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Sino-German Energy Transition Project

Innovative distributed generation and storage

German and European experiences and perspectives for China

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Contents

1 Summary: Energy transition requires innovative distributed generation

Achieving the emission abatement targets set by the Paris Agreement necessarily entails the expansion of renewable energy, including at distribution grid level (distributed generation). Indeed, decentralised generation assets, and solar PV in particular, have become more important in both Germany and China in recent years and are set to grow further. To enable their integration into the system and ensure overall security of supply, both TSO and DSO have to take dedicated measures to meet the challenges arising from the variability of feed-in that most of these generation technologies entail. Apart from network expansion, the activation of flexibility plays a key role, i.e. the use of electricity storage technology, most notably batteries, and DSM (demand side management) for both market and network purposes. While both distributed generation and flexibility technologies exist today, further technological innovation is still crucial for two reasons: Firstly, cost degression of technologies such as solar PV and batteries will contribute to the cost efficiency of the energy transition, making them realistic in both industrialised and non-industrialised economies. Secondly, innovative technologies have the potential to address several challenges of existing technologies, such as excessive land use, environmental pollution in manufacturing and energy inefficiency.

To promote innovation, governments pursue innovation policies. Both the EU and Germany have launched comprehensive programmes to support R&D in the field of energy transition technologies, including for generation, flexibility and grid management. Moreover, Germany has a network of energy research institutes covering the whole spectrum from fundamental to industrial research. China is currently the leading manufacturer of solar PV equipment and has invested in battery production as well. It also has an impressive innovation record in these fields. Given the challenges of distributed generation and its importance for a carbon-neutral future, it is, however, recommended that China expands its focus and includes new generation, storage and IT technologies in its innovation efforts. In particular, given the ambitious global abatement targets, the energy transition requires battery technologies that do not use rare raw materials to meet future global demand. Future systems will be operated on the basis of innovative software that can be used to control load and generation. Apart from lab-based R&D, technological progress often occurs through the deployment of new assets (learning by doing). It is advisable for China to roll out innovative technologies in the field of distributed generation and decentralised storage in order to improve them and build on its existing capabilities.

2 Distributed generation, decentralised flexibility and the need for innovation

In Germany, decentralised installations make up a significant proportion of today's installed renewable energy capacity. Solar PV in particular plays an important role. Due to the production fluctuations, the system requires more and more flexibility to ensure a stable electricity supply. One important flexibility option is the use of electricity stores. Even though a variety of storage technologies at distribution level already exist, innovations can contribute towards solving current problems, further reducing costs and accelerating the energy transition. China has drastically expanded its renewable energy generation capacities at system level over the past two decades. However, its vast potential for distributed generation is still underdeveloped. Innovation can help to facilitate the adoption that will help China to achieve its emission abatement targets.

2.1 Role of decentralised generation and decentralised flex[1]

Germany is committed to climate neutrality by 2045. In the electricity system, the federal government is aiming for an 80% RES (renewable energy sources) proportion by 2030. Currently, wind and solar PV are the dominant renewable technologies in the electricity system. Achieving the 2030 target will require further expansion of those technologies. Specifically, the government is planning an installed capacity of 215 GW solar PV, 30 GW offshore wind and 115 GW onshore wind by 2030.

As at 2021, Germany had achieved an installed RES capacity of 138 GW: 64 GW onshore and offshore wind power and 59 GW solar PV. RE in total contributed about 51% to electricity generation in the first half of 2022.[2]

RE installations at distributed level currently make up a significant part of this electricity generation, with solar PV being the dominant technology. The most common applications are rooftop solar systems and open field solar. Approximately two million systems were installed in Germany in 2019. PV with a capacity of less than 10 kW contributed around 7 GW to the total installed capacity. Small-scale PV of up to 1 MW capacity made up about 60% of the total installed capacity. Open field PV contributes only small amounts to the installed capacity of small-scale PV, as shown in Figure 1.

In a future low-carbon electricity supply system, the role of distributed generation will further increase. Today, prosumers are already consuming electricity where it is produced.

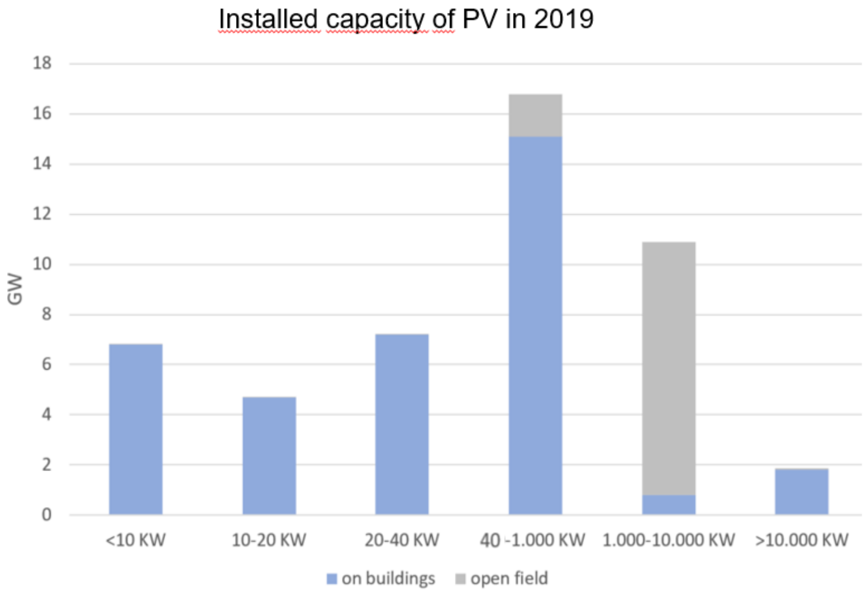


Figure 1: Installed capacity of PV in 2019[3]

However, the expansion of RE generation poses a challenge for the electricity system: The fluctuation of variable RE feed-in creates technical problems in the grid. At distribution level, these include thermal overloads of network devices, violation of voltage limits, backfeed issues and phase imbalances. Fluctuations can also lead to stability issues at system level.

Flexibility measures are key to solving these network issues. For the distribution grid, flexibility refers to the increased use of electricity storage, mostly batteries, and demand side management (DSM). As the proportion of variable renewable energy increases, electricity systems will need more flexibility services.[4] [5]

As for electricity storage, batteries are currently the most relevant technology at distribution grid level. Batteries can provide services such as load shifting, balancing power, spinning reserves and black start capacity. With these services, batteries can also reduce transmission network constraints and defer the need for major infrastructure investments. Behind the meter, batteries can contribute to an increase in self-consumption and the improvement of power quality for the customer.[67]

2.2 Need for innovation & cost degression of existing technologies

A variety of generation technologies and electricity storage solutions currently exist. Reaching the climate goals and the specific electricity generation targets will require further, massive expansion of RE. The increasing proportion of fluctuating electricity in the system thereby demands higher levels of flexibility. Besides conventional storage options, innovative solutions are needed to fulfil these flexibility demands.

The most important benefit of innovation is cost degression. Cost degression describes the process whereby production costs decrease as the scale increases. In the case of stationary Li-ion batteries, for example, costs already decreased by about 60% between 2014 and 2017. The additional potential for cost degression until 2030 is about 54–61%.[8] A detailed overview of the potential cost degression of different batteries is provided in section 4. Not only batteries but also generation technologies can benefit from innovations and the corresponding cost degression. The cost degression of PV cells, for example, is available in section 3.

Moreover, existing solutions of both generation technologies and storage technologies face a variety of challenges. Land-use conflicts, acceptance problems and material resource issues are just some examples. New technologies can offer solutions to these problems. Innovations are not only able to solve problems with new technologies, but also to increase the efficiency of existing technologies. With regard to solar PV, the current cycle of innovation is about 2–4 years and results in an efficiency increase of about 0.6% per year.

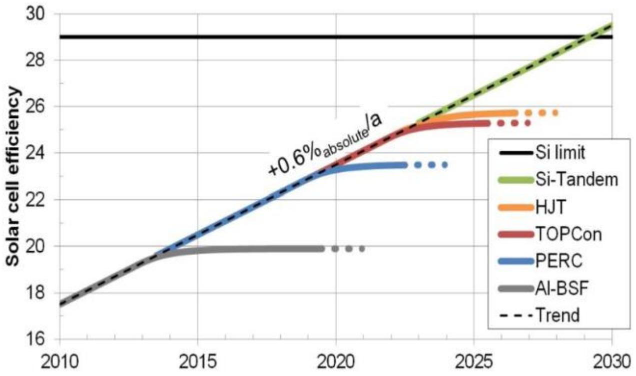


Figure 2: Development of efficiency of solar cells[9]

2.3 Government role in innovation

Innovations are an important pillar of the energy transition, and have been since its beginnings in the 1990s. The two main technologies driving the energy transition in the electricity sector today are based on wind and solar radiation. Their economic deployment in many countries is possible due to several innovative steps in the past. In the case of wind power, the use has developed and improved over centuries: Historical research suggests that wind was first used as an energy source in antiquity, both in Egypt and in China, to power various machines. During the Middle Ages, windmills were built as an agricultural tool to grind grain, shaping the landscape of coastal areas, such as in the Netherlands. Windmills designed for electricity generation were invented at the end of the 19th century in parallel in Scotland, Denmark and the United States. During the early and much of the middle phase of electrification, windmills were a niche technology, used mainly in regions not yet connected to a grid system. However, innovative research continued in several countries. In the wake of the ‘70s energy crisis, the German federal government decided in 1979 to commission the construction of a wind power pilot project to improve the existing technology with a view to deploying it in the electricity system, which at the time was dominated by lignite, hard coal and nuclear power. The wind turbine GROWIAN was constructed in a location near the North Sea. With a power rating of 3,000 kWp and a turbine house with a height of 100 metres, it was the largest of its kind when it went into operation in 1983. Though it served as a spectacular example of government-sponsored R&D, the project did not live up to expectations in terms of output and reliability. Thus, it was only after 1991, when commercial developers were permitted by law to connect their wind mills to the network in return for a fixed tariff, that the technology developed into a technically reliable and increasingly economical source of electricity. For the decade from 2010 to 2020, IRENA reports a cost reduction of 40% on average for onshore wind generation and 29% for offshore, with potential for further cost reductions in the future.

The historical development of wind power reflects two paradigms used in the economics of innovation: innovation based on government sponsored R&D aimed at improving a technology, and innovation of technologies under learning by doing, i.e. continuous improvement by application. Economists make the case that investments in innovation by the private sector tend to be insufficient, as innovators cannot reap the full benefit of their new product or production technology: Imitators who have not borne the cost of innovation will soon obtain a share of the market. Governments therefore support innovation activities by establishing technical research institutes or through research grants to industrial laboratories. In the field of renewable energy, the GROWIAN project serves as an example. Some innovations, however, are the result of regular use of a technology and the associated gradual improvements, rather than forward leaps instigated by innovation from a research lab ("learning by doing" paradigm). In particular, these can lead to substantial reductions in the cost of technology over time. Moreover, cost reductions can arise from the expansion of production facilities and are therefore a consequence of increased demand. This justifies government-sponsored support programmes for new technologies that are aimed at their deployment rather than R&D. The feed-in-tariff programme of the Renewable Energy Act (EEG) of 2000 is an example of this type of government intervention.[10] It is widely thought to have contributed to the spectacular cost degression in wind and solar PV technologies over the past two decades.[11] Today, both wind and solar PV are considered to have reached market maturity in Germany. Support mechanisms are therefore likely to be phased out in the coming years.

2.4 EU and German R&D policy

Policy makers in Germany and the EU recognise the importance of innovation for the energy transition and, more generally, for economic development. Consequently, they have put in place several publicly funded programmes aimed at supporting R&D and innovation.

For the EU, research and development is an important policy area. The renowned Horizon Europe framework programme has a total budget of EUR 95.5 billion for the years 2021–2027, distributed via a tender process to research groups organised in supra-national teams across the EU. To promote research for the energy transition, the EU has developed the European Strategic Energy Technology Plan (SET), which coordinates national research efforts and promotes cooperation among EU countries, companies and research institutions in line with the overall energy policy targets of the EU. Ten actions have been identified, which cover the whole innovation chain – from research to market uptake – and a financing and regulatory framework. They include integrating renewable technologies in energy systems, reducing technology costs, resilience and security of energy systems, and competitiveness in the global battery sector and e-mobility. The plan has an overall governance structure for measuring key performance indicators (KPIs), which is aimed at effective interaction of the partners. It encompasses 13 SET Plan working groups, designed to implement different aspects of the actions, and the SET Plan Steering Group, consisting of high-level representatives from EU countries as well as Iceland, Norway, Switzerland and Turkey.

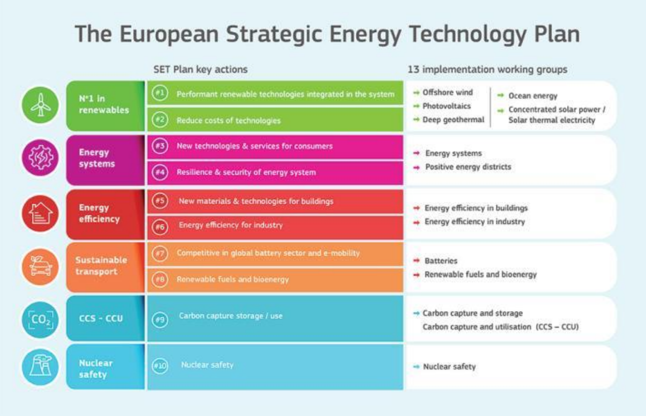


Figure 3: EU SET Plan governance structure

The EU has also created European Technology and Innovation Platforms (ETIPs) as a further tool for the implementation of the SET Plan, involving EU countries, industry and researchers in key areas. The ETIPs promote the market uptake of key energy technologies by pooling funding, skills and research facilities. In particular, ETIP Wind and ETIP Solar promote the improvement and the system integration of the two renewable energy technologies.

At national level, the German government has launched its first High-Tech Strategy in 2006. This strategy has been improved several times. The last High-Tech Strategy[12] is High-Tech Strategy 2025, which was published in 2018 and intends to support research and innovation. Focus areas are Health and Care, Sustainability, Climate Protection and Energy, Mobility, Urban and Rural Areas, Safety and Security and Economy and Work 4.0 (Field of Action I). The strategy also includes investment in training and continuing education and the involvement of society (Field of Action II). In the area of sustainability and climate protection, the strategy includes Realworld Laboratories to support the transition from research to demonstration and market introduction.

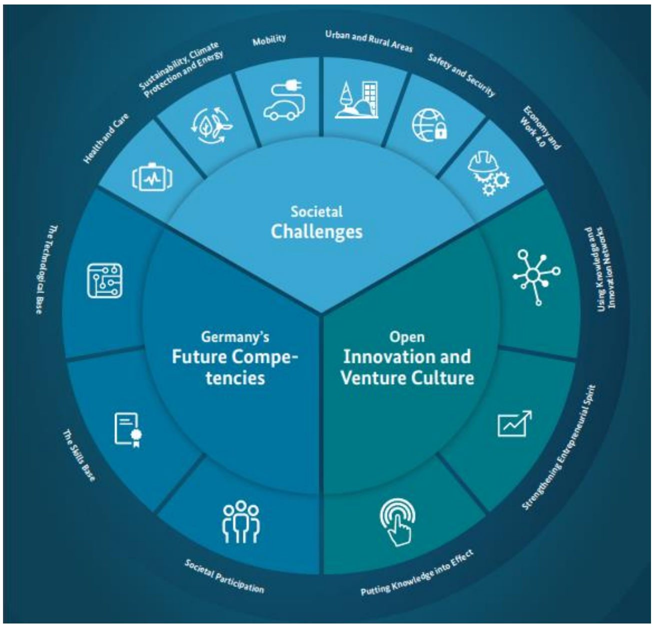


Figure 4: German High-Tech Strategy 2025

Energy research at Fraunhofer-Gesellschaft

Fraunhofer-Gesellschaft is a German association for applied research. Founded in 1949, Fraunhofer-Gesellschaft currently operates 76 institutes and research units throughout Germany. Over 30,000 employees, predominantly scientists and engineers, work with an annual research budget of EUR 2.9 billion. Fraunhofer generates EUR 2.5 billion of this from contract research, commissioned to a considerable extent by German industry.

Ten Fraunhofer Institutes, distributed in different parts of Germany, work in the field of energy research, including the Fraunhofer Institute for System and Innovation Research (ISI), Fraunhofer Institute for Solar Energy Systems (ISE), Fraunhofer Institute for Wind Energy Systems (IWES) and Fraunhofer Institute for Energy Economics and Energy Systems (IEE). The research spans a wide spectrum, from laboratory work and the administration of technical pilot projects, through to economic and technical simulations.

In 2020, Fraunhofer Gesellschaft founded ENIQ, a Berlin-based energy platform to coordinate the energy research among the different institutes.

The German ministry for education and research is currently developing a new comprehensive strategy: the future strategy for research and innovation.[13] This strategy, once approved by the other ministries, will replace the previous High-Tech Strategy. In the energy sector, the current draft focuses, among other things, on the development of new technologies, such as Carbon Dioxide Removal (CDR), sustainability as a topic in education, international cooperation in science, protection of biodiversity and the establishment of sustainable agriculture.

The strategy aims to establish the basis for cross-sectoral cooperation for innovation and research until 2025. Moreover, the strategy implements indicators to measure the development of innovation and research. The draft proposes, for example, 3.5% of BIP investments in R&D and an increase in the number of formations until 2025. The strategy also includes the establishment of a German agency for innovation and technology transfer. Cooperation at EU and international level is also of high importance.

Germany has a prominent position in science, research and development. It has a large number of special institutes in the faculties at universities. The most important public research institutions in Germany include the non-university institutions of Fraunhofer-Gesellschaft, the Helmholtz Association of German Research Centres, the Leibniz Association, the institutes of the Max Planck Society and the federal institutes with research tasks. A number of academy institutes, as well as institutes sponsored by the federal states and municipalities, should also be mentioned here.

2.5 Relevance for China

Like Germany and the EU, China is also keen to promote its energy transition. The Chinese government committed to peaking its CO_2 emissions before 2030 and reaching climate neutrality before 2060. The country has set itself the target to reach around 25% of non-fossil fuels in its primary energy consumption and 1,200 GW of solar and wind capacity by 2030. According to China's plan, the proportion of non-fossil fuels of total energy consumption should already amount to 80% by 2060. These ambitious goals require a massive expansion of renewable energies as well as great advances in low-carbon technologies.

With 1,063 GW by the end of 2021, China already has the world's largest installed capacity of renewable energies. Last year alone, the amount of new wind and solar capacity added in China was as much as Germany's total capacity. In particular, solar power (31.1% of the total added capacity in 2021) is currently experiencing massive buildout.[14] In 2021, China became the world's largest country in terms of incremental photovoltaic installed capacity for the ninth consecutive year.[15] However, similar to Germany, successfully integrating the rapidly increasing amount of fluctuating RES into the power system is also a major challenge for China. Higher levels of flexibility are therefore much needed to reduce the pressure on the power grid and ensure the security of supply.

As already reported in our preceding report on distributed energy,[16] the proportion of distributed solar PV in China has been gradually increasing since 2016.[17] Nonetheless, it so far only accounts for a relatively small proportion of China's overall solar capacity. Residential solar PV is still a fairly new phenomenon, which is slowly gaining momentum in China. Up until now, much of its growth was due to China's Poverty Alleviation PV programme, which promotes the deployment of distributed solar in rural areas. From 2017 to 2021, total rooftop installations in China increased from 19.4 GW to 27.3 GW.[18]

With regard to battery energy storage, China had over 4 GW installed at the end of 2021. 1.2 GW of this is on the grid side, while most of the remainder is located at power plants.

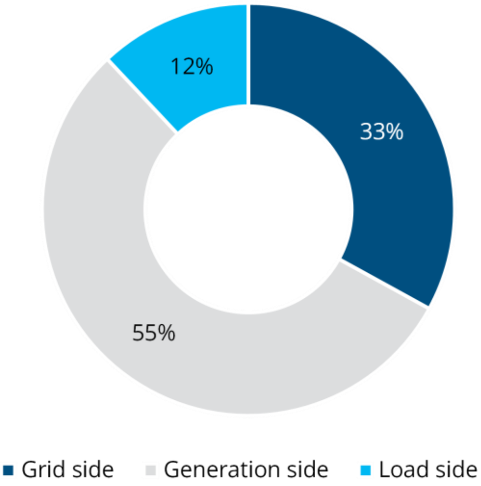


Figure 5: New energy storage by location
Source: GIZ 2022[19]

The country continues to invest heavily in battery storage. According to a recent report by the China Electric Power Planning & Engineering Institute (EPPEI), China is expected to have 55 GW of battery energy storage on the grid during the 14th Five-Year Plan (FYP; 2021–2025) period.[20] By 2030, it aims to reach 100 GW storage capacity.[21] As for user-side storage, safety concerns and economic considerations have so far restricted the technologies' considerable development in China.

Innovation in this field, including cost degression and safety improvement, can thus help China with the wider adoption of distributed energy technologies and, by doing so, help to accelerate the country's energy transition.

Within the last two decades, technological innovation has become a strategic pillar of China's development. Meanwhile, the country has become a world leader in several key energy technology areas, including solar PV, wind turbines and battery storage technologies. The Chinese government's focus on innovation, particularly R&D, is expected to remain a key priority in the future.[22] It is one of the most prominent themes in China's current 14th FYP and it includes the target to increase R&D intensity by more than 7% every year until 2025. At the recent 20th party congress, China's innovation ambitions in the science and technology field were reiterated once again.

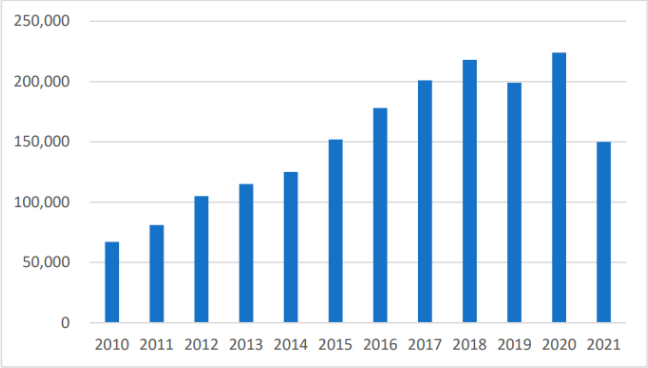


Figure 6: Number of green patent applications in China (2010–2021)
Source: Wang 2022[23]

Although not perfect, the number of patent registrations is one way to measure the innovation activity of a country. In this regard, China has undoubtedly developed into an important contributor to innovation in the field of renewable energy.

3 Innovative generation technologies – beyond conventional solar PV

In the field of generation technologies, a variety of new technologies are currently under development. Innovation in generation technologies include both improvements to large-scale technologies such as wind and distributed generation assets such as solar, as well as new generation technologies, such as Perovskii panels or tidal energy. These new solutions can increase efficiency, reduce costs and solve issues of conventional renewable generation technologies. China is currently the world leader in the manufacturing of solar PV modules and it contributes to the development of the technology. Broadening its approach to include further distributed generation technologies would benefit both its own and the global market.

3.1 Overview of innovative distributed generation technologies

A variety of innovative generation technologies to increase RES generation are already under development in different stages. These innovative technologies are mainly new applications for wind and PV, but also other technologies, such as tidal energy or combined solutions. Solar PV in particular has seen an immense decrease in costs due to new technologies and innovations over the past decades,[24] as shown in Figure 7 below. There are also other generation technologies at distribution level that can benefit from cost degression, such as small-scale biomass.

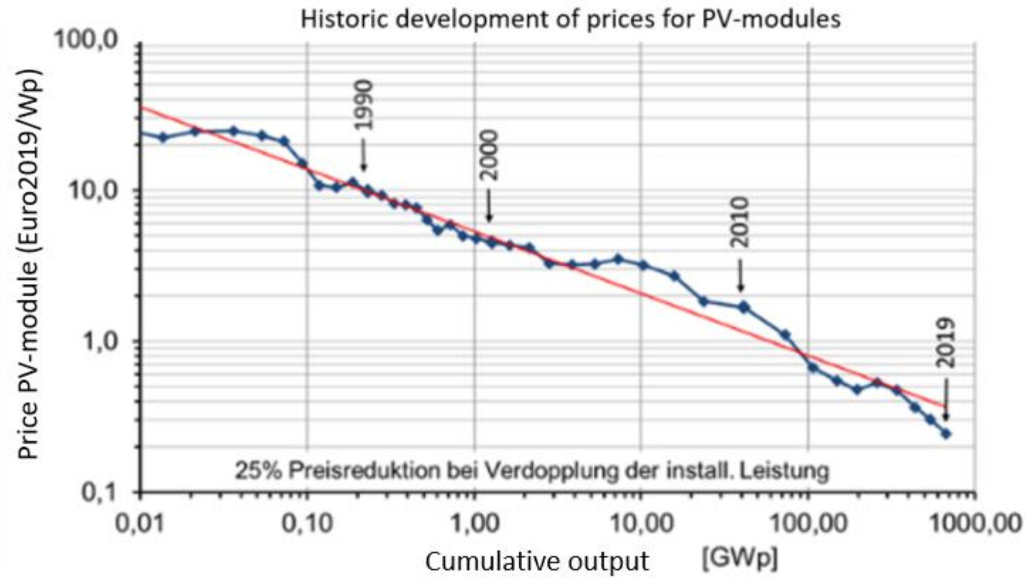


Figure 7: Historical development of prices for PV modules[25]

Examples of innovative generation technologies include:

Perovskii panels are innovative PV cells which enable higher efficiency. These cells can reach an efficiency level of more than 20%.

Agri-PV enables the combined use of agricultural land use and PV generation. This dual use increases the efficiency of land utilisation and can therefore help to reduce land-use conflict. Germany harbours great potential for Agri-PV. The spectrum ranges from the cultivation of special crops and intensive arable crops with special PV mounting systems, to using land for extensive grazing with marginal adjustments on the PV side.

Floating PV refers to PV panels that float on water. The cooling effect of the water surface can also lead to a higher electricity yield than on land.

Building integrated PV is the integration of photovoltaic modules into the building envelope. Building structures are additionally used for electricity production close to consumption.

Road-integrated PV is the incorporation of solar modules into and near train rails or roads, especially highways. This can be in the form of a rooftop or noise barriers, for example, or between railway tracks.

Skysails[26] refer to power kites at a height of about 200–400 meters. The kites are powered by wind, and as they reach the correct height, they unwind a tether from a winch on the ground. This drives a generator which finally produces the electricity.

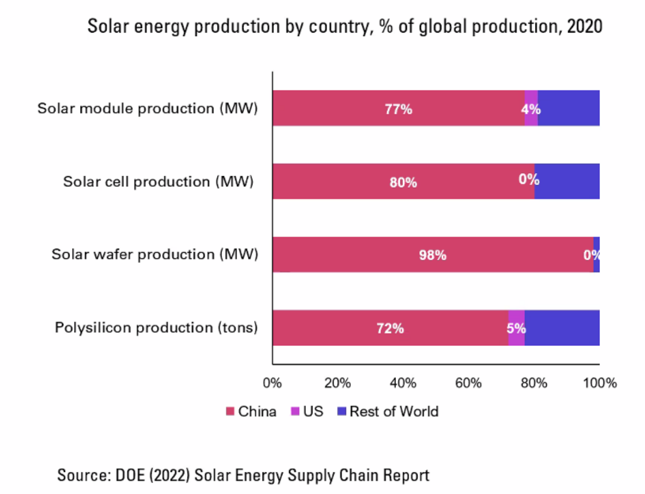
Combined rooftop PV and wind[27] refers to hybrid systems of both PV and wind. These exist in small-scale for rooftop use.

Tidal hydro power[28] works in a similar way to wind turbines. The blades that turn a rotor to a generator are run by tides. They can be placed on the seabed, where there is a strong tidal flow.

3.2 Potential role in China

China is the undeniable world leader when it comes to solar PV manufacturing. The global solar supply chain is fully dependent on it: The country's global share in all the manufacturing stages of solar panels (such as polysilicon, ingots, wafers, cells and modules) exceeds 80%, and it is home to 10 of the world's top solar PV equipment suppliers.[29] In 2021, China exported more than USD 28 billion worth of panels and other equipment.[30]

Most importantly, the country has played a fundamental role in bringing down global costs for solar PV, which has had a great impact on the global energy transition. Over the years, China has also gradually shifted from a sheer solar PV technology manufacturer to a frontier innovator. This has happened as a result of many factors, including China's unique approach to joint ventures and corporate partnerships, a large domestic market, inter-company technology-based competition, as well as supportive government policies and research infrastructure.[31]


Solar energy production by country, % of global production, 2020

Source: DOE (2022) Solar Energy Supply Chain Report

Figure 8: Solar energy production by country
Source: DOE 2022[32]

In the past decade, the country has emerged as a major source of PV cell and module-level innovations, and its proportion of global patenting is constantly increasing. Since 2011, China's constant innovation has also helped reduce the emissions intensity of solar PV production by half.[33]

In the 14th FYP period and beyond, Chinese policy makers have expressed the intention to continue being the top producer of solar PV and the leading developer of innovative PV technologies. Next-generation PV designs are already the focus of Chinese government laboratories and universities, and industry labs are progressively following the same path.[34]

As explained above, there are several innovative technologies for distributed generation that are likely to complement solar PV in the future. Given both its vast potential for domestic deployment and the likely global demand for these technologies in the future, China would be advised to broaden its industrial approach. This can include R&D efforts as well as policy-driven roll-outs of new technologies to improve them along the deployment learning curves.

Example: Chinese solar PV supplier

LONGi Green Energy Technology: *Solar power technology company founded in 2000 in Xi’an (Shaanxi)*

In 2021, LONGi Green Energy Technology was named the world’s leading solar manufacturer. Its portfolio includes innovative solutions such as floating PV or Agri-PV. LONGi is certified as a national enterprise R&D innovation lab for solar wafers, cells, modules and other PV solutions. On 31 December 2021, the company’s number of granted patents stood at 1,387 and its investment in R&D totaled CNY 12.36 billion.

Some of the companies’ technological innovations include the diamond wire wafer-slicing technology (resulted in at least CNY 30 billion of savings in annual production costs across the entire industry), the RCZ silicon crystal-growing technology (features high-speed crystal growth, multiple loading and large charging capacity) and the large PERC solar cell technology (solved initial degradation issues of monocrystalline silicon products and accelerated cell efficiencies). Recently, its p-type silicon heterojunction cells set a new global record in efficiency (26.12%).

LONGi is also leading the way in the promotion of the rooftop solar PV expansion. It has recently launched a WeChat mini programme, where users can obtain one-stop rooftop solar power services, including power purchasing, installation, maintenance and loan applications.

4 Innovative electricity storage – beyond lithium-ion batteries

Electricity storage can provide a range of flexibility services to the system, particularly the grid. The most common type at distribution level is battery storage. Even though a range of small-scale battery and storage solutions exist, innovations are still needed to contribute to cost degression, increase efficiency and solve current issues such as the limited availability of resources. As for solar PV, China has also built up important manufacturing capacities for lithium-ion batteries. In the future, it will have to broaden its industrial approach in order to contribute to the development of further innovative storage technologies for both domestic use and for export purposes.

	Distribution grid			***Transmission grid***
	Households / small businesses	**Trade and services**		**Industry**
	Microstorage < 100kW	**Small-scale storage 1–10 MW**	**Medium-scale storage 10–100 MW**	**Large-scale storage 100–1000 MW**
Months				Power-to-Gas
Days/weeks			Pump storage	Pump storage Power-to-Gas
Hours/days	Batteries	Batteries	Pump storage Compressed air storage Batteries	Pump storage Compressed air storage
Minutes/hours	Batteries	Batteries	Batteries	Pump storage Compressed air storage
Seconds/minutes	Super capacitor Coil	Flywheel generator Batteries	(Pump storage) (Compressed air storage) Batteries	(Pump storage) (Compressed air storage)

Table 1: Overview of different types of electricity storage and their connection to the grid (source: BFE 2022)

4.1 Overview of innovative technologies

The rationale for the deployment of flexibility technologies is explained in section 2. Depending on the type of storage, they can provide different services to the grid (for detailed information, see the report “Decentralized Flexibility and Integration of Renewable Energy”).[35] The most important services of decentralised storage include:

- Bulk energy services, including arbitrage and electricity supply capacity
- Ancillary services, including black start and voltage support C
- Customer energy management services, including power quality and increased self-consumption of solar PV
- Off-grid, including solar home systems and mini-grid services[36]
- Distribution infrastructure services including distribution upgrade deferral and voltage support

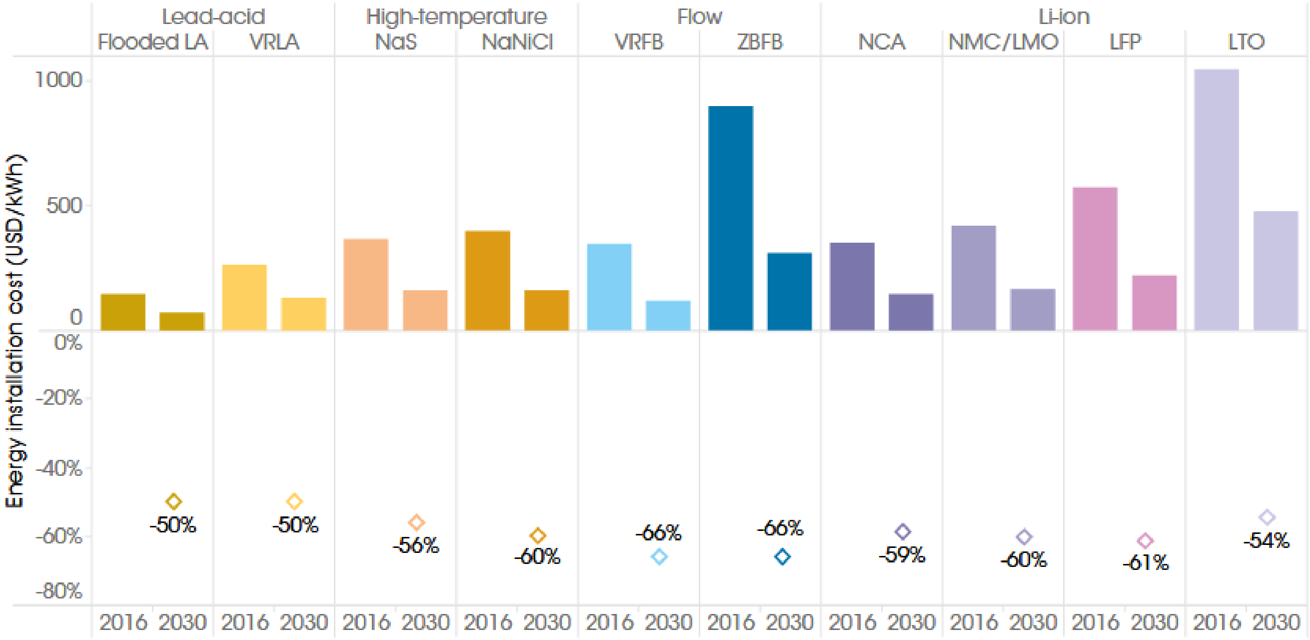
Though many players are exploring innovative energy storage technologies, in Germany conventional battery storage is still the most popular. Germany’s distributed energy storage systems have grown exponentially over the last two years as costs decline and product options expand. As of 2022, Germany had over 500,000 installed PV storage systems with a total storage capacity of about 4.4 GWh and a storage output capacity of about 2.5 GW.[37] These storage systems can contribute significantly to the integration of distributed electricity by increasing the proportion of self-consumption and reducing peak loads and peak solar feed-ins.

The most common type of small-scale electricity storage systems are batteries. They can store electricity for seconds up to days. Conventional batteries are lithium-ion batteries, zero-emission batteries, redox flow batteries, lead-acid batteries and sodium-sulfur batteries.

These types of batteries are commercially available. Nickel-cadmium batteries are also still in use, but regulations in the EU prohibit new applications, with only a few exemptions. Batteries mostly offer high efficiency, but some also have the disadvantage of safety risks due to high operating temperatures.

A variety of innovative solutions are currently under development. The potential cost degression of new solutions until 2030 is at least 50%. The potential varies depending on the technology (see Figure 9 below). Flow batteries, for example, could show a cost degression of 66% by 2030 compared to 2016.

In addition, these innovative solutions can contribute to addressing current challenges. One of those is the demand for energy and resources for the production of batteries. As the importance of batteries in the electricity system increases, so does the need for resources and energy for its production. The production of batteries is highly energy intensive. New solutions can increase the lifecycle and therefore contribute to a lower energy demand. Moreover, conventional batteries require specific, limited raw materials, such as lithium. In addition, raw materials such as copper, cobalt and nickel have various environmental effects, such as eutrophication, human toxicity and biotoxicity.



Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.

Figure 9: Battery electricity storage system – installed energy cost-reduction potential[38]

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[39]

Current research and development focuses on both the improvement of existing lithium-ion batteries and on alternatives to lithium-based batteries. Lithium-ion and future lithium-based batteries are called high-energy battery technologies due to their high energy density (amount of energy the battery can hold per unit of mass). It might be worth investing in targeted research on improving already established energy storage technologies other than LIBs and alternative technologies with potential for stationary applications.[40] [41] [42] More details about current innovations and research into new battery technologies can be found in the Appendix 6.1.

Smart grids

To leverage the full potential of flexibility in the electricity network, smart grids are needed. Smart grids consist of hardware, which includes a communication medium and smart meter to collect data and allow communication between the components. A smart grid also requires software, including a communication program for data exchange between devices and systems.

Research is also being conducted in the area of smart meters to improve efficiency, for example, and bi-directional charging of electric vehicles. This research includes hardware as well as software. Powerful AI-based software tools are expected to play an important role in matching demand and supply with high proportions of variable renewable energy in the future.

Apart from batteries, there are other promising storage technologies in different stages of development. These include:

- Thermal storage, e.g. Carnot batteries
- Gravity storage, e.g. in combination with wind power plants
- Small-scale hydrogen storage

These technologies are described in detail in the Appendix 1.1 to 0. Once fully developed, they will serve different purposes in the electricity supply system – gravity storage can provide ancillary services, thermal and hydrogen storage generation/load shifting.

4.2 Potential role in China

China's current 14th FYP has placed an unprecedented emphasis on energy storage development. So far, high costs have been an obstacle to the large-scale deployment of energy storage systems. One of the main goals stated in the strategic plan is therefore to decrease the per unit cost of energy storage by 30% by 2025 in order to make energy storage more cost competitive. This will lead to a drastic cost decrease starting in 2025. According to the plan, the commercialisation of all new types of energy storage systems, except pumped hydro, should be completed by 2030. Extending the useful lives of energy storage systems is another strategic focus of China's innovation efforts. In August 2022, China also established a national energy storage industry innovation alliance, dedicated to promoting technology innovation in this sector.[43]

The planned cost degression and technological innovation is not only vital for reaching China's carbon neutrality goal, but will also have a great impact on the competitiveness and wider adaptation of the energy storage industry worldwide.

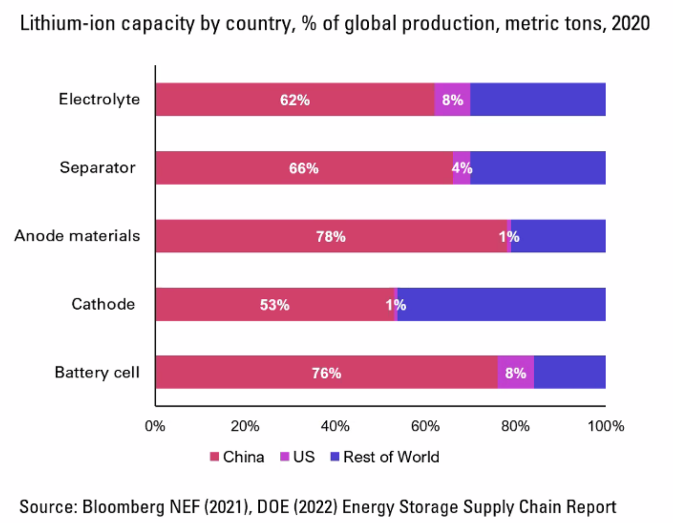

Figure 10: Lithium-ion capacity by country

Source: BloombergNEF (2021); DOE (2022)[44]

At present, the world is heavily dependent on China's global lithium battery supply. In a market worth CNY 600 billion (EUR 83 million), China's lithium-ion batteries for energy storage manufacturing reached 32 GWh in 2021.[45] According to Bloomberg, China now controls about 90% of the global battery storage manufacturing capacity.[46]

Over the 14th FYP period, China plans to further push the development of all types of battery energy storage systems, including sodium-ion, novel lithium-ion, lead-carbon and redox flow.[47]

As with distributed generation technologies, more than just one dominant technology will be needed to meet the needs of the energy transition. To serve its own future demand for electricity storage and to open up new export opportunities, China should broaden its approach to R&D in this field. Given the ambitious targets of the Paris Agreement, both the technological and market potential are likely to be vast.

5 Conclusion: Innovation is essential for the future of distributed generation

Innovation is an important driver for the energy transition. The fast cost degression of solar PV and – to a lesser extent – wind generation technologies has contributed to the acceleration of their adoption over the past decade. More innovation is required, both to further reduce the cost of the transition and to solve several challenges that are apparent today, including scarcity of raw materials, environmental pollution (other than carbon emissions) and spatial planning concerns.

This holds true in particular for distributed generation and storage technologies. From many scenario-based studies into the future of electricity supply, it is clear that these distributed generation technologies will play an important role in a carbon-neutral energy system to cover local demand. Storage technologies are needed to accommodate the fluctuating feed-in associated with many renewable sources. Further cost reductions in established technologies such as solar PV and lithium-ion batteries, based on both advances in R&D and an accelerated learning curve, will decrease the cost of adoption in industrialised countries and facilitate their deployment in emerging and developing economies.

Apart from reducing costs, innovative generation and storage technologies can optimise the use of space, improve the toxicity of existing technologies and replace or complement others based on rare raw materials. They therefore have the potential to facilitate and accelerate the expansion of distributed generation.

Examples include:

- Perovskii panels optimise the use of space, as they can be attached to otherwise unused surfaces, such as the façade of buildings or walls used to encircle property.
- Agri-PV panels allow for both the generation of electricity and the use of land for agricultural production.
- Redox-flow batteries use materials such as vanadium, for which there is a broader raw material base than for the lithium that is widely used in lithium-ion batteries.

A gravity battery stores energy temporarily in the form of potential energy of a lifted mass, using excess energy from the grid to raise a mass and retransforming it into electricity by dropping it afterwards. This type of storage avoids the use of rare and toxic materials.

With regard to innovation, governments play an important role: Economists have argued that, due to spillover effects, R&D efforts by industry are likely to be inefficiently low. This problem is certainly even more acute in the case of clean energy technologies, the marketability of which often depends on government policies, i.e. governments must create the regulatory environment enabling their development and adoption. In Europe, both the EU and Germany pursue ambitious R&D policies aimed at creating innovations for the energy transition. Among others, these include considerable funding for research grants.

As for the implementation, a network of German research institutes is dedicated to supporting the energy transition, including 10 institutes of Fraunhofer Gesellschaft. However, innovation includes several stages beyond R&D. Support programmes for the deployment of innovative technologies contribute to their expansion and to cost degression: Feed-in-tariffs used to promote solar PV and other renewable technologies a decade ago provide an illustration of this effect. Apart from such initial support, the market design has to allow for small-scale renewable energy feed-in and its integration into the market and the grid. Similarly, the economic viability of electricity storage crucially depends on regulatory choices such as the design of network tariffs and ancillary services, and improvements to the regulatory environment are required to make use of the full potential of batteries for the energy transition. Quite clearly, initial support programmes and adaptations of the market framework are very likely to be required for new innovative technologies as well.

China has built up a large and impressive manufacturing industry for both solar PV and electricity storage devices, making an important contribution to the global energy transition. Moreover, a large number of patents bear testimony to its commendable R&D efforts in these fields. At this stage of the energy transition, it is advisable that it broadens its perspective: By investing in R&D for new, promising technologies, and by deploying them locally, it would be able to add important technologies for the energy transition that would eventually meet the growing demand in the global market. Apart from R&D efforts, this should include initial support for these technologies on their road towards marketability. Such policies would help to achieve the ambitious emission abatement targets of the Paris Agreement, both within China and, via exports, outside China.

6 Appendix: Innovative energy storage technology factsheets

6.1 Electric energy storage

Factsheet 1: Metal-O2/air battery

Name	***Metal-O_2/air battery***
Basic information	Metal-O2/air batteries make use of oxygen contained in air as cathode "material". For the anode, concepts exist for the use of different metals such as Li, Na, Mg, Al or Zn. Due to the comparatively high cell voltage and low weight of lithium, Li-air batteries are a focus of research. The bottle-neck is that reversibility is complicated by contamination due to usage of air. Furthermore, power density suffers from the stability of the Li anode.[48]
Technology readiness level	Reversible metal-air batteries require strong progress in R&D and disruptive solutions for many components. Laboratory Li-air models have low power densities. The kinetics of the reactions must be significantly improved.[49]
Potential	Metal-O2/air batteries have a high theoretical energy density, as no dead weight is required for host materials (Li-air system can theoretically achieve energy density of 3,450 Wh/kg). Such batteries will potentially have a low price due to dispensing with expensive cathode materials. Experts anticipate market entry of Li-O2 batteries with > 300 Wh/kg and > 500 cycles in 2030.[50]
Application	Slow kinetics of the reactions involved make the use of Me-Air/O_2 in vehicles rather unlikely. Me-Air/O_2 could initially be used as a stationary storage system (ESS), since additional equipment such as BMS, compressors or oxygen storage (Li-O2) would not have a negative impact. Lack of cycle stability is of concern to ESS applications. Concepts are conceivable, with extremely high storage capacity and low cycle rates, similar to pumped storage operation.[51]
Pilot project	A pilot project of the company e-Zinc will store excess wind generation capacity in a zinc-air battery system at Bull Creek, Texas, USA. It is one of several upcoming e-Zinc field demonstration projects, including e-Zinc's USD 1.3 million project with the California Energy Commission for backup services.[52] Form Energy expects to have a 1 MW / 150 MWh pilot installation of its iron-air system deployed at Minnesota-based utility Great River Energy by 2023.[53]

Factsheet 2: Metal-sulfur battery

Name	***Metal-sulfur battery***
Basic information	Metal-sulfur batteries use redox potential of metal anode and sulphur cathode. The most relevant metals considered are lithium (metallic lithium), sodium and magnesium, in that order. Concepts also exist for the use of Si/C anodes, which could increase the number of cycles that can be achieved.[54]
Technology readiness level	Li-S have the highest level of development among the Me-S systems. They are already being tested and used as prototypes and in small series. Widespread commercialisation has not yet taken place. The technology development is located in the area of applied research. Prototypes with a high cyclability of several 1,000 cycles exist on a laboratory scale, and cells from pre-commercial production achieve about 100 cycles at an energy density of 350 Wh/kg.[55] Na-S batteries have been used for some time in stationary applications as a high-temperature variant with molten active materials. For safety reasons, the development of systems which operate at room temperature is desirable, but still needs basic research.[56] Ma-S might benefit from the development of other metal-sulfur chemistries, but extensive research and development is still needed.[57]
Potential	The long-term vision for Li-S is to achieve > 500 cycles, 600 Wh/kg or 600 Wh/l. Na-S and Mg-S are expected to benefit from the findings for Li-S and thus follow the Li-S development. For Na-S room-temperature batteries, market entry is expected after 2030 with 200 Wh/kg. In the mid-term, those RT Na-S batteries might achieve > 300 Wh/kg, < 80 EUR/kWh, and in the long-term > 500 Wh/kg with > 500 cycles. For Ma-S batteries, the long-term vision (> 2045) is 400 Wh/kg, a battery life of 15–20 years with 1,000 cycles and < 80 EUR/kWh.[58]
Application	Li-S prototypes are already being used in flight applications for their high energy density per unit of weight. Automotive applications are conceivable, but the low power density and volumetric energy density are problematic. For room-temperature Na-S and Ma-S, the main applications are seen in the field of stationary energy storage due to their comparatively low volumetric energy density but low anticipated costs.[59] The main applications for high-temperature Na-S systems include load-levelling, adjusting supply and demand imbalances on grids, stabilising renewable energy integration and offering backup power.[60]
Pilot project	Zeta Energy has raised USD 23 million from Moore Strategic Ventures to develop and commercialise its lithium-sulfur (Li-S) battery system (2022).[61] High temperature Na-S battery systems from Japanese industrial ceramics company NGK Insulators have been paired by BASF with green hydrogen production from wind power (2020), for example, and used to support the stable operation of electric power systems at Japan Aerospace Exploration Agency or absorb fluctuations from a 5 MW PV project in Mongolia (2021).[62]

Factsheet 3: Sodium-ion battery

Name	***Sodium-ion battery***
Basic information	The working principle is similar to lithium-ion batteries. Sodium ions shuttle between the cathode and the anode through the use of organic solvent or aqueous electrolytes.[63] • Anode materials: C, Sn • Cathode materials: Prussian Blue Analogue, Layered Metal Oxide, Sodium (Na) Super Ionic Conductor (NASICON) An important aspect of sodium-based battery chemistries is the high resource availability and a relatively low price compared to lithium.
Technology readiness level	The market maturity of the technology can be regarded as relatively advanced. Estimated performance parameters for 2023 from the Association of European Automotive and Industrial Battery Manufacturers (EUROBAT) are: Recycling Rate (50 %), Calendric Life (15 years), Energy Throughput (4000 FCE), Fast Recharge Time (30 min), Volumetric Power Density (500 W/l), Gravimetric Power Density (300 W/kg), Volumetric Energy Density (310 Wh/l), Gravimetric Energy Density (160 Wh/kg).[64]
Potential	Estimated performance parameters for 2030 from the Association of European Automotive and Industrial Battery Manufacturers (EUROBAT): Recycling Rate (90%), Calendric Life (30 years), Energy Throughput (6,000–12,000FCE), Fast Recharge Time (5 min), Volumetric Power Density (600-850 W/l), Gravimetric Power Density (380–700 W/kg), Volumetric Energy Density (350–700 Wh/l), Gravimetric Energy Density (200–450 Wh/kg) [65] The development effort for commercialisation is estimated to be moderately high and significantly lower compared to other post-LIB technologies. The long-term development of the performance parameters is thought to be the same as for the development for LIBs, and a convergence to more than 70% of the corresponding values of LIBs is expected. Existing Li-ion production lines could be used and a developed Na-IB technology can be expected to deliver cost savings compared to LIBs. Prices of 60 EUR/kWh are possible by 2050, and a price advantage of 20% over lithium-based systems could develop if lithium becomes scarce.[66]
Application	Due to the low price and the comparatively low energy density, application fields are mainly seen in the ESS sector and in the low-cost consumer sector.[67]
Pilot project	Smart Sodium Storage System (S4) project integrated sodium-ion battery cells into 5 kWh modules with built-in battery management systems and demonstrated this technology in conjunction with a custom-developed Energy Management System coupled with renewable generation at Sydney Water's Bondi Sewage Pumping Station.[68]

Factsheet 4: Redox-flow battery

Name	***Redox-flow battery***
Basic information	Redox flow batteries (RFB) are based on two liquid electrolytes, separated by an ion-permeable membrane. The electrolytes present in separate circuits have an electrochemical potential with respect to each other and can be reduced or oxidised by ion exchange through the membrane. In vanadium-based RFB (VRFB), the stability of vanadium ions in different valences is exploited. At the positive electrode, tetravalent vanadyl sulfate can be oxidised, while at the negative electrode V(III), sulfate is reduced. Another type of RFB uses the redox reaction of zinc and bromine (Zn/Br). The energy stored in the system can in principle be scaled by the volume of the electrolytes (tanks) and the available power via the contact area of the electrolytes with the membrane.[69]
Technology readiness level	Small series on the market, 35 ct/kWh storage costs.[70]
Potential	Next years: extensive market entry, lifetime 10 (Zn/Br) – 15 Years (VRFB), efficiency 75%, 15 ct/kWh storage costs[71] > 2030: lifetime 15 (Zn/Br) – 20 Years (VRFB), efficiency 85%, 5-10 ct/kWh storage costs[72]
Application	Applications without space and weight limitations, as RFB have a low energy density. Possible applications are seen at all levels of stationary storage, due to the scalability of the systems (arbitrage, EE integration, black start, back-up, micro grid, off-grid etc.)[73]: • Charge/discharge time: > 1hour – 1week • Power: 10 kW – 20 MW • Energy: 100 kWh – 800 MWh
Pilot project	Applications already exist in the area of peak load shifting (time scale ~h) on a regional level or as domestic storage. Producers for redox-flow batteries for domestic storage purposes are the companies Schmid and Volterion.[74]

Factsheet 5: Lead-carbon accumulator / PbC battery

Name	***Lead-carbon accumulator / PbC battery***
Basic information	In PbC batteries, a combination of lead and carbon structures is used as a negative electrode. The operating principle can be described as a combination of a lead-acid battery and an asymmetric supercapacitor. The possibility of ion deposition in the electrolyte/carbon double layer of the electrode allows for higher charging rates compared to conventional lead-acid systems. The mixture of lead and carbon prevents the sulfation of the negative electrode, which allows the battery to be stored for long periods without equalising charge, and deeper discharge is possible at higher numbers of cycles. Currently available cells have energy densities of between 25 and 30 Wh/kg or 70–80 lifetime of about 2,000 cycles. Pb as a raw material is considered comparatively uncritical, plus Pb can be taken directly from lead-acid battery recycling (> 95% recovery rate). The resource availability regarding natural graphite (anode) is comparable to the situation for LIBs regarding lithium.[75]
Technology readiness level	Market-ready. PbC-batteries are already commercially offered by a few manufacturers.
Potential	Optimisation, especially with regard to the amount of carbon in the anode. Widespread market entry can be achieved in 2025 at a price of 90 EUR/kWh and an energy density of > 35 Wh/kg. Further optimisation of the technology is expected, both in terms of performance parameters, but mainly with regard to the costs, which could in principle be reduced to 50 EUR/kWh and thus below the targets of LIBs.[76]
Application	ESS, Frequency Regulation, Load Levelling, Micro Hybrid[77]
Pilot project	Axion Power International's PbC batteries look like conventional car batteries, but they come in 12 and 16 V versions and weigh about 30–35% less. The company builds these into 480 V racks and into utility-scale power stores called PowerCube. These systems respond in 55 ms and are applied in frequency regulation.[78]

6.2 Thermal energy storage

Factsheet 6: Carnot battery

Name	***Carnot battery***
Basic information	Carnot battery (CB) cycles consist of electricity to heat and/or cold conversion, thermal energy storage (TES) and a thermal power cycle. CBs also allow for the addition of thermal streams to the charge and/or discharge process (thermal integration) with the target of improving the overall CB performance. The most prominent thermodynamic cycles proposed in the CB field are: Brayton pumped TES (Brayton PTES), Rankine pumped TES (Rankine PTES), Liquid Air Energy Storage (LAES).[lxxix]
Technology readiness level	Well-known technical processes and equipment.
Potential	The technology could be viable for grid-scale energy storage, as CBs are designed for large storage capacities. Carnot batteries have no geographical constraints and, compared to other batteries, they offer the potential for electricity-heat coupling. Among CBs, Rankine PTES has the lowest round-trip efficiency of 61.6 % and LCOS of around 230 USD/MWh. LAES and Brayton PTES are comparable, with round-trip efficiencies of 52.8 % and ~48 %, and average LCOS of 330 and 369 USD/MWh, respectively. LAES integration with external processes can improve system round-trip efficiency and bring down LCOS significantly. However, the profitability of thermally integrated PTES is still unclear, as concepts specifically designed for waste heat recovery in industrial processes pose competition.[lxxx] CBs also have the potential to reuse existing Rankine steam cycles, replacing what once was supplied by fossil fuels with a Carnot battery and thus phase out coal power plants, for example.[lxxxi]
Application	Either in stand-alone operation or in conjunction with coal, natural gas, concentrating solar or nuclear power plants, CBs are able to provide: power supply and thermal services, RES integration, plant flexibility, arbitrage, ancillary services, peak shaving, off-grid operation.[lxxxii] CBs can also help to avoid grid congestion and transmission line reinforcements.[lxxxiii]
Pilot project	50 MWh CO2 heat pump units have been installed in Esbjerg, Denmark, to replace medium-sized district heating plants.[lxxxiv] For the Highview Power project, seven LAES 50 MW/300MWh (each) are under development in Asturias, Cantabria, Castilla y Leon and Canary Islands, Spain.[lxxxv] Siemens Gamesa has already developed two Rankine PTES pilot plants in Hamburg, one in 2014 and another in 2019. The plants utilise restive heating, air as heat transfer fluid and volcanic rocks as heat storage (up to 600°C). The power cycle is composed of a steam turbine, and possible outputs are electricity, process steam for industrial processes and water for district heating or cooling. The plants have a round-trip efficiency of 45% and offer electrical power up to 1,400 kW and a capacity of 12,000 kWh. Siemens claims a 1 GWh storage project could be commissioned as early as 2025.[lxxxvi]

6.3 Mechanical energy storage

Factsheet 7: Wind turbine combined with pumped storage

Name	***Wind turbine combined with pumped storage***
Basic information	Wind turbines with integrated water storage tanks and a storage basin allow for the simultaneous production and storage of electricity. The pumped storage can serve as a flexible short-term storage facility and help to balance out grid fluctuations. Compared to regular pumped storage power plants, it requires less space and has a lower impact on the landscape. Large pumped storage power plants can store much greater amounts of electricity, but small storage facilities are also sufficient to compensate for short-term fluctuations in the production of a wind farm.
Technology readiness level	Pilot project installed and operational.
Potential	• Suitable locations for similar projects are rare: The combination of wind turbine and pumped storage power plant necessitates a location that offers at least 150 metres of height difference between the towers and the water basins in the valley. • However, the lower impact on the landscape has the potential to reduce local opposition to future projects.
Application	Only pilot project was constructed in combination with onshore wind park. The water battery can absorb surplus electricity from the power grid and release it again when needed. It is connected to a transformer substation.
Pilot project	Pilot project in Gaildorf, Baden Württemberg. Consists of four turbines with a combined capacity of 13.6 MW. The upper basin is divided into four small water basins that are directly integrated into the wind turbines. Water reservoirs (active basins) are built into the foundations, and the towers stand in what is known as a passive water basin. These are connected via pipes to the lower basin 200 metres below, which has a volume of 160,000 cubic metres. The pumped storage power plant stores up to 70 MWh.

Factsheet 8: Gravity battery

Name	***Gravity battery***
Basic information	A gravity battery is a type of storage power plant in which electrical energy is temporarily stored in the form of potential energy of the lifted element. The gravity battery uses excess energy from the grid to raise a mass to generate gravitational potential energy and subsequently drops the mass to convert potential energy into electricity through an electric generator. The decisive difference between the gravity battery and normal conveyor systems is the fact that the stored energy is converted into heat in a conventional brake during the downward movement, but is converted back into electrical energy.
Technology readiness level	Pilot project installed. First marketed projects started.
Potential	• Simple, affordable materials used may offer environmental benefits over conventional pumped storage and batteries and make the system price-competitive. Bricks used are made of recycled waste products. • Potential and future demand for pumped storage is huge. • Energy Vaults EVx storage generation is supposed to reduce the friction loss to 15–20%. With lithium battery storage, 10–13% of the electricity used is lost between charging and discharging. • Performance of the system does not decrease over time, unlike with lithium-ion batteries.
Application	Thus far, gravity batteries are co-located with solar or wind plants. Gravity storage is particularly suitable for applications that require a constant power supply with discharge times between two and twelve hours. Energy Vault project in Australia is set to have grid connection and will hence become integrated with the local grid for the state of Victoria.
Pilot project	Pilot projects include *Gravitricity* in Edinburgh, Scotland, and *Energy Vault* in Castione-Arbedo, Switzerland. Gravitricity uses a 15-meter, 250-kilowatt gravity battery. Energy Vault stores electricity using a crane that raises and lowers blocks of concrete. Energy Vault has announced a notice of award from Meadow Creek Solar Farm for the deployment of a 250 MW / 500 MWh grid-connected battery in Victoria, Australia.

6.4 Chemical energy storage

Factsheet 9: Small-scale hydrogen storage

Name	***Small-scale hydrogen storage***
Basic information	The electrolyser uses the surplus electricity from the photovoltaic system to split processed water into hydrogen and oxygen. The hydrogen gas can be stored in tanks and converted back into electricity and heat with a time delay. Fuel cells, which are also available as electricity-generating heaters, reverse the electrolysis process, producing electricity and heat. Hydrogen has the advantage that it can be stored in tanks with low energy losses over longer periods.
Technology readiness level	Marketable and available.
Potential	Picea system has been shown to have an efficiency level close to 90% due to utilisation of waste heat. Lavo system offers a 30-year guarantee. High prices of the systems.
Application	For single households, apartment buildings and small businesses. The storage systems are designed for self-sufficiency but can be connected to the grid.
Pilot project	Multiple pilot projects. **Picea**: Home power solutions (HPS) • Picea is a system for detached and semi-detached houses that combines electricity storage, heating support and living space ventilation. • A lithium-ion battery with 20 kWh stores energy for the short-term electricity demand. • The energy generated by a photovoltaic system can be converted and up to 2400–3000 kWh stored. The hydrogen is produced with an integrated electrolyser. A fuel cell converts the energy stored in hydrogen back into electrical energy. • Storage system can be operated in isolation or connected to the grid. • System uses waste heat of power conversions to heat. **Lavo**: • Prosumer hydrogen station that uses integrated hybrid hydrogen batteries combining rooftop solar plants and green hydrogen. • Lavo combines hydrogen storage, fuel cell and electrolysis into a compact system with a 40 kWh storage system that can supply a household for two to three days. • System is much smaller and cheaper than the picae system. At the same time, the efficiency of power conversions is lower due to the absence of a waste heat converter.

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Bibliography

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[1] Dena, "Verteilnetzstudie", https://www.dena.de/themen-projekte/energiesysteme/flexibilitaet-und-speicher/

[2] https://strom-report.de/strom/

[3] EG in Zahlen – 2019, Bundesnetzagentur, 2020, at https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEGinZahlen_2019_BF.pdf?__blob=publicationFile&v=3#:~:text=EEG%20in%20Zahlen%202019%201%20Vorwort%202%2F83%2031.12.2019,%28Anzahl%29%207.222%20602%2015.122%2011%2028.363%201.467%201.868.1561.920.943.

[4] Additional information about flexibility measures is available in the report "Flexibility Technologies and Measures in the German Power System": https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/Flexibility_Technologies_and_Measures_in_the_German_Power_System.pdf

[5] Additional information about the flexibility potential of data centres is available in the report "Data centre flexibility in Germany and China": https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/EnTrans/Data_centre_flexibility_in_Germany_and_China.pdf

[6] Dena, "Decentralized Flexibility and Integration of Renewable Energy", https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/Decentralized_Flexibility_and_Integration_of_Renewable_Energy_EN.pdf

[7] Further information about flexibility measures at distribution grid level are available in the report "Decentralized Flexibility and Integration of Renewable Energy": https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/Decentralized_Flexibility_and_Integration_of_Renewable_Energy_EN.pdf

[8] IRENA, "Electricity Storage Costs", https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

[9] Fraunhofer, "Kurzgutachten Innovative Energietechnologien", https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/211005_DLS_Gutachten_Fraunhofer_ISE_final.pdf

[10] Mennel (2012), Das Erneuerbare-Energien-Gesetz – Erfolgsgeschichte oder Kostenfalle? Wirtschaftsdienst 92 (13)

[11] Benekin (2021), Was wir für die EEG-Umlage bekommen haben: Seid stolz – be proud!, PV Magazin

[12] BMBF, "High-Tech Strategy 2025", https://www.bmbf.de/SharedDocs/Publikationen/de/bmbf/FS/31538_Forschung_und_Innovation_fuer_die_Menschen_en.pdf?__blob=publicationFile&v=7

[13] BMBF, "Zukunftsstrategie", https://www.bmbf.de/bmbf/de/forschung/zukunftsstrategie/zukunftsstrategie_node.html

[14] Arendse Huld, "The Status of China's Energy Transition and Decarbonization Commitments", China Briefing, 22 April 2022, at https://www.china-briefing.com/news/earth-day-2022-whats-the-state-of-chinas-energy-transition/

[15] "China Clean Energy Syndicate 2022 Vol. 26", Energy Iceberg, 28 September 2022.

[16] "Decentralized Flexibility and Integration of Renewable Energy", dena and GIZ, August 2022, at https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/Decentralized_Flexibility_and_Integration_of_Renewable_Energy_EN.pdf

[17] For the difference in the definition of distributed energy in China, refer to page 25 of our report "Decentralized Flexibility and Integration of Renewable Energy".

[18] "Longi sets more solar power units on household rooftops", China Daily, 7 August 2022, at https://www.chinadaily.com.cn/a/202207/08/WS62c785c4a310fd2b29e6b34a.html

[19] GIZ, "Energy in China Newsletter", Issue 62, September 2022.

---

[20] GIZ, “Energy in China Newsletter”, Issue 62, September 2022.
[21] “China Plans for Cheaper, Longer Lasting Energy Storage by 2025”, Bloomberg News, 21 March 2022, at https://www.bloomberg.com/news/articles/2022-03-21/china-plans-for-cheaper-longer-lasting-energy-storage-by-2025
[22] “Tracking Clean Energy Innovation: Focus on China”, International Energy Agency (IEA), 2022, at https://www.iea.org/reports/tracking-clean-energy-innovation-focus-on-china
[23] Ye Wang, “Has China Established a Green Patent System? Implementation of Green Principles in Patent Law”, Sustainability 2022, 14.
[24] Fraunhofer, “Kurzgutachten Innovative Energietechnologien“, https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/211005_DLS_Gutachten_Fraunhofer_ISE_final.pdf
[25] Fraunhofer, “Kurzgutachten Innovative Energietechnologien“, https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/211005_DLS_Gutachten_Fraunhofer_ISE_final.pdf
[26] https://skysails-power.com/how-power-kites-work/
[27] https://www.pv-magazine.com/2021/12/07/hybrid-wind-solar-generator-for-rooftop-applications/
[28] https://www.eia.gov/energyexplained/hydropower/tidal-power.php
[29] “China Clean Energy Syndicate 2022 Vol. 26”, Energy Iceberg, 28 September 2022.
[30] “China’s Clean Energy Dominance May Face Challenge in Batteries”, Bloomberg News, 17 February 2022, at https://www.bloomberg.com/news/articles/2022-02-17/china-s-clean-energy-dominance-may-face-challenge-in-batteries
[31] “Tracking Clean Energy Innovation: Focus on China”, International Energy Agency (IEA), 2022, at https://www.iea.org/reports/tracking-clean-energy-innovation-focus-on-china
[32] “Solar Photovoltaics”, The U.S. Department of Energy (DOE), 24 February 2022, at https://www.energy.gov/sites/default/files/2022-02/Solar%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf
[33] “Solar PV Global Supply Chains”, International Energy Agency (IEA), July 2022, at https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary
[34] “Tracking Clean Energy Innovation: Focus on China”, International Energy Agency (IEA), 2022, at https://www.iea.org/reports/tracking-clean-energy-innovation-focus-on-china
[35] Dena, “Decentralized Flexibility and Integration of Renewable Energy”, https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/Decentralized_Flexibility_and_Integration_of_Renewable_Energy_EN.pdf
[36] IRENA, “Electricity Storage Costs”, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf
[37] Jan Figgener et al, “The development of battery storage systems in Germany: A market review (status 2022)”, 15 March 2022, at https://arxiv.org/abs/2203.06762
[38] IRENA, “Electricity Storage Costs”, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf IRENA, “Electricity Storage Costs”, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf
[39] IRENA, “Electricity Storage Costs”, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf IRENA, “Electricity Storage Costs”, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf
[40] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)” (2017).
[41] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)” (2017).
[42] Edström, Kristina. “Battery 2030+ roadmap” (2020).
[43] “Alliance formed to boost energy storage”, China Daily, 9 August 2022, at https://www.chinadaily.com.cn/a/202208/09/WS62f1c199a310fd2b29e711dd.html

---

[44] “Solar Photovoltaics”, The U.S. Department of Energy (DOE), 24 February 2022, at https://www.energy.gov/sites/default/files/2022-02/Solar%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf; “New Energy Outlook”, BloombergNEF, 2021.
[45] “China’s lithium-ion battery output surges in 2021”, Xinhua, 27 February 2022, at http://english.www.gov.cn/archive/statistics/202202/27/content_WS621b6715c6d09c94e48a58a4.html
[46] ”China’s Clean Energy Dominance May Face Challenge in Batteries”, Bloomberg News, 17 February 2022, at https://www.bloomberg.com/news/articles/2022-02-17/china-s-clean-energy-dominance-may-face-challenge-in-batteries
[47] “China to slash costs of energy-storage systems for industry to leapfrog the world by 2030, according to five-year plan”, South China Morning Post (SCMP), 24 February 2022, at https://www.scmp.com/business/article/3168078/climate-change-china-slash-costs-energy-storage-systems-industry-leapfrog
[48] Thielmann, Axel, et al. ”Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[49] Thielmann, Axel, et al. ”Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[50] Thielmann, Axel, et al. ”Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[51] Thielmann, Axel, et al. ”Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[52] “e-Zinc Signs Pilot Project Deal with Toyota Tsusho Canada Inc.“, Yahoo! Finance, 1 June 2022, at https://finance.yahoo.com/news/e-zinc-signs-pilot-project-130000579.html
[53] Ryan Kennedy, “Multi-day iron-air batteries reach commercialization“, pv magazine, 5 August 2021, at https://www.pv-magazine.com/2021/08/05/multi-day-iron-air-batteries-reach-commercialization/
[54] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[55] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[56] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[57] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[58] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[59] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[60] Andy Colthorpe, “Coal-dependent Mongolia’s first solar-plus-storage project will use NGK’s sodium sulfur batteries”, Energy Storage News, 25 March 2021, at https://www.energy-storage.news/coal-dependent-mongolias-first-solar-plus-storage-project-will-use-ngks-sodium-sulfur-batteries/
[61] Cameron Murray, “ROUNDUP: California VRFB microgrid trial complete, Acciona tries zinc-bromide batteries, Lithium-sulfur startup Zeta nets US$23m financing”, Energy Storage News, 7 February 2022, at https://www.energy-storage.news/roundup-california-vrfb-microgrid-trial-complete-acciona-tries-zinc-bromide-batteries-lithium-sulfur-startup-zeta-nets-us23m-financing/
[62] Andy Colthorpe, “Coal-dependent Mongolia’s first solar-plus-storage project will use NGK’s sodium sulfur batteries”, Energy Storage News, 25 March 2021, at https://www.energy-storage.news/coal-dependent-mongolias-first-solar-plus-storage-project-will-use-ngks-sodium-sulfur-batteries/
[63] “Battery innovation roadmap 2030”, EUROBAT, 2020.
[64] “Battery innovation roadmap 2030”, EUROBAT, 2020.
[65] “Battery innovation roadmap 2030”, EUROBAT, 2020.
[66] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[67] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[68] Shi Xue Dou, “The Smart Sodium Storage Solution (S4) Project – Final Project Report“, The University of Wollongong, 2022, at https://arena.gov.au/assets/2022/07/smart-sodium-storage-system-final-report.pdf
[69] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[70] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[71] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[72] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[73] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)”, Frauenhofer ISI, 2017.
[74] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)“, Frauenhofer ISI, 2017.
[75] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)“, Frauenhofer ISI, 2017.
[76] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)“, Frauenhofer ISI, 2017.
[77] Thielmann, Axel, et al. “Energiespeicher-Roadmap (Update 2017)“, Frauenhofer ISI, 2017.

---

[78] Paul Dvorak, “Advanced lead-carbon (PbC) battery sports advantages for grid stability“, Windpower Engineering & Development, at https://www.windpowerengineering.com/advanced-lead-carbon-pbc-battery-sports-advantages-grid-stability/

[lxxix] Vecchi, Andrea, et al. “Carnot Battery development: A review on system performance, applications and commercial state-of-the-art.”, Journal of Energy Storage, 2022.

[lxxx] Vecchi, Andrea, et al. “Carnot Battery development: A review on system performance, applications and commercial state-of-the-art.”, Journal of Energy Storage, 2022.

[lxxxi] Geyer, D. D. M., et al. “Repurposing of Existing Coal-Fired Power Plants into Thermal Storage Plants for Renewable Power in Chile. ”, Bonn, Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), 2020.

[lxxxii] Vecchi, Andrea, et al. “Carnot Battery development: A review on system performance, applications and commercial state-of-the-art.”, Journal of Energy Storage, 2022.

[lxxxiii] “Energy storage - Recharging the energy transition”, Siemens Gamesa, accessed on November 3, 2022 at https://www.siemensgamesa.com/en-int/explore/innovations/energy-storage-on-the-rise

[lxxxiv] Vecchi, Andrea, et al. “Carnot Battery development: A review on system performance, applications and commercial state-of-the-art.”, Journal of Energy Storage, 2022.

[lxxxv] Vecchi, Andrea, et al. “Carnot Battery development: A review on system performance, applications and commercial state-of-the-art.”, Journal of Energy Storage, 2022.

[lxxxvi] “Energy storage - Recharging the energy transition”, Siemens Gamesa, accessed on November 3, 2022 at https://www.siemensgamesa.com/en-int/explore/innovations/energy-storage-on-the-rise

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