WORLD ENERGY COUNCIL

FIVE STEPS TO ENERGY STORAGE

Innovation Insights Brief | 2020

In collaboration with the California Independent System Operator (CAISO)

ABOUT THE WORLD ENERGY COUNCIL

The World Energy Council is the principal impartial network of energy leaders and practitioners promoting an affordable, stable and environmentally sensitive energy system for the greatest benefit of all.

Formed in 1923, the Council is the premiere global energy body, representing the entire energy spectrum, with over 3,000 member organisations in over 90 countries, drawn from governments, private and state corporations, academia, NGOs and energy stakeholders. We inform global, regional and national energy strategies by hosting high-level events including the World Energy Congress and publishing authoritative studies, and work through our extensive member network to facilitate the world's energy policy dialogue.

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ABOUT THIS INSIGHTS BRIEF

This Innovation Insights brief on energy storage is part of a series of publications by the World Energy Council focused on Innovation. In a fast-paced era of disruptive changes, this brief aims at facilitating strategic sharing of knowledge between the Council's members and the other energy stakeholders and policy shapers.

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EXECUTIVE SUMMARY

As the global electricity systems are shaped by decentralisation, digitalisation and decarbonisation, the World Energy Council's Innovation Insights Briefs explore the new frontiers in energy transitions and the challenges of keeping pace with fast moving developments. We use leadership interviews to map the state of play and case studies across the whole energy landscape and build a broader and deeper picture of new developments within and beyond the new energy technology value chain and business ecosystem.

The topic of this briefing is **energy storage**. We interviewed energy leaders from 17 countries, exploring recent progress in terms of technology, business models and enabling policies. We showcase these in 10 case studies. While the brief addresses energy storage as a whole, most insights are focused on electrical storage. **Our research highlighted that today's mainstream storage technologies are unlikely to be sufficient to meet future flexibility requirements resulting from further decentralisation and decarbonisation efforts.** Furthermore, a restricted focus on lithium-ion batteries is putting the development of more cost-effective alternative technologies at risk.

Our findings are based on interviews conducted with the following organizations:

- ACWA Power
- Avalon Battery
- BP
- Bright Source
- CAISO
- CPUC
- DBL Partners
- Delft University of Technology
- DNV GL
- Emerald Ventures
- Energy Storage Association
- Everoze
- Fluence
- HighView Power
- Hydrostor
- Iberdrola
- IERC
- IHS Markit
- Ion Venturest
- Kraftblock
- Noor Energy 1
- Nrstor
- ON Energy Storage
- Piller
- RTE
- Siemens
- Siemens Gamesa
- Stem, Inc
- Storengy
- SunRun
- The Energy Institute
- UC Berkeley
- Valhalla
- Verbund
- Vestas
- Zola Electric

A detailed list of the interviews with innovators, energy users and producers can be found at the end of this brief. Annex 4 provides a list of acronyms and abreviations.

With major decarbonising efforts to remove thermal electric power generation and scale up renewable energies, the widespread adoption of energy storage continues to be described as the key game changer for electricity systems. Affordable storage systems are a critical missing link between intermittent renewable power and 24/7 reliability net-zero carbon scenario. Beyond solving this salient challenge, energy storage is being increasingly considered to meet other needs such as relieving congestion or smoothing out the variations in power that occur independently of renewable-energy generation. **However, whilst there is plenty of visionary thinking, recent progress has focused on short-duration and battery-based energy storage for efficiency gains and ancillary services**; there is limited progress in developing daily, weekly and even seasonal cost-effective solutions which are indispensable for a global reliance on intermittent renewable energy sources.

The synthesis of thought leadership interviews and case studies with 37 companies and organizations from 17 countries helped derive the following key takeaways and also provide the impetus to the solution steps that we discuss in detail later in this brief:

KEY TAKE AWAYS

1. **SHARED ROADMAPS**
   Energy storage is a well-researched flexibility solution. However, while the benefits of energy storage are clear to the energy community, there has been limited bridge-building with policy-makers and regulators to explore the behavioural and policy changes necessary to encourage implementation.

2. **MARKET DESIGN - ACCESS & STACKING**
   Market access and the ability to stack different services simultaneously will enable cost-effective deployment of energy storage, regardless of the technology.

3. **MORE THAN BATTERIES**
   Energy storage is too often reduced to battery technologies. Future-proofing our energy systems means considering alternative solutions and ensuring technologies have equal market opportunities. Demonstration projects of such technologies are necessary to disprove bias towards specific technologies.

4. **SECTOR COUPLING**
   Energy storage presents a sector coupling opportunity between hard-to-abate sectors, such as mobility and industry and clean electricity. Different vectors of energy can be used, including heat, electricity and hydrogen.

5. **INVESTMENT**
   Relying on investments by adjacent sectors such as the automotive sector is not enough. The energy sector must adopt more aggressively technologies aligned with the end-goal: affordable clean energy for all.

INTRODUCTION

Since 2009, the Council has been conducting a global survey of critical energy issues for its horizon scanning tool (Issues Monitor). This horizon scanning tool is a reality check of what energy leaders perceive as action priorities and what they perceive as uncertainties toward their respective energy transitions. It enables an understanding of the world energy agenda and the evolution of priorities on a historical and geographical basis. Since 2015, the global perspective is that energy storage and renewables are action priorities, meaning that energy stakeholders from across the globe are working to incorporate these technologies into their energy transition portfolios. In addition, World Energy Scenarios published in 2019, highlights that the pace of change is dependent on deployment and further development of energy storage.

As electricity systems evolve, there is an industry-wide recognition of the necessity to deploy additional new and flexible storage solutions. These flexible solutions are essential to meet new demand for diverse needs (including transport), to enable the reliable integration of intermittent renewables, to facilitate the cost-effective switching between supply and storage. Nonetheless, **significant progress remains to be achieved globally in terms of developing supportive policy and market frameworks for energy storage**. The interviews conducted as part of this brief very clearly show where and how deployments of energy storage are occurring.

Energy storage is a well recognised flexibility tool, both for electrical and thermal storage. However, as noted from the key takeaways drawn from the thought leadership interviews and case studies, there are missing elements that are preventing energy storage from providing their potential benefits. Industry, policy makers and regulators need common understanding derived from shared roadmaps. Market design needs to evolve to enable the access for new storage service opportunities and should be technology agnostic because energy storage needs to be more diversified than batteries. Adjacent sectors may provide new storage solutions beneficial for the energy system and investment should explore all potential storage technologies. Using these takeaways as foundational building blocks, we explore a set of helpful steps for energy storage developers and policymakers to consider while enabling energy storage. These steps are based on three principles:

1. encourage whole system thinking,
2. focus on energy storage as an "affordable and deeper" decarbonisation option, and;
3. advocate for technology-openness.

STEP 1: Enable a level playing field

- Clearly define how energy storage can be a resource for the energy system and remove any technology bias towards particular energy storage solutions
- Focus on how energy storage can contribute to a better energy transition

STEP 2: Engage stakeholders in a conversation

- Engage all relevant stakeholders to explore all potential energy storage needs
- Consider whether alternatives may be more suitable than energy storage

STEP 3: Capture the full potential value provided by energy storage

- Provide equitable access to ESS to all energy market services and products
- Stack revenues through the ability of storage technologies to offer multiple simultaneous market services
- Explore sector coupling opportunities with industry

STEP 4: Assess and adopt enabling mechanisms that best fit to your context

- Learn from & with others to identify those policies that best suit to your circumstances
- Ensure that there is no bias against or for behind-the-meter energy storage

STEP 5: Share information and promote research and development

- Maintain a long-term horizon in mind and promote R&D, especially for long duration storage
- Promote information sharing across the industry and beyond

In addition to the interview process to identify the enabling steps in the next section, we also prepared 10 case studies to showcase a variety of technologies at different stages of development which can provide daily, weekly and even seasonal solutions. These case studies can be found in the Annex I and focus on:

- Different energy storage applications
- The business models implemented
- The conditions for replicability of the different projects
- The value creation and cost-effectiveness of different case studies
- The lessons learned, whether they are technical, economic or regulatory

List of case studies (in alphabetical order by technology):

Project	Technology	Focus	Location
Angas A-CAES Project	A-CAES	Australia's first Advanced Compressed Air Energy Storage (A-CAES) facility	Australia
HighView Power	Cryogenic energy storage	Long-duration energy storage	United Kingdom
Siemens Gamesa Renewable Energy	Electric Thermal Energy Storage	Large-scale, long-duration solution	Germany
Project Centurion	Hydrogen	Feasibility study on storing 100% hydrogenin salt caverns	United Kingdom
ON Energy Storage	Lithium-ion battery	First industrial BESS to provide frequency regulation in Mexico	Mexico
Experion Energy Program	Lithium-ion battery	Large scale BTM deployment program	Canada & USA
IERC StoreNet	Lithium-ion battery	Residential storage to operate in the form of virtual power plant	Ireland
Kennedy Energy Park	Lithium-ion battery	Wind, solar and battery hybrid power plant solution	Australia
RINGO project	Lithium-ion batteries	Transmission congestions relief	France
Noor Energy 1	Molten Salt	Hybrid CSP and PV power station	United Arab Emirates
Espejo de Tarapaca	Pumped hydro	Seawater pumped hydro storage	Chile

Figure 1 – Sample overview of storage technologies

	ELECTRICAL		MECHANICAL			ELECTROMECHANICAL			CHEMICAL	THERMAL
	Superca-pacitors	SMES	PHS	CAES	Flywheels	Sodium Sulfur	Lithium Ion	Redox Flow	Hydrogen	Molten Salt
Maturity	Develop-ing	Develop-ing	Mature	Mature	Early commer-cialised	Commer-cialised	Commer-cialised	Early commer-cialised	Demon-stration	Mature
Efficiency	90-95%	95-98%	75-85%	70-89%	93-95%	80-90%	85-95%	60-85%	35-55%	80-90%
Response Time	ms	<100 ms	sec-mins	mins	ms-secs	ms	ms-secs	ms	secs	mins
Lifetime, Years	20+	20+	40-60	20-40	15+	10-15	5-15	5-10	5-30 years	30 years
Charge time	s - hr	min - hr	hr - months	hr - months	s - min	s - hr	min - days	hr - months	hr - months	hr - months
Discharge time	ms - 60 min	ms - 8 s	1 - 24 hs+	1 - 24 hs+	ms - 15 min	s - hr	min - hr	s - hr	1 - 24 hs+	min - hr
Environmen-tal impact	None	Moderate	Large	Large	Almost none	Moderate	Moderate	Moderate	Depend-ent of H2 production method	Moderate
Possible applications by technologies										
Power quality	✓	✓			✓	✓	✓	🤞		
Energy arbitrage			✓	✓	🤞	✓	✓	✓	🤞	✓
RES integration		✓			✓	✓	✓	✓	✓	
Emergency back-up					✓	✓	✓	✓	🤞	
Peak shaving			✓	✓		✓	✓	🤞	🤞	🤞
Time shifting			✓	✓		✓	✓	🤞	🤞	🤞
Load leveling			✓	✓		✓	✓	🤞	🤞	🤞
Black start						✓	✓	✓	🤞	🤞
Seasonal storage			🤞	✨					🤞	🤞
Spinning reserve		🤞			🤞	✓	✓	🤞	🤞	
Network expansion			✓	🤞		✓	✓	🤞	🤞	🤞
Network stabilisation	🤞	✓			🤞	✓	✓	🤞		
Voltage regultation	🤞	🤞			🤞	✓	✓	✓		
End-user services	🤞	🤞			🤞	✓	✓	🤞		

Sources: Interviews, Schmidt et al. (2019), Das et al. (2018)
H2 = Hydrogen, RES = Renewable energy source, RE = Renewable energy, SMES = Superconducting magnetic energy storage, PHS = Pumped hydroelectric storage, CAES = Compressed-air energy storage
Note: The Council has reviewed available literature to build this table. In our review, technology specifications differ greatly based on the source.

- ✓ for proven
- 🤞 for promising
- ✨ for possible

Enabling Energy Storage

STEP 1: Enable a level playing field

Whilst the energy sector in many countries recognise the importance of energy storage, regulatory frameworks currently hold back its cost-efficient deployment. For instance, the lack of a clear definition of energy storage in many jurisdictions leads to uncertainty about how energy storage devices should be treated under enforced regulations.

A. CLEARLY DEFINE ENERGY STORAGE IN A WAY THAT KEEPS TECHNOLOGY OPTIONS OPEN

Energy storage is the capture of energy produced at one time for use at a later time. Regardless of the technology, today, most regulatory frameworks do not reflect the role and value that energy storage can provide. In many markets, storage is classified as a load-modifying resource or, in some cases, it is classified both as a generation asset and as a load resource. This leads to energy storage systems often facing double charges, paying levies on both the consumption and production of electricity.

Within electricity, interviewees insisted on the idea of storage to be established as a separate asset class, next to generation, transmission/distribution, and consumption. This would ensure that regulatory frameworks recognise the unique aspects of energy storage vis-à-vis the other assets.

> **"Energy storage systems are not generating assets; they are not load-absorbing assets; they have the potential to provide a broad range of services, from integrating renewables to deferring transmission upgrades. In any situation, the questions we need to ask are – what job or jobs does the storage need to do, what technology will best fit that need, and are the business and regulatory structures in place to ensure it can?"**
>
> **MADINA MUKHANOVA, FLUENCE**

While most of recent discussions are focused on electric energy storage, the definition of energy storage should enable cross-sectorial interfaces. This enables a more flexible operation of the electricity grid, while providing clean fuels from renewables for the decarbonisation of other sectors.

The definition should not focus on a specific storage family in order to allow for the development of new technologies. This has been extensively seen in the development of batteries in the past. The same applies to potential applications of energy storage, which may continue to develop in the years to come as systems continue changing.

B. REMOVE ANY TECHNOLOGY BIAS TOWARDS A CERTAIN ENERGY STORAGE TECHNOLOGY

The past decade has been marked by growing interest in both conventional and advanced energy storage technologies. As the case studies demonstrate, recent research has focused on advanced batteries, new mechanical systems based on compressed air and flywheels, and chemical based storage technologies (e.g. hydrogen).

Based on the findings of our interviews, the World Energy Council considers that a wide range of energy storage technologies will be needed to address the challenges of the energy transition. Yet, recent publications, press coverage and events of the energy storage industry has been very focused on battery-only innovation, in particular lithium-ion. However, lithium-ion batteries may not be fit for a series of requirements of future energy systems, in particular fast charging and long duration storage integration. These markets, in turn, must open to other technologies.

> **"What struck me is the recognition that lithium-ion is not going to be the only solution to the utility scale storage challenge that we have. By that, I mean a storage device that will allow us to charge and discharge as frequently as we want, for as long as we want. That's the utopia. And there's a lot of attention going in all directions."**
>
> **PADDY PADMANATHAN, ACWA**

In this context, is it is crucial that the system and different enabling frameworks remain technologically neutral.

> **"I don't think policy makers should try to choose winners and losers in terms of technology. I believe that if the regulatory authority wants to promote storage, they need to define the characteristics and use cases, avoiding the determination of whether it should be based on lithium-ion, hydro or any other technology."**
>
> **RODOLFO MARTINEZ CAMPILLO, IBERDROLA**

The bias towards a technology can be intentional, by referring to energy storage as battery storage for example. It can also be unintentional, as was the case in California's energy storage mandate. In 2013, utilities in California were mandated to procure 1,325 megawatts of energy storage by 2020. While this approach led to the development of projects, it focused on lowest cost and provided relatively short timeframes for projects to be executed. According to several interviewees, this created a bias toward lithium ion battery projects, as it is seen as relatively low risk.

> **"I would have loved to see California policymakers take an approach which signalled that more is needed to be learned about technologies, and even kind of requiring or encouraging multiple types of storage technologies to be deployed, even if some of them are higher risk and higher cost.Because ultimately, it's not about solving a near term problem, it's about demonstrating technologies and solutions that will hopefully have a broader applicability around the world."**
>
> **ANDREW CAMPBELL, ENERGY INSTITUTE AT HAAS, UC BERKELEY**

C. FOCUS ON HOW ENERGY STORAGE CAN CONTRIBUTE TO A BETTER ENERGY TRANSITION

In part, the focus on energy storage results from broader decarbonisation efforts through the development of renewable energies. It is therefore crucial to consider the contribution of these systems to the reduction of greenhouse gases, considering the grey energy[1] consumed by the construction of the storage system itself.

[1] Grey energy is the hidden energy associated with a product, meaning the total energy consumed throughout the product's life cycle from its production to its disposal.

> **"With many of today's storage solutions, including molten salts, we are dealing with very damaging, very corrosive, very sensitive and toxic material, which all have to be disposed of at the end of life in a careful, responsible way. What I would like to see is much more attention and effort to reuse, rather than just dispose. Some attention is starting to go towards that. Because quite a lot of the material that we are using comes from finite resources. Beyond the environmental damaging consequences, there is also the issue around continuing to extract more and more new material, which also has its own environmental impact."**
>
> **PADDY PADMANATHAN, ACWA POWER**

Battery recycling is an aspect that is becoming increasingly important. On the one hand, this is motivated by the shortage of certain materials - often precious - necessary for the manufacture of electrochemical cells. On the other hand, this is due to several recent legislations, which require significant reductions in energy intensity of processes to obtain mineral material.

Life cycle analysis (LCA) is one of the methodologies to assess the environmental impact of productive systems. For batteries, a LCA entails looking at four phases of a battery's life: obtaining the required minerals, manufacturing, utilization, and finally collection and recycling (or disposal) of the product at the end of its useful life. While a lot of focus has been given to batteries' environmental footprint, it is crucial that the same is applied to other types of energy storage technologies.

More broadly, it would be helpful to consider how energy storage can help to improve the performance of the whole energy system by improving energy security, allowing more cost-effective solutions and supporting greater sustainability to enable a more just and better energy transition. The Council's Energy Trilemma tool could help frame how energy storage options could more effectively help achieve the decarbonisation goals set by policy.

STEP 2: Engage stakeholders in a conversation

The need for energy storage is not yet widely accepted. Moreover, there is only limited understanding of the challenges and a lack of common vision for the future of energy storage among relevant stakeholders (see Figure 2). This is largely due to the fact that energy systems may not have an immediate need for energy storage due to a low renewable penetration.

A. ENGAGE ALL RELEVANT STAKEHOLDERS TO EXPLORE ALL POTENTIAL ENERGY STORAGE NEEDS

As the energy transition progresses, significant volumes of intermittent renewable generation will join the electricity system and introduce new associated system costs that must be accounted for. On the one hand, dealing with the intermittency of renewables means that system operators have to activate ramping resources more frequently to meet demand. On the other hand, the fact that renewables must be located where they are most productive means that they are typically not found close to the population (consumer) centres. This requires dedicated transmission infrastructure to connect supply and demand.

The first conversation to have with these stakeholders is whether energy storage is necessary in the assumed context. Energy storage should not be developed for its own sake. Competing technologies for energy storage exist, including demand side responses, flexible generation, smart grids, etc. Storage is desirable if (a) there is significant variability in the source of power which requires some tailoring to conform to the desired profile of power demand and (b) alternative approaches are insufficient (or insufficiently competitive) to satisfy this tailoring requirement.

If energy storage is perceived as a necessity, the priority is to get stakeholders to reflect upon future grid operations. In particular, they should assess the potential energy storage needs necessary to be able to develop suitably reliable systems in a timely manner.

> **"We need to make sure that everybody quits installing 200 megawatts of solar without a balancing act together. This is to avoid having to connect another power plant which maybe uses coal turbines. They need to provide fully reliable and dispatchable renewables since the development, not several years after."**
>
> **JAVIER CAVADA, HIGHVIEW POWER**

Increasingly, intermittent producers are taking responsibility and hybrid renewable energy projects are emerging as a solution for a reliable, affordable and dispatchable integration of renewable energies to solve critical needs. Such projects could allow renewables to participate in capacity markets and be stored for use during peak demand periods that would otherwise require natural gas peaker plant generation.

However, the concept faces important regulatory and policy barriers. To start with, most systems do not have a hybrid project capacity accreditation. Accreditations exists for solar and wind and many operators are developing a capacity accreditation for battery storage. Even so, specialised accreditation remains almost non-existent for hybrid projects. Other barriers include interconnection, dispatch and compensation issues. These are all issues which can be solved by engaging the different stakeholders from an early stage of the development of energy storage: regulators, system operators, customers, utilities, etc.

Figure 2: Energy storage opportunities for different stakeholders

ELECTRICITY SYSTEM OPERATORS

- Economically optimize infrastructure by deferring network strengthening investments
- Integrate intermittent power generation by ensuring a stable supply of electricity
- Secure supply / demand balance forecasts by optimizing peak
- Have more efficient system services that leverage the performance of storage facilities

UTILITIES

- Energy storage can be a means of decarbonising the fleet. In other words reduce the need to build gas peakers.
- Defer expensive new investments and reduce the risk of long-lived capital projects not being used
- Address both long-term regulatory requirements and short-term needs, such as reliability and deferring the construction of new substations
- Explore new opportunities by providing advisory services (e.g. Australia) or selling advanced analytics and data-management services (e.g. USA, ComEd)

DISPATACHABLE PRODUCERS

- Combine conventional generation and storage to improve operational and environmental performance
- Optimize the sizing of facilities by coupling production and storage
- Anticipate future capacity requirements and take advantage of capacity market (if existent)
- Protect medium and long-term economic risks (e.g. carbon price)

INTERMITTENT PRODUCERS

- Anticipate the regulatory constraints on storage obligations for intermittent producers
- Consolidate installed capacity to participate in existing/future capacity market
- Develop synergies to increase competitiveness

COMMERCIAL & INDUSTRIAL CONSUMERS

- Manage energy bills by integrating storage at the heart by peak load reduction
- Generate revenues and explore providing services in capacity market
- Secure energy supply and ensure the quality of power for different facilities

RESIDENTIAL CONSUMERS

- Minimise reliance on the grid and manage energy bills through savings from time-of-use rates where these exist
- Residential batteries could be linked together and dispatched to deliver grid support services
- Reducing the peak load on the local grid network and optimizing individual circuit loading can make local nodes safer and more reliable, and allow utilities to delay some capital upgrades

STEP 3: Capture the full potential value provided by energy storage

The main challenge for energy storage is that not all its potential benefits (e.g. savings on capital expenditure required to install peaking plants, reduced expenditure on transmission and distribution grid reinforcement, etc.) can be captured by arbitrage, or through the provision of ancillary services on the basis of contractual arrangements. This is due to the fact that the benefits arising from these services are spread widely across different industrial participants with limited ability to appropriate the full rent from activities they undertake. In most countries, there is a missing market issue due to uncaptured positive externalities from storage activities.

A. PROVIDE EQUITABLE ACCESS TO ENERGY STORAGE SYSTEMS TO ALL MARKET SERVICES AND PRODUCTS

Along with the popular "time shifting" application, energy storage can also be used for a multitude of other applications, including transmission and distribution investments deferral, ancillary services, energy arbitrage, etc. Today, modern energy storage technologies and their participation in the electricity system are still being tested in some of the most advanced markets in the world. An enabling regulatory environment that allows energy storage to compete on an equal basis with other flexibility providers will be essential to sustain growth of storage in the energy industry. It is also crucial that clear rules of access for energy storage into those markets are established.

> **"An important aspect is the allowance of energy storage to participate in the wholesale market. For ancillary services, storage can do a better job than any other resource today. It is faster to respond, and it is cleaner."**
>
> **STEPHEN COUGHLIN, FLUENCE**

On this topic, several recent regulatory changes outlined below are expected to have huge impacts on energy storage.

Enacted in February 2018 in the United States, the FERC 841 regulation directs grid operators to remove barriers to the participation of energy storage in wholesale capacity and energy and ancillary service markets. In addition, FERC 845 revises the definition of a generating facility to account for electricity storage and recognise its unique characteristics as technically neither generation nor load. Within the European Union, the Clean Energy for All Europeans package opens up electricity markets to energy storage.

In China, utility scale energy storage has been driven by state-run projects. China's National Energy Administration announced that the ancillary services market will be transitioning from a basic compensation mechanism to a market integrated model with spot energy prices by 2020. That, along with technological maturity and subsequent cost reductions, are key factors that will contribute to the exponential growth in the nation's energy storage market through to 2024.[2]

B. ALLOW STORAGE PROJECTS TO OFFER MULTIPLE SERVICES SIMULTANEOUSLY

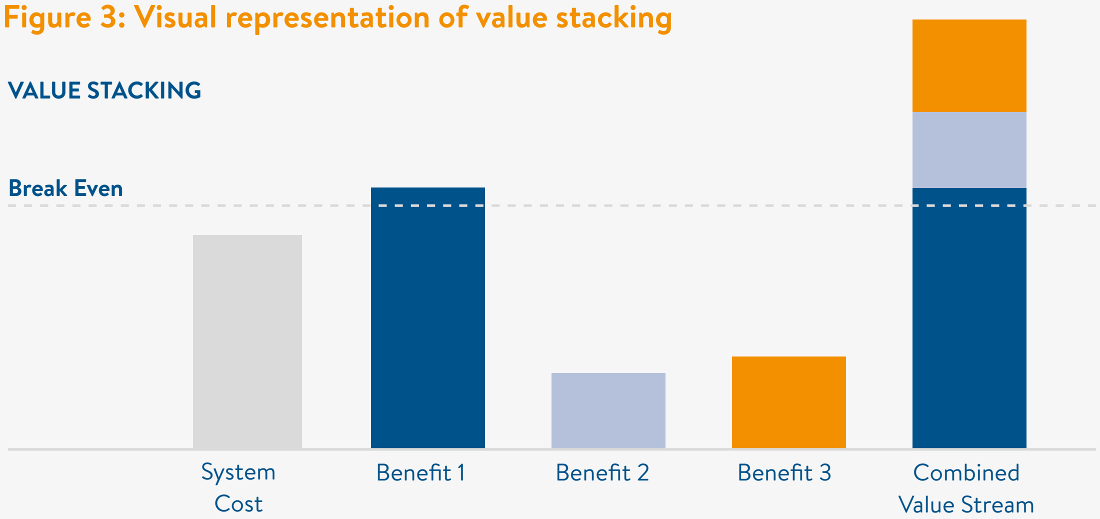
One of the most important benefits of a well-designed and optimized energy storage system is the opportunity for "stacking services," i.e. leveraging the same equipment, system, or process to deliver multiple benefits that maximize financial impact. With today's evolving rate structures, market demands and incentive programs, system return-on-investment has become a more complex and economically beneficial, based on the value of stacked services.

[2] https://www.woodmac.com/press-releases/china-to-become-largest-energy-storage-market-in-asia-pacific-by-2024/

"To accelerate the development of behind-the-meter electric energy storage, multiple, stacked services need to be valued. Currently, most systems are deployed for one of three single applications: demand charge reduction, backup power, or increasing solar self-consumption. This results in batteries sitting unused or underutilized for well over half of the system's lifetime."

JULIAN JANSEN, IHS MARKIT

Figure 3: Visual representation of value stacking



Yet, while utilities and regulators have played with the idea of value stacking, and even adopted minor changes to capitalize on energy storage's different applications, value stacking on a large scale remains to be widely implemented. In January 2018, the California Public Utilities Commission (CPUC) approved new market rules for energy storage aimed at enabling the resources to stack incremental value and revenue streams through the delivery of multiple services to the wholesale market, distribution grid, transmission system and other uses. In the order, the CPUC acknowledged that current market rules, including utility standard contracts and program tariffs, fail to support the ability of an energy resource to access more than one service.[3]

"The business model for energy storage relies on value stacking, providing a set of services for customers, a local utility and the grid for example. By having two or three distinct contracts stacked on top of each other you are being paid for the different services. For this, you need to measure very granularly the different services to avoid double payments. Regulatory paradigms need to evolve to allow for that contracted effort. This is not yet in place in most territories."

POLLY SHAW, STEM

Another stacking opportunity is through the use of Artificial Intelligence (AI). AI opens a lot of possibilities to maximize the returns from an energy storage project. This includes performing predictive analytics, machine learning, big data and grid-edge computing. Data can be captured and analysed on loads, power generation, weather, nearby grid congestion and electricity rates.

[3] https://www.cleanenergylawreport.com/energy-storage/california-adopts-rules-for-evaluating-multiple-use-energy-storage-resources/

> **"The entire secret sauce behind energy storage is not the hardware product but in the software, which governs the charge and discharge and its operation as a network. Increasingly using AI for predictive analytics, weather patterns, load behaviour of buildings, rate design options available to customers, anticipating load behaviour and deciding whether to charge or discharge to maximise economic value for the customer."**
>
> **POLLY SHAW, STEM INC**

AI is also key to stack different contracted revenues. It can drive the "delivery" of unused energy stored in a network of batteries, as a virtually-integrated resource to those grid locations that need power. For example, on a given day, an ESS may be able to perform renewable energy firming while also helping to manage time-of-use charges and participate in demand response programs. However, the amount and timing of each manoeuvre would depend on cloud cover, the building's operational schedules and load requirements, and other factors on a given day. Without an intelligently optimized approach, this could result in missed financial opportunities and negative impacts on battery performance or operating life.

> **"It's all about optimizing through sophisticated algorithms that are typically AI driven to be able to capture as much value as possible while preserving the integrity and the degradation profile of your battery system."**
>
> **MOE HAJABED, NRSTOR**

The speed and complexity of this task requires advanced artificial intelligence. It could be a network of thousands of mixed energy storage units (electrical, thermal, others) installed at consumers, end-users or on highly used sites, such as industrial installations.

C. EXPLORE SECTOR COUPLING OPPORTUNITIES WITH INDUSTRY

Energy storage, besides the use of batteries, is gaining momentum to enable the electrification of passenger vehicles. Thermal and chemical energy storage (see Kraftblock and Siemens Gamesa case studies) (e.g. hydrogen) are emerging as key enablers of sector coupling. Simply put, sector coupling acts as a link between clean energy sources and consumers such as industry or households.

> **"We really built this for sector coupling, and not only just for arbitrage or battery replacement. Nine years ago, we recognised that there was a need for large-scale, long-duration green flexibility."**
>
> **HASAN ÖZDEM, SIEMENS GAMESA**

Thermal energy storage can capture the heat generated by industry, to be sold by companies when the price of energy is highest, therefore creating a new revenue stream. Steel companies, for example, could de-couple their fuel supply from their electricity generation: a way to store the heat from flue gases and use it to generate electricity and sell it at peak prices.

> **"For example, if you run a wind farm next to an industrial complex, you can store the excess wind power in heat and release the heat as processed heat into the industrial complex. You can also do district heating, or you can produce electricity using a steam turbine again."**
>
> **MARTIN SCHICHTEL, KRAFTBLOCK**

In addition, companies such as Siemens Gamesa are looking into using thermal storage to transform conventional power plants. Where contemporary gas, coal or nuclear power generation facilities emit heat as a byproduct, there is also room for volcanic stones. The rest of the components, the electrical and civil infrastructure, can be reused. With this "brownfield" approach, an old power plant can become a modern, large-scale energy storage plant. Storage can likewise optimize energy intensive industries, such as the steel industry.

Hydrogen is gaining attention as a form of chemical energy storage. Its capacity to store large quantities of renewable energy sources over long periods of time further demonstrates its significance in the clean energy transition. Hydrogen can contribute to decarbonisation by acting as a storage medium for renewable energy sources and in doing so reach sectors which still rely on fuels and where electrification alone is insufficient. Processed hydrogen provides high-grade heat that can be used in transport as fuels, in industries as feedstock and in agriculture for fertilisers.

> **"We see hydrogen as a logical extension of our value chain to make and sell not only green electricity, but also green hydrogen. We see green hydrogen as an energy carrier in transportation, as a process gas, in the steel industry, or in refineries, but also is a very valuable seasonal storage medium, because it's a gas, it's got quite high energy density, which can be potentially stored in underground storage systems, and will help us to shift large amounts of energy between summer and winter."**
>
> **RUDOLF ZAUNER, VERBUND**

The storage potential of hydrogen is particularly beneficial to power grids, as hydrogen allows for renewable energy sources to be kept in large quantities and over long periods of time. This means that hydrogen can help significantly improve the flexibility of energy systems by balancing power generation when it is either too much or not enough and in so doing boost energy efficiency throughout Europe.

These applications could lead to an improvement of the energy system, in both energy efficiency issues and environmental perspectives.

STEP 4: Adopt enabling mechanisms that fit your context

A. LEARN FROM AND WITH OTHERS TO IDENTIFY THOSE POLICIES THAT BEST SUIT YOUR CIRCUMSTANCES

Around the globe, different jurisdictions are working to push energy storage forward. According to the interviews conducted, decarbonisation targets are a key factor in the implementation of policy reforms in the area of energy storage.

Different countries take a different route depending on how their electricity system is structured. For example, the United Kingdom is known for emphasizing agile regulation and competition.

> **"In the UK, the regulator has worked on identifying and addressing regulatory and policy barriers to storage. For instance, there's a problem of kind of double charging, where storage is penalised by having to pay levies on both the imports and exports of electricity. That's now being reviewed. There were issues with the licence categorization of storage, and a whole suite of issues that have been logged in a paper called upgrading our energy system. The UK's approach is not to directly support, but rather to try to remove the regulatory friction, to kind of unleash the power of the market."**
>
> **FELICITY JONES, EVEROZE**

Other countries take different approaches, including direct subsidies, energy storage mandates, incentives in the form of Renewable Energy Certificates, etc. The table below provides insights into how different jurisdictions are working on the topic.

Figure 4: Successful Enabling Policy Initiatives

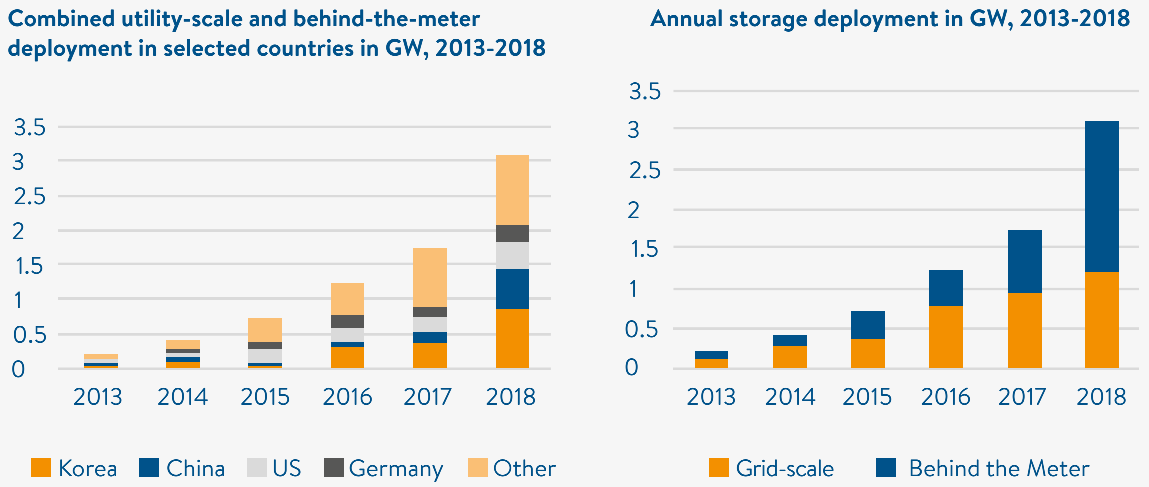
Jurisdiction	Policy Initiatives
California (USA)	**Focus: Facilitate RE integration/energy transition** • Procurement target of 1.325 GW for the state's 3 IOUs by 2020 • An updated procurement target in 2016 to add an extra capacity of 500 MW • Significant increase in the Self Generation Incentive Program (SGIP) funding; strong R&D funding to support ES, that scale-up new ES technologies • California Energy Storage Roadmap published 2014 • Several new policies and rules that particularly create BTM and utility-scale energy storage markets, remove interconnection challenges, and ensure the role of bulk energy storage in the state's renewable energy landscape.
European Union	**Focus: clean energy transition, system flexibility, energy security** • RD&D Funding • Energy storage's role part of the Clean energy for all European Package • Focus is on reducing barriers by focusing on non-discrimination, competitive procurement and fair rules in relation to network access and charging • Wide definition of 'energy storage' adopted, encompassing both reconversion to electricity or conversion into another energy carrier.

	• Energy storage recognized as a distinct asset class, separate from generation • Battery Europe: research and innovation platform of the EU
Germany	**Focus: facilitate large-scale RE integration, provide system flexibility** • RD&D Funding • Power-to-X and hydrogen research initiatives • Roadmap/Strategy published 2011 • Residential solar + storage loan program
Japan	**Focus: facilitate large-scale RE integration, resilience to extreme weather events** • For BTM storage: subsidies for net zero energy houses + subsidies for households' resiliency to backouts caused by natural events
New York (USA)	**Focus: Economic development, DR, ancillary services, upgrade deferrals** • Energy Storage Roadmap in 2016 with goals of 2 GW in 2025, and 4 GW in 2035 • Creating new regulatory and market mechanisms to accelerate use of Energy Storage • Creating standardized codes and regulations universally accepted by all jurisdictions across the State.
Republic of Korea	**Focus: RE integration, climate change, industrial support for manufacturers** • Renewable Portfolio Standard program: REN projects paired with energy storage benefit from a higher Renewable Energy Certificate (REC) multiplier • The government has tripled the level of discount on electricity retail rates for C&I customers with storage systems
United Kingdom	**Focus: Grid flexibility, system balancing, renewables integration, ancillary services** • RD&D Funding + Energy Entrepreneurs Fund • Storage eligible under Renewables Obligation and Feed-in Tariff • Licence exemptions for small capacity storage systems • Proposed modified generation licence for large scale storage systems • Regulator working to remove barriers to energy storage deployment
USA (Federal)	**Focus: Significant focus for RE integration and climate change, DR, ancillary services. Now unclear.** • Enacted in February 2018, FERC 841 directed regional grid operators to remove barriers to the participation of electric storage in wholesale markets; markets have to be redesigned to recognise the unique characteristics of storage as technically neither generation nor load

B. ENSURE THAT THERE IS NO BIAS AGAINST BEHIND-THE-METER ENERGY STORAGE

Historically, companies, grid operators, independent power providers, and utilities have invested in energy-storage devices to provide a specific benefit, either for themselves or for the grid. As storage costs fall, ownership is broadening. As noted in the interviews, while BTM has historically been driven by a logic of self-consumption, it is increasingly driven by the opportunity to provide system-level services. In addition, whilst utilities tend to mostly be associated with front-of-the-meter energy storage, they are more and more getting involved with behind-the-meter projects to provide front-of-the-meter applications.

Figure 5: Energy storage deployment levels & BTM storage expansion figures.



Source: IEA, 2019

> "Customers want choice and they want independence. The world is moving towards a decentralized system, where customers want to generate their own electricity and want to have control over their electricity costs. This is becoming a main driver for behind the meter installations. But it all depends on the market, and the ability to monetize assets by providing services to the grid."
>
> **MOE HAJABED, NRSTOR**

Despite the acceleration of BTM storage deployment, many regulations do not currently allow these assets to, for example, receive payment for deferral services, to provide grid services through bilateral contracts in non-liberalized markets or to bid into wholesale markets in liberalized markets.

> **"There are a lot of jurisdictions in the world where you're simply not allowed to generate electricity on the grid. Being able to do that has a tremendous benefit in terms of proving the operation and economics of combined solar and battery projects on a lot of commercial or industrial sites. The degree to which structures within countries allow consumers to generate their own power and manage their own usage is a huge driver of the adoption of these kinds of technologies."**
>
> **MATT HARPER, AVALON BATTERY**

Additional focus should therefore be given to reducing barriers by focusing on non-discrimination, competitive procurement and fair rules in relation to network access and charging.

STEP 5: Share information and promote RD&D

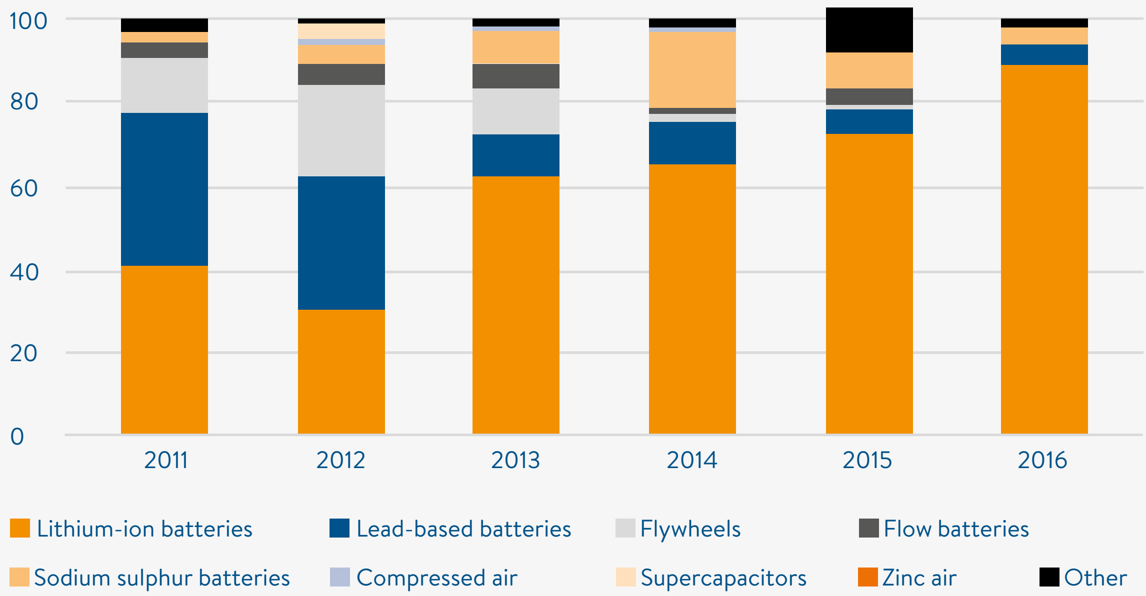
A. MAINTAIN A LONG-TERM HORIZON IN MIND AND PROMOTE R&D, ESPECIALLY FOR LONG DURATION STORAGE

Conventional energy storage technologies, including pumped or reservoir-based hydro-electric facilities, and lead-acid batteries, have existed for more than a century. The past decade has been marked by growing interest in both conventional and advanced energy storage technologies. Attention has been given to advanced batteries (e.g. flow, lithium ion, NaS), new mechanical systems based on compressed air and flywheels, and thermal and gas (i.e. hydrogen and methane) based storage technologies.

Nonetheless, battery technology, particularly in the form of lithium-ion, is getting the most attention and has progressed the furthest. Lithium-ion technologies accounted for more than 95% of new energy-storage deployments in 2015[4]. Following substantial investments from the consumer electronics and automotive sectors, the average price of a lithium-ion battery pack dropped by 85% between 2010 and 2018[5].

[4] BNEF, 2019
[5] BNEF, 2019

Figure 6: Technology mix in storage installations excluding pumped hydro, 2011-2016



Source: IEA, 2019

As highlighted by many interviewees, the transition to a decarbonised future is unlikely to be enabled by a single energy storage technology. For example, long life cycles are especially important for grid applications. Future markets such as integrating fast charging and long duration storage are likely better suited to other technologies than lithium-ion batteries.

As storage requirements move beyond the five to six hour threshold, technologies with low duty-cycle degradation at full depth of discharge, low material costs, and long lifetimes will be required to provide those lower costs than what most analysts believe Li-ion can achieve.

> **"There are a lot of people that think that 24/7 storage solutions technology is right around the corner but that's not true, it has a long way to go."**
>
> **LUIS MEEHRSON, SIEMENS CHILE**

However, the direction of recent investments, with the exception of a few flagship investments (e.g. Energy Vault, HighView Power, Gravitricity, etc.) indicate that the industry's agenda is still focused on battery technology. Venture capital investments in energy storage technology companies exceeded $1.9 billion in Q3 of 2019 alone and have continued to increase[6]. This money flows increasingly from acquisitions as well as non-traditional sources, including venture capital funds targeting risky and early-stage technologies (e.g., Breakthrough Energy Ventures), consortia of utilities targeting later-stage

[6] I3 insights, December 2019

commercialization (e.g., Energy Impact Partners), and a growing number of incubators and accelerators[7]. **Overall, less than 10% of the $1.9 billion was channelled towards non lithium-ion technologies.**

> **"Lithium-ion batteries have been around us for a long-time but happen to have been scaled up to the industrial level. It became an obvious area of interest and investment. Investors and policy makers are less comfortable and aware around other technologies. This is also related to risk appetite and finance and the fact that REN have been given extraordinary returns that are relatively risk free. In turn, there seems to be a lock in effect related to lithium ion-batteries."**
>
> **HASSEN BALI, ION VENTURES**

The deployment and system integration of energy storage technologies depends to a large extent on the strength of R&D efforts.

> **"We still don't know that much about a lot of storage technologies and this should be approached as a research development and demonstration activity. This means it should be government-driven. Politicians want to see things happen in a time frame that is relevant for their time in elected office and that can create a bias toward doing something quickly. But I think energy storage is an area where we should have a long-term horizon in mind."**
>
> **ANDREW CAMPBELL, ENERGY INSTITUTE AT HAAS, UC BERKELEY**

In addition to supporting technical innovation, there is a priority for demonstrating the practicability and commercial viability of storage projects in a range of applications. Demonstration projects are an opportunity to gather valuable knowledge about the market applications and commercial arrangements for energy storage systems.

> **"There are a lot of people crying for innovations in the energy system. But when you come up with something, the first question is whether this has been running for at least 10 years? This makes it challenging to then develop anything at large scale."**
>
> **MARTIN SCHICHTEL, KRAFTBLOCK**

B. PROMOTE INFORMATION SHARING ACROSS THE INDUSTRY

Beyond the cost of technology, today's focus is on economic profitability and the development of the sector. Nonetheless, the interviews conducted as part of this brief highlighted the general lack of awareness related to enabling energy storage and financing demonstration projects.

[7] https://www.greentechmedia.com/articles/read/how-do-cleantech-startups-get-funded-in-2019#gs.1qgfzo

> **"Most utilities or transmission operators have never seen a battery contract, they have no idea how to create one. All these things are really being created in the industry as we speak."**
>
> **SUDIPTA LAHIRI, DNV GL**

For non-utility-owned projects, the focus was on dependable offtake revenue contract to provide a steady stream of project cash flow. Offtake revenue contracts for front-of-meter battery storage projects usually take one of three forms: the energy storage tolling agreement, the capacity sales agreement or the hybrid power purchase agreement (PPA). The energy storage tolling agreement and capacity sales agreement are similarly structured and typically govern the sales of products and services from a stand-alone storage project. In contrast, the hybrid PPA applies to a renewables or conventional energy generation project (e.g. solar, wind, gas or other project) integrated (and typically co-located) with a storage project.

> **"Compared to financing a solar project, the financing structures that would stand behind large scale storage are still somewhat unclear and immature. You think about the massive deployment of solar that has allowed it to get some of those very, very low levelized numbers, part of it is the cost reduction of the technology itself. But really, a lot of it is financial innovation and engineering around how these projects get financed, how they get operated, and how those costs are spread out over a very, very long-time horizon. Storage, I think, is still in that transition period."**
>
> **MATT HARPER, AVALON BATTERY**

Offtake revenue contracts for behind-the-meter battery storage projects include transactions for the sale of products and services provided by a battery system to a utility (utility services agreements, including demand response contracts), transactions for products and services provided by a battery system to a commercial or industrial (C&I) host customer on whose site the battery is installed, as well as transactions combining both features.

FUTURE OUTLOOK

The need of energy storage in the energy system is well recognized. Energy storage provides benefits through flexibility and through the possibility of better linking of various energy and economic sectors. The interviews conducted as part of this brief signal that the applications and technologies which will dominate the market will depend on two things:

1) Whether the energy sector decides to push forward a wide range of technologies or continues to limit energy storage to battery storage

2) Energy storage is integrated as part of long-term energy policies and enabling regulatory frameworks, market incentives and support of demonstrations are provided

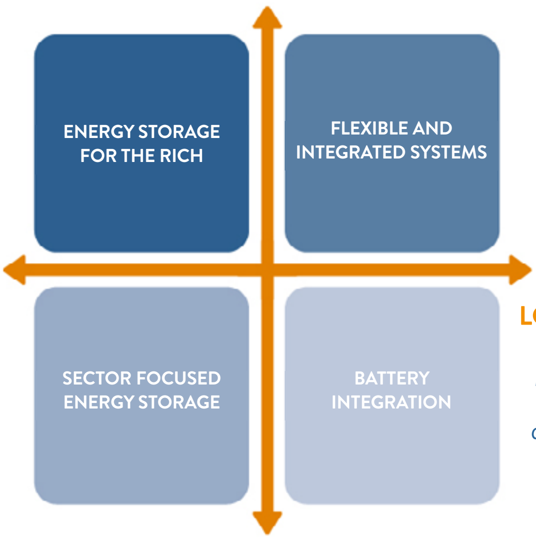
Energy storage is unique in the sense that it can truly provide benefits to all actors of the value chain, whether energy producers, distributors, system operators or consumers. Taking a whole-system view is therefore the only way to avoid falling into narrow definitions of the topic which may restrict the development of innovative technologies and applications. Education and dialogue between all stakeholders is therefore key.

INVESTMENTS PUSH A WIDE RANGE OF TECHNOLOGIES TO SCALE

A range of technologies are developed, including seasonal storage, by those bound to legally binding decarbonisation targets. Nonetheless, adoption remains limited to a handful of countries due to inadequate frameworks. Restricted regional deployment limits cost reductions through economies of scale.

A wide range of technologies become cost-effective to deal with seasonal variations, have intermittent renewables provide 24/7 reliable power and provide system services to the grid. Sectors such as electrified mobility, industrial processes using heat and power systems are well integrated through storage

LACK OF ENABLING REGULATORY FRAMEWORKS AND MARKET INCENTIVES



ENERGY STORAGE IS INTEGRATED AS PART OF LONG-TERM ENERGY POLICIES

Today's energy storage applications mature, focusing on short-duration services. Investments continued to be led by the automotive sector, focusing on batteries. The energy sector is a technology adopter rather than developer. Storage systems are poorly integrated between various application sectors (transportation, buildings, energy networks)

BIAS TOWARDS BATTERY STORAGE PERSISTS

Batteries increase in performance and reliance on rare materials drops. They are well integrated to different sectors, especially transport and buildings. Behind-the-meter energy storage dominates with a growing number of prosumers. Clean seasonal storage and long-duration storage remain very expensive and needs continue to be met by fossil fuel based plants.

ANNEX 1 |

Case Studies from around the Globe

ANGAS A-CAES PROJECT, ANGAS ZINC MINE, AUSTRALIA

Australia's first Advanced Compressed Air Energy Storage (A-CAES) facility

Hydrostor's Angas Project is Australia's first Advanced Compressed Air Energy Storage (A-CAES) facility. A-CAES is an emissions-free, long duration energy storage technology. It combines mining techniques with mechanical systems to produce a fuel-free, grid-scale energy storage system using compressed air that can be flexibly sited.

Energy Storage Applications

Load shifting	Frequency regulation	Synchronous inertia	Grid stability support

Located at a mine near Adelaide, the facility will repurpose underground infrastructure as the A-CAES system's air storage cavern. The 5 MW facility will be dispatched into the National Electricity Market to provide synchronous inertia, load shifting, frequency regulation, and support grid security and reliability.

A-CAES technology uses electricity from the grid to run a compressor, producing heated compressed air. During charging, compressed air displaces water out of the cavern up a water column to a surface reservoir, and during discharge water flows back into the cavern forcing air to the surface under pressure where it is re-heated using the stored heat and then expanded through a turbine to generate electricity on demand.

- **Status:** Under construction Scale: 5 MW, 10MWh
- **Technology:** Purpose-built air storage cavern
- **Cost of the project:** AUS $33 million
- **Financing:** The project has been awarded a combined total of $9 million of grant funding from the Australian Renewable Energy Agency (ARENA) and the Government of South Australia Renewable Technology Fund.

Conditions for replicability

- Ability to draw from different revenue streams
- Willingness of local stakeholders to invest in demonstration projects
- Not geographically constrained, deployable at both greenfield and brownfield sites

Value creation & Cost effectiveness

The project aims at demonstrating the potential for large-scale A-CAES to replace retiring fossil assets and integrate renewables, supporting grid reliability and emissions reductions. This project is particularly interesting due to its ability to replace retired fossil plants, repurpose existing mining infrastructure, and defer the need for new transmission. Long system life (30+ years) and unlimited cycling with no replacement required make this system advantageous.

WHAT DID WE LEARN?

- The project benefits the local community by converting a brownfield site into a clean energy project that drives economic development, including cleantech jobs and skills development.
- This solution can be flexibly located where required on the grid.
- One of the main challenges is associated with engineering and modelling to accurately predict performance with limited operating history.
- Angas A-CAES Project may open up opportunities throughout Australia for the build-out of full-scale (50+ MW), long-duration (4-24+ hours), long-life (50+ years) projects, adding clean energy capacity and boosting reliability of power supplies.

HIGHVIEW POWER CRYOBATTERY, UNITED KINGDOM

Long duration, large scale cryogenic energy storage

Highview Power's cryogenic energy storage is large scale, long-duration energy storage solution. It uses compressed air in a modularly assembled plant to provide cheap and long-term renewable energy storage.

Energy Storage Applications

Time-shifting	Synchronous voltage support	Frequency regulation	Synchronous inertia	Black start

Previously known as liquid air energy storage, Highview's technology employs liquid air as a storage medium. The system uses off-peak or excess energy to clean, compress, and cool air to -196°C. The liquified air is then stored in insulated tanks at low pressure. When energy is needed the liquid air is drawn from the tanks and pumped to high pressure, reheated, and expanded – resulting in a high-pressure gas which is used to drive turbines to generate energy.

The lifespan of the system is greater than 30 years. It can utilise industrial waste heat and cold from applications. The system is fully scalable and flexible, with no geographical constraints. The plant itself is deployed and built as modular pieces.

- **Status:** Commercialisation
- **Scale:** MW and MWh to GW and GWh
- **Technology:** Liquid air energy storage

Highview pioneered its CRYOBattery technology at a pilot plant in Slough. It then evolved at a demonstration plant in Pilsworth, Greater Manchester, UK, which has been successfully operating since 2018. The Pilsworth plant was the first in the world to demonstrate cryogenic energy storage technology at grid scale. It was funded for £8 million from the UK government

In October 2019, HighView Power announced that a 200MW facility could achieve a levelised cost of storage of US $140/MWh.

Conditions for replicability

- Commitment to retire fossil fuel-based plants
- Risk of unstable grid due to REN penetration
- Ability for storage to provide different revenue streams, e.g. stability services

Value creation & Cost effectiveness

HighView Power argues that this storage solution is the cheapest in terms of marginal cost of energy storage. The main values of this technology are its large scale, no geographical restriction and no pollution and safety risk.

WHAT DID WE LEARN?

- These plants are addressed to industrial clients and interface between transmission and distribution.
- Economic viability depends on client's needs and can answer priorities ranging from relief on grid congestion to increased renewable energy penetration in the grid.
- This system is best suited to renewable energy developers that need large scale storage for ensuring 24/7 renewable energy supply. Also applicable to companies with decentralised operations that need to rely on storage to complement the grid.
- The storage plants can be used as standalone systems or can be connected to thermal generation plants, steel mills and LNG terminals to make them more efficient.

SIEMENS GAMESA RENEWABLE ENERGY, HAMBURG, GERMANY

Demonstrator Plant Electric Thermal Energy Storage (ETES)

In June 2019, Siemen Gamesa Renewable Energy (SGRE) successfully started operating its 130MWh Hamburg demonstrator Electric Thermal Energy Storage (ETES) facility. This project is considered a key disruptor of the large-scale (>100MW) and long-duration (several days) energy storage space.

Energy Storage Applications

Peak shaving / Reserve capacity	Energy arbitrage	Ancillary services (reg down)	Heat storage & sales

SGRE started working on the R&D associated with this project in 2011, foreseeing a need for long-duration and large-scale energy storage technologies. In 2014, its test site and proof of concept for high-temperature storage of 700kW power and 5MWh storage capacity was inaugurated. As a consortium with the local utility, Hamburg Energie, the Technical University of Hamburg, the ETES **demonstrator plant** was developed. This project is funded by the German Federal Ministry for Economic Affairs and Energy. The site has 5.4MW of charging and 1.2MW of discharging power and **24h storage capacity**. With a resistive heater, air is heated to more than 600°C and stored in **1000t of volcanic rocks**, after which 480°C/65bar steam is generated, and electricity generated in a steam turbine.

Value creation & Cost Effectiveness

- Stated 80% of off-the-shelf technology, low cost level of 90-100 EUR/kWh
- In the large-scale (>100MW) and long-duration (up to days), ETES could become the more efficient and cost-effective technology versus competing storage technologies
- With the brownfield approach of retrofitting old steam power plants into ETES facilities ('ETES:Switch'), whereby steam cycle and operational process remain in place, capacity-specific total cost could be reduced to 40 EUR/kWh

Technology: Electric Thermal Energy Storage (ETES)

Demonstrator (2019):

- Status: Operational
- Charge/Discharge Power: 5.4/1.2 MW
- Storage capacity: 130MWh
- Cost: 27 USD MM
- Financing: public financing (6th German Energy Research Program)

Pilot Project (2020+):

- Charge/Discharge Power: 85/30MW
- Storage capacity: 1GWh

Commercial Platform (2025+):

- Charge/Discharge Power: >100MW
- Storage capacity: >1GWh
- Efficiency: 45%
- Capacity-specific total cost (~90-100 EUR/kWh (greenfield))

Replicability & Market Design

- Currently, many electricity markets have recognition criterion for the capacity product of 4 to 6 hours. Leveraging ETES' long-duration feature & resulting economies of scale hinges on a capacity market design change, or BESS might outperform
- In the absence of competitive wholesale electricity markets, ETES could become highly replicable in off-grid, isolated applications to allow full decarbonization

WHAT DID WE LEARN?

- Multiple years of extensive R&D went into the optimization of the thermal isolation and fluid flow control algorithms for the electrical thermal storage process
- Decoupling of charging (air heater), discharging (steam turbine) and storage (stone chamber) capacities enables economies of scale for larger storage capacities and allows for more operating flexibility
- With its Heat Sales capability, ETES has an important and distinctive feature vs. other storage technologies, allowing it to tap into district heating and difficult to decarbonize (industrial) process heat markets
- Existing running or stranded conventional power plants can be given a second life through conversion to low-cost ETES storage facilities, thereby preserving employment

PROJECT CENTURION, RUNCORN, UNITED KINGDOM

100MW Power-to-Gas (P2G) energy storage feasibility study

This project explores the electrolytic production, pipeline transmission, salt cavern storage and gas grid injection of green hydrogen at an industrial scale. The feasibility study explores the system design and costs and will assess the business case for deployment. This use case focuses on the storage of 100% hydrogen aspect of this project.

Project Centurion's goal is to scale up the production of low carbon hydrogen for industrial uses, mobility and heating. As part of the project, Storengy is working on repurposing existing salt caverns for hydrogen storage. This could be the largest energy storage system at the interface between the gas and electricity networks.

The project focuses on hydrogen from electrolysis to industrial, transport and heat demand in the Runcorn area. Storage is needed as a buffer between supply and demand. According to Storengy, one of the strengths of the Centurion pilot plant is that it is connected to an existing industrial and energy infrastructure, which makes its realisation possible within a relatively short timeframe.

Conditions for replicability

- Availability of salt formations which can be developed into salt caverns or existing caverns to be repurposed
- Technical expertise of hydrogen storage
- Large scale demand for hydrogen or strong governmental and/or industrial commitment to develop hydrogen

Energy Storage Applications	
Seasonal storage	Sector coupling

- **Status:** Ongoing, deliverables due beginning of 2020
- **Technology:** existing salt caverns to be repurposed
- **Cost of the project:** Approximately £500,000
- **Financing:** Innovate UK, a UK government initiative which aims at helping industries de-risk technologies is contributing to about half of the cost of the project (£226,611). The rest of the costs are covered by the project partners ITM Power, INOVYN, Storengy, Cadent and Element Energy.

Value creation & Cost effectiveness

Hydrogen storage in salt caverns is significantly cheaper than storage in above ground metal tanks, but more expensive than natural gas storage. This is nevertheless related to required studies as well as the need to develop tailored equipment. Once hydrogen becomes a more standard product, the costs of storage will only be marginally more expensive than natural gas adjusting for energy density and very competitive for bulk storage of renewable energy. Today, the main challenge is the lack of market and there is no business model just for hydrogen storage.

WHAT DID WE LEARN?

- Storengy is looking into the pros and cons of repurposing vs developing new caverns for hydrogen storage. Repurposing involves making changes to the equipment but can lead to time savings as the creation of a cavern takes several years. The project HySecure will be looking into developing new caverns for hydrogen storage. The results of both will be available in the first quarter of 2020.
- A way to scale up gas storage is by creating caverns in series to reduce the cost drilling and workover rigs.
- Imagining a world of large-scale hydrogen demand, to deliver at peak demand, you could 1) size your production to meet this peak or 2) size your production at a lower level and add storage. Storengy believes that there is a technical and economic optimum to be found by not oversizing production but instead creating buffer capabilities to avoid creating assets that are going to remain idle for long periods of time.
- Today, the CAPEX for storing natural gas in in salt caverns is of 100 £/MWh. For hydrogen, it is of 1,200 £/MWh today and is expected to drop to 600 £/MWh in 10 years according to Storengy.

ON ENERGY STORAGE, PUEBLA, MEXICO

First industrial BESS to provide frequency regulation in Mexico

Inaugural project developed with Beetmann Energy, provides peak shaving, retail arbitrage and power quality improvement services for a textile factory in Puebla, Mexico. Turnkey delivery and operation using proprietary energy management system under a bSaaS (battery storage as a service) contract.

Energy Storage Applications	
Frequency regulation	Peak shaving

ON Energy Storage is a Florida based start-up which provides energy storage battery management solutions. Founded in 2016 as a venture of NorthPoint Group, the company is focused on storage markets in key Latin countries, such as Peru, Colombia and Mexico. With this project the company entered the Mexican market with an innovative combination of an industrial services contract with a textiles company, combined with the monetization of ancillary services to grid operator CENACE, a novelty in the country. ON Energy Storage implements turnkey energy storage solutions as well as focusing on energy management software.

Conditions for replicability

- Political, regulatory & tariff certainty
- Monetization of ancillary services
- Contract Standardization & Financing

- **Status:** in operation
- **Scale:** 30kW / 60kWh
- **Technology:** Lithium Ion
- **End Customer:** Textiles factory
- **Cost of the project:** n/a
- **Financing:** financed by provider with equity
- **Business Model:** design, turnkey delivery & operation under a 5-10 year battery services contract with customer, with additional sales of ancillary services to ISO

Value creation & Cost effectiveness

After two months' operation, all metrics and capacity reduction aims were met. Metering & monitoring allowed for additional customer value creation through voltage regulation, reactive power, power factor correction and backup power (replacement of engines). Continuous data processing can be levered to find additional value, but it challenges prices services and depends on customer sensitivity. Success will depend on superior, self-learning algorithms and smart commercial people that can maximize value and demonstrate this to customers.

WHAT DID WE LEARN?

- Certainty and transparency around regulation and tariffs is essential for growth in BESS deployment in Mexico
- Given current retail capacity prices, peak shaving alone does not justify BESS systems yet, additional value streams like ancillary services and customer specific values like power quality and backup power are needed
- Main future value drivers, against the penetration of low-marginal cost RES, will be capacity reduction and ancillary services, with only a limited role expected for arbitrage
- Market expected to shift from a high risk/high return, equity financed market to a securitization & commercial bank driven no-money down model based on a PPA or lease
- Even though energy efficiency and power quality value blocks are tailor-made solutions, standardization of the commercial offering is key to allow for aggregation and platform financing
- Batteries are more mobile then solar PV and have high residual values, so customer value can be created with opt-out structures

EXPERION ENERGY PROGRAM, NORTH AMERICA

Large scale behind–the-meter (BTM) energy storage deployment program

Honeywell and NRStor are to develop and operate 300 megawatts (MW) of BTM battery energy storage systems (BESS) across the U.S. and Canada starting early 2020. Operated remotely, these systems will provide customers with electricity cost savings, improved sustainability and resiliency.

Energy Storage Applications

Bill management	Power Quality	Resiliency	Peak shaving	Ancillary services

The energy storage systems will be supported by two remote operations centers that use proprietary artificial intelligence-based peak prediction and value stack optimization algorithms. These centers will automatically start the battery systems to maximize savings for commercial and industrial customers. Honeywell's advanced control technologies will enable precise battery dispatch along with network security and cybersecurity protection.

- **Status:** Under deployment
- **Scale:** 300 MW
- **Technology:** Lithium-ion batteries + Honeywell software
- **Customers:** Mostly manufacturing customers, with two objectives, 1) to reduce the overall cost of electricity and 2) achieve their sustainability targets.
- **Business model:** NRStor C&I provides energy storage as a service under a turn-key build, own, and operate business model that doesn't require a capital outlay from the customer. The battery systems are placed at customer host facilities. Once the projects are in operation, they monetize it, and by capturing the different revenue streams reduce the overall cost. Agreements are anywhere between 10 to 20 years in duration, that are funded through infrastructure investors.

Conditions for replicability

- Commitment to retire fossil fuel-based plants
- Risk of unstable grid due to REN penetration
- Ability for storage to provide different revenue streams, e.g. stability services

Value creation & Cost effectiveness

This programme is attractive to C&I customers as 1) it does not require a capital outlay from the customer 2) NRStor operates and monetises the battery storage system.

WHAT DID WE LEARN?

- These plants are addressed to industrial clients and interface between transmission and distribution.
- Economic viability depends on client's needs and can answer priorities ranging from relief on grid congestion to increased renewable energy penetration in the grid.
- This system is best suited to renewable energy developers that need large scale storage for ensuring 24/7 renewable energy supply. Also applicable to companies with decentralised operations that need to rely on storage to complement the grid.
- The storage plants can be used as standalone systems or can be connected to thermal generation plants, steel mills and LNG terminals to make them more efficient.

IERC STORENET, DINGLE, WEST KERRY, IRELAND

Virtual network battery storage

The StoreNet project deployed lithium-ion batteries in 20 homes as residential battery storage systems to operate in the form of virtual power plant in Dingle to integrate with energy supply and demand management and operate at scale across a community.

Energy Storage Applications	
Load-levelling	Customer price-reduction

- **Status:** Complete
- **Scale:** 20 households
- **Technology:** Networked Lithium-ion battery
- **Cost of the project:** €1.12m
- **Financing:** This pilot project is a joint venture by consortium formed by the different stakeholder

StoreNet is a joint research project by a consortium of Irish energy stakeholders: **The International Energy Research Center** (IERC), **Electric Ireland, ESB Networks** and **Solo Energy**.

This pilot project provides local network services, including localised network voltage support, ability of battery storage to offer **ESB Networks** non-wires solutions to operating the network and reducing consumption at peak times to offset new capacity requirements. These are delivered via **FlexiGrid VPP platform** and the **ESB Networks' SERVO platform.** When aggregated, the systems acts as a Virtual Power Plant.

Conditions for replicability

- Control and communication of virtual network
- Public acceptance of new technology
- Integration to grid poses a challenge as the lithium-ion batteries
- Stakeholder cooperation

This has load levelling applications for the network operators. enables consumers with renewable energy production means to become prosumers.

Stakeholders used this project as a platform to explore and plan around innovative business models. The Consortium benefited from learning how to design virtual powerplant architecture (functionality, ICT communication requirements) capability for battery advanced control function support.

Value creation & Cost effectiveness

One of the objectives of this pilot project is to determine the economic viability for stakeholders and consumers. Currently, the upfront cost of battery installation is paid by stakeholders. Consumers benefit from lower price of energy by charging batteries when the prices of electricity is low or with on-site renewable production and using that stored energy when demand peaks and the price is high.

WHAT DID WE LEARN?

- Today, most storage projects operate in an environment of a lack of appropriate regulations, or even definition of storage. Such projects fall under the closest regulation. In this case, under the umbrella regulations on microgeneration in Ireland, as regulations at the national do not yet exist and are only now being developed at EU level.
- Despite the technology being ready, deploying the technical capability to operate, monitor and manage the virtual network and to coordinate it with the grid remains a challenge.
- Relying on local communities to assist in customer awareness, understanding and acceptance of the technology is a crucial step in introducing new "smart" technology in homes.

KENNEDY ENERGY PARK PHASE I, FLINDERS SHIRE, QUEENSLAND, AUSTRALIA

Wind, solar and battery hybrid power plant solution

Phase I of the Kennedy Energy Park is the first project combining 3 technologies in Australia that allows generation for a greater portion of the day. The project aims to build industry knowledge and demonstrate viability to private sector financiers.

Energy Storage Applications	
Grid stabilisation	Time shifting

The Phase I is a joint project between Windlab and Vestas and is part of the former's larger 1,200 MW Kennedy Energy Park. Quanta services also contributes to the construction of the park. This hybrid power plant is operated by a Vestas customised control system.

This hybrid project helps to respond to the challenge of integrating intermittent renewable energies to the market and to reduce the marginal loss factor in transmission.

The hybridisation aspect of the plant is ensured by Vestas' proprietary Active Output Management 4000 (AOM 4000) service for 15-years.

Value creation & Cost effectiveness

To maximise cost effectiveness, the plant has to produce when the cost of energy is high on the market. This project has the objective to add renewable energy to the grid at a low marginal cost, driving prices down. Vestas also provides ongoing support through backend engineering and the use of their control system for the entire hybrid power plant.

- **Status:** Under completion
- **Scale:** 2MW of battery storage, 60 MW of renewable power
- **Technology:** Wind turbine and solar generation; Lithium-ion battery storage; Vestas' proprietary control system
- **Cost of the project:** AUS $160 million
- **Financing:** Australian Renewable Energy Agency (ARENA) provided sub-ordinated refundable grant of $18m, while Clean Energy Finance Corporation (CEFC) contributed $94m of non-recourse debt finance for the project.

The Kennedy Energy Park has a 10- year offtake agreement with CS Energy for the supply of renewable electricity and large-scale generation certificates. The offtake agreement does not take 100 percent of the output from the project; that is, some merchant risk was retained. Although the power cannot quite be considered "dispatchable" (available on demand), the relatively flat block of power was a good selling point in negotiating the offtake agreement.

Conditions for replicability

- Technology is mature and scalable
- Must have access to sufficient renewable energy sources and efficient system control
- Must have effective market signal mechanisms for optimised cost effectiveness

WHAT DID WE LEARN?

- The main complexity in developing the project resulted not from the technology but from grid connection and associated regulatory issues.
- Challenges included coordinating with other projects connecting to the grid and being on a weak line with not many interconnections to other parts of the grid.
- The next steps will be focused on achieving a coordinated response to fluctuating energy prices on the market to produce energy when prices are high to maximise revenue.
- Colocation isn't necessary for hybrid power plants, as long as grid access and coordination models are well defined. Colocation of solar and wind can be challenging.
- The cost efficiencies include common infrastructure for connection to the grid as well as shared roads, electrical equipment, and site amenities.

NOOR ENERGY 1, DUBAI, UNITED ARAB EMIRATES

Hybrid concentrated solar power (CSP), photovoltaic (PV) and storage solar power station

The project will possess an energy storage capacity of 15 hours, delivering power 24 hours a day. This project is the fourth phase of Mohammad Bin Rashid Al Maktoum Solar Park in Dubai, which will reach a total capacity of 5,000 megawatts by 2030. The plant is expected to allow a saving of 1.6 million tons of CO_2*.*

Energy Storage Applications

Time shifting

The Dubai Electricity and Water Authority (DEWA) awarded a build-own-operate (BOO) contract for the 700MW Noor Energy 1 CSP plant to a consortium led by ACWA Power in September 2017.

The contract has a 35-year power purchase agreement, under which DEWA will off-take electricity from the independent power producer (IPP) project at US **$0.073 per KWh,** known as the lowest **24 hours** energy from CSP with energy thermal storage tariff, competitive with fossil fuel-based power generation.

DEWA and ACWA Power signed an amendment to increase the plant's generating capacity to 950MW by adding a 250MW PV facility, in October 2018.

Conditions for replicability

- Availability of funds for upfront investment
- Requires large portion of available land with appropriate solar resources + need of energy for several hours after sunset in such location
- Requires a high degree of country stability due to the long term PPA structure

Value creation & Cost effectiveness

Economies of scale, an optimized combination of solar technologies and an innovative 35-year power purchase helped drive down project costs. The parties involved expect that this kind of breakthrough will lead to larger scale CSP +PV projects, particularly in the GCC region.

Competitiveness of tariff for 24h due to the use of thermal storage from a renewable source is now an unquestionable source of energy used as base load, competing with fossil fuel, where investment and solar resources are available.

- **Status:** Under construction, operational by the end of 2022
- **Scale:** 700 MW of CSP + 250 MW of PV power generation + 15 hours of storage
- **Technology:** CSP with Central Tower & Parabolic Trough + up to 15h thermal storage + Solar Photovoltaic
- **Cost of the project:** US $4.3bn – largest renewable project's investment in the world
- **Financing:** the project has been banked by several lenders, participating with $2.8 billion of debt, while the $1.5 billion of equity was provided by DEWA (51%) , ACWA Power (24.99%) and China's Silk Road Fund (24.01%) of the total project equity.
  As of November 2019, the project is set to achieve the lowest Levelised Cost of Electricity in the UAE of US $0.024 per KWh for the 250MW photovoltaic solar panels technology, and US $0.073 for the 700MW CSP technology, the lowest worldwide.

WHAT DID WE LEARN?

- The storage capacity of this project relies on molten salt tanks with huge capacities, more than 24,000 cubic meters. More than 550,000 tonnes of molten salt are required to fill these tanks. This represents almost half of China's annual production in 2016. Availability of procurements need to be ensured during bidding stage.
- Providing the developer during the planning and RFP stage flexibility to develop creative solutions tailored to the specific context in question was key.
- Lenders showed reserve towards large scale CSP projects, which resulted in a more restrictive Debt Service Coverage Ratio compared to more established renewables projects.
- Developers/offtakers to consider permits from civil aviation due to the height of the tower (260m) and the number of heliostats (70,000) to avoid air traffic disruptions and impact of glint and glare.
- Accessibility and logistics are a key challenges when building a project at this scale. In the case of Noor Energy 1, over 250 trucks would deliver materials every day and at this stage of the project over 2,500 people work on the site.

RINGO PROJECT, FRANCE

Pilot project: transmission congestion relief using energy storage

Ringo is a project led by RTE, the French TSO, to pilot using energy storage systems to relieve congestion instead of constructing extra power lines. It consists of batteries placed at either end of a transmission line to absorb excess renewable production and discharge during peak demand, controlled by a proprietary algorithm.

Ringo currently consists of three battery sites. It is a test for the control system of the networked batteries. The batteries will charge under peak renewable production and discharge during peak demand, helping to relieve grid congestion. The batteries are bought directly from manufacturers, to provide a tested and reliable service. The focus of the project is to test the feasibility of this solution and to refine a control algorithm.

From 2020 to 2023, the batteries will be operated solely by RTE. From the beginning of 2023, they will be open to be used by third parties for potentially multiple uses such as frequency regulation, demand and supply adjustment, congestion resolution and energy arbitrage, among others.

Energy Storage Applications	
RES integration	Grid congestion relief

- **Status:** Pilot project – under construction
- **Scale:** approx. 12MW / 24MWh at each site
- **Technology:** Lithium-ion batteries; LMP (lithium metal polymer) battery; control system algorithm
- **Cost of the project:** €80 million
- **Financing:** RTE is the sole investor and stakeholder for the project.
  As the grid operator cannot disrupt the market by injecting electricity into the grid, a simultaneous battery storage and retrieval system has been designed to operate at three locations in the network. These battery storage systems will be placed where the lines are congested and absorb large amounts of fluctuating renewable energy resources.

Conditions for replicability

- Where to deploy the batteries has proven to be a challenge due to stringent laws regarding safety and soil artificialisation in France
- Experience issues with grid congestions
- Authorisation from relevant regulatory body for a TSO to run this kind of project

Value creation & Cost effectiveness

Considering the nature of the project, the economic model is not yet entirely defined. However, key points to follow include the price of batteries, which will determine technology penetration on the market, as well as finding a complementary revenue stream to grid frequency regulation. The latter presents only a minor activity which cannot account for the cost of the solution.

WHAT DID WE LEARN?

- There is no business case for energy storage to defer building new transmission lines without value stacking
- The amount of space, as well as safety regulations surrounding the installation, considered as an industrial installation, pose a challenge to the deployment of the solution in France.
- Batteries can only absorb a fraction of the renewable power produced during extended periods.
- Although this project is intended to limit the need for new transmission lines by extending the capacity of current infrastructure, batteries still cannot compete with a complete power line in terms of capacity.

ESPEJO DE TARAPACÁ, CHILE

Colossal solar-plus-storage installation in the Atacama desert

The project takes advantage of the unique geographic characteristics of the Atacama Desert for a pumped storage hydroelectric plant. The site distinguished by a high coastal cliff located close to the ocean which contains natural surface concavities, makes it ideal for the storage of seawater.

The plant has a capacity of 300 MW and will work in conjunction with Cielos de Tarapacá, a 600 MW photovoltaic power plant.

The target for the two plants is 1,500GWh-a-year. This system allows response to demand during the night with stored renewable energy from the day. Water is pumped from the Pacific Ocean into the reservoirs with surplus energy from the Cielos de Tarapacá PV plant, and released during periods of demand. Allows for storage and 24/7 distribution of renewable energies, taking advantage of the high solar radiation in Chile.

This system is projected to optimise the transmission grid and store renewables cheaply, despite heavy initial investment.

Value creation & Cost effectiveness

Offers 24/7 PPA renewable to private client in the power generation market segment (regulated distribution model). Regulation is changing to adapt transmission networks to the new asset type represented by the plant.

Energy Storage Applications

Time shift for high PV production

- **Status:** Securing funding
- **Scale:** Large-scale
- **Technology:** x3 100MW reversible turbines
- **Cost of the project:** US$543 million
- **Financing:** US$60 million awarded by the Green Climate Fund (GCF). The project sponsors expect it to hit financial close in 2020, followed by the start of construction in the same year. Commercial operation is slated to come in 2025.

  The scheme – which represents 35 million tonnes in CO2 savings – comes to fill a support gap for Chilean energy storage, according to its promoters.

Conditions for replicability

- Combined with the PV powerplant, Cielos de Tarapacá, the installation relies heavily on local geographical characteristics (cliffs, ocean, high solar radiation).
- Considerable initial investment to build infrastructure and subsequent debt.

WHAT DID WE LEARN?

- Extensive planning, permitting and customer engagement periods to involve all stakeholders in the project.
- It has proven difficult to find investors for project of this scale.
- Project will entail the building of 18km of transmission lines and employ up to 600 workers
- Storage is multi-service and therefore allows to stack different revenue streams, albeit within currently inadequate regulatory framework.

ANNEX 2

State of Storage Technologies

This chapter builds on the insights from interviews and provides a broader overview of the state of energy storage technologies.

Energy storage technologies are commonly classified according to storage principle, or family. There are five energy storage families. The members of a family may change in accordance with technological evolutions, but the five categories reflect the five storage principles. Therefore, the examples in each category should not be seen as an exhaustive list of potential family members.

CHEMICAL	**- Ammonia** **- Hydrogen**	**- Drop-in Fuels** **- Methanol**	**- Synthetic Fuels** **- Synthetic Natural Gas**
MECHANICAL	**- Adiabatic Compressed Air** **- Diabatic Compressed Air**	**- Liquid Air Energy Storage** **- Pumped Hydro**	**- Gravity** **- Flywheels**
ELECTRICAL	**- Supercapacitors**	**- Superconducting Magnetic ES (SMES)**	
THERMAL	**- Latent Heat Storage** **- Sensible Heat Storage**	**- Thermochemical Storage**	
ELECTRO-CHEMICAL	**- Classic Batteries:** Lead Acid, Li-Ion, Li-Polymer, Li-S, Metal Air, Na-Ion, Na-NiCl2, Na-S, Ni-Cd, Ni-MH	**- Flow Batteries:** Vanadium Red-Ox, Zn-Fe, Zn-Br	**- Hybrid Supercapacitors**

Source: EASE

ELECTRICAL ENERGY STORAGE

Electrical energy storage refers to storage of energy in the form of electric field or magnetic field. Supercapacitors and Superconducting Magnetic Energy Storage (SMES) technologies store electrical energy directly and are becoming viable and safer charging alternatives to batteries.

Supercapacitors

Supercapacitors are also known as ultra-capacitors or electrochemical double-layer capacitors. Conventional capacitors consist of two conducting carbon-based electrodes separated by an insulating dielectric material. When a voltage is applied to a capacitor, opposite charges accumulate on the surfaces of each electrode. The charges are kept separate by the dielectric, thus producing an electric field that allows the capacitor to store energy. Supercapacitors utilize an electrochemical double-layer of charge to store energy. As voltage is applied, charge accumulates on the electrode surfaces. Ions in the electrolyte solution diffuse across the separator into the pores of the electrode of opposite charge. However, the electrodes are engineered to prevent the recombination of the ions. Thus, a double-layer of charge is produced at each electrode.

Supercapacitors are high-power, low-energy devices that can react very quickly. Due to the absence of a chemical reaction (unlike batteries), they can withstand a very high number of cycles (up to 100,000). They are highly efficient (from 80% to 95%), but, because the voltage varies linearly with the charge contained in the system, they require power electronics to ensure steady output.

ADVANTAGES

- High efficiency
- High cycle-fatigue life
- Scalable/ flexible
- High power

DISADVANTAGES

- Low energy
- Require power conditioning to deliver steady state output power
- Expensive per unit of energy capacity

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

New materials for supercapacitors: Researchers have developed new materials that are highly stable even under higher voltage and high current thus resulting in improved performance. In addition, it allows higher single-cell voltage that reduces the stack number and allows devices to be more compact.

Device upgradation: Device innovations for next generation supercapacitors are being emphasized in research phase. These include AC-line filtering supercapacitors, redox electrolyte enhanced supercapacitors, piezoelectric and electrochromic supercapacitors.

Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage devices (SMES) store electricity in a magnetic field generated by current flowing through a superconducting coil. The coil, made from a superconducting material, has no resistance when current is passed through it, reducing losses to almost zero. However, to maintain the superconducting state, a refrigeration system (e.g. using liquid nitrogen) is used.

As well as the coil and the refrigeration system, SMES require power electronics such as Alternating Current/Direct Current (AC/DC) converters to control the flow of the current into and out of the coil that charges and discharges the SMES. They also need a physical structure to mechanically support the coil, which is subjected to magnetic forces during operations, providing protection and additional equipment for system control.

SMES react almost instantaneously and have a very high cycling life. They require limited maintenance and can achieve high efficiencies, with only between 2% and 3% losses resulting from AC/DC converters. However, due to the high energy requirements of refrigeration, the complexity of the system and the high cost of superconductors, SMES are currently at an early demonstration phase and are only suitable for short-term storage.

ADVANTAGES

- High Power Density
- Quick response and charging time
- High efficiency and low maintenance

DISADVANTAGES

- High cost of energy
- Complexity of the system
- Need to be kept at cryogenic temperatures

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Next generation superconducting wires: The next generation wires are being investigated such as high current cables, instead of single composite conductor strand. They bring greater control of device inductance for higher power output in SMES and more optimisation of superconducting windings for stability and robust manufacturing.

Superconducting coils: Different coils are being designed and tested to increase the maximum stored energy in the coil. High temperature superconductors are also being investigated. The These would be a key component to a cost-effective grid-scale SMES system that would offer megawatt hours of stored energy and thereby support a growing infrastructure for renewable energy.

ELECTROCHEMICAL ENERGY STORAGE

Electrochemical energy storage involves storing electricity in chemical form with the benefit that both electrical and chemical energy share the same carrier, the electron. This form of storage is one of the most traditional of all energy storage technologies. Conventional Batteries are categorized according to their chemical composition are based on electrochemical reactions while flow batteries rely on two separately stored electrolytes to decouple their power and energy capacities.

Sodium Sulfur batteries (Na-S)

A sodium-sulphur (NaS) battery system is an energy storage system based on electrochemical charge/discharge reactions that occur between a positive electrode (cathode) that is typically made of molten sulphur (S) and a negative electrode (anode) that is typically made of molten sodium (Na). The electrodes are separated by a solid ceramic, sodium beta alumina, which also serves as the electrolyte. This ceramic allows only positively charged sodium ions to pass through. The battery temperature is kept between 300° C and 360° C to keep the electrodes in a molten state, i.e. independent heaters are part of the battery system.

Compared to lithium-ion batteries, sodium sulfur batteries typically have a much longer useful life. 15 years or 4500 cycles is typical. Their efficiency is around 85% and they have a response time of 1 millisecond.

ADVANTAGES

- High energy density
- High charging and discharging efficiency
- Long cycle life

DISADVANTAGES

- Need of thermal management
- Thermal self-discharge limits parking time
- Safety concerns due to reaction of sodium with sulfur

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Enhanced performance for room-temperature NaS battery: Room-temperature NaS batteries currently suffer from rapid capacity fading and low reversible capacity. A nanomaterial is being manufactured which can act as a superior cathode thus suitable for large-scale production and commercialisation.

Development of next generation sodium sulfur batteries: Ongoing research is focusing on improving the performance of the batteries in terms of capacity retention and battery life. In addition, chemistry of electrodes, electrolytes, separators and cell configuration are being researched further to make NaS an integral part of smart grid solutions.

Lithium Ion Batteries

A lithium-ion (Li-ion) battery is an advanced battery technology that uses lithium ions as a key component of its electrochemistry. During a discharge cycle, lithium atoms in the anode are ionized and separated from their electrons. The lithium ions move from the anode and pass through the electrolyte until they reach the cathode, where they recombine with their electrons and electrically neutralize. The lithium ions are small enough to be able to move through a micro-permeable separator between the anode and cathode. In part because of lithium's small size (third only to hydrogen and helium), Li-ion batteries are capable of having a very high voltage and charge storage per unit mass and unit volume.

The use of lithium ion batteries has grown significantly in recent years. They offer some distinct advantages and improvements over other forms of battery technology. Lithium ion technologies have benefitted from significant investment in recent years due to their versatility that enables them to be deployed in a wide variety of applications, many of which show important synergies in terms of technology development.

Global manufacturing for Li-ion cells has ramped up considerably, and plans to further expand capacities continue. With the dominance of Li-ion batteries in the EV market and the synergies in the development of Li- ion batteries for EVs and stationary applications, the scale of deployment that Li-ion batteries are likely to experience, will be orders of magnitude higher than for other battery technologies. Although the bulk of the capacity has been announced in Asian facilities, a consortium of several German companies recently announced the creation of a 35 GWh per year Li-ion cell production plant in Germany.

ADVANTAGES

- Very high energy density
- Low maintenance
- No requirement for priming
- Relatively low self-discharge
- High rated voltage

DISADVANTAGES

- Highly reactive and flammable
- Requires recycling programs and safety measure
- Natural Degradation
- Suffers from aging effect

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Silicon Anode: Inserting small amount of graphite particles into graphite anode of Li-ion batteries can boost achievable cell energy density. Overcoming low electrode lifetimes through improved silicon nano-particle and electrode designs is the research focus.

High voltage electrolytes: By allowing charging voltages of up to 5 volts (given current systems often capped at 4.4 volts in order to limit electrolyte oxidation and protect cell lifetime), the energy density of Li-ion batteries can be significantly increased, with new electrolytes showing promising stability.

Redox Flow Batteries

The electrochemical process in flow batteries is comparable to that in conventional batteries. Ions contained in the electrolytes move from the negative and positive electrodes, upon charging and discharging, through a selective polymer membrane. A cooling system is usually needed, as charging and discharging releases heat. Unlike conventional batteries, flow batteries contain two electrolyte solutions in two separate tanks, circulated through two independent loops. The chemical composition of the electrolyte solution defines the sub-categories of batteries, the most important being Vanadium Redox (VRB) and Zinc-Bromine (Zn/Br). This more complex design allows the dissociation of power (defined by the number of cells in the stack and the size of electrodes) and energy (defined by the volume and concentration of the electrolytes).

Operational temperature is usually between 20°C and 40°C, but higher temperatures are possible, provided plate coolers are used to avoid over-heating the plates. Flow batteries are usually between 65% and 80% efficient, allow approximately 10,000 to 20,000 cycles, and have a short response time. Vanadium Redox Flow Battery (VRFB) is the only redox flow battery that has been used in large scale applications around the world, e.g. Australia, Europe, Japan and United States for extended periods of time.

ADVANTAGES

- Independent energy and power sizing
- Scalable for large applications
- Longer lifetime in deep discharge
- Long cycle life (10,000+ full cycles)

DISADVANTAGES

- More complex than conventional batteries
- Early stage of development
- High cost of vanadium and current membrane designs

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Reduction in material cost: Lifecycle costs are determined by chemical stability of the electrolyte together with stability of membranes and electrodes that largely determine the overall reliability of the system. Reducing the cost of material and improving performance, e.g. of membrane conductivity and electrode kinetics are the efforts currently ongoing to reduce system costs.

Improved membranes: Although exact membrane characteristics may differ depending on specific flow chemistry, improved membranes are being innovated as they can unlock widespread use of redox flow battery. The better membranes have the potential to offer low area resistivity, longer lifetimes, chemical resistance to electrolyte pH, etc.

CHEMICAL ENERGY STORAGE

Chemical storage refers to the use of electricity to produce a chemical, which later can be used as a fuel. This fuel can be used to support a thermal load or for electricity generation or transportation. Three pathways for chemical energy storage are production of Hydrogen (H_2), Ammonia (NH_3) and Synthetic Gas ($CO + H_2$), with hydrogen being received as one of the most attractive alternatives.

Hydrogen

Hydrogen energy storage technologies are based on the chemical conversion of electricity into hydrogen. Electrolysis is used to split water (H_2O) into its constituent elements, Hydrogen (H_2) and Oxygen (O_2). Due to its low atomic mass, it has an unrivalled specific energy. The electrolysis process can be reversed (i.e. hydrogen and oxygen generate electricity and water) to feed electricity back into the grid, using a fuel cell. Otherwise, hydrogen can be passed through heat engines in a similar way to natural gas, to produce electricity. Hydrogen can be stored in three main ways, each with different implications for the energy capacity of the system and its layout: as a gas in very large underground caverns within geological formations or in high-pressure tanks; as a liquid in cryogenic tanks; or as solid or liquid hydrides (e.g. ammonia, magnesium).

Hydrogen-storage technologies can capitalize on the experience of the chemicals and petrochemicals industries, which have long used hydrogen as a feedstock. These technologies have minimal environmental impacts and are highly reliable and responsive. However, some losses are unavoidable during the conversion and reconversion process, and investments in conversion facilities are required.

ADVANTAGES

- Scalable from distributed to long-term, large scale storage
- Low detrimental effect on environment

DISADVANTAGES

- Low round trip efficiency
- High capital cost
- Safety concerns
- Low energy density at ambient conditions

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Pressure vessels for hydrogen storage: Development of new pressure vessels shapes and sizes is being undertaken by many companies and R&D institutes. These pressure vessels have special frameworks and mountings to fit the designs of existing and new automobile models.

Transportation and Storage of Hydrogen: One of the innovative solutions being looked at to transport hydrogen is use of unique liquid carriers to charge and release hydrogen. These carriers have six to eight times higher storage capacity than high pressure transportation and are considerably less expensive.

MECHANICAL ENERGY STORAGE

Mechanical storage takes the form of either potential energy or kinetic energy storage. Pumped Hydro, Compressed Air and Flywheel energy systems are the best known.

Pumped Hydro Storage (PHS)

Pumped hydro storage (PHS) stores energy in the form of gravitational potential energy and makes use of two vertically separated water reservoirs located at different heights. During off-peak electricity demand, low-cost electricity is used to pump water from the lower to the higher elevated reservoir using a pump and turbine unit which are attached to a reversible electric generator or motor system. During periods of high electricity demand, power is generated by releasing water from the upper reservoir that drives the turbines and is then fed to the grid.

Greater than 95% of global energy storage is met by PHS and for years, it has offered a cost-effective way to provide large-scale storage solution and supporting grid balancing services. To achieve greater efficiency, flexibility and faster response times, PHS developers are now using variable speed pump turbines that facilitate better tuning of grid frequency thus contributing to grid stability.

80%[8] of the existing over 180 GW of pumped storage capacity is located in Europe, China, Japan and the United States. IHA estimates the total energy stored within the world's PHS projects to be up to 9,000 GWh. In comparison, the total energy stored within utility scale batteries is estimated at just 7 GWh.

While new storage technologies are gaining worldwide attention, PHS is expected to grow to 78 GW of additional capacity to be commissioned by 2030[9], with the highest growth in PHS installations over the next five years expected to be in China.

ADVANTAGES

- Established technology deployed at scale
- Long project life-time of 60 years that can be extended up to 100 years
- Rapid ramping potential
- Very low self-discharge

DISADVANTAGES

- Environmental concerns due to relatively low energy density
- High initial investment costs result in longer return on investment
- Depends on availability of water and geographically suitable sites

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Pumping water into rock fissures: PHS developers are increasingly looking at using bi-directional injector generator to pump water into rock fissures at high pressures, enabling operation with increased mechanical efficiency and storage of energy in flatter areas where conventional PSH may not be possible

Coupling PHS with other storage technologies as future avenue of potential growth: As part of upgrading existing PHS facilities, players are looking at coupling storage solutions such as Li-ion batteries to utilise their short reaction time. This would help in further integration of VRE.

[7] IEA, March 2019: https://www.iea.org/newsroom/news/2019/march/will-pumped-storage-hydropower-capacity-expand-more-quickly-than-stationary-b.html
[8] IHA, 2018.

Compressed Air Energy Storage (CAES)

CAES is centered on the concept of energy storage in the form of pressurised air. Excess or off-peak electricity is used to mechanically compress air in a chain of compressors for storage into existing or purpose-built confined underground space (salt mines, salt caverns or aquifers). Air heats up during compression phase and in the diabatic CAES systems, this heat is released to atmosphere. When energy demand is high, the pressurised air is released from the reservoir and expands in a turbine, thus generating electricity.

In adiabatic CAES systems, heat during compression cycle is stored which is later used to heat the released air through heat exchangers in the expansion cycle. This is an advanced concept in comparison to diabatic systems which often use natural gas as a combustion fuel in turbine chambers to heat the released air during expansion phase (to improve turbine efficiency). As a result, the advanced adiabatic CAES systems address the environmental concerns of CO_2 emissions in diabatic CAES systems. Similarly, isothermal CAES storage process involves maintaining a near constant temperature, allowing the air to be compressed to relatively higher pressures. This eliminates the need for natural gas combustion and the expansion can deliver energy on its own.

The market for CAES systems had remained underdeveloped for several reasons, such as lack of investment given the cost uncertainty and lack of scalable projects. Diabatic CAES systems are the only commercialised systems as of 2019. However, increasing number of demonstration projects coupled with technological developments in the CAES systems, are likely to drive the market for CAES storage. North America is the largest market followed by Europe, with several new CAES projects to be commissioned between 2020 – 2024.

> **"The advantage of CAES is we can either build the underground cavern or leverage existing infrastructure. CAES projects are sizeable. We can go really where the grid needs that capacity. CAES uses less water in comparison to other mechanical storages like hydro. Overall we use about 95% less water during operation."**
>
> **GREG ALLEN, MANAGING DIRECTOR, HYDROSTOR AUSTRALIA**

ADVANTAGES

- Large energy and power capacity
- Durable and highly sustainable allowing for limitless cycles of charging and discharging
- No degradation of capacity over time
- Competitive and more cost effective

DISADVANTAGES

- Constraints on availability of suitable storage caverns
- Existing designs rely on gas burners
- Traditional systems are inefficient because of inherent heat losses

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Alternative Storage Facilities: Man-made salt caverns are not always geologically available. Alternative storage vessels are being investigated. For instance, artificial pressure tanks have the advantage of being compatible with distributed applications. Researchers are also looking at using depleted gas fields and ways to eliminate the risk of air mixing with residues of other gases.

Storage of heat generated during compression: Companies are looking at storing the heat generated during compression in mediums such as insulated hot water tanks and crushed rocks, which is then re-injected to the system for expansion, thus improving system's efficiency to 60-70% and reducing costs. Other thermal management and storage systems that can be scaled-up are also being extensively researched.

Flywheel Energy Storage (FES)

Flywheels storage system involves converting electrical energy to rotational energy via a flywheel rotating in a frictionless container. During off-peak electricity demand, the flywheel motor draws electricity from the grid to accelerate the rotor to very high speeds. Vacuum enclosure and magnetic bearings allow the flywheel to keep spinning without additional power for a long time (several days), thus reducing the energy loss. When energy needs to be extracted from the system, that is, the grid needs more power, the inertial energy of the rotor is switched to drive a generator, thus producing electricity. As a result, the speed of the wheel is reduced.

Two types of flywheels are available depending on the speed of rotation. The conventional low speed flywheels (<10,000 rpm) are usually made of heavier metallic material, generally steel and the high speed flywheels (10,000-100,000 rpm) are made of advanced composite materials. The main components of the flywheel system include stator, bearings, power convertor, a spinning rotor connected to motor-generator and an enclosure. The system requires limited maintenance and has a longer lifespan than batteries (up to 20,000 cycles). Given the fast response times of flywheel systems, they are generally used for short- term storage among other applications.

> **"Flywheel is a very reliable system that doesn't look-insensitive for temperatures at all, or at least not as batteries. That makes it even more robust for high temperatures. It is really a well-established and mature technology. The big advantage to the other technologies is bi- directionality, the capability of taking energy if required and giving energy at the same speed at the ambient temperature. It has robust lifetime and can last 20 years or longer and we have them running for a long time."**
>
> **FRANK HERBENER, PRODUCT MANAGER, PILLER**

ADVANTAGES

- High power density (swift charging and discharging)
- High performance in terms of cycle efficiency
- Low environmental impact
- Low cost maintenance
- Long cycle life without degradation

DISADVANTAGES

- Low energy density with high rate of self-discharging over time
- Difficult/expensive replacement of bearings as cost of materials production is high
- Prone to external shocks and high-energy failures

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Using easily accessible materials: Access to buying materials for magnets is scarce. Upcoming projects are developing magnets made from new types of cheaper materials. In addition, high temperature superconducting materials for bearings are being investigated to improve performance and reduce friction losses.

Reducing the rate of self-discharge: Researchers are looking at improving the existing systems by keeping cylinders in the air using nanomagnets that would involve highly precise control. Advanced control systems are being developed to ensure reliability and safety.

THERMAL ENERGY STORAGE

Thermal energy storage refers to storage of thermal energy by heating or cooling a storage medium such as molten salt, water and phase change materials (PCMs). This section focuses on molten salt energy storage.

Molten Salt Energy Storage (MSES)

MSES, one of the most dominant thermal storage technologies, involves heating the molten salt by the concentration and reflection of solar energy in concentrating solar power (CSP) plants. Molten salt is a non-flammable and non-toxic mixture of 60% sodium nitrate and 40% potassium nitrate. It can serve both as a heat transfer and energy storage medium and allows the use of higher temperatures (up to 550 - 570 degrees C against conventional oil which can be heated up to 400 degrees C) and smaller storage tanks.

Direct storage uses salt that is kept in liquid form in an insulated cold tank. It is pumped through pipes to a receiver tower where it gets superheated through sunlight reflected by the CSP panels and is then sent to a hot, insulated storage tank. The hot salt is then pumped through a super-heater, and then goes through a conventional steam generator driven by steam that drives turbines, thus generating electricity. The salt is then returned to the cold storage tank and the process restarts. In contrast, indirect-storage designs use one material as the heat transfer fluid (HTF) and a second (molten salt) for thermal storage.

Molten salt is capable of storing energy for up to 20 hours, thus working 24 hours a day for several days in the absence of sun or during rainy days. It could play an important role in countries with high direct normal irradiance, such as the MENA region.

ADVANTAGES

- Exceptional heat transfer capability
- Commercial and low cost
- Integration with CSP lowers Levelised Cost of Electricity (LCoE)

DISADVANTAGES

- Molten salts can be corrosive
- Must not be allowed to freeze
- Limited to CSP technology for power applications

TECHNOLOGICAL & OPERATIONAL INNOVATIONS

Retrofitting coal power stations: The Carnot Batteries would store energy as molten salt thermal energy, which can not only store and deploy a large amount of energy to the grid when it's needed, but also provide assistance and financial incentive to close up coal plants at a faster rate.

Combination of both solar receiver and storage in the same unit: Normally tanks are far from the solar receiver. Researchers have developed a methodology to place both the receiver and storage on the ground, under a beam-down optical reflecting system.

ANNEX 3

Energy Storage Applications

Power Quality	Use energy storage to provide a high level of power quality above and beyond what the system offers (e.g. critical load) to some customers.
Energy Arbitrage	The purchase of wholesale electricity while the locational marginal price (LMP) of energy is low (typically during nighttime hours) and sale of electricity back to the wholesale market when LMPs are highest.
RES integration	Use of storage to mitigate rapid output changes from renewable generation due to: a) wind speed variability affecting wind generation and b) shading of solar generation due to clouds. It is important because these rapid output changes must be offset by other "dispatchable" generation.
Emergency back-up	In the event of grid failure, energy storage paired with a local generator can provide backup power at multiple scales, ranging from second-to-second power quality maintenance for industrial operations to daily backup for residential customers.
Peak shaving	Refers to leveling out peaks in electricity use by industrial and commercial power consumers.
Time shifting	Energy time shift involves storing energy during low price times, and discharging during high price times.
Load leveling	Load leveling usually involves storing power during periods of light loading on the system and delivering it during periods of high demand.
Black start	Black start is the use of energy storage to restore the system or a power plant or a substation after a black-out, as some electricity is needed which cannot be drawn from the grid.
Seasonal storage	Seasonal energy storage is the storage of energy for periods of up to several months.
Spinning reserve	Generation capacity that is online but unloaded and that can respond within 10 minutes to compensate for generation or transmission outages. 'Frequency-responsive' spinning reserve responds within 10 seconds to maintain system frequency. Spinning reserves are the first type used when a shortfall occurs.

Network expansion	Use of modular storage to: a) defer the need to replace or to upgrade existing T&D equipment or b) to increase the equipment's existing service life (life extension). Storage for T&D equipment life extension is especially compelling for the aging fleet of underground circuits which are quite expensive to replace or to upgrade.
Network stabilisation	Energy storage used for network stabilisation improves T&D system performance by compensating for electrical anomalies and disturbances such as voltage sag, unstable voltage, and sub-synchronous resonance.
Voltage regulation	Voltage regulation ensures reliable and continuous electricity flow across the power grid. Voltage on the transmission and distribution system must be maintained within an acceptable range to ensure that both real and reactive power production are matched with demand.
End-user services	Energy storage used by end-use customers in a variety of facets to reduce electric bills. Can be used to eliminate demand charges, charge during off-peak to reduce peak consumption, etc.

ANNEX 4

Acronym Reference Sheet

ACRONYM REFERENCE SHEET

A-CAES: Advanced compress air energy storage
BESS: Battery energy storage systems
BTM: Behind-the-meter
C&I: Commercial-and-industrial
CAES: Compressed air energy storage
CSP: Concentrated solar power
DR: Demand Response
ES: Energy solutions
ESS: Energy storage systems
ETES: Electric thermal energy storage
EV: Electric vehicle
FES: Flywheel energy storage
FOM: Front-of-meter
HTF: Heat transfer fluid
IOU: Investor-owned utility
ISO: Independent system operator
LCoE: Levelised cost of electricity
Li-ion: Lithium-ion
LNG: liquified natural gas
MSES: Molten salt energy storage
NaS: Sodium-sulfur
P2G: Power-to-gas
PHS: Pumped Hydro Storage
PPA: Power purchase agreement
PV: Photovoltaic
R&D: Research & development
RD&D: Research, design & development
RE: Renewable Energy
REC: Renewable Energy Certificate
REN: Renewable Energies
RES: Renewable energy sources
RFP: Request for proposals
SMES: Superconducting Magnetic Energy Storage
TSO: Transmission service operator
VRE: Variable renewable energy

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