Storing energy: A major building block for our energy future

White paper

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Intro

Our energy world is changing – fast. We face a global push towards decarbonization. The share of renewables is rapidly increasing, leading to a fluctuating power supply. Power generation is more and more decentralized. At the same time, energy demand keeps increasing, requiring a steady and uninterrupted supply of energy. To master these challenges, we need to create new energy systems that can reach the goal of creating a global, carbon-neutral economy by the middle of the century.

To reach this goal, we need flexible, net-zero energy systems that enable sector coupling with new ways of generating, storing, and using energy. Renewable power plays a central role in this regard, since it can be transferred to all energy consuming sectors (as heat, electricity, or e-fuel), be it buildings, mobility, industry, or agriculture. In turn, there won't be any need to burn fossil fuels, meaning these sectors will also decarbonize.

For this vision to become reality, various building blocks must be in place. The generation of renewable energy (especially via PV and wind) still must increase significantly; intelligent, data-driven tools capable of managing a decentralized energy system have to be rolled out; current fossil power plants either need to be phased out or, in the meantime, be converted to more efficient low-emission plants; and hydrogen production must become more affordable. And while all this may seem like a tall order, the fact is these building blocks are necessary for

fighting climate change while ensuring affordable and reliable energy for everybody. The world is already moving in this direction – admittedly at different speeds in various places, but the direction is unmistakable.

Arguably the most important element of this vision will be energy storage, allowing steady energy flow, grid stability, and 24/7 availability of renewable power. Storage systems help build the new energy world. Specifically, **batteries** play an important role today and into the future, as they allow the balancing of load differences, provide peak capacity and ancillary services to the grid, make (micro) grids smarter – and, as an additional benefit, they enable carbon-free black-start capabilities. Additionally, **rotating grid stabilizers (RGS)** support grid stability by replacing system inertia of conventional power generation units. Furthermore, **thermal energy** storage systems capture heat produced by renewable energy or from waste heat or exhaust gas. They can be used for district heating, to decarbonize industrial heat systems, or to unlock large capacities for firming renewable power output. Finally, **green hydrogen** will enable long-term (e.g. seasonal, island, remote) storage that, in combination with other storage solutions, allows the efficient coupling of all sectors of the economy. So, simply put, without energy storage systems, the future we all strive for will not come about.

In this paper, we'll give an overview of energy storage systems and outline the priorities lying ahead of us for creating our energy future. We'll show what they can do today, what their potential is for the future, and which hurdles may still need to be addressed. Although there are certainly challenges, the path ahead is clear – energy storage will be the central element for making our economy flexible, resilient, and reliable while keeping it sustainable and carbon-free.

"Energy storage will be essential for the transition to a decarbonised economy based on renewable energy sources. As electricity generated by wind or solar energy is not always available in the quantities needed, we will need to store more. Apart from technologies that we already know work well like pumped hydro storage, a number of technologies will play a crucial role in the future, such as new battery technologies, thermal storage or green hydrogen. These must be given market access to ensure a constant energy supply for European citizens."[1]

Claudia Gamon
Member of the European Parliament

1 European Parliament (2020): Boost energy storage in EU to help spur decarbonisation [Website 'News European Parliament'; press release].

Today: Stability is key

Today, utilities, transmission system operators, and industries confront a variety of challenges. Regardless of their location and varying demands, they face social pressure to decarbonize while at the same time, risk ruining their reputations if they appear to be acting too slowly. As long as they emit CO_2, they sometimes pay a high price for it. And once energy utilities close down fossil-fired power plants, they'll need to manage stranded assets.

At the same time, with the increasing share of renewables, another challenge arises: the need for stability – of the grid, energy prices, and the flow of energy. As renewables fluctuate, energy prices tend to be more volatile, while operators are challenged to cost-efficiently match energy supply and demand and ensure grid stability. That's why energy producers respond to a downturn in renewable supply by relying on fossil-fired power plants. And if there is more renewable power than needed, they may have to curtail output, thereby wasting valuable green energy when demand is fully met.

So, what can you do? While today's energy producers respond to grid fluctuations by primarily relying on fossil-fired power plants, energy storage solutions will take on a dominant role in fulfilling this need in the future. That's why today, battery storage systems are being used more and more as an efficient way of supplying and consuming power when needed. Likewise, using pumped storage hydropower is highly beneficial, as it provides the additional advantage of rebuilding the power grid in the event of a systemwide blackout. Additionally, rotating grid stabilizers are being used to ensure grid stability, and supercapacitors will enable power dispatch within milliseconds to counter frequency changes.

Battery energy storage systems

Batteries that store energy in the form of chemical energy are a rather mature technology. Currently, they are the top choice when it comes to storing green energy for balancing load differences in the grid. While they continue to be improved, they economically solve a variety of issues that arise when trying to decarbonize. Batteries support carbon-free energy production, as they address the volatility of renewable energy sources by storing energy when it's available in abundance and providing it when there's a shortage.

Batteries are also flexible, as they allow fast supply of energy when needed. They're also plannable and reliable. Additionally, batteries help power producers avoid curtailment, which is mostly an involuntary

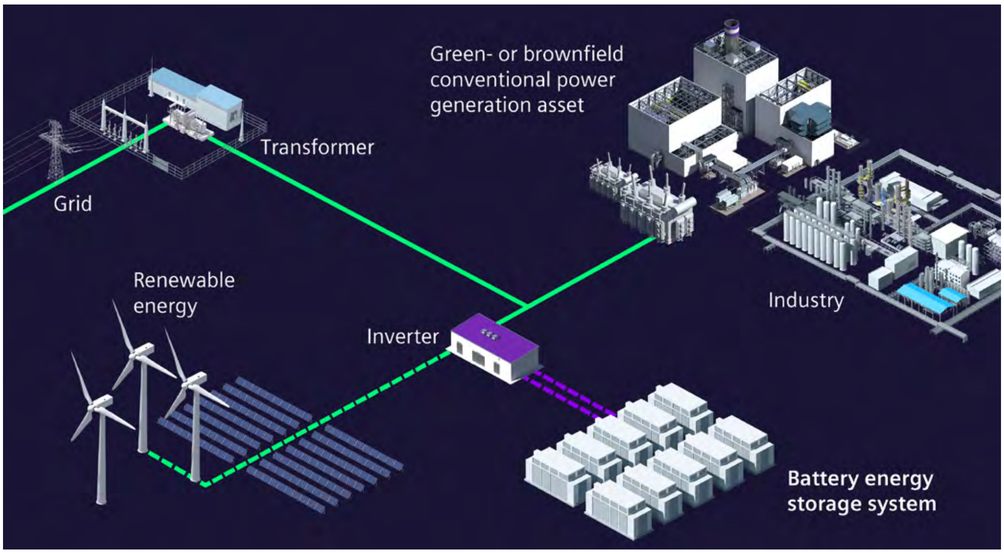


Fig. 1: Batteries support carbon-free energy production, as they address the volatility of renewable energy sources by storing energy when it's available in abundance and providing it when there's a shortage.

Fig. 2: For industrial assets batteries enable electrical peak shaving by supplying electricity demand during peak hours.

reduction of energy output. So, when considering energy storage solutions today and as part of any future scenario, batteries address common concerns on the road to decarbonization.

As mentioned above, battery storage is already being used as an efficient method of supplying power when needed. For example, large offshore vessels and drilling platforms employ it not only to minimize the use of diesel generators, but also reduce CO_2 and NO_x-emissions. In combination with rotating grid stabilizers, batteries are being used to ensure grid stability and support frequency regulation, thereby meeting demands of an energy market driven by renewables. In power plants, batteries enable "black-starts" which render CO_2-producing diesel engines obsolete. Batteries are also directly connected to the grid as standalone solutions so they can help with fluctuating power supply and demand as well as provide peak power. Moreover, combining renewables, such as wind farms with battery storage, can help manage power depending on current needs. So, unsurprisingly, battery usage keeps increasing in today's energy world. And as their production cost steadily continues to decrease, their storage capacity continues to increase.

However, we haven't unlocked the full potential of batteries yet. In the coming years, batteries will be able to help virtually expand grids (by providing and consuming electricity) and managing grid congestion. That, in turn, allows companies to flexibly handle the increase in energy demand. For industrial assets, batteries will enable electrical peak shaving by supplying electricity demand during peak hours. And they also make energy arbitrage feasible – storing energy when it is cheap and selling it when prices are high. Finally, with decreasing technology costs, it will become even easier to integrate batteries as part of power plants.

However, some open questions remain. First, today's batteries have limited capacity, meaning they can only store enough energy to provide power for a few hours, and they degrade over time. Second, the continued use of rare elements in battery production raises environmental issues and concerns over the dependency on countries supplying them. Nevertheless, through continued research and development, rare elements should become less significant. And this goes along with the importance of finding sustainable ways for either reusing or recycling batteries as well as developing new battery concepts, such as metal-free flow batteries that may achieve longer discharge periods. Overall, batteries are one option among many, and the potential shortcomings of one solution are easily matched by others, such as rotating grid stabilizers, thermal, mechanical, or hydrogen storage.

Pumped hydro

Globally the most widely deployed bulk energy storage solution, pumped hydro is one of the most mature and proven technologies, as hydro power has been used for millennia. It is based on a simple law of nature: gravity. When there is an energy surplus, water is pumped from a lower, often artificially constructed reservoir uphill to

Fig. 3: Globally the most widely deployed bulk energy storage solution, pumped hydro is one of the most mature and proven technologies. It is based on a simple law of nature: gravity.

another reservoir. Then when needed, water is allowed to flow downhill again through turbines, thereby creating energy. Pumped hydro systems are also capable of supplying reactive power when there is an imbalance in the grid, thus decreasing the risk of black-outs.

Pumped hydro is cost-efficient and climate neutral and allows for long-term storage on a very large scale – no other storage solution comes close. Especially in countries with a lot of hydro power, such as China, the US, Canada, Norway, and Austria, pumped hydro is a major force towards decarbonization, as it enables storing a large amount of energy (so-called high-capacity firming). If the asset is connected to the grid, pumped hydro can be used for frequency response when there is a power disturbance in the grid and its frequency needs to return to a stable level. Additionally, hydro power plants are easy to control and can provide flood protection and water supply for cities and industries. They are also highly efficient and have a long lifecycle of 50 to 100 years.

But as mature and widespread as the technology is, pumped hydro's potential has not yet been exhausted. Globally, there are many locations available for new, large, pumped hydro power plants, although the environmental impact and public opinion of such an undertaking requires careful consideration. Additionally, larger initial investment is necessary, but this pays off in long-term, low-risk returns down the line.

Finally, smaller pumped hydro plants are possible even in regions that have highly developed energy infrastructures. Very small pumped hydro plants can be an option for hybrid installations, for example, in connection with wind or solar power; or by pooling several small plants in order to form a virtual power plant, enabling them to participate in the capacity market.

Rotating grid stabilizers

As the need for power from renewable sources increases, fluctuating power is not the only concern for power generation. Another important challenge is that with less conventional synchronous power generation, grid frequency is getting more sensitive due to the reduced number of rotating machines. Grid operators are already faced with the challenge of providing sufficient system inertia of synchronous generators with high rotating masses to avoid black-outs due to fast frequency and voltage drops.

Fig. 4: A rotating grid stabilizer (RGS) provides additional system inertia and short circuit power to the grid.

A rotating grid stabilizer (RGS) solves this challenge by providing additional system inertia and short circuit power to the grid; RSGs are used at critical grid locations worldwide today. A typical RGS system consists of a synchronous condenser and a flywheel. The flywheel stores energy as rotational energy. As soon as the grid frequency drops, the flywheel responds, resulting in balanced and more stable grid frequency. The task of the synchronous condenser is to connect the flywheel to the electric grid, thus helping to stabilize the grid. The main differentiator to other energy storage systems is that RGSs are neither controlled by software nor humans. Based on their physical behavior, they automatically and inherently provide a system response that stabilizes the grid.

This way, RGSs also enable the grid to handle fluctuating renewable infeed. As they release no emissions, they are as environmentally sound as the energy that feeds them. And they are cost-efficient, as their lifetime ranges from about 30 to 40 years. Additionally, by replacing the system inertia that is currently being supplied by fossil power plants, RGSs enable a share of renewables of up to 100 percent. Another benefit they provide is the repurposing of conventional power plants, which might otherwise be phased out by reusing their infrastructure (generator, grid connection, etc.) and providing these assets a second life.

Supercapacitors

Supercapacitors are similar in functionality to rotating grid stabilizers, but their integration is based on power electronics, and they actively contribute to stabilizing the grid in times of sudden disturbances. Compared to batteries, supercapacitors have a relatively low energy but high-power density, which allows them to be charged and discharged much faster than batteries. And supercapacitors are economical – thanks to their low losses, small footprint requirements and easy maintenance, low lifetime expenditures can be achieved.

Supercapacitors also enable virtual grid expansion, storing as well as providing energy, and digitally emulate system inertia (the so-called grid forming control). Compared to rotating grid stabilizers, supercapacitors require less space. Another important feature is their relative operational flexibility. While rotating grid stabilizers are largely defined by their physical specifications, the operation of supercapacitor plants can easily be changed with a software update.

Today, supercapacitors are commonly used at wind and solar farms for instant and uninterrupted power supply. At wind farms, they are also used to adjust rotor blades, whereby this process requires high power within a short period of time. And while supercapacitors are still a fairly new technology when used as energy storage for power generation and grid stability, they offer great benefits, specifically in times of short power fluctuations. In such situations, they can immediately supply the energy needed in the quantity needed with the help of capacitors, thus preventing a power failure and large-scale blackouts. However, as good as all of this sounds, one needs to keep in mind that supercapacitors are still a fairly new technology that does not yet have major demonstration projects in the field.

Fig. 5: Supercapacitors actively contribute to stabilizing the grid in times of sudden disturbances.

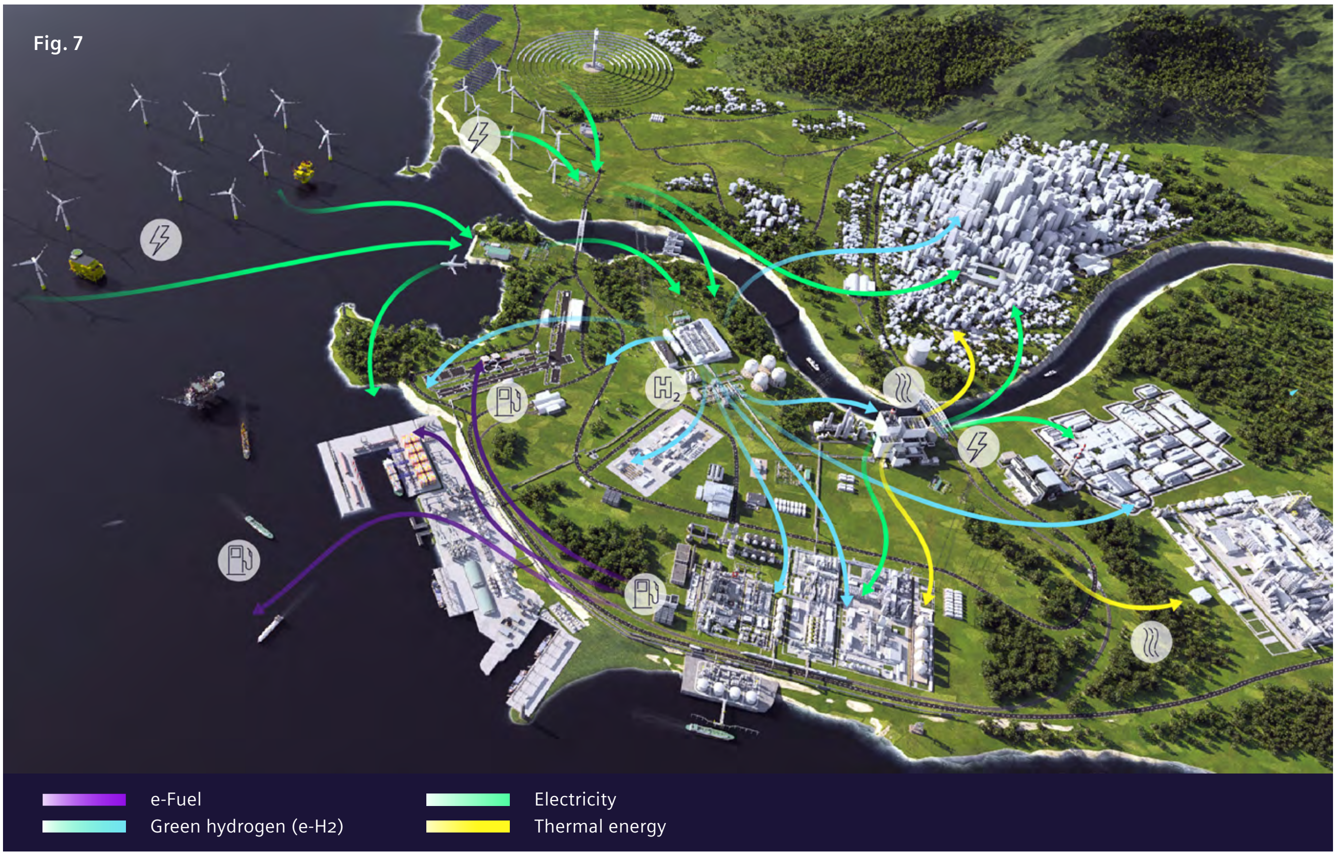
Tomorrow: Sector coupling accelerates

As we look 5 to 10 years ahead, we will see the benefits of sector coupling at a local and regional level. For example, power-to-heat via heat pumps will open a new green concept for heating buildings, or even provide process heat for industry. At the same time, more storage solutions, such as compressed air energy storage (CAES) or thermal energy storage, will enter the market, each forming building blocks for a new energy system. Also, as the share of renewable energy continues to increase, sector coupling offers further opportunities to replace fossil fuels by enabling e-mobility.

Even more than today, we will also see governments push sector coupling through legal frameworks, ensuring that countries are heading towards a carbon-free economy. The consequence: permits for plants using fossil fuels will become difficult or even impossible to obtain. This also implies that more reliable power from the grid is removed, thereby increasing the need for longer storage durations. At the same time, governments will offer subsidies ensuring all relevant players are supported on this path.

Fig. 6: Thermal energy storage can make use of heat produced by renewable energy, ranging in discharge duration from mid-term to long-term storage.

Fig. 7



Thermal energy storage

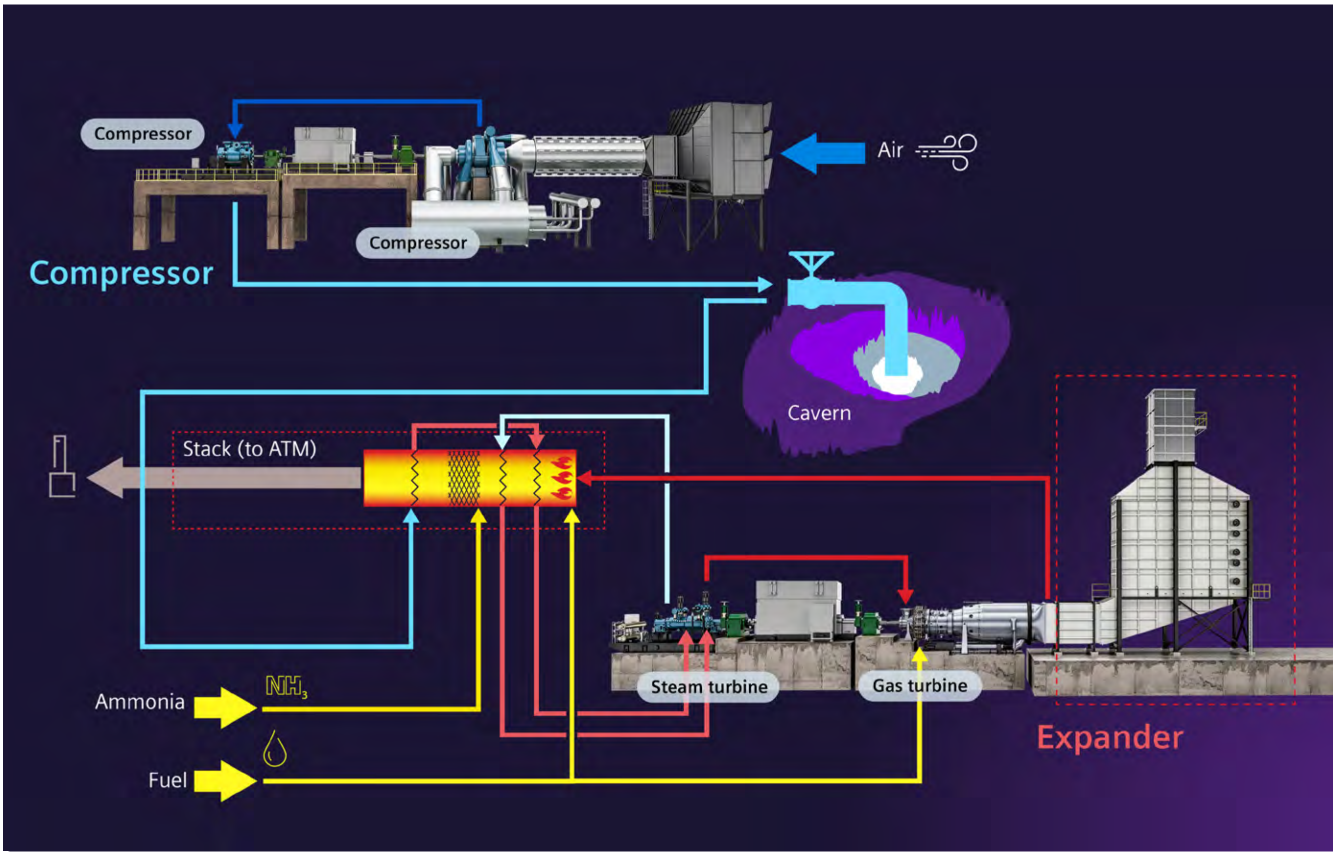
Thermal energy storage supports decarbonization by handling another important building block to a future energy system: heat. It makes use of heat produced by renewable energy or captured from waste heat or exhaust gas, ranging in discharge duration from mid-term to long-term storage. It improves a plant's efficiency by helping to reduce cost and improve the energy yield. A great variety of mediums can be used, such as liquid salt, stone, sand, steam, gases, ceramics, or pressured hot water – all of which are hardly environmentally harmful. It allows to feed thermal energy across sectors back into various processes and make them more flexible, including heating as well as cooling applications, for buildings or industrial processes. Renewable electricity can be fed into thermal storage via resistive heating, which helps decarbonize heat production as well as balance availability and demand for thermal energy. So the potential is undoubtedly great, as heating is, for example, Europe's largest energy consumer that use more energy than mobility or electricity sectors.

Mechanical energy storage

Next to pumped hydro, compressed air energy storage (CAES) is another mechanical storage solution that offers a reliable, cost-effective, and long-duration energy underground storage solution at grid scale. It's especially attractive in areas where geography does not support pumped hydro.

The idea of using compressed air for power plants is not new. Today, there are two power plants in operation using compressed air to store energy in salt caverns when demand is low, and reusing it when demand is high. One of these plants was completed in Huntorf, Germany in 1969, the other in McIntosh, Alabama in 1991, which Siemens Energy helped build. There, stored compressed air is turned into electricity by co-firing it with natural gas and / or hydrogen and combusting it in a turbine. The more green hydrogen or other green fuels are used in this process, the more CO_2-emissions are reduced even further. And in case you're wondering why CAES for power plants hasn't been used more widely so far, it's simply because the demand for longer storage durations just isn't there yet. But that's changing.

Fig. 8: CAES storage units dissipate part of the compression heat into the atmosphere with intercoolers. The air must be reheated before it is returned to the CAES cycle.



In future power plants, CAES-solutions can use electric motor driven compressors to capture the excess energy generated by renewables by storing the compressed air underground. Then, during hours of higher grid demand, the compressed air is withdrawn from storage, heated, and routed to expansion turbines to generate electricity. This allows operators to engage in energy arbitrage – storing energy when prices are low, selling it when prices are high. Grid-scale CAES can also store energy long-term, thereby ensuring the availability of a firm energy resource, which can be dispatched as needed to meet system demand as well as provide grid support services, such as regulation, spinning reserves, and transmission optimization.

Finally, compressed air storage is an attractive solution for industrial applications requiring compressed air, such as drilling or cleaning, thereby eliminating the need for transforming mechanical energy back into electricity.

Thermo-mechanical energy storage

Thermo-mechanical storage combines the technology of heat storage and mechanical energy storage, enabling both the discharge of electricity (primary use case) and heat (secondary use case) depending on one's needs, be it power generation, district heating or industry applications. Three prominent examples are liquid air energy storage (LAES), pumped heat energy storage (PHES), and adiabatic compressed air energy storage (A-CAES). All three are well suited for bulk energy storage, as they are geographically not constrained as pumped hydro. They also have a long lifecycle, as all the components are well tested and known to be very durable. And as they combine the advantages of both thermal and mechanical energy storage technologies, it enables a variety of applications, such as re-electrification or supplying process heat.

Fig. 9: The expansion and compressor train of a compressed air energy storage (CAES).

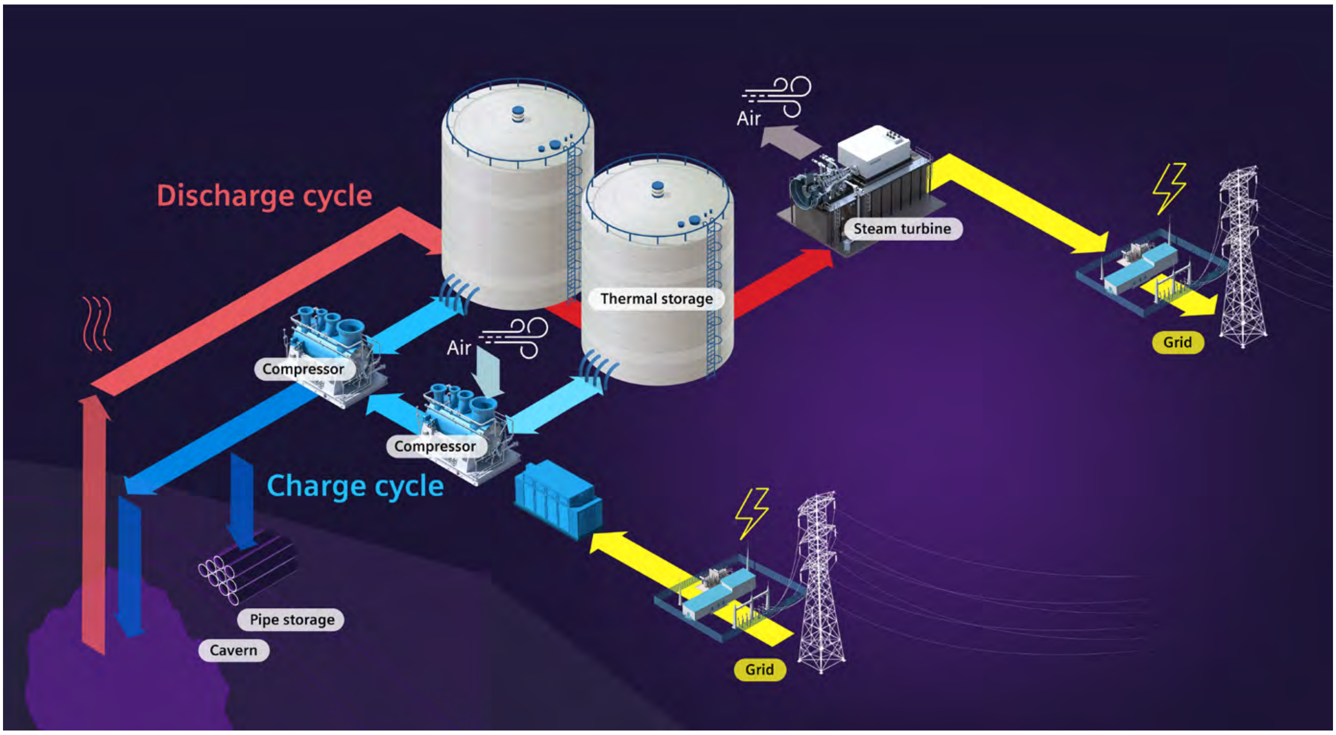
Liquid Air Energy Storage works by compressing and cooling air repeatedly, so that when air is expanded again in an insulated container, it cools down even more and enters a liquid state. It has a relatively high energy density – about 10 to 20 times as high as compressed air energy storage. By reversing these steps, the stored energy and cold air can be used in the context of both industrial applications and power generation. Pumped heat energy storage uses both electricity and heat pumps to store thermal energy in tanks with warm and cold materials. When needed, the stored energy can be used to produce electricity or as heat / cold for industrial applications. Adiabatic compressed air storage stores heat created during the compression and enables reusing it once the air is released. The advantage: no natural gas needs to be used to heat up the released air, thereby reducing CO_2-emissions.

In the context of renewable power plants, all three can help prevent curtailment, and thereby support decarbonization. Also the materials used for these solutions are non-toxic and not harmful to the environment. However, the technologies are not completely mature. The ongoing development of various components shows promise of improving performance and lowering costs.

Finally, one other variety of thermal-mechanical energy storage needs to be mentioned – storage systems that store and release heat for the purpose of driving mechanical systems, namely steam turbines for electricity generation. For example, in case of concentrated solar power plants, surplus thermal energy can be stored, e.g., in salt tanks. Likewise, surplus electricity, e.g., from wind, can be turned into green thermal energy by using resistive heating. The stored thermal energy can then be turned back into electricity with the help of a steam turbine. This configuration helps prevent curtailment, improve grid stability, and decouple heat from electricity generation.

This technology is already being used, for example, in two concentrated solar power plants in the Granada area in Spain, each having a power output of around 50 MW. Although thermal storage is a proven technology, it will have to compete with other technologies, such as batteries, pumped hydro, or compressed air storage.

Fig. 10: Adiabatic CAES cycle stores energy in the form of pressurized air in a cavern, while compression heat is stored in a thermal storage. For re-electrification, both forms of energy are being utilized.



Outlook on a CO_2 free economy

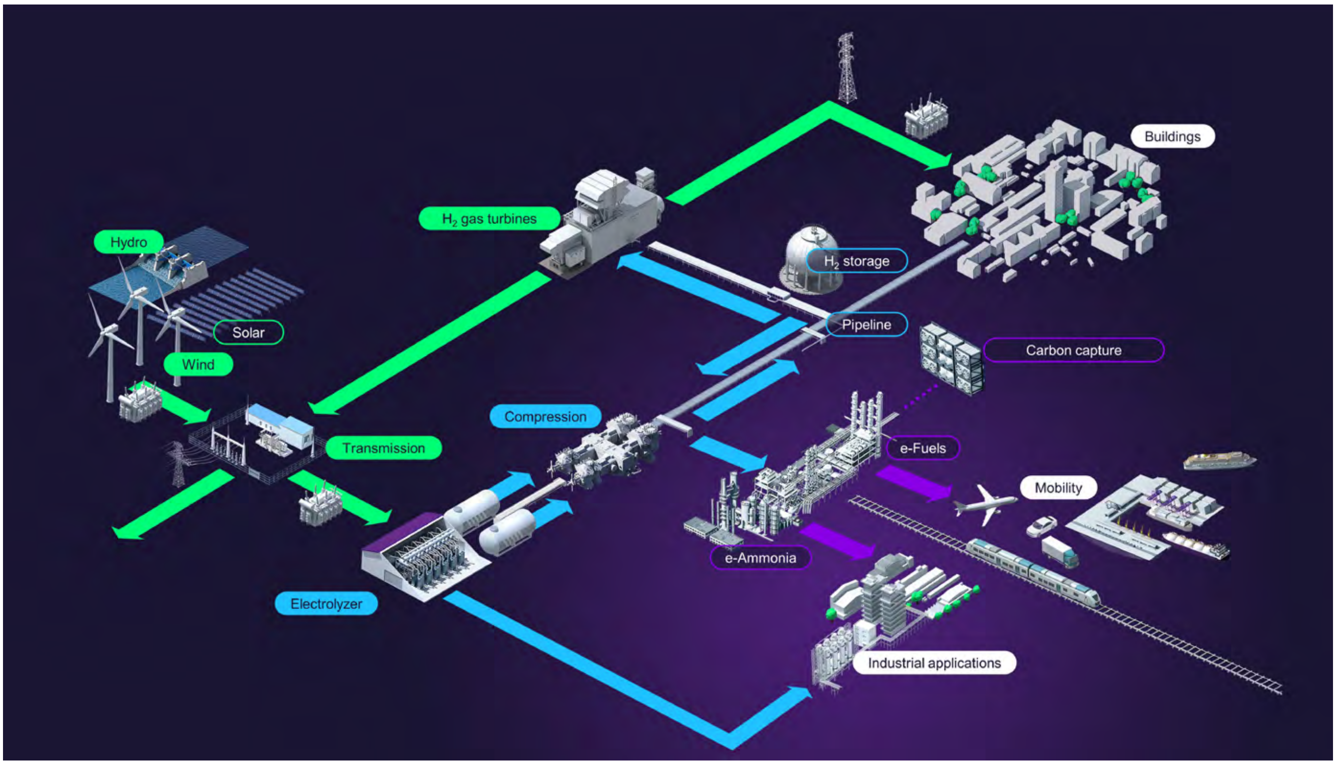
Twenty years from now, with the share of renewables continuously rising and ultimately reaching 100% of energy generation, utilities, transmission companies and industry will be able to create a CO_2-free economy. In order to achieve this goal, power plants, as we know them, will have become hybrid plants, laying the foundation for the new energy economy. They will include 100% green gas turbines that ensure steady energy flow, thermal storage, heat pumps for district heating, and electrolyzers for producing hydrogen. Batteries and thermo-mechanical storage for producing green electricity will also be part of the mix. And especially hydrogen will enable long-term energy storage in addition to producing feedstock for synthetic fuels, such as methanol, combustible fuel for heat, or CO_2-free metal production.

Positive consequences: There would no longer be any need to curtail energy, as utilities can capture excess renewable energy by storing it in the form of hydrogen or use long-term storage for seasonal balancing to address a mismatch of supply and demand. And as it enables transferring energy to all consuming sectors of the economy having integrated energy storage systems, be it buildings, mobility, industry, or agriculture, the entire economy is being decarbonized.

Hydrogen storage

There is no shortage of hydrogen – it is the most common element on earth. And because it is very reactive, hydrogen is bound in other molecules, mostly in the shape of water, H_2O. Currently, around 70–100 million tons of hydrogen are produced globally every year mostly from steam methane reforming or autothermal reforming. About half of this hydrogen is used to synthesize ammonia, which in turn forms the basis for urea, ammonia

Fig. 11: Sector coupling: Storing large quantities of hydrogen underground or in tanks allows one not only to store fluctuating renewable energy, but also to use it for various sectors of the economy.



phosphate, and other chemicals. Hydrogen is also used in refineries for hydrocarbon cracking. In the food industry, hydrogen is used, e. g., for fat hardening.

However, steam reforming is not entirely green, as it emits CO_2: When steam reacts with natural gas, it produces synthetic gas or syngas, a mixture of hydrogen and carbon monoxide. CO is shifted to CO_2, which is usually emitted to the atmosphere. But if CO_2 is sequestered, hydrogen can be produced with minimal CO_2 emissions. In comparison, the generation of green hydrogen via electrolysis of water with electrical energy from renewable sources is completely free of CO_2 emissions right from the beginning.

Green hydrogen forms an excellent long-term energy storage, and in the future, it will enable seasonal power-to-power storage on a large scale. By using H_2-capable gas turbines, engines, and / or fuel cells, re-electrification helps secure electricity supply in periods of low renewable energy supply, e. g., due to lack of wind.

Compared to all the other storage solutions mentioned before, it also enables several other applications. It can be used directly as fuel for mobility or as a feedstock for various industries. Via synthesis with carbon dioxide (from biogenic and unavoidable industrial emissions or direct air capture), it can be converted into synthetic, sustainable e-fuels, such as e-methanol, e-ammonia, e-diesel, e-jet fuel, or other carbon-based chemicals.

That’s not to say there aren’t challenges. One major challenge is the current lack of infrastructure for distributing and storing hydrogen. But this will change, as green hydrogen production becomes more economical and scalable. In a transition phase, we can use existing gas infrastructure, such as pipelines, gas stations, or caverns. Green hydrogen production, however, requires a massive expansion of renewable power generation capacity such as wind and solar, which ultimatively results in zero CO_2 emissions.

The potential is great. Storing large quantities of hydrogen or other synthetic liquids allows one not only to store fluctuating renewable energy, but also to use it for various sectors of the economy. We estimate that coupling via hydrogen has the potential of reducing primary fossil energy consumption by 50% even while power demand grows by 25%.[2] Despite given efficiency losses, it is the most economic long-term storage for renewable energy.

2 Power-to-X: The crucial business on the way to a carbon-free world. Siemens Energy White Paper, 2019.

So, what's holding us up?

In principle? Nothing, really. Today, the transition to a new decarbonized energy future is being set in motion. But we also have to recognize that the path to a decarbonized energy system is not a given either – it varies from country to country with a mix of technologies being used to meet emissions goals. Also, while we foresee no major technological hurdles, we still need research and development. And that also means it will take huge sums of investments for solutions benefitting everybody in the coming years and decades. We also need close cooperation between policy makers, the private sector, and companies for efficient as well as affordable energy solutions, including those for energy storage. And with the world embarking on a decarbonization journey, it's clear that a mix of complementary energy storage systems will be an essential part of it.

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