, it is co-located with other renewable energy sources, such as wind and solar, to provide a reliable and sustainable energy supply using two different sources with shared transmission infrastructure.

The advantages of PHES include: minimal environmental impact; sources are potentially plentiful, clean and reliable; and it has a very long lifetime. It also has a high efficiency of up to 80% and, depending on the size of the reservoirs, can store large amounts of energy for a long time, making it particularly attractive for grid-scale applications. It can be started manually (without the need for electricity), and can be deployed quickly to respond to sudden changes in demand or supply of electricity. The disadvantages include: a high upfront cost and lengthy construction time, geographical constraints and constant requirements for maintenance. Furthermore, there can be uncertainty about water reserves (especially in periods of drought) and difficulty producing electricity if water is unavailable. Conversely, overflow can also have negative impacts.[35]

Despite PHES being a tried and tested technology, innovations still exist within this domain, especially when addressing the geographical constraints and the need for a non-salient water supply. For instance, the Okinawa power plant in Japan is the world's first PHES project to use seawater.[36] Several projects from around the world are also using old mines, subsea or underground locations for their projects (e.g., Dutch start-up Ocean Grazer).[37]

The following case study illustrates why PHES remains one of the most advantageous large-scale storage options:

Case study 1: Iberdrola – Tâmega giga-battery project

Iberdrola has built one of the largest energy storage infrastructures in Europe, the Tâmega giga-battery in Portugal (Figure 4). With support from the Portuguese Government and investment of more than €1.5 billion, including funding from the European Investment Bank, the project involves three dams with a combined capacity of 1.16 GW. This represents a 6 per cent increase in the total installed electrical power in the country.

Alto Tâmega and Daivões are 'run of the river' hydropower plants that generate electricity. At the same time, Gouvães is a large pumped *storage* plant that uses the Daivões reservoir as a lower reservoir. The complex will be capable of producing 1,766 GWh per year – enough to meet the energy needs of 440,000 homes – and will have a storage capacity of 40 million kilowatt-hours (kWh), equivalent to the energy consumed by 11 million people during 24 hours in their homes. Gouvães and Daivões started operations in early 2022, and Alto Tâmega will be operational in spring 2024.

In addition, two wind farms will be built and linked to the giga-battery, converting the complex into a hybrid power plant. Generating electricity from both wind and hydropower will enable supply and demand management, depending on the availability of both resources and market conditions. It will also improve efficiency by feeding the dam pumping system to recover water for upstream reservoir storage in periods of high wind.

Tâmega will eliminate 1.2 million tonnes of CO_2 emissions annually and diversify Portugal's power-generation sources. It will also promote economic activity in the region: it is estimated that during the construction phase, 3,500 direct jobs and 10,000 indirect jobs will be created, 20 per cent of them from neighbouring towns. Iberdrola has provided specialised training for welders and safety training to local staff.

The project also has an ambitious socio-cultural and environmental action budget of more than €50 million, directly benefiting seven municipalities. The environmental impact statement includes a number of ecological system compensation measures, such as the reforestation of over 1,000 hectares and the planting of 17,000 cork oaks. The biggest challenge in executing the project was the engineering required to construct the three large dams and their associated hydroelectric plants. Still, the project was carried out on time and following the highest safety, environmental and quality standards.

Once completed, the Tâmega giga-battery will provide 880 MW of pumping capacity to the Portuguese electricity system, an increase of more than 30 per cent compared with the capacity available to the country today. These kinds of projects are crucial to provide the flexibility needed to move towards a renewables-based electricity system and a net zero economy.

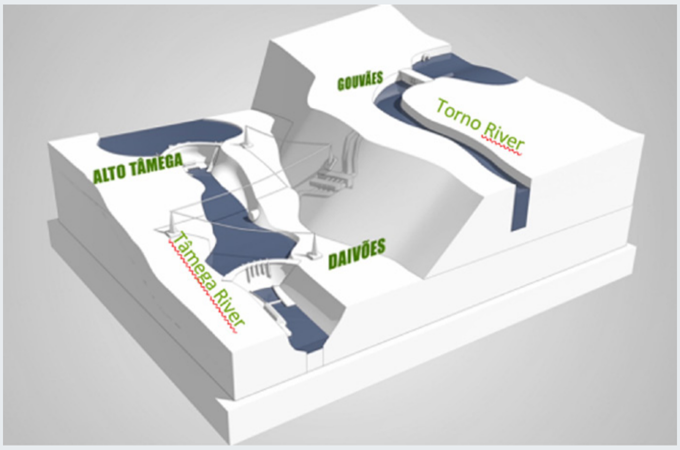


Figure 4: Iberdrola's Tâmega giga-battery project (source: Iberdrola)

3.3 Gravity energy storage (GES)

GES is another type of mechanical ESS that uses the force of gravity to store energy. The idea behind GES is to store potential energy by raising a heavy object against the force of gravity and then releasing the object to generate energy as it falls back down. Several types of GES systems exist, but the most common ones use large weights or masses, such as concrete blocks, water or flywheels, which are lifted to a certain height and then released to generate electricity from the kinetic energy.

GES is considered a promising technology for large-scale energy storage, as it has the potential to store vast amounts of energy for extended periods. Unlike batteries, which can store energy for only a few hours or days, GES systems can store energy for days, weeks or even months and, therefore, could provide services such as peaking capacity, load balancing and energy arbitrage (supply and demand balancing). However, GES systems require significant upfront capital investments and large amounts of land, making them less suitable for use in urban areas.

Although GES is currently an immature technology, it has the potential to provide long-term energy storage similar to CAES or PHES.[38] It can also be cost-competitive, despite the high upfront capital cost. Given these advantages, and the relatively simple scientific principle underlying it, quite a few projects are under development and being implemented. One of them is Gravitricity, an Edinburgh-based green engineering start-up. In April 2021, the group successfully trialled its first gravity battery prototype: a 15 metre (49 foot) steel tower suspending a 50 tonne iron weight that goes up inch by inch during periods of excess capacity and is released when demand is high.[39] Following the success of its small-scale pilot, the company is now looking to convert underground mine shafts into 'gravity batteries' by applying the same above-ground principle.

Another leader in the GES space is the Swiss company Energy Vault. Located in a valley in southern Switzerland, Energy Vault's impressive prototype, constructed of steel and concrete, rises more than 20 storeys high, firmly establishing the company as a leader in the field of gravity batteries. Using AI-controlled cranes, when the supply of green energy exceeds demand, a pair of 30-tonne blocks are lifted upwards, which generate enough energy to power thousands of homes when they are subsequently lowered during times of increased demand. Having received approximately $402 million (£325 million) in funding, and with its technology thoroughly tested and proven, Energy Vault is now poised to introduce a commercial version of its system. This new version, called EVx, is designed with aesthetics in mind and features a modular building that uses a trolley system to store thousands of weights.[40]

3.4 Hydrogen-based electricity storage solutions

Hydrogen energy storage is a type of chemical energy storage whereby electricity is transformed into hydrogen using electrolysis; this energy is then recovered by burning the gas in a combustion engine or a fuel cell. It is used in various industrial applications such as glass, fertiliser, steel and chemical manufacturing, which are sectors that urgently need to reduce their carbon footprints. In 2021, the global hydrogen energy storage market was valued at $14.69 billion. It is expected to grow and reach $21.64 billion by 2030 at an approximate compound annual growth rate of 4.4 per cent.[41]

Although hydrogen has very low round-trip efficiency (approximately 35 per cent – see Table 2 above) and faces strict government regulations due to safety issues, it remains one of the best options for storing large quantities of electricity for long periods. One example is the Australian Denham Hydrogen Demonstration Project, in the small, remote coastal town of Denham, Western Australia. Once operational, it is expected to produce about 13 tonnes of green hydrogen a year from two 174 kW electrolysers powered by a dedicated 704 kW solar farm. The hydrogen will then be used to power a fuel cell that will help to provide round-the-clock solar energy to about 100 homes.[42]

3.5 Carnot batteries (CBs)

CBs are a form of ESS that employs thermal storage. During charge, an electric input is used to establish a temperature difference between two thermal reservoirs; this temperature difference then drives a power cycle for electricity production during discharge. The term CB encompasses several thermo-mechanical storage concepts, such as LAES and pumped thermal energy storage (PTES)[43], as well as other variations which use materials that include but are not limited to hot water, molten salt, packed bedrocks and sand. Even though thermal energy storage technology was patented almost a century ago, it has been recently reinvigorated by the increasing need for ESSs. The term CB was coined as recently as 2018.

As CBs and ESSs using thermal storage are relatively new, their advantages and disadvantages are not well defined. Based on pilot projects, it can be concluded that key benefits are flexibility in the choice of geographical location, a small environmental footprint, a high life expectancy of 20–30 years, low maintenance costs and the scope to repurpose previous fossil fuel facilities. However, given the nascent stages of development and the variability in its manifestations, evidence is scant about the round-trip efficiency of this storage method.

Given the recent developments in CB technology, many projects at various stages are underway:

- In January 2018, Chile inaugurated a formal process for decarbonising its energy system with an agreement between the Ministry of Energy and Environment, coal power companies (Enel, AES Gener, Engie and Colbún) and the Chilean Association of Power Generators (AGC). Existing coal generation facilities will have to be either converted or replaced, for example, with systems like the recently announced 50 MW/500 MWh LAES facility in the Atacama region (a region with one of the highest levels of solar irradiation in the world) to fully decarbonise the electricity system.[44]
- In June 2018, Highview Power launched the first grid-scale LAES plant with a capacity of 5 MW/15 MWh, which is located in the UK at Bury, near Manchester. [45]
- In July 2021, Vantaa Energy declared plans to construct a seasonal thermal energy storage plant in Vantaa, Finland, with a storage capacity of 90 GWh. The million cubic meter storage plant will include hot water caverns around 60 metres underground in bedrock. [46]
- In January 2022, the EU and the European Investment Bank chose Malta Inc., the grid-scale thermal energy storage provider, to execute the Sun2Store thermal energy storage project in Spain. It is a 1,000 MWh/10-hour duration ESS that combines pumped heat technology with molten salt. The project will be developed in partnership with Alfa Laval.[47]
- In July 2022, the world's first commercial sand battery was inaugurated in a town called Kankaanpää in western Finland. It is connected to a district heating network and is heating residential and commercial buildings such as family homes and the municipal swimming pool. The battery is operated by the company Polar Night Energy, while the district heating network is run by an energy utility called Vatajankoski. [48]

Section 4

Supercharging the way: business opportunities and challenges

As ESSs are poised to become a major part of power systems, it is important to understand that they are just one tool in a wide and expansive toolkit to make the power sector greener and more resilient. Nevertheless, the development in ES technologies, as well as increased attention from a variety of stakeholders, means that there are many opportunities in the ES market for companies to capitalise on. However, as discussed later in Section 5.2, the scale of these opportunities can be appropriately estimated only when the use case is clearly defined, the upfront and long-term costs are properly modelled, and they are coupled with the right mix of power sector reform and grid upgrades and modernisation.

4.1. Opportunities to innovate

4.1.1 Harness the potential for 'value stacking'

Energy storage has the potential to enhance power system flexibility and reliability through a variety of services that support the smooth and stable functioning of the grid despite increased VRE penetration rates. This multi-use tactic, referred to as 'value stacking,' can increase energy storage use and improve project economics by allowing it to serve a broad range of services rather than a limited subset.[49] Policymakers also need to implement adequate compensation mechanisms for businesses investing in such solutions to ensure the financial viability of these investments, as effective value stacking will require regulatory adjustments.

4.1.2 Hybrid energy storage solutions

Hybrid energy storage solutions (HESS) solutions can help to cover short, mid, and long term fluctuations in a future sustainable, 100 per cent renewable energy system.[50] As discussed in Section 3, given the various pros and cons and technical specifications of different ES technologies, no one solution is ideally suited for every use case. As explained by Greentech Media, most solutions "are typically designed for high-power applications (i.e. 'sprinter' mode that provides lots of power in short bursts) or energy-dense applications (i.e. 'marathon' mode that provides consistent lower power over long durations), and there are lifetime, performance, and cost penalties for using them in unintended ways". HESS solutions, however, typically combine both sprinter and marathon technologies to fulfil applications that have diametrically opposed requirements, for example, fast response versus peak shaving. [51]

HESS solutions can come in countless iterations designed to the specific needs of any given system. Some currently deployed examples are power-to-heat/battery, battery/battery and supercapacitor/battery. As an example of a power-to-heat/battery HESS system, AEG has developed a power conversion system in Munich, Germany, as the key element operating the power management and controlling both the battery and the heating system. This power conversion system and all the equipment required for grid connection (e.g. transformer and switch gear) are used for both the batteries and the heater. The platform allows for all typical applications of standard battery energy storage, in particular frequency regulation. However, by combining both systems, the capacity of the thermal storage adds to the battery storage capacity.[52] Hybrid solutions are not restricted to the configuration of multiple ESSs. They can combine a single ESS with other readily available technologies to provide targeted support in the power sector and to end-users as needed. For instance, a USA-based company called Consolidated Edison has been making a push for mobile solutions by packing standard batteries into transportation vehicles. One of these projects, the Transportable Energy Storage System, will package li-ion batteries, power conversion systems and thermal control systems into a 500 agag/800 kWh trailer-mounted system that "would potentially replace mobile diesel systems" for use in emergencies. When not in use, the Transportable Energy Storage System could provide services to the wholesale market while stationed at a Con Ed facility in Astoria – a use that is technically feasible but will require regulatory changes to become a standard business practice. [53]

Case study 2:
EDF – A low carbon storage, mobility and electricity superhub

Launched in 2022, Energy Superhub Oxford (ESO) is one of the UK's most ambitious urban decarbonisation projects. Showcasing innovative energy storage capabilities, EV charging, low carbon heating and smart energy management technologies, the project aims to save 10,000 tonnes of CO_2 emissions per year, rising to 25,000 tonnes per year by 2032.

This BESS is helping National Grid ESO to integrate more renewables, balance grid frequency and increase the resilience of the electricity system. It is situated alongside National Grid's Cowley substation and is the first grid-scale battery in the UK to connect directly to the high-voltage transmission network (Figure 5). This has opened up the transmission network to other storage project developers who are applying for similar connections, which will support the significant amount of storage needed for the electricity grid of the future.

The BESS consists of a 50 MWh li-ion battery and a 5 MWh vanadium flow battery, which operate as a single energy storage asset. The project received £6 million in funding from UK Research and Innovation to explore how the characteristics of these two different battery technologies can be used to support the electricity grid. The project showcases the vanadium flow battery's new overdrive technology, which can boost the battery's power from 1.2 MW to 2 MW when needed. This helps to address the challenge of degrading li-ion batteries by allowing the vanadium flow battery, which does not degrade, to do much of the heavy lifting in providing a frequency response service. The optimum charge–discharge schedule for the battery is determined by a combined energy management system that communicates with the optimisation and trading engine to provide the National Grid with electricity very quickly when needed.

One of the major strengths of ESO has been the partnership model that saw EDF Renewables work in close collaboration with Oxford City Council, National Grid, *Wärtsilä*, Habitat Energy and Invinity Energy Systems to overcome the challenges thrown up during such an innovative project. The challenges included: planning obstacles, which required close working with the council and three different planning authorities; construction challenges related to installing the battery and cable in a limited space; and dealing with the implications of COVID-19. However, learning continues – for example, the hybrid operation of the li-ion and flow batteries in frequency response mode remains a work in progress.

Figure 5: Cowley Battery (Source: EDF)

4.1.3. Incorporating novel digitalisation technologies

Developments in big data, artificial intelligence (AI) and blockchain technologies offer opportunities for grid upgrades and modernisation for greater efficiency (such as smart meters). They also provide the potential for including ESS at the grid-scale and for distributed FOM and BTM applications. This is believed to be an emerging industry trend,[54] as nearly half of the respondents to the survey carried out by the authors of 'Digitalization and the Future of Energy Storage' confirmed that digitalisation technologies are a core part of their business strategy and 5 per cent of them said that they proactively invest in such technologies. Improved operational efficiency (54 per cent), improved decision-making (42 per cent) and helping innovation (39 per cent) through digital technologies were identified by the storage industry as the top priorities for their digitalisation strategies. [55]

EnergyTag is a digital initiative that features a consortium of power companies. It is trying to accelerate the RE transition by allowing users to verify their energy as they consume it by providing hourly certificates.[56] Similarly, a company called Leap is collaborating with National Grid to reduce electricity consumption at four of its New York City offices during times when conservation is most critical to the regional electric grid. Leap's application programming interface and automated technology platform enable distributed energy resources, including thermostats, EV chargers, and heating, ventilation and air conditioning systems, to respond to real-time pricing signals. In this way, it aims to contribute crucial flexibility to a stressed grid.[57]

4.1.4. Focusing on circularity of materials

Many of the constraints facing ESS relate to the use of critical raw materials that may not be readily available during the early stages of commercialisation. Therefore, leaning into a circular solution can be viable and provide various opportunities and synergies. Capitalising on this, Melbourne-based company Relectrify has received an AUD 1.49 million grant from the Australian Renewable Energy Agency to advance its commercial-scale battery and inverter system using repurposed second-life EV batteries, giving them an additional lifetime of 3,000 charge–discharge cycles. EV batteries are often replaced once they have degraded to less than 80 per cent of their initial storage capacity. While this degradation results in a loss of mileage for EVs, the batteries still retain adequate storage capacity for stationary energy storage systems.[58]

Similarly, French company Stolect's CB uses refractory materials for heating, such as basaltic rocks or recycled ceramics, greatly amplifying the potential to reduce environmental impacts and also the cost of the battery (according to pilot studies, it could be three times cheaper than li-ion batteries in the long run).[59]

4.1.5. Deploy distributed storage solutions throughout the sector

Distributed storage solutions enable a variety of stakeholders (such as individual prosumers, businesses, and residential and commercial buildings) to actively participate in the electricity distribution system by storing energy, thereby enhancing the system's ability to use clean energy sources. They can form a crucial element of the energy system's modernisation through smart grids and other related services.[60]

Although distributed technologies vary, noteworthy recent developments have been in relation to an uptake in BTM battery solutions that have the potential to enhance the reliability and security of electricity supply, [61] and also in sector-coupling solutions (such as with EVs in the transportation sector and heat pumps in the buildings sector).

While BTM solutions provide opportunities, they also provide challenges, as they are truly decentralised and based on consumer decisions and behaviour, making them unpredictable and difficult to co-ordinate. Furthermore, consumers may deploy BTM solutions solely for personal cost benefits instead of being incentivised to benefit the wider power sector. Therefore, they require robust demand-side management for the power sector to truly harness the ESS benefits. For example, decision-makers could enable the interconnection of BTM storage and guide customer decisions in a way that can also support grid needs through appropriate policy design.[62]

The growth of EVs and the phasing out of internal combustion engine vehicles is due to occur in various countries and presents an immense opportunity for distributed ES. A joint study from the Leiden Institute of Environmental Sciences in the Netherlands and the US National Renewable Energy Laboratory suggested that EV batteries could meet short-term energy storage demands from the global grid as early as 2030.[63] The study considered: the projected growth of the EV market and power demand; the overall patterns of driving habits in global markets including China, India, the EU, the USA and the 'rest of the world' category; and the climate impacts on battery life and degradation.

Case Study 3:
iGrid Solutions – EV truck charging management through integration with logistics facility electricity usage

iGrid Solutions has partnered with Isuzu Motors to integrate its energy management platform, the R.E.A.L. New Energy Platform®, into GATEX, a commercial vehicle information infrastructure that provides fleet management and support services for EVs in Japan.

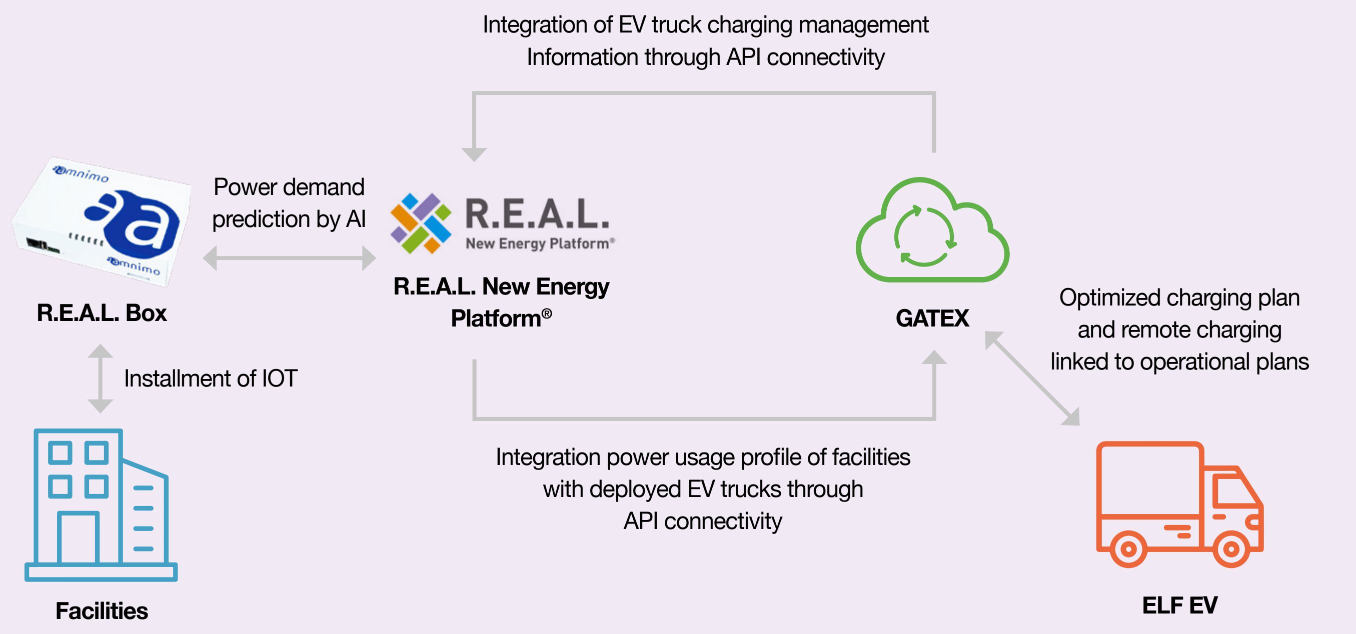
The widespread adoption of EVs is leading to an increasing need for optimal EV charging solutions and enhanced facility-side management capabilities. For example, in the case of using EV trucks for delivery services, they operate during the day and charge in a concentrated manner during the night. This pushes up peak demand for electricity at this time, resulting in increased electricity costs. The integration of the R.E.A.L. New Energy Platform® into GATEX is aimed at addressing such challenges.

The Platform enables highly accurate surplus power prediction and automatic control of distributed energy sources through AI. It collects information on solar power generation, the charging/discharging status of batteries and EVs, and power demand, and then sends this data to the cloud (Figure 6). The AI on the cloud performs highly accurate predictive analysis by combining the received data with external information such as power market prices calculate surplus solar power and create scenarios for automatic control of distributed energy sources, such as solar PVs, batteries, and EVs. This enables energy management through surplus power distribution from solar PVs via power purchase agreements (PPAs) as well the most efficient use of distributed energy sources via automatic control. GATEX is expected to integrate EV charging schedules and operational plans, and enable remote management of the charging process.

The integration of the functionalities, along with the utilisation of AI, leads to a demand-supply adjustment of renewable energy. This allows logistics centres to enter into PPAs that incorporate renewable energy without the apprehension of generating surplus electricity. This is critical for the decarbonisation of logistics, as switching from diesel vehicles to grid-connected EVs reduces the CO_2 emission intensity by 20-30% under Japan's current electricity mix. Still, if EVs are charged exclusively with renewable energy, it reduces emissions by 90%.

To make the project a success, iGrid has collaborated with other industries from the transport and energy sectors and combined various technologies such as AI, Internet of Things, electricity, and automobiles. To integrate these different elements comprehensively, it has been important to overcome barriers related to different types of expertise by sharing knowledge and using an open innovation approach.

Figure 6: Optimised charging management based on the facility power usage profile (source: iGrid Solutions)



4.2. Challenges to overcome

4.2.1 Cost – actual and perceptual

While technical analyses of various ES technologies have begun to abound in the academic literature and industry reports, the analysis of economic benefits is still in the nascent stages, as many solutions are in the early stages of development and/or deployment. Therefore, businesses and policymakers face a considerable challenge to devise models of economic viability. This problem is further compounded by the fact that multiple models can be used to conduct a cost–benefit analysis of ES technologies. Evaluation has been done via the levelized cost of storage (LCOS) calculation, production-cost models and market-based models. Each of these methods results in a different kind of monetary value: the LCOS can be defined as the total lifetime cost of the investment in an ES technology divided by its cumulative delivered electricity, and it provides a standalone average break-even cost; production-cost models provide overall cost savings gained for the entire power system from ES deployment; and market-based models provide the compensation that storage would receive if it were to compete in the market (both wholesale and ancillary).[64]

Given the lack of a standardised method to evaluate ES technologies, there is disagreement about whether they are economically viable. Some argue that their economic prospects are not very bright at the current LCOS levels and because of uncertainty surrounding revenue generation. [65] However, others argue that technology costs are falling as adoption accelerates, and that revenue generation will improve as legal/regulatory frameworks adapt to the new landscape. [66]

Aside from the long-term costs and value of ES technologies, businesses and governments also must contend with the upfront cost of deployment (e.g. the construction costs for a PHES or GES plant can be considerable; similarly, building grid-scale battery systems can require substantial investment). Although the immediate outlay can be significant, as discussed above, the savings and value might not be realised in the short or medium term. Therefore, policymakers need to create an enabling environment for investment.

However, the issues surrounding the costs of ES technologies are also a crisis of perception. [67] Many stakeholders mistakenly believe that deployment and development of these technologies are expensive, but that is rapidly changing as the costs fall due to technological advancements and the economics improve. To properly incorporate storage into regulation and fully capitalise on its capabilities, it is imperative to understand the services that storage can provide and the value these services bring to the energy mix. Therefore, it is vital to distinguish between the costs of a technology, the profitability of a technology and the *value* of the technology.[68] This distinction is important as it helps all stakeholders (specifically investors and regulators) to better understand the financial feasibility of a storage project.

4.2.2 Outdated regulatory frameworks

As with any emerging technology, ES technologies face a lag in the regulatory and legal framework catching up with technological developments. Many current policies and frameworks do not consider the changing nature of the power sector and the ongoing evolution of storage solutions. Unsupportive regulation presents a significant institutional and financial barrier for businesses to invest in ES.

One of the primary regulatory barriers is the lack of a standard definition. In most countries, ES is not explicitly defined in most electricity markets as an activity or an asset. Therefore, it differs from other activities in the electricity market, such as generation, transmission, distribution and supply.[69] This definitional ambiguity leads to many different adverse outcomes, such as a lack of clarity about energy storage ownership and also problems in maximising revenue as ES projects are not able to participate in capacity and ancillary markets.

Section 5

Recommendations

Policymakers can enable a transition to a greener grid and low carbon power sector by employing ES technologies effectively, both in itself and as part of a larger policy toolkit. Governments can achieve this by fostering efficiency and resilience through managing end-user demand, creating an enabling financial and regulatory environment, and leveraging co-operative synergies between stakeholders when and where possible. Below, we list some of the steps governments could take to support and incentivise business action in ES technologies.

5.1 Tailor storage solutions to the country context

As discussed in previous sections, current VRE topography in each country context is quite variable as ESSs must be adapted to the specificities of each respective environment. Because many countries are at a different stage and pace of RE development – and have unique geographical, social, political and economic constraints (not to mention specific regulatory, financial and policy frameworks) – it is highly important for businesses and policymakers to develop consensus on what effective solutions will look like and clearly define what goals they are trying to achieve.

Decision-makers can look at several indicative metrics to identify whether energy storage might be an appropriate solution to emerging system needs. These include increasing ramping requirements for conventional power plants, high or spiking electricity production costs, high levels of renewable energy curtailment, regular local and/or regional power disruptions, and the presence of significant targets for renewable energy deployment or power sector decarbonisation. Storage solutions can be included in long-term power sector planning to identify their role in the most cost-effective mix of capacity and generation resources. Given this complicated landscape, the right analytical tools (for technical and economic viability) are critical for informing ES investment decisions.

5.2 Provide regulatory certainty

Given the nature of the power sector and the multiple stakeholders involved, policymakers have an important role in defining a conducive regulatory landscape. To that end, they can take a variety of measures that can assist the government as well as businesses. Governments can:

- **Establish clear and transparent regulations for ES,** including rules for siting, permitting and interconnection. These regulations should be technology-neutral and designed to support the integration of storage into the grid.
- **Create a level playing field** through ensuring that ES is treated fairly compares to other resources. This can include establishing clear rules for compensation, such as tariffs or market mechanisms that reflect the value of storage to the grid.
- **Provide long-term visibility** by setting clear goals for energy storage deployment and establishing policies to support those goals. This can include setting targets for storage deployment, establishing funding mechanisms and creating programmes to support storage development.
- **Support grid planning** by requiring utilities to consider ES as part of their planning processes. This can help identify opportunities for storage deployment and ensure that storage is included in any long-term planning.

5.3 Enabling financial environment for investment

As the cost and *perceived* cost can be significant challenges for business to invest in ES research, development and deployment, providing the right financial incentives can be crucial for an effective policy. Instruments such as grants, subsidies, tax incentives or low-interest loans can help to reduce the risks associated with investing in new technology and encourage businesses to take a long-term view.

5.4 Supplementing supply-side policies with demand-side management

Utilising demand-side flexibility will be essential in achieving high levels of renewable energy generation and facilitating the transition towards a more sustainable energy system. End-users can actively participate in managing and balancing the grid if they have access to energy management systems and communication infrastructure.

There are many types of demand response programmes, ranging from direct compensation-based programmes, to savings-based schemes targeted at household, commercial and industrial users. End-users are rewarded for their willingness to be flexible in their energy use in response to grid conditions or peak hours, which results in a more reliable grid, fewer outages and deferral in investments in additional generation capacity.

However, the potential for flexibility on the demand side has not yet been fully exploited. According to the International Energy Agency,[70] the net zero scenario milestone has 500 GW of demand response brought onto the market by 2030, which would need a tenfold increase from deployment levels in 2020. There are several obstacles to overcome, including a fragmented regulatory framework, inadequate market products for small end-users, and the lack of standard measurement and quantification methods. [71] Aside from government intervention, distributed solutions deployed by businesses can also greatly enhance demand-side management, especially when coupled with novel digitalisation platforms and technologies (e.g. EnergyTag, mentioned in Section 4.2).

5.5 Leverage cross-border synergies through international co-operation

Given the nature of electricity, it is a sector rife for international co-operation, and its generation, transmission and distribution need not be restricted by national borders. International co-operation can create regional ‘power pools’, thus reducing reliance on fossil fuels by allowing countries to share RE resources (e.g. landlocked countries can access offshore wind). These power pools could also reduce the need for ESSs and curtailment, while also enabling a broader range of ESS options to be deployed to meet the storage needs.

A good case study is Nordic co-operation on energy and electricity matters. The Nordic co-operation on energy has been widely regarded as a leading model of regional co-operation, being the most integrated in the world. Since the establishment of the Nordic Council of Ministers in 1972, energy co-operation has remained a priority item on its agenda. [72]

The benefits of this co-operation have been evident across the entire region, and its advantages continue to accrue to this day. Given the diverse energy sources available across the Nordic countries, their complementarity has facilitated close collaboration, enabling them to leverage each other’s strengths both in generation and storage. As a result, this system has provided benefits to both businesses and the public throughout the region, leading to a reliable energy supply and a consistent increase in the proportion of sustainable energy.

In a planning and prospect study for a power pool in North Africa (Algeria, Egypt, Libya, Morocco, Mauritania and Tunisia) by IRENA, the association has concluded that this co-operation can help these countries diminish their reliance on fossil-fuel-generated electricity by 2040. [73] The report states that “the region stands to benefit from falling renewable energy costs and its ample endowments of wind and solar energy, as well as from increased interconnections, more battery storage deployment and, potentially, even green hydrogen production”.

Section 6

Concluding remarks

The renewable electricity transition is a critical element of meeting global climate targets, and storage is a key enabler for reliable, affordable renewable electricity. But the adoption and deployment of energy storage technologies comes with a range of challenges, including a fragmented policy landscape, outdated regulatory frameworks, uncertainty surrounding cost-benefit analyses and high upfront investment requirements. The overall policy landscape lacks cohesion, and businesses face significant uncertainty, which can create a barrier to investment.

Nonetheless, the costs of ES technologies are falling, technological developments are rapidly accelerating, and the value ES can bring to the energy mix is increasingly recognised. This has translated into more business interest and more investment. As well as growth and improvement in tried and tested ESSs, there are many innovative technologies under development, such as hybridised solutions, distributed iterations, incorporating novel digital technologies such as AI and blockchain.

Optimal design for ES solutions is contingent upon various factors and needs to be tailored to each country's specific requirements, including geographical, political and economic circumstances. Both businesses and policymakers have instrumental roles: the former by investing and innovating and the latter by serving as a convening force and ensuring an enabling environment for investment and progress. Policymakers and businesses must continue to work in tandem to harness the potential of the ES sector, and the central role it can play in achieving net zero targets.

Annex

Types of grid-scale electricity storage:

1. Electrochemical storage

Electrochemical energy storage is a technology that involves the conversion and storage of electrical energy in chemical form. It is a process that involves the use of electrochemical cells or batteries to convert electrical energy into chemical energy and vice versa. During charging, the batteries or electrochemical cells convert electrical energy into chemical energy and store it. During discharge, the chemical energy is converted back into electrical energy and used to power devices. It is one of the most widely used ESS technologies and includes single-use primary charge batteries, secondary charge batteries (such as lead-acid (LA), lithium-ion, nickel-cadmium (Ni-Cd), sodium sulphur (NaS), sodium-ion (Na-ion), solid-state and metal air batteries) and flow batteries (such as vanadium redox, polysulphide bromide and zinc bromine).

The advantages of secondary charge batteries include a long history of research and development, a round-trip efficiency of between 75–90%, high performance, and lower maintenance, while the disadvantages include a limited number of charge–discharge cycles, complications in terms of waste discharge, and battery degradation costs.[74]

The advantages of flow batteries include high specific energy, good energy efficiency control, capability of rapid charge, adequate power density for most applications, and low environmental impact. The disadvantages include high self-discharge rate, requirement of auxiliary systems for circulation and temperature and possible safety issues.[75]

2. Mechanical (or kinetic) energy storage

In mechanical ESS, the energy is stored by transforming between mechanical and electrical energy forms. When the demand is low during off-peak hours, the electrical energy consumed by the power source is converted and stored as mechanical energy in the form of potential or kinetic energy. During peak hours, the mechanical energy is transformed back into electrical power.[76] They are categorised into four different categories: pumped hydro energy storage (PHES), gravity energy storage (GES), compressed air energy storage (CAES), and flywheel energy storage (FES). PHES and GES have been covered in Section 2 of the briefing.

a) Compressed air energy storage (CAES)

CAES is an energy storage technology that stores energy by compressing the air. The amount of stored energy depends on the volume of the storage container as well as the pressure and temperature at which the air is stored. The reliance of PHES on specific geological formations and the associated environmental concerns can make new developments difficult. CAES was developed as an alternative to PHES and has proven to be a promising method of energy storage due to its high reliability, economic feasibility, and low environmental impacts overall.[77]

b) Flywheel energy storage

The FES system is a mechanical energy storage device that stores mechanical energy by utilising kinetic energy, i.e., the rotational energy of a massive rotating cylinder. A flywheel, magnetic bearings, an electrical motor/generator, a power conditioning unit, and a vacuum chamber are the five essential components of a modern flywheel system.[78]

The advantages of FES are fast response, low overall costs, high charge-discharge cycles, and a round-trip efficiency of 85%; while the disadvantages are limited discharge time, high standing losses, and constant maintenance requirements.

3. Chemical storage

Chemical energy storage (CES) systems are typically employed for long-term storage of energy in chemical form. In this approach, energy is stored in the chemical bonds between the atoms and molecules of the materials, and the stored energy can be released through chemical reactions. This process involves a change in the composition of the materials as the original chemical bonds break and new ones are formed, leading to the release of the stored energy. Chemical fuels currently dominate electricity generation and transportation worldwide. Coal, gasoline, diesel fuel, natural gas, LPG, propane, ethanol, and hydrogen are examples of common chemical fuels. These fuels are first converted into mechanical energy and then transformed into electrical energy, which is utilized to produce electricity. Hydrogen, synthetic natural gas, and solar fuel storage systems are the primary types of low-carbon CES systems.

4. Electrical energy storage

The EES systems store energy in an electric field without converting the electrical energy into other forms of energy. EES systems are classified into two types: electrostatic energy storage systems and magnetic energy storage systems. The capacitors and supercapacitors (SC) are electrostatic energy storage systems. The superconducting magnetic energy storage (SMES) is a magnetic energy storage system.

For SC, the advantages are higher power and energy density compared to normal capacitors, highest round-trip efficiency (up to 96%), speed charging ability and faster response time, as well as being environmentally friendly. The disadvantages are that the self-discharge rate is high, they have low energy density compared to batteries, and cannot be utilised in AC and high-level frequency circuits.[79]

For SMES, the advantages are that power capability is high, there is a 95% round-trip efficiency, there are minimal environmental impacts, and they have a faster response time and capability of deep discharges; the disadvantages are their lower energy density and use of raw materials, and that their operation and manufacturing processes are expensive.[80]

5. Carnot batteries (or thermal energy storage)

Put simply, carnot batteries (CB) store electricity as thermal energy. During charge, an electric input is used to establish a temperature difference between two thermal reservoirs. This temperature difference then drives a power cycle for electricity production during discharge. Hence, CB charge and discharge processes involve, respectively, forward and backwards conversion between electricity and heat, while the storage phase consists of thermal energy storage (TES). The term CB encompasses several thermo-mechanical storage concepts, such as liquid air energy storage (LAES) and pumped thermal energy storage (PTES)[81] as well as other variations which use materials that include but are not limited to hot water, molten-salt, packed bed-rocks, and sand. Even though TES technology was patented almost a century ago, it has been recently reinvigorated given the increasing need for ESS, and the term CB was coined as recently as 2018.

a) Liquid Air energy solutions

In LAES, the air is stored in the liquefied state in special cryogenic containers, unlike conventional CAES, where the air is stored in a compressed gaseous state in underground caverns.

b) PTES:

Currently, PHES handles more than 99% of large-scale energy storage. PHES stores energy by transferring water between two reservoirs at different altitudes via a pump or turbine but its installation depends on geographical constraints. PTES systems are one intriguing alternative storage solution. This innovative technology has been around for a few years and is currently being tested in pilot plants.

PTES technology includes storing energy as heat, which can be sensible or latent. It is built on a high-temperature heat pump cycle that converts electrical energy into thermal energy and stores it in two enormous reservoirs, followed by a thermal engine cycle that converts the stored thermal energy back into electrical energy.[82]

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