24/7 Clean Power

A Climate Technology White Paper

Mark Daly
Amanda Ahl
Yiyi Zhou

June 16, 2022

BloombergNEF

Table of contents

24/7 clean power: an introduction

Introduction

24/7 clean power

This paper outlines the key strategies for delivering 24/7 clean power. Specifically, we analyze technology innovations, and the early-stage companies developing them. It contains the following sections:

1. **New power capacity:** How can new forms of dispatchable power generation and energy storage reduce the cost of providing round-the-clock zero-emissions power? This section does not examine lithium-ion battery innovations. (pages 8-34)
2. **Power grid technology:** How can improvement in grid technology and demand-side power management reduce the overall cost of providing zero-emissions power? (pages 35-47)

This paper provides data and context on new technologies, evaluates proposed innovation in the field and suggests ways to overcome potential challenges. Innovation in new power supply and grid technologies is important. We highlight 59 startups that are working in the area.

BNEF Pioneers: hunting for innovation

This is one of three reports to be published following the 2022 BNEF Pioneers awards.

BloombergNEF's annual Pioneers competition identifies and recognizes innovators developing new technologies to tackle some of the most important challenges in the fight against climate change.

Each year, the Pioneers competition focuses on three innovation challenges.

For the 2022 program the challenges were:

1. Providing round-the-clock zero-emissions power (the focus of this research note)
2. Scaling long-term carbon removal (research note available here)
3. Decarbonizing aviation (research note available here)

For more information about the Pioneers competition, please visit https://about.bnef.com/bnefpioneers/

Why did BNEF choose 24/7 power as a challenge for this year's Pioneers?

Driving power sector emissions down to zero is essential to achieve a net-zero economy. The electrification of energy demand in all other sectors is only effective under the assumption that power sector emissions fall to zero.

A 2017 meta analysis of power sector models found that while creating a net-zero power system based solely on variable renewable power was possible, this would require a significant overbuild of capacity to ensure reliable power supply. Power systems based solely on variable renewables were several times more expensive than systems where 80% of power was supplied by variable renewables.

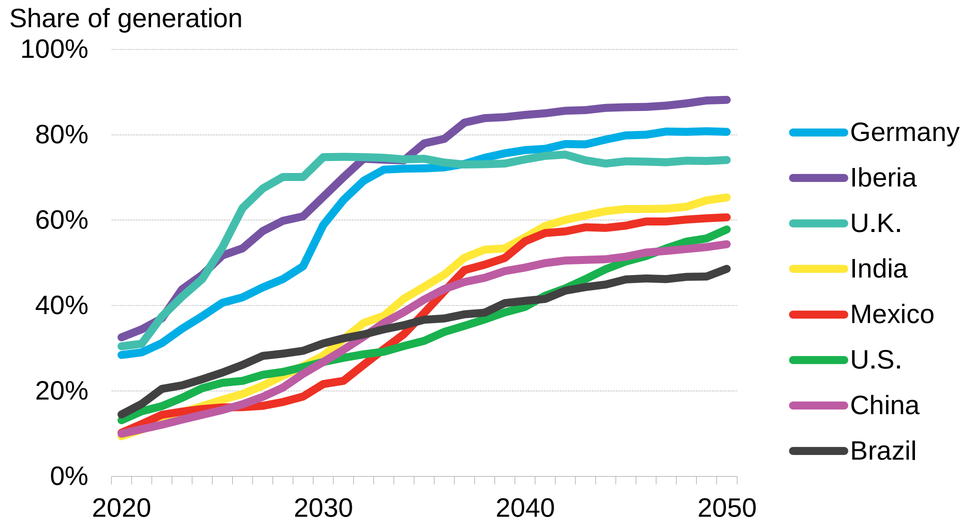
BNEF's power sector modeling estimates that wind and solar build maxes out at around 70-90% of generation. This occurs because variable renewable plants all begin to produce power at the same time, increasing fleet-wide curtailment, which in turn lowers capacity factors and weakens the economic case for each additional plant.

Novel technologies for energy storage, generating zero-carbon dispatchable power and making better use of variable renewable power supply, are therefore likely to be essential in bringing about a net-zero power system cost-effectively. A portfolio of novel resources will be more effective in decarbonizing the power system because:

- Different technologies have different cost structures, which means each technology can fill its own niche within the power system – operating with a generation profile that is optimal for its cost structure. For example, a hydrogen plant can provide peaking capacity while nuclear energy will likely provide baseload.
- A portfolio of resources prevents lock-in to a single technology, which may be more expensive than expected or have unexpected consequences

While the deployment of variable renewable resources is still accelerating, and will not reach saturation until at least the 2030s, it is imperative to invest in and develop next-generation power sector technologies now so that they are commercially viable by the time they are needed. Many of the technologies discussed in this report are unlikely to be deployed until 2030.

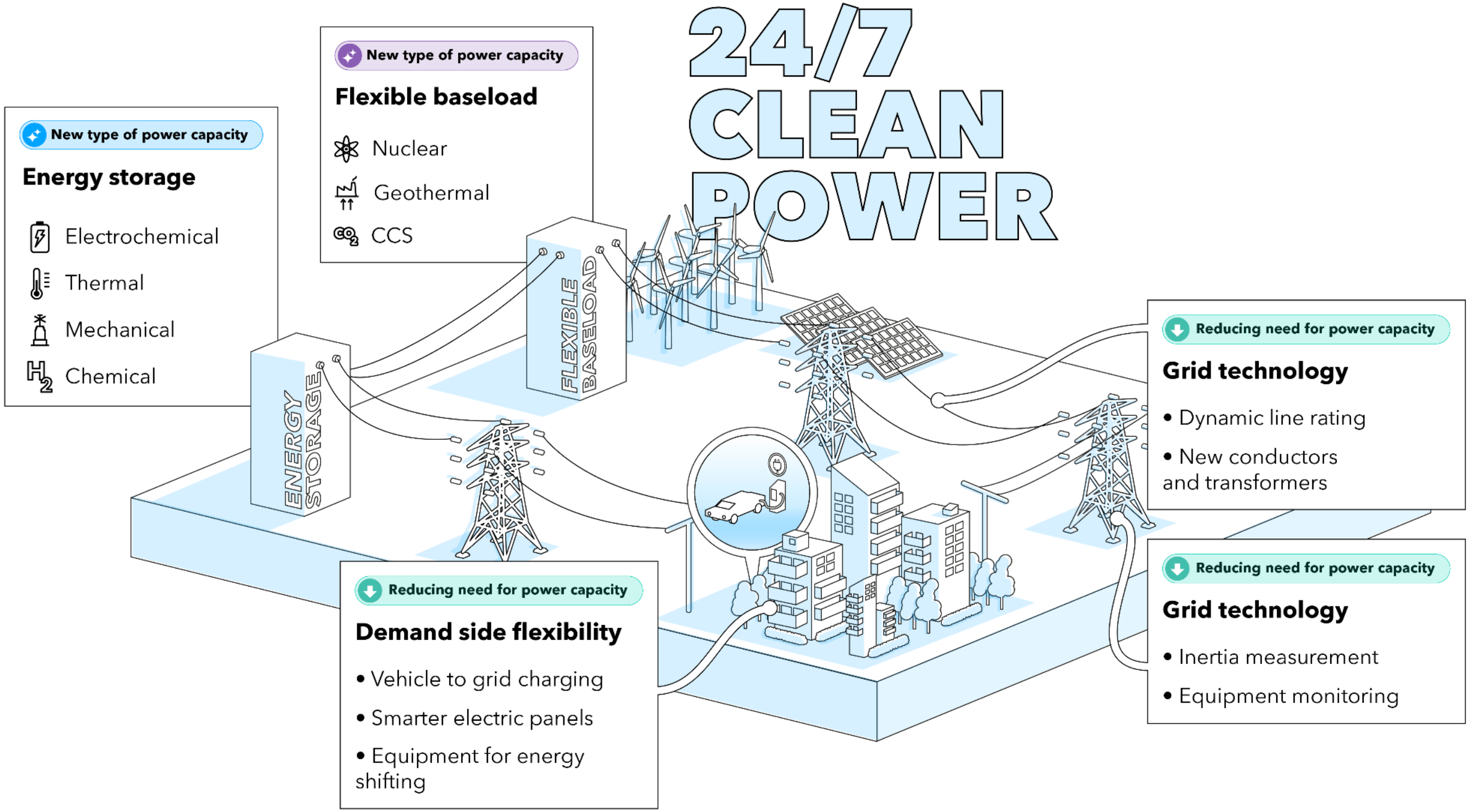
Share of generation by solar and wind in BNEF's New Energy Outlook 2020



Source: BloombergNEF Note: Projections as per BNEF's Economic Transition Scenario where changes are driven by techno-economic trends and market forces.

BloombergNEF

Overview of technologies covered in this note



Source: BloombergNEF Note: CCS is carbon capture and storage

Innovation map of 24/7 clean power technologies

New power capacity

Flexible baseload

Nuclear
- Fission: NuScale, Kairos Power
- Fusion: Commonwealth Fusion Systems, tae Technologies

Geothermal
- Closed-loop: Eavor, GreenFire Energy
- EGS and SHR: Fervo Energy, AltaRock
- Drilling: HydroVolve, Hyper Sciences, Quaise

Post-combustion carbon capture
- MTR Membrane Technology & Research, ION Clean Energy, Svante, Chart, carbon clean

Supercritical CO_2 turbines
- Indirect: Echogen power systems, gti, Heliogen
- Direct: Linde, NetPower

Energy storage

Mechanical energy storage
- Gravity: Energy Vault, gravitricity
- Compressed-air: Cheesecake Energy, Hydrostor
- Novel pumped hydro: RheEnergise, Quidnet Energy

Chemical energy storage
- IHI, Siemens, Monash University, Mitsubishi

Electrochemical energy storage
- Flow batteries: Primus Power, ESS Inc
- Abundant materials: eos, Form energy

Thermal energy storage
- Sensible thermal: Malta, Vast Solar
- Latent: liquid air: Highview Power, Energy Dome

Power grid technology

Power-flow optimization
- Managing inertia: reactive technologies, Skeleton Technologies, Synvertec
- Modeling power flow: Ampacimon, LineVision, newgrid
- Controling power flow: Smart Wires, Switched Source

Distributed energy resource integration
- EV charging: Nuvve, ev.energy, WiTricity
- DER software: AutoGrid, LO3 Energy, Blue Frontier, OhmConnect
- Smart panels: Span, Atom Power

Next-generation components
- New line materials: TS Conductor, VEIR, AssetCool
- Advanced switches: menlo micro

Source: BloombergNEF. Note: EGS is enhanced geothermal systems. SHR is superhot rock. DER is distributed energy resources.

BNEF Pioneers 2022 winners

Challenge 1: Providing round-the-clock zero-emissions power

Energy Dome has invented a CO_2 battery to make long-duration energy storage an economically viable proposition.

Kairos Power has developed a novel advanced nuclear reactor technology to complement renewable energy sources.

Reactive Technologies helps grid operators, electric utilities, and regulators to measure grid inertia more accurately.

Nuvve offers a vehicle-to-grid (V2G) technology to manage power flow between EV batteries and the grid.

For more information on this year's winners please see *Climate-Tech Startups to Watch in 2022: BNEF Pioneers Winners*

New power capacity

New power capacity technologies

A power system composed solely of variable renewables would be extremely expensive compared with deploying renewables and dispatchable power such as nuclear, geothermal, CCS and long-duration storage. However, these resources are currently expensive and innovation will be needed to help drive down costs, encourage deployment and create a low-cost zero-carbon power system.

What do we need?

In a power system where a significant share of generation is intermittent, dispatchable technologies are needed to make up the gap when intermittent technologies do not produce. Power modeling studies have shown that a range of technology options differing in cost structure will deliver the least-cost power system.

This is because different cost structures mean it makes sense to run technologies with different generation profiles. It is more economic to run high-capex, low-opex plants (e.g. nuclear) as baseload at very high capacity factors. These baseload technologies, however, would be extremely expensive to use for peaking. On the other hand, it would also be expensive to run low-capex, high-opex (e.g. hydrogen turbines) at high capacity factors. This technology would much more likely fill the role of peaking capacity. Peaking capacity and baseload will be able to deliver a lower cost power system deployed together rather than alone.

What should we tackle first?

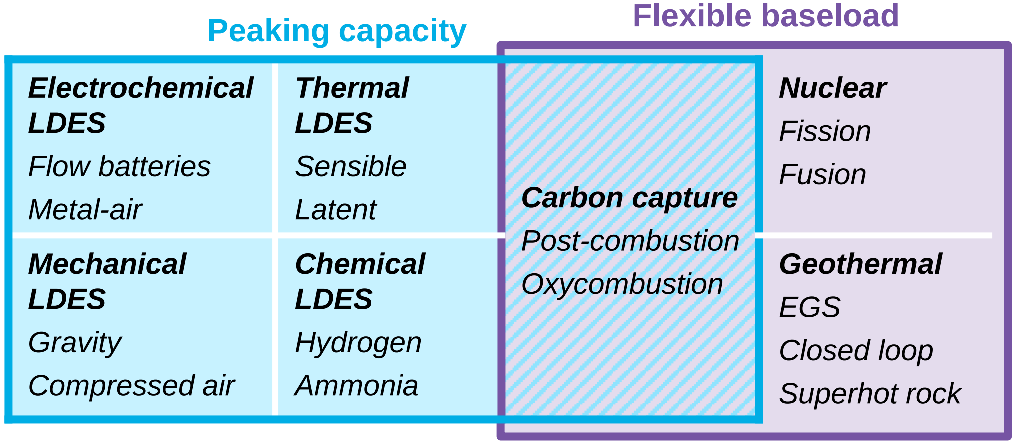
Technologies that can generate profits in a near-term power system will be easier to scale in the next decade. Storage technologies that target the 4-12 hours duration market could outcompete lithium-ion batteries on cost. Whereas systems with 100+hours of storage will not be necessary for 15-20 years and will struggle to scale without policy support.

Technologies that decouple energy supply from international commodity markets (e.g. geothermal, mechanical and thermal storage) could also see near-term significant uptake as they improve energy security in a time where this is increasingly salient.

Why is it hard?

It will take many technologies discussed in this section more than a decade to reach their cost targets. Chemical energy storage relies on cheap hydrogen. Nuclear fusion has yet to produce more energy than it consumes. Even at scale, many of these technologies' cost targets do not compete with the levelized cost of electricity provided by solar and wind. While they carry a cost premium, they produce dispatchable power. There is no mechanism today, however, for them to be financially rewarded for this dispatchability. Capacity markets – which pay power plants for their availability – usually only reward up to four-hours of power output, a duration that can already be economically delivered with li-ion batteries, a mature technology.

The role of dispatchable generation technologies in a zero-carbon power system



Source: BloombergNEF. Note: LDES stands for long-duration energy storage (i.e. energy storage with an output duration of more than 4 hours). This note does not explore innovation in lithium-ion batteries.

Nuclear energy

Nuclear power is already a reliable and zero-carbon source of power but concerns around its cost and safety have caused the industry to stagnate. A new class of fission reactors hopes to cut costs by redesigning systems so that expensive elements of traditional plants, like huge concrete containment units, are no longer needed. Simultaneously, private capital has started to pour into nuclear fusion startups, as development expands beyond the confines of large-scale government-funded programs. Regardless of technological progress, the nuclear industry faces huge barriers to deployment. The earliest these new technologies will reach the market is 2030. They will all need to deal with social reluctance to deploy novel nuclear technologies and surpass stringent regulatory barriers.

New approaches and technologies

Making reactors smaller: One approach to advanced nuclear is to simply make the reactors smaller. This will make plants cheaper and modular, meaning units can be taken offline one by one for maintenance.

Advanced reactors: The next-generation of nuclear reactors hope to reduce costs by redesigning heat transfer methods and fuels to reduce operating pressures and prevent nuclear proliferation. These advances could make safe nuclear energy cheaper to build.

Fusion: Fusion promises two main benefits over fission: less nuclear waste, and no risk of runaway meltdown. Most funding for fusion development has gone to large proof-of-concept government projects that are attempting to demonstrate a net energy gain reaction. Private companies, however, have raised billions in the past year with plans to develop and commercialize smaller fusion reactors.

Limitations

Social acceptance: Nuclear continues to have less political support than other clean energy technologies and while nuclear is safe, it is not zero-risk. Even if it was, this would be a difficult perception to change in the public psyche.

Regulatory barriers: New nuclear technologies face more regulatory barriers than any clean energy technology due to the potential for failure. Nuscale – a small modular reactor company – reportedly spent $500 million in getting permission from the US nuclear energy regulator to build its reactor design.

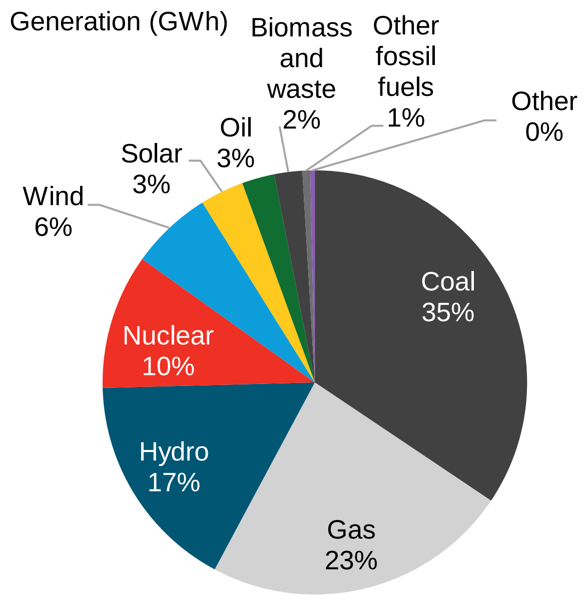
Poor knowledge: Advanced reactor designs are so novel that it is difficult for regulatory agencies to certify the safety of the technologies. People with the relevant knowledge are likely to be quite involved in the development of the new reactor designs.

Potential solutions

Retrofitting: Co-locating nuclear plants with old thermal power infrastructure should be cheaper as existing infrastructure can be leveraged to accelerate project development and lower capital costs.

Private energy consumers: The nuclear industry has been driven by government support due to the enormous size of the projects. As smaller reactors come online, large industrial power consumers (e.g. steel, chemical plants) could catalyse the industry by building onsite nuclear.

Global generation share (2020)

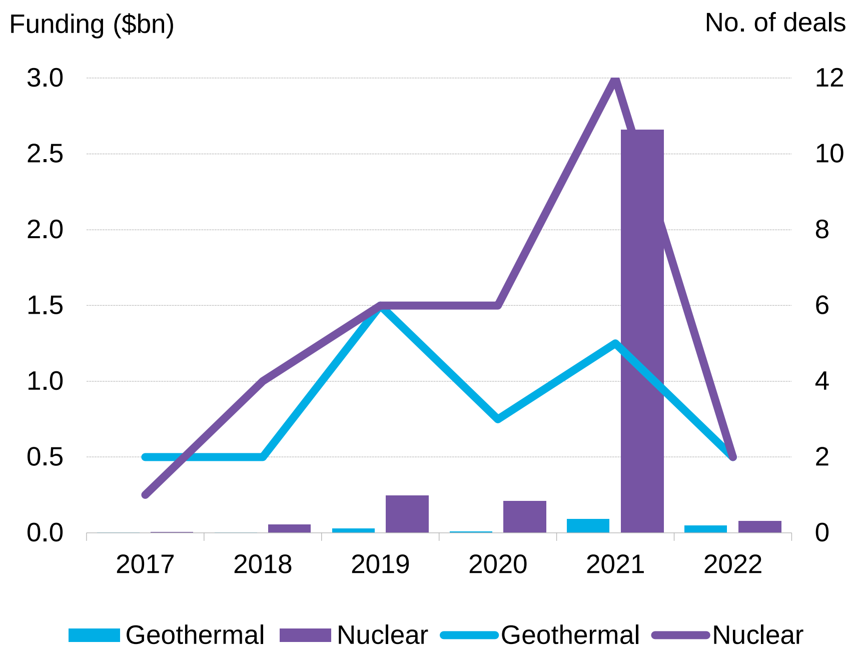


Source: BloombergNEF

Nuclear energy

		How does it work?	Maturity
Small modular	NUSCALE Power for all humankind	Nuscale's small modular reactor is a 4.5 x 23 meter, 700 ton vessel that uses conventional light water cooling and runs on 4.95% enriched uranium. The reactor has a power generation capacity of 77MW. Nuscale's reactors will be manufactured offsite and then delivered in three segments to a site to get installed. Nuscale wants to cut nuclear capex costs by 60% with its Nth-of-a-kind facilities.	Nuscale has completed the sixth and final phase of the US Nuclear Regulatory Commission's (NRC) design certification application. In September 2020, it received Standard Design Approval which allows customers to develop nuclear plants using Nuscale's designs. Utah Associated Municipal Power Systems aims to build the first power plant using Nuscale's design by 2029-2030. The project will consist of 12 reactors.
Low-pressure	Kairos Power	Kairos Power is developing an advanced 140MW fluoride salt-cooled high-temperature reactor. Its coolant can operate under atmospheric pressure and the reactor uses TRISO (tri-structural ISOtropic fuel). Operating at low pressure eliminates the need to construct an expensive reactor containment vessel, reducing the cost and physical footprint of the plant.	Following an extensive pre-application engagement with the US Nuclear Regulatory Commission, Kairos is in the process of developing its Hermes 35MW thermal pilot project, which will evolve into additional renditions prior to full-scale deployment of its commercial reactor. It does not anticipate sales pre-2030.

VCPE funding for geothermal and nuclear technologies



Source: BloombergNEF, CB Insights

Nuclear energy's most direct competitor in the long run is geothermal. Their high-capex, low-opex cost structure means they would likely serve the same baseload generation role in a zero-carbon power system. BNEF counts 66% more investment rounds for startups developing new nuclear technologies and 14.2x more dollars invested compared to geothermal.

Nuclear energy

Fusion

Commonwealth Fusion Systems

How does it work?

Commonwealth Fusion systems is using an adaptation of the tokamak approach to fusion used in the International Thermonuclear Experimental Reactor (ITER) – the 25 billion euro international research project – to build its Sparc reactor. Its key innovation relates to the use of yttrium barium copper oxide high-temperature superconducting magnets, which it hopes will simplify reactor design to lower costs. Its 50-100MW pilot reactor will be 2% the size of ITER and attempt to demonstrate a net energy gain.

Maturity

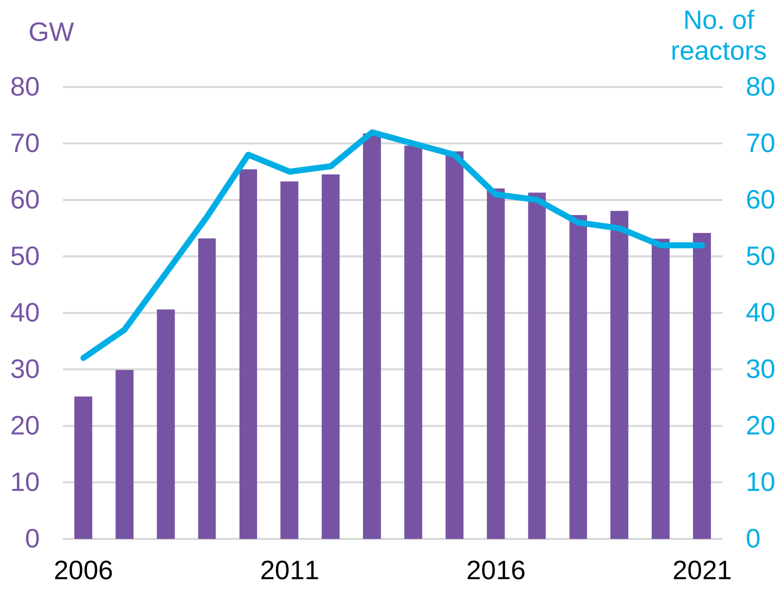
CFS was founded in 2018 as a spinout of MIT's Plasma Science and Fusion Center. The company has raised just over $2 billion since its founding, $1.8 billion of which came in its Series B in December 2021. It has disclosed 32 investors, including some of the most well-known deep tech climate investors such as The Engine, Breakthrough Energy Ventures, Lowercarbon Capital, Khosla Ventures and Bill Gates.

TAE Technologies

TAE is developing a neutronic fusion power – a different approach to the tokamak. TAE's approach requires higher temperatures because it fuses hydrogen and boron, rather than deuterium and tritium like most other efforts. This difference may also mean, however, that there are even less concerns about waste than other fusion companies, and it thus may be easier to gain operating licenses.

TAE was founded in 1998 and has raised $880 million. TAE's most recently completed device is its Norman reactor, which successfully demonstrated its objective of heating a plasma above 30 million degrees Celsius and keeping it stable for 30 milliseconds. It plans to start testing its next device, Copernicus, in 2023-2024. The $250 million project will deliver temperatures of up to 150 million degrees and will validate the ability to achieve net energy.

Nuclear reactors under construction



Source: BloombergNEF, International Atomic Energy Agency

Geothermal energy

Geothermal energy is currently reliant on subsurface permeability and heat. This has limited the scale of the industry. New approaches to geothermal involve subsurface engineering so that projects can be developed wherever there is heat – a far less stringent requirement. This can involve fracking to crack rocks (enhanced geothermal systems) or drilling long subsurface loops (closed-loop). Novel geothermal will only succeed with lower-cost, higher-performance drilling technologies. The industry must address issues relating to potential seismic risk, as well as long project development timelines, to scale quickly. Co-producing heat and power and leveraging existing power infrastructure (e.g. turbines, grid connections) could help boost the economics of geothermal projects.

New approaches and technologies

The aim of new geothermal approaches is to expand global geothermal power capacity by making it less dependent on subsurface features, and thus location. This simultaneously boosts project economics.

Enhanced geothermal systems (EGS): Normal geothermal energy relies on natural permeability so fluids can absorb energy by flowing through hot rock. EGS create artificial permeability by fracking rocks.

Closed-loop: Rather than fracking rock to create an artificial reservoir, closed-loop systems drill long sections of pipe that are sealed, so the fluid carrying energy from the subsurface never touches the rock.

Superhot rock: SHR projects use fluid hotter than 375°C (i.e. the supercritical point of water). SHR projects could produce 4-10x more electricity per well than traditional geothermal projects, but challenges remain.

Limitations

Seismic activity: Novel geothermal approaches that use fracking to create artificial subsurface reservoirs have been associated with increased levels of seismic activity, though proponents argue safety protocols negate this risk if followed.

Drilling costs: The competitiveness of new geothermal technologies are highly reliant on step changes in drilling and cost performance.

Project timelines: Geothermal plants can take up to eight years to develop, so novel approaches will take time to come to market.

Price premium: Even optimistic cost estimates for some novel geothermal technologies have higher levelized costs than solar and wind. Current power markets do not yet reward the reliability provided by geothermal energy.

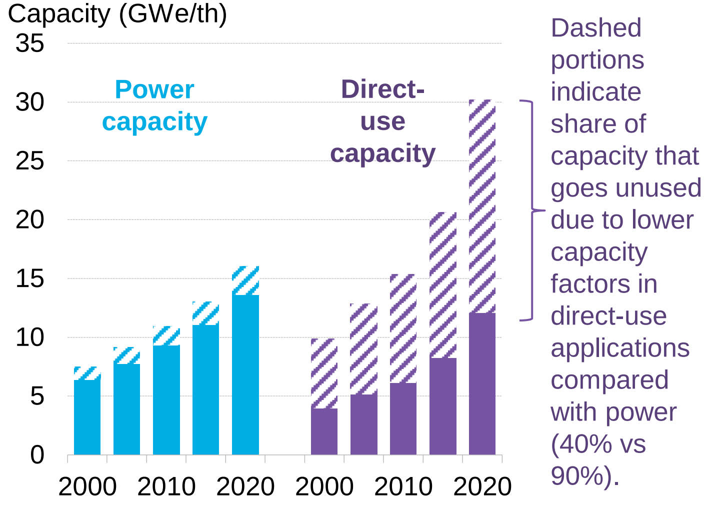
Potential solutions

Supply district heating: Low-temperature resources will be more competitive in supplying district heating as they have much larger efficiency losses converting to power.

Co-locate with old thermal assets: SHR projects could be used to refire old thermal power plants if drilling technology is sufficiently advanced, saving enormously on plant costs.

Enhance flexibility: While geothermal is a reliable energy source, power markets do not yet reward reliability. Integrating elements of flexibility into power plants (i.e. using the reservoir as an energy store) could allow plants to engage in power price arbitrage.

Global geothermal capacity

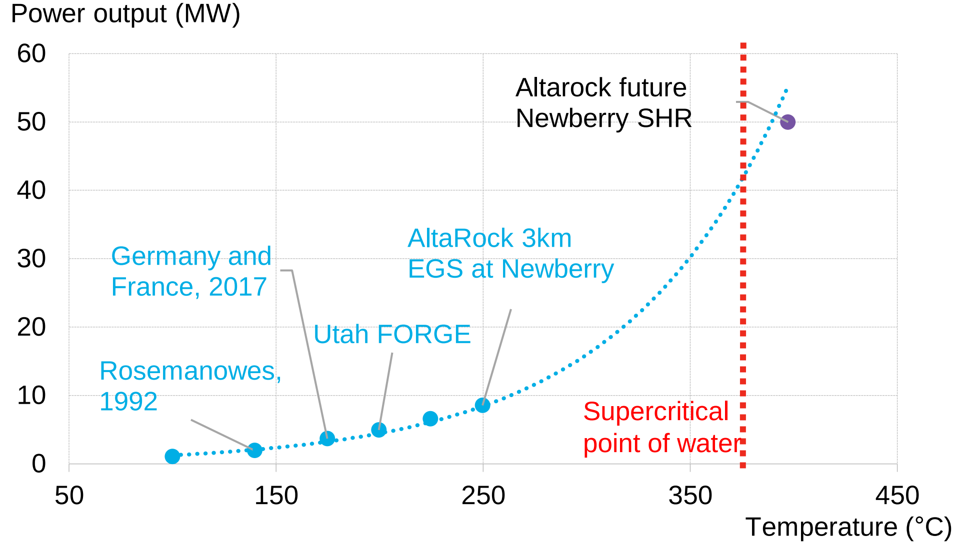


Source: BloombergNEF, Direct utilization of geothermal energy 2020 worldwide review

Geothermal energy

		How does it work?	Maturity
EGS	FERVO ENERGY	Fervo uses directional drilling, as well as advanced sensing and modeling technologies, to improve its ability to develop enhanced systems. For example, it uses fiber-optic sensing – where fiber-optic cables are deployed down boreholes – to obtain continuous measurements along the full depth of the borehole. This contrasts with the more traditional strategy of using discrete datapoints to estimate downhole conditions using interpolation. In February 2022, Fervo Energy was granted $4.5 million from ARPA-E to develop its FervoFlex technology. The project is designed to store multiple days worth of energy. While the project description did not detail how energy would be stored, BNEF believes it is likely a geomechanical storage process like Quidnet Energy's. During periods of low power prices, a greater amount of fluid is injected into the surface to build up pressure. The parasitic load of pumping water can then be lowered in periods of high power prices without reducing power capacity. Research suggests round-trip efficiency could be 60-90%.	Fervo was founded in 2017. In April 2021, it raised $28.4 million at a reported valuation of $65.5 million. Investors include Breakthrough Energy Ventures, Congruent Ventures and drilling contractor Helmerich & Payne. Fervo also signed an agreement with Google to supply 24X7 clean power.
Super hot rock	ALTAROCK	AltaRock Energy is a leading SHR geothermal project developer. It wants to use EGS methods in superhot rock conditions to develop cost-competitive geothermal energy. Its IP is in integrating the various processes of geothermal development rather than drilling, sensing or materials that enable the process.	The company has raised a total of $65 million. In September 2021, it announced results of a technoeconomic feasibility study of a SHR project at Newberry Volcano in Oregon, in partnership with Baker Hughes. The analysis estimated that the project could deliver power at an LCOE* of <$0.05/kWh. The study estimated that a demonstration SHR well system will be constructed by 2025 and the plant will be commercially developed by 2030. *LCOE is levelized cost of electricity.

Power output potential of 60kg/s of geothermal fluid at different temperatures



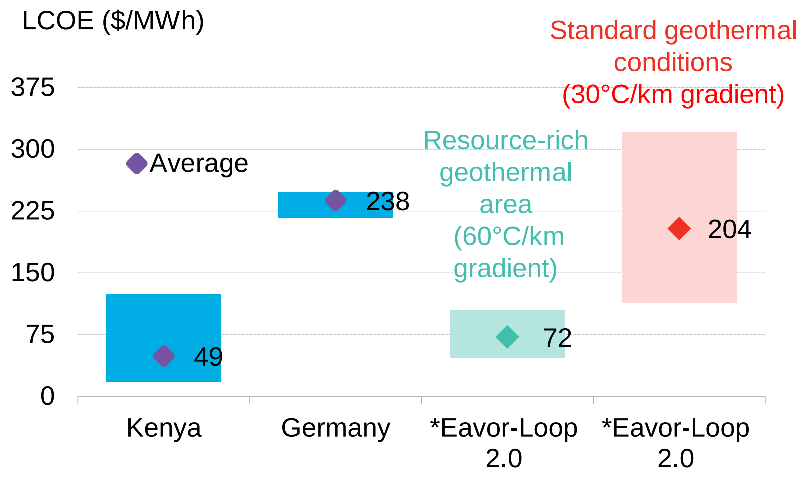
Source: BloombergNEF, AltaRock Energy

Geothermal energy

Closed-loop

	How does it work?	Maturity
Eavor	Eavor builds its closed-loop systems by drilling and casing the vertical portions of its well in the same way traditional wells are made. It then drills around 90km of lateral wells that make up the majority of its closed loop. A cross section of the system looks like a big pitchfork that has been dug into the ground. The length of drilled section in Eavor's system is orders of magnitude more than a traditional plant would need; it is particularly reliant on improved drilling.	Eavor was founded in 2017 by veterans of the oil and gas industry. The company has raised $83 million and counts BP Ventures and Chevron Technology Ventures among its investors. In 2019, it built its first loop in Canada as a proof of concept. Eavor is building a $223 million, 8MW plant in Germany that will provide both heat and power.
GreenFire Energy	Greenfire Energy's closed-loop system is a pipe deployed down a single borehole (also known as co-axial closed loop). The pipe is divided into an inner and outer section by a smaller pipe inside it. Fluid is pumped down the outside where it absorbs heat from the hot rock and pumps it to the surface though the center of the pipe. Greenfire is targeting the retrofit of old, failed geothermal wells to eliminate drilling costs, rather than attempting greenfield development in the near term like most geothermal startups.	Greenfire Energy was founded in 2014. In 2022, it raised a Series A, which included funding from Baker Hughes and Helmerich & Payne (a Fervo investor). Greenfire has a demonstration plant in California, a commercial project in the Philippines, and another in development in Japan. It says it is in discussion with eight of the top 10 largest geothermal developers.

LCOE of geothermal in Germany, Kenya and for Eavor-Loop 2.0, 2021



*Modeled costs. Not real project data

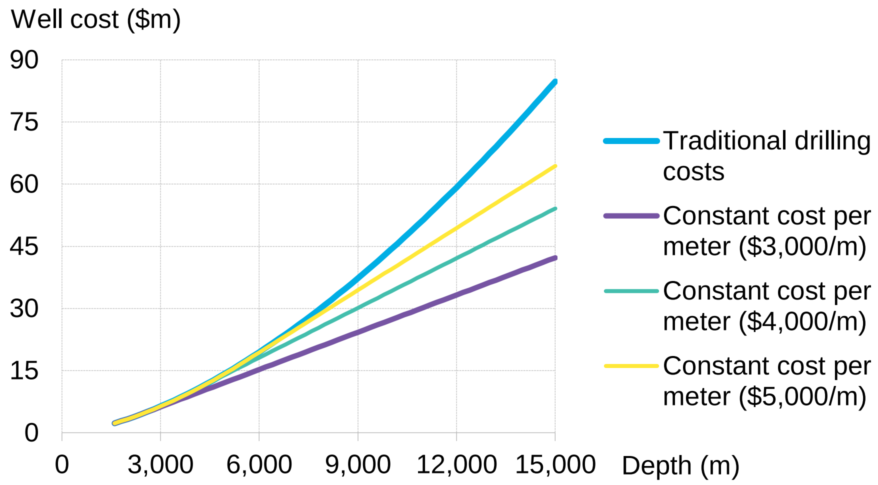
Source: BloombergNEF, Technoeconomic performance of Eavor-Loop 2.0

A study from the National Renewable Energy Laboratory in the US estimated that the proposed closed-loop geothermal system design of startup Eavor could produce power at a levelized cost of electricity (LCOE) of $70 per megawatt-hour (MWh) with good geothermal resources, and $204/MWh in more standard conditions. The results were highly dependent on low-cost, high-performance drilling metrics that have yet to be demonstrated in the field.

Geothermal energy

		How does it work?	Maturity
Shallow drilling	HYPER SCIENCES	Hypersciences' geothermal IP is centered on its Hyperdrill product. This drill contains a tube through which high-velocity low-cost projectiles made of plastic and concrete are fired every 2-3 seconds. These projectiles impart their kinetic energy into the rock ahead of the drill, weakening it. Hypersciences says the drill has boosted rates of penetration by 5x in field trials set in hard rock formations. Drill bits also last longer because they are grinding through weakened rock.	Hypersciences hopes to commercialize its drill by early 2023. The company is anticipating it will need a large amount of capital to scale its products in the coming years. It is currently in the midst of raising a $30 million venture round with plans to IPO in 4Q 2022-1Q 2023. This timeline is a three-month delay on what it presented in August, 2021.
Shallow drilling	HydroVolve	Hydrovolve has developed a drill that uses 'percussive impulse energy' to weaken the rock ahead of it, in the same way Hypersciences uses projectiles. Hydrovolve claims the drill increases the rate of penetration by 10x and cuts the cost of geothermal wells by 50%.	Hydrovolve was founded in 2011 and there is little information available publicly on the company. Its GeoVolve Hammer drill, the one with geothermal applications, was only announced in January 2022.
Deep drilling	QUAISE	Quaise's drill uses a gyrotron to generate electromagnetic radiation in the form of millimeter waves. These waves are directed down a borehole through a waveguide (a metal pipe acting like a fiber-optic cable) heating the rock at the bottom of the borehole into a vapor. While Quaise's process is expensive per meter drilled, its costs stay relatively constant, making it potentially tens of millions of dollars cheaper to drill to 10km, where superhot rock is available virtually anywhere in the world.	Quaise spun out of MIT's Fusion Research Center. It has raised $75 million to date. Its technology has been proven at lab scale and the company aims to demonstrate it in the field by 2024, with AltaRock.

Estimates of geothermal well completion costs, by depth and cost function



Source: BloombergNEF

Post-combustion carbon capture

Post-combustion carbon capture – where CO2 is removed from the flue gas of a traditional power plant, rather than through a pre-treatment step – is the most viable technology option for CCS in the power sector. Second-generation post-combustion capture technologies, which make use of new sorbents, membranes or cryogenic gas separation, hope to deliver capture at a cost of under $50/tCO2, competitive with European carbon prices. Most of these technologies have the drawback that they only capture 90% of emitted CO2, making the power source low-carbon rather than zero-carbon. Reducing the energy requirements for sorbent regeneration and the durability of capture materials will be key in lowering costs.

New approaches and technologies

There are three types of CCS for power: pre-combustion, oxyfuel and post-combustion. This slide focuses on post combustion, which is cheaper than pre-combustion. Oxyfuel combustion is covered separately in the section on CO_2 turbines.

New sorbents: Sorbents are the materials that filter the CO_2 out of flue gas. New liquid or solid adsorption sorbents could reduce the energy intensity of sorbent regeneration, a core cost driver of post-combustion capture.

Membranes: Membrane separation of CO2 from flue gas, as an alternative to sorbents, is another technology being explored that has the potential to be more energy efficient than sorbent approaches.

Cryogenics: An even more novel approach is to cool flue gas from power plants to the point where CO2 will condense. It can then be separated from the flue gas and stored.

Limitations

Only 90% of carbon captured: Post-combustion capture is not a net-zero technology. It must be paired with carbon removal to be truly zero carbon.

High energy requirements or poor durability: Sorbents eventually saturate with carbon and need to be regenerated – i.e. stripped of the carbon so they can absorb more. This is a very energy intensive process contributing to cost. Lower energy filtration mechanisms such as membranes may still be expensive as they are not durable and need to be regularly replaced.

Time to market: Capture equipment needs to be demonstrated before industrial sites will provide huge capital outlays to build it. Once demonstrated, manufacturing also must scale up. These long timelines mean that even without delays, it will be years before carbon capture is widely deployed.

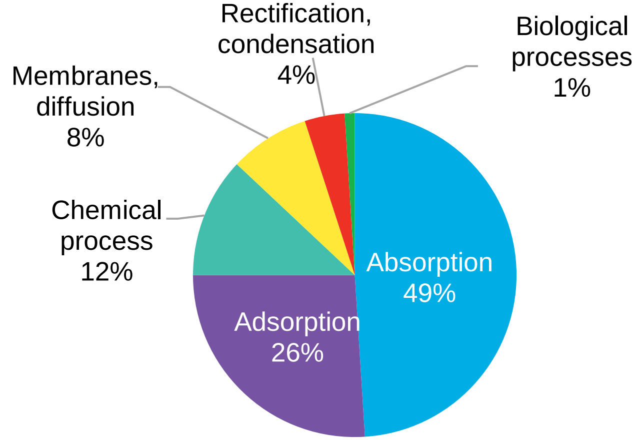
Potential solutions

Equipment design: Designing more efficient methods for contacting flue gas and sorbents can reduce the size of equipment, cutting capex.

More efficient regeneration: Finding sorbents that can be regenerated more efficiently is essential in cutting carbon capture opex.

Combine separation steps: Different separation mechanisms (e.g. membranes, sorbents) work better at different levels of temperature and CO2 intensity. Combining separation mechanisms could result in a more efficient overall process.

Distribution of post-combustion carbon capture patents, 2020



Source: BloombergNEF, Technology Scouting Carbon Capture: From Today's to Novel Technologies

Post-combustion carbon capture

BNEF pioneers

How does it work?

Maturity

Absorption

ION CLEAN ENERGY

ION Clean Energy is developing a liquid absorbent post-combustion capture process that is 90-98% efficient. It says its novel liquid absorbent outperforms industry standard materials. Its other innovation is the use of 3D printing in the manufacturing of the devices used to contact the sorbent and flue gas – optimizing for cooling, mass transfer, liquid hold up and pressure drop. A techno-economic analysis for its equipment on a coal plant estimated that ION's systems could cut capital costs by 38% and opex by 28% compared with traditional systems, resulting in a cost of $39-45/tCO2 captured on a coal plant.

ION has run several pilot projects in the US and Norway to demonstrate its technology but has yet to announce a major installation. The company received a $5.8 million grant from the US DoE in 2019.

carbon clean

Carbon Clean has developed a proprietary liquid solvent as well as a gas-liquid contactor design to reduce the size of carbon capture equipment, while improving performance. It is targeting a competitive capture cost of $30/tCO2 for flue gases with CO2 concentrations of 3-25%.

It has attracted $35.3 million in funding from strategic investors including cement-maker Cemex, Equinor Ventures and Chevron Technology Ventures. Its focus going forward is to commercialize the technology at 10tCO2/day and 100tCO2/day with select partners for roll out in 2022-2023.

Adsorption

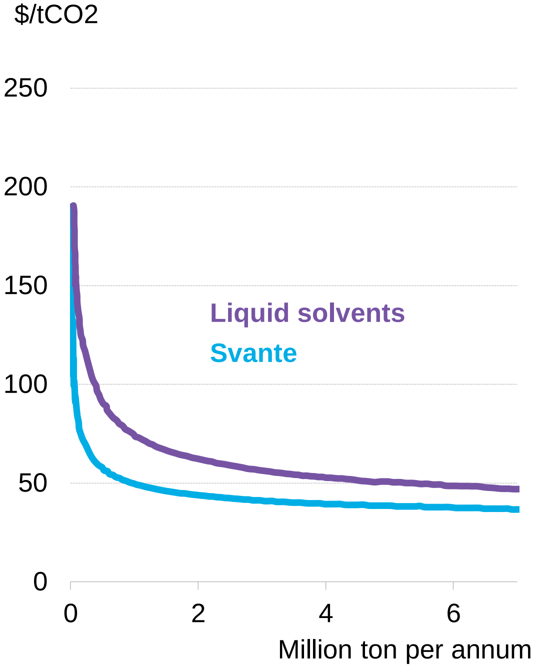
Svante

Svante makes a solid adsorption system, which means the CO2 adheres to a surface rather than being absorbed by a liquid, and targets a cost of $50/tCO2. Its innovation is in how it layers sorbents into structured sheets. This is material agnostic and it should be able to incorporate new sorbents (e.g. functionalized silica, metal organic frameworks) as they are developed.

Svante has two pilot plants in Canada that capture 1 and 30 tons of CO2 per day. The company has raised $138 million, $100 million of which was in 2021, and counts Chevron, Suncor and the Oil & Gas Climate Initiative as strategic investors.

Both Svante and Carbon Clean are targeting more difficult to abate industries such as steel and cement but their equipment could be used in the power sector. Their cost estimates may not translate to power.

Cost of capture for liquid solvents and Svante

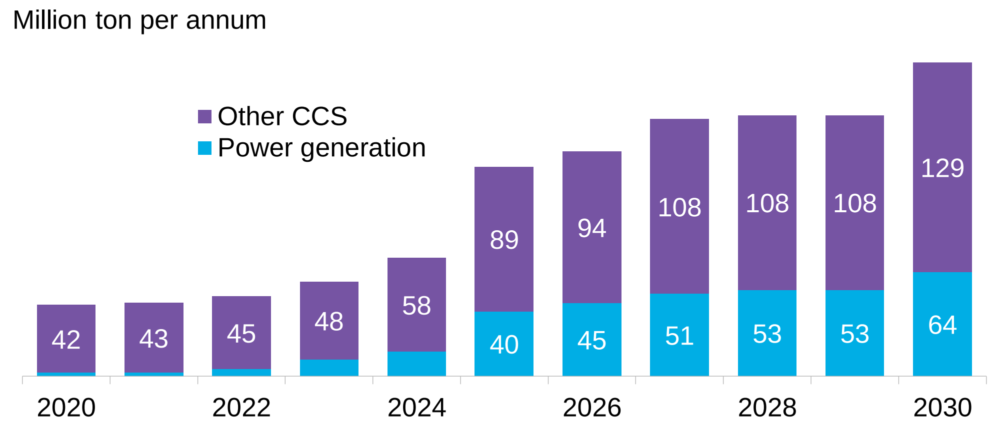


Source: BloombergNEF, Svante

Post-combustion carbon capture

		How does it work?	Maturity
Membrane	MTR MEMBRANE TECHNOLOGY & RESEARCH	MTR's IP is its Polaris polymeric membrane that it says is the world's first commercial membrane for industrial capture. MTR has two solutions, one of which captures about 60% of carbon and the other 90% of carbon. The 60% option is cheaper and captures carbon at a cost of \$40/tCO_2.	MTR was founded in 2010 and has received a consistent stream of grant funding from the US Environmental Protection Agency totaling \$3.4 million. Its has only run pilot carbon capture projects to date.
Cryogenic	CHART	SES's process works by cooling flue gas to -140°C, causing the gaseous CO_2 to desublimate into a solid, skipping the liquid phase. The solids are separated, and CO_2 is pressurized for transport and storage. Its process captures 95-99% of CO_2 from concentrations ranging from 4-28%.	Sustainable Energy Solutions' (SES) largest system captures 1 tCO_2/day. Its field tests were conducted with utility-scale power plants, cement plants, heating plants and more. SES is currently trying to scale its capture process to 10-80tCO_2/day. In 2020, SES was acquired by industrial equipment maker Chart Industries – also a Svante investor – for \$20 million.

Global carbon capture capacity



Source: BloombergNEF. Note: Installed capacity as of August 2021. Rest is forecast.

New power capacity

Supercritical CO_2 turbines

Supercritical CO_2 (sCO_2) turbines use CO_2 as a working fluid rather than water/steam used in traditional turbines. sCO_2 have yet to be commercialized but have several theoretical benefits over steam turbines: greater efficiency, 10x smaller, lower water consumption, more capable of ramping and efficient at smaller scales. sCO_2 turbines can operate via closed-loop where heat transfers to the turbine system through a heat exchanger (indirect), or CO_2 from a combustion reaction can drive the turbine (direct). These direct sCO_2 turbines can be constructed to capture almost 100% of the carbon from the combustion reaction (known as oxyfuel CCS). While sCO_2 turbines have theoretical benefits, there are still engineering challenges with the design of turbomachinery. Smaller sizes, and dense fluids, means the turbines rotate at much higher speeds, requiring the design of new sealants, shafts and bearings. Air separation costs are a key component of direct sCO_2 costs.

New approaches and technologies

The two types of sCO_2 turbine cycles have different applications but the same benefits.

Indirect: sCO_2 turbines of this kind contain a closed-loop system of CO_2. Heat from some energy source is given to the closed loop through heat exchangers. This is suitable for use with non-fossil energy sources and/or waste heat recovery.

Direct: Direct sCO_2 turbine cycles burn either coal or gas in the presence of oxygen. This produces a pure stream of CO_2 that flows into and drives a turbine. Some of the CO_2 is recycled back into the combustion chamber to manage gas composition and temperature, and the rest sequestered. Direct sCO_2 cycles are a subcategory of pre-combustion carbon capture processes, known as oxycombustion.

Limitations

Turbomachinery challenges: sCO_2 turbomachinery is much smaller and more power dense than traditional turbomachinery. While this has benefits it means they must rotate at greater speeds, introducing challenges around shaft and bearing design as well as aerodynamics.

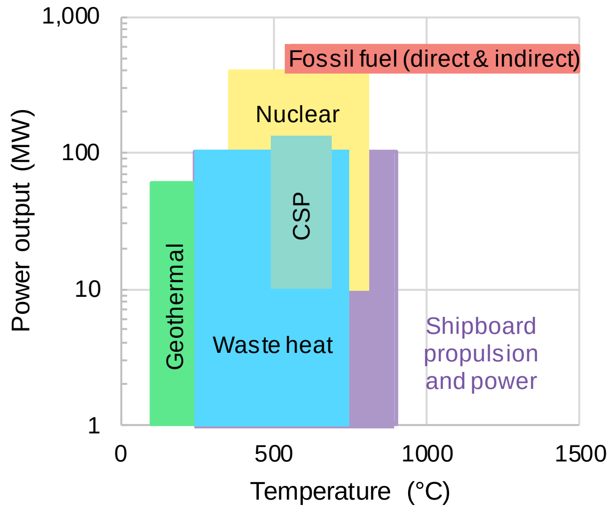
Air separation is expensive: Even though oxycombustion captures a larger amount of carbon than post-combustion capture, it is more expensive per unit of carbon captured due to the cost of air separation to produce the oxygen in which combustion happens. For direct sCO_2 turbines to be cost competitive, the efficiency gain from using the turbine must outperform the energy penalty of air separation.

Potential solutions

New air separation processes: Air separation is currently done by cooling air streams into liquids. Advances in carbon capture – e.g. membranes, sorbents – could translate to making air separation cheaper.

Flexible air separation units: Direct sCO_2 turbines need pure oxygen streams. It could potentially be cheaper to ramp up and down on oxygen production – based on electricity prices – and store it, rather than consistently producing it from onsite power generation. This would make the most sense in regions with volatile power prices – that is, high renewables penetration.

Overview of supercritical CO_2 power applications



Source: BloombergNEF, Review of supercritical CO_2 technologies and systems for power generation

Supercritical CO_2 turbines

		How does it work?	Maturity
Direct	NET Power	NET Power's sCO_2 turbine cycle – known as the Allam-Fetvedt cycle – is a direct sCO_2 that burns natural gas as an input. NET's turbine design captures more than 99% of CO_2 created from gas combustion, much higher than any post-combustion carbon capture technologies. A 2018 technoeconomic analysis of the study found it could produce power at a levelized cost of $91.91/MWh, a cost premium of 33% compared with a natural gas combined cycle plant.	The Allam cycle was patented in 2011. NET Power is in part owned by 8 Rivers Capital through which it is financing development of new projects. NET Power commissioned its first plant (50MW) in 2018. In the last year, the company has developed a pipeline of three projects amounting to 910MW in capacity across the US and UK. In March 2022, 8 Rivers also announced a $100 million investment from SK Materials in a joint venture to deploy its technology across Asia.
Direct	Linde	Linde Engineering is developing flexible air separation units with its Flexasu project, funded by Germany's Federal Ministry of Education and Research. The project is adapting pipelines, valves, heat exchangers and compressors to be more resilient under rapid changes in temperature and pressure and attaching larger storage tanks. This project is not specifically targeted at sCO_2 turbines but could pair well with direct sCO_2 turbines, where air separation is a cost driver.	
Indirect	gti	The supercritical transformational electric power (STEP) project - run by the Gas Technology Institute in partnership with GE, SwRI and the US DoE – is constructing a 10MW sCO_2 turbine in San Antonio, Texas. This turbine will be an indirect sCO_2 recompression Brayton cycle and will demonstrate the performance of first of a kind turbomachinery components including recuperators, compressors and seals. The aim of STEP is to explore turbine components so that sCO_2 turbines can ultimately scale to hundreds of megawatt.	The US DoE awarded $84 million to the STEP project and the remaining $35 million was funded by GE, GTI and SwRI. The turbine is under construction and testing is set to begin in 2023. The group demonstrated a 1MW turbine of this kind in 2018 and hopes to get the technology to a tech-readiness level of 7 by 2023 (where 9 is the max level). SwRI is a not-for-profit organization that has received over $120 million in funding to help develop sCO_2 turbines.
Indirect	Echogen power systems	Echogen Power Systems has developed an 8MW sCO_2 turbine with applications in waste heat recovery. Echogen modeling estimates that the use of its sCO_2 turbine in bottoming cycles for gas plants could decrease the levelized cost of power by 4-20%, compared with using steam-based bottoming cycles.	Echogen was founded in 2007 and has raised $58.8 million. It first licensed its turbine to GE for marine applications in 2013 and announced a new partnership with Siemens in 2021 for use in the oil and gas sector.
Indirect	Heliogen	The firm is developing the use of intelligent control systems to improve the economics of concentrated solar power. It is also exploring the use of sCO_2 turbines in CSP plants.	Heliogen is a Breakthrough Energy Ventures backed firm that went public via reverse merger in 2021 at a valuation of $2 billion. Heliogen was awarded $39 million by the US DoE to build and operate a CSP plant with a 5MW sCO2 turbine. Heliogen committed $31.1 million of its own funds to the project.

Electrochemical energy storage

Lithium-ion batteries are currently the most competitive energy storage technology up to four hours of duration. As renewables penetration increases, the average duration requirement of storage systems must extend to 6-12 hours and beyond, according to BNEF modeling. Lithium-ion system cost scales linearly with storage duration, which means that beyond four hours, it may not be the most cost-effective electrochemical technology. Low-cost, low-performance metal-air cells, or flow batteries that have decoupled the cost of energy and power components, could be better suited to serve as long-duration storage. To date, these technologies have had little success due to a limited track record and the fact they do not have any competitive advantage over lithium-ion in today's power market.

New approaches and technologies

Flow batteries: Flow batteries are electrochemical systems that store energy in a liquid electrolyte that is pumped – that is, flows in and out of reservoirs – to an ion-exchange membrane, where ions move between the reservoirs, storing or discharging energy. Flow batteries could be better-positioned for long-duration storage because they need larger reservoirs, rather than more electrochemical cells, like lithium-ion systems, to extend their storage duration.

Abundant materials: Instead of eliminating the need to make more cells, another strategy for extending battery duration at low cost is to make cells from extremely low-cost materials. While these batteries have poorer cycle lives or lower energy density than lithium-ion, they could be a more cost-effective technology for long-duration energy shifting. Examples of chemistries include iron-air, zinc-based and sodium sulfur.

Limitations

Reliance on high-value minerals: Flow batteries often rely on high-value materials that make them expensive. Vanadium has been one of the most commonly used materials in flow batteries and its cost has ranged from $100-150/kWh, which will not be competitive.

Regular discharging: Some flow battery chemistries may need to be cycled to prevent dendrite formation, constraining the periods across which they must arbitrage power prices. Pricing arbitrage over these periods will only be profitable as renewables penetration gets extremely high, and other technologies (e.g. baseload generation) that compete in the short run may become much more technically capable and cheaper.

Project risk: Long-duration electrochemical storage has a history of failure making projects difficult to finance.

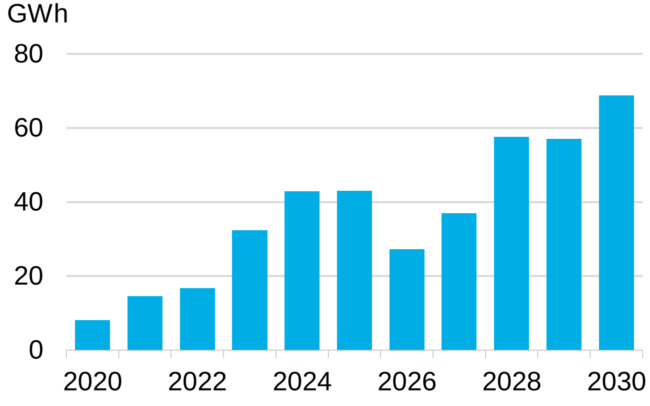
No demand for ultra-long duration: Storage technologies that store multiple days worth of power will be very difficult to commercialize in the short run without specific policy support.

Does not provide inertia: Electrochemical energy systems provide no rotational mass to the grid, unlike other systems discussed here, which impacts power quality. This is an increasingly valuable service as renewables penetration runs higher.

Potential solutions

Reduce need for cycling: Innovations that prevent or slow the formation of dendrites would help reduce the need for cycling flow batteries, extending their lifetime and making them more flexible.

Flow battery addressable market

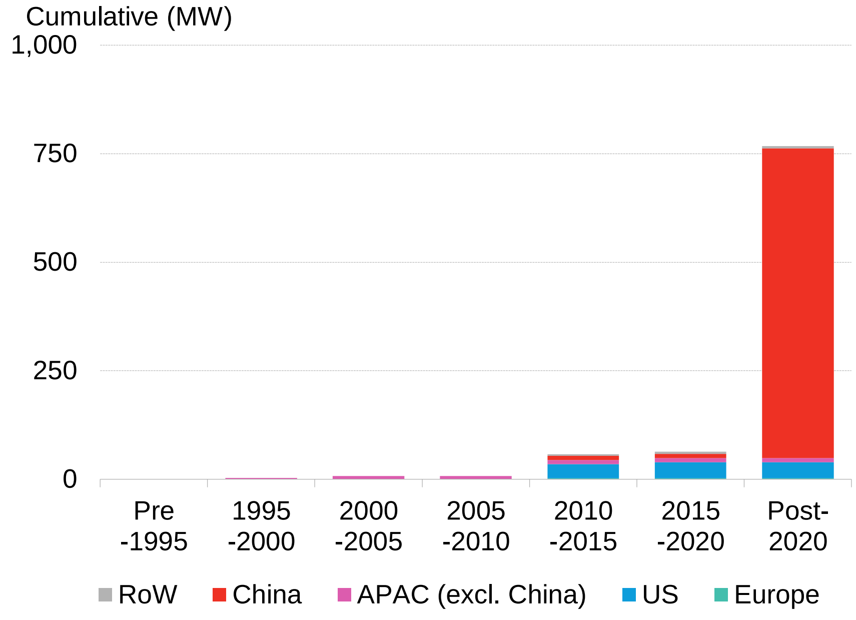


Source: BloombergNEF. Note: Methodology available here.

Electrochemical energy storage

Flow batteries		How does it work?	Maturity
	PRIMUS POWER	Primus Power makes a zinc-bromine flow battery, with a storage duration of five hours. Primus' battery is characterized as having a 20-year lifetime, low safety risk and low-cost inputs. It experiences a low round-trip efficiency of 70% and needs to be fully discharged every few days to prevent dendrite formation.	Primus Power was founded in 2009. In its early years, it received R&D and demonstration funding from ARPA. The company has raised larger and larger venture rounds every two years or so since then, for a cumulative funding of $99 million. Primus is particularly notable for its endurance in an industry that has seen many failures. Primus was one of only three companies surveyed in a 2020 BNEF report on emerging storage tech to have a commercial project (16 companies in study).
	ESS INC CATALYZING A CLEANER FUTURE	ESS has developed an iron flow battery that offers storage for periods of 4-12 hours.	ESS, like Primus Power, is one of the longest surviving players in the flow battery sector. The company raised $52 million before going public via reverse merger in October 2021 at a $1 billion valuation. The company has yet to report any revenues but has projected $8.6 million for 2022. ESS received a boost in 2021 when MunichRe agreed to cover the technology for the first 10 years of system life, reducing the risk of deploying the technology. It also announced a partnership with Softbank to deploy 2GWh of storage through 2026.

Cumulative installed capacity of flow batteries



Source: BloombergNEF

BNEF estimates that about 263MW of flow battery capacity has been built – less than 0.1% of lithium-ion storage adoption. Nevertheless, the industry's pipeline is strong with over 700MW in announced projects, most of which are located in China.

Electrochemical energy storage

Abundant materials

How does it work?

Maturity

Form energy

Form Energy is developing an iron-air battery system based on reversible oxidation (rusting). Form's battery consists of an iron anode, an air cathode and water-like electrolyte. When the battery is charging, the rusty iron anode is de-rusted and turns to metallic iron. To discharge, it absorbs oxygen, making the anode rusty again. Form says that it is aiming to design systems that can store 100 hours of power at a competitive cost, longer than most energy storage technologies under development.

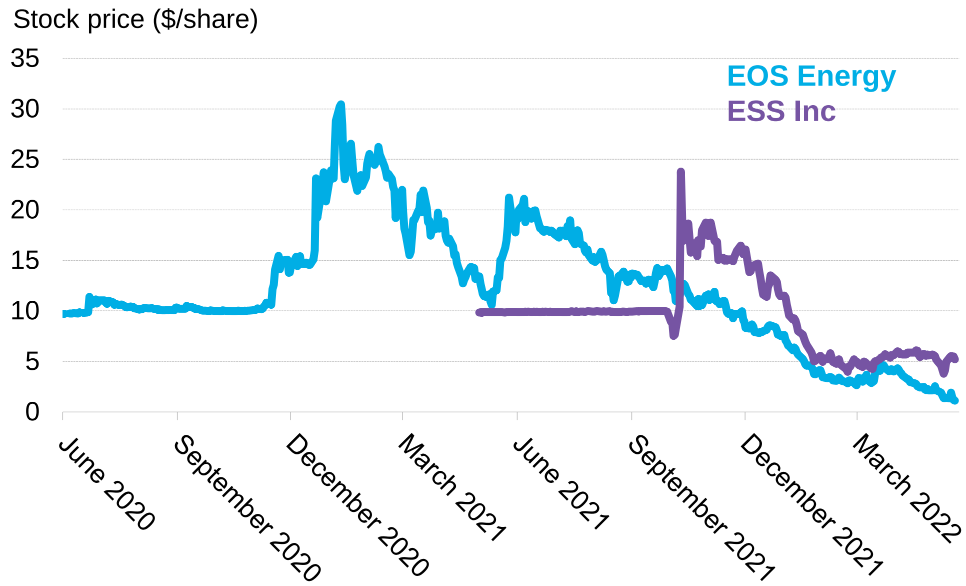
Form was founded in 2017, has yet to construct a plant but has raised $327 million. It was most recently valued at $1.1 billion, and investors include several industry stakeholders and climate-tech specialist funds such as The Engine and Energy Impact Partners. Form is aiming to commission its 1MW pilot plant with Great River Energy in Minnesota by 2023, before a larger rollout the following year.

eos

Eos Energy Storage has developed a zinc-based electrochemical energy storage system. Eos' battery has a 15-year life and will last around 5,000 cycles. It is targeting a storage duration of 3-12 hours. The companies patent library suggests the battery is a zinc-air or zinc-halide battery.

Eos went public via reverse merger in November 2020 at a valuation of $500 million. It generated $4.6 million in revenue in 2021 and forecasts $207 million revenue by 2023.

Stock price of EOS Energy Enterprises and ESS Tech Inc.



Source: BloombergNEF

Mechanical energy storage

Mechanical energy storage relies on winches, pumps and compressors to raise some mass or compress a fluid. To discharge energy, the pressure or weight is released, which drives a turbine to produce power. No fundamental breakthroughs are needed to commercialize mechanical energy storage, as the concept is simple, just more efficient designs and supply chains. Mechanical systems can also provide inertia to the power system that electrochemical storage cannot provide as they have rotational mass. Because of the technology simplicity, the main way to reduce the cost of systems is to scale projects and supply chains. This could make projects very prone to nimbyism, as mechanical systems have low energy density and thus a large physical footprint.

New approaches and technologies

Gravity: A gravity storage system stores energy by raising a mass, and then drops it to convert potential energy into electricity by spinning an electrical generator. The gravity storage typically consists of a tube, weight, cable and coil.

Novel pumped hydro: Pumped hydro is the world's most mature energy storage technology but limited by location. It is a sub-category of gravity storage. Creating new subsurface storage reserves and high-density fluids to increase the energy density of pumped hydro systems could boost capacity beyond current limitations.

Compressed air (CAES): CAES is a mature energy storage technology. Electricity runs a motor that compresses air. To generate, electricity the air is expanded to run a turbine. Novel approaches that use better thermal systems (adiabatic, isothermal) aim to boost efficiency from 50% to 75%.

Limitations

Siting requirements: Many mechanical storage systems require physical features such as mine shafts, mountains or salt caverns to act as an energy reservoir. Some argue that the emissions intensity of non-site-specific systems may be comparable to natural gas due to the large amount of embodied emissions in the concrete and steel used.

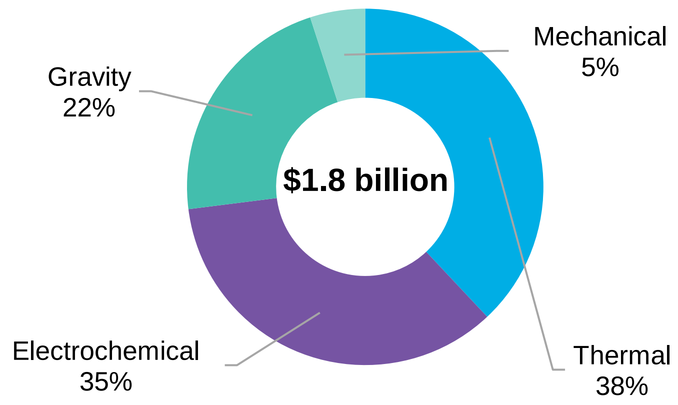
Project size: Mechanical storage will need to be on a grand scale to be cost competitive. This combined with most system types' low energy density means projects will be very large, generating concerns around land-use and potential public backlash. Energy Vault's systems could take up four times more space than a similarly-sized lithium-ion project.

Low efficiency: Mechanical storage tends to have lower round-trip efficiency than electrochemical systems.

Potential solutions

Develop good site locations: Mechanical energy storage is largely an engineering challenge rather than a scientific one. Technology will improve and costs will fall as projects scale. Larger projects will also encounter obstruction in the form of nimbyism much in the same way wind power has in Germany. Developers should look for sites that are remote in regions that have favorable policy environment for long-duration storage (for example, China).

Long-duration storage cumulative private fundraising by technology type, 2001-October 2021



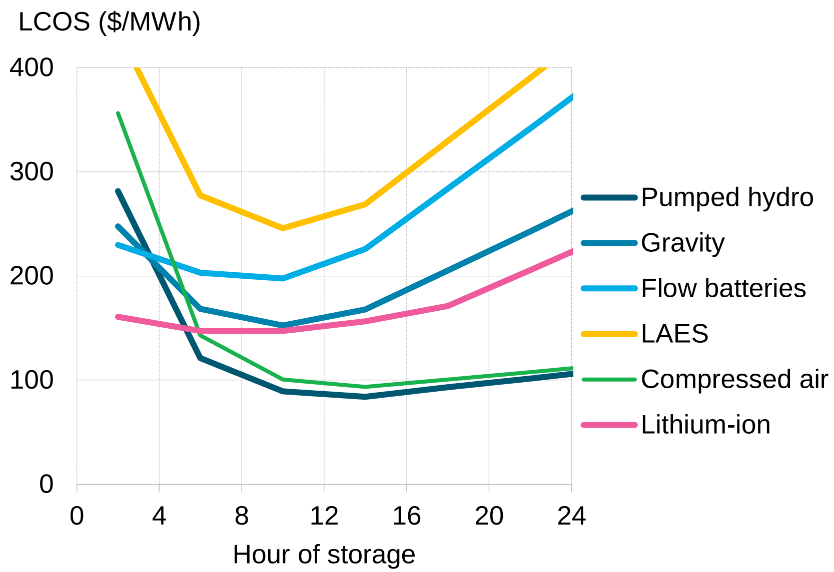
Source: BNEF, Pitchbook. Note: This chart represents VC/PE investments of 40+ long-duration storage start-ups developing thermal storage, mechanical storage and flow batteries and other non-lithium long-duration batteries. Data updated as of Oct 2021. Data does not include investments in lithium-ion battery technologies, hydrogen storage, traditional pumped hydro and others.

Mechanical energy storage

Gravity storage

	How does it work?	Maturity
ENERGY VAULT Enabling a Renewable World	Energy Vault’s technology raises 30-ton bricks to store potential energy. Its original system design included a 120m-tall crane that would stack blocks in a circle around it. Its most recent EVRC system design is a cube that is 45% shorter and looks more like a warehouse. It uses elevators on the sides of the cube, rather than a crane, to raise blocks. It is targeting 2-12 hours storage duration. Many in the industry are sceptical of the feasibility of Energy Vault’s systems. There are concerns about the low energy density and scalability of its systems.	Despite having only one operational site – a 5MW/20MWh pilot plant in Switzerland – Energy Vault is perhaps the world’s most well-known mechanical storage startup due to its huge funding rounds. The company went public via reverse merger in January 2022 at a $1.1 billion valuation. In March 2022, it commenced construction of a 100MWh hour system in China.
gravitricity	Gravitricity’s systems use a series of winches to raise and lower 500-5,000 metric ton weights up and down disused mining shafts 150-1,500m deep. Gravitricity’s current projects are too early stage for it to have outlined target storage durations.	Gravitricity has built a 250kW test demonstrator. In January 2022, the European Investment Bank committed consulting time to help the company develop a Czech-based project. Gravitricity aims to build another 4-8MW test site in 2022. To date, the company has received a total of $2.4 million in grant funding from the UK Government and has raised $3.4 million in unattributed venture funding.

Levelized cost of storage comparison



Source: BloombergNEF. Note: LAES is liquid-air energy storage. Thermal energy excluded from this analysis.

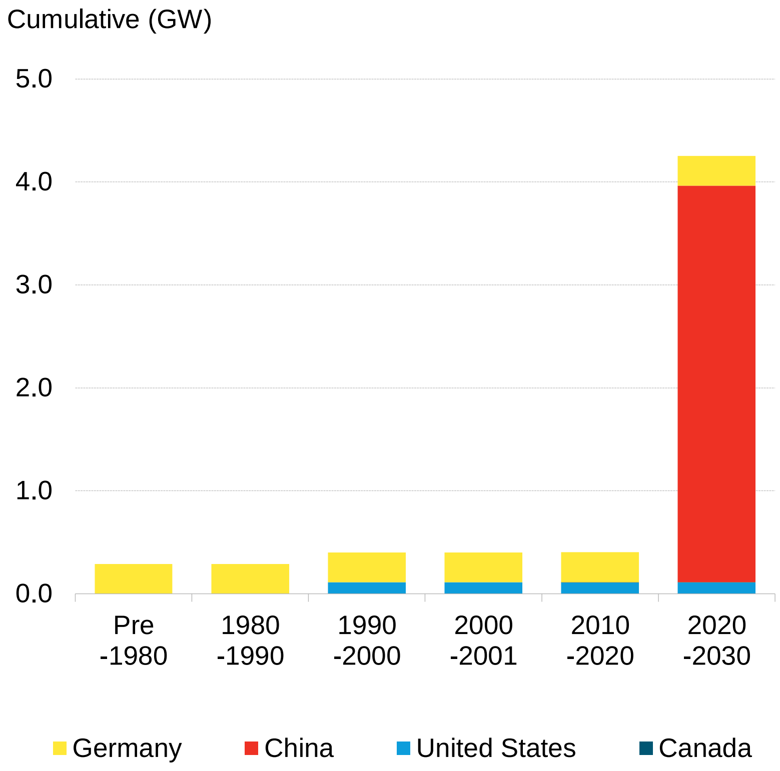
Pumped hydro and compressed air energy storage are currently the only two long-duration energy storage technologies that BNEF estimates undercut lithium-ion on cost at longer durations. Other technologies such as flow batteries or liquid-air energy storage have the potential to be better suited for long-duration storage but must become cheaper if they are to compete.

Mechanical energy storage

Compressed air

	How does it work?	Maturity
Cheesecake Energy	Cheesecake Energy is developing an adiabatic CAES system. CAES systems generate heat when air is compressed. This is usually wasted, meaning that systems must burn natural gas to reheat the air on expansion (to prevent component freezing). Cheesecake instead uses a thermal energy store to store the heat generated during compression. This heat energy can then be used to reheat the compressed air on expansion, replacing the use of natural gas. Cheesecake is reusing old truck engines and gas storage tanks to reduce its capex costs. It says it is targeting medium-duration storage, which is indicative of more than four hours.	Cheesecake Energy was incorporated in 2016 but spent years exploring components suitable for its process. It has gained pace in 2021, raising $1.4 million from Shell Ventures, Imperial College London, and Innovate UK.
HYDROSTOR	Hydrostor is also developing an adiabatic CAES that uses a thermal store to reuse heat, rather than burn natural gas. Rather than using storage tanks like Cheesecake, Hydrostor is storing compressed air in purpose-built caverns where hydrostatic compensation is used to maintain the system at a constant pressure during operation. This means it is using water reservoirs on the surface that connect to the caverns to maintain constant pressure. It is targeting 8 hours of storage duration.	Hydrostor has developed two pilot sites in the single digit MW range and has 1.1GW in capacity (three projects) at some stage of development. The company was founded in 2010 and raised four undisclosed rounds. In January 2022, Goldman Sachs invested $250 million in the company.

Compressed air storage historic build and installation forecast



Source: BloombergNEF

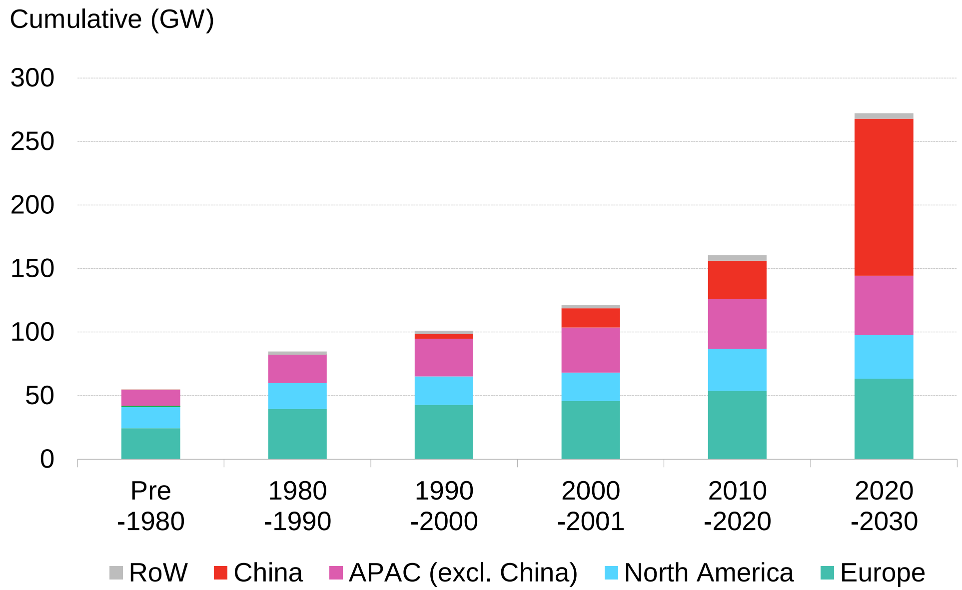
Compressed-air energy storage is the most mature long-duration energy storage technology, besides pumped hydro, having first been deployed in the 1970s in Germany.

Mechanical energy storage

Novel pumped hydro

	How does it work?	Maturity
Quidnet Energy	Quidnet has developed what it calls geomechanical pumped storage. Traditional pumped hydro pumps water uphill where it is stored in a reservoir. To discharge, water flows down the hill where it powers turbines. Quidnet is instead drilling wells near bodies of water and pumping pressurized water into these wells to store energy. To release energy, a pressure valve on the well is released causing water to flow to the surface where it drives a turbine. Quidnet says the geological conditions for its wells are widely available, making it more scalable than traditional pumped hydro systems.	Quidnet currently has five projects located in the US and Canada. It was founded in 2013 and has raised a total of $35 million in funding. Quidnet counts drilling company Schlumberger as an investor – highlighting the potential that oil and gas companies see in alternative energy technologies that could leverage their expertise. In this case, drilling.
RheEnergise	RheEnergise has developed a fluid called R19, 2.5x denser than water, to replace water in pumped hydro systems. By using denser fluid, RheEnergise can shrink the size of pumped hydro systems and also construct them at lower altitudes than currently available for pumped hydro. This makes pumped hydro more scalable and more cost competitive, because the bulk of costs are related to construction. RheEnergise hopes to develop these systems at a 10-50MW scale.	RheEnergise is one of the earliest stage startups covered in this note. The company has not publicly disclosed any private investment but has received £500,000 ($662,570) in grants, mostly it seems from the UK government. The company is also attempting to raise money through crowdfunding.

Pumped hydro storage capacity



Source: BloombergNEF

Thermal energy storage

Thermal storage systems store energy by heating and/or cooling various materials. The heat store discharges, driving turbines through steam production or liquefied gas expansion. Current capacity largely uses molten salt and is co-located with concentrated solar power plants. Thermal storage is valuable because it can be flexibly sited, can provide ancillary services, is suitable for near-term duration requirements of 4-12 hours and novel systems are relatively energy dense. Some systems, however, may endure high energy losses to the environment, meaning they have to regularly cycle. They also have low round-trip efficiencies. While these could be improved by co-producing heat and power, co-production would constrain a plants' ability to sell energy during periods of high power prices.

New approaches and technologies

Sensible heat: Sensible heat storage involves storing energy in a material by increasing the temperature of the material – and then decreasing the temperature to discharge it. Materials used in sensible heat storage tend to be inexpensive and safe (e.g. water, molten salts, sand, rocks, or liquid metals). Current sensible heat storage capacity – for power applications – is largely co-located with concentrated solar power plants.

Latent heat: Latent-heat storage, also known as phase-change storage, stores and releases energy by inducing a phase change in some materials. Liquid-air energy storage is a type of latent-heat storage. It uses electricity to cool gas until it turns into a liquid. This cooled liquid can then be stored in tanks. The liquid can then be reheated into a gaseous state and that energy can power a turbine.

Limitations

Energy losses: Sensible energy storage must be charged and discharged regularly because the energy store loses energy to the environment at a fast rate.

Short lifetimes: Thermal storage systems have lifetimes in the range of 5-15 years, which is similar to electrochemical storage systems. This is shorter than the lifetimes of mechanical systems which last 20-50 years.

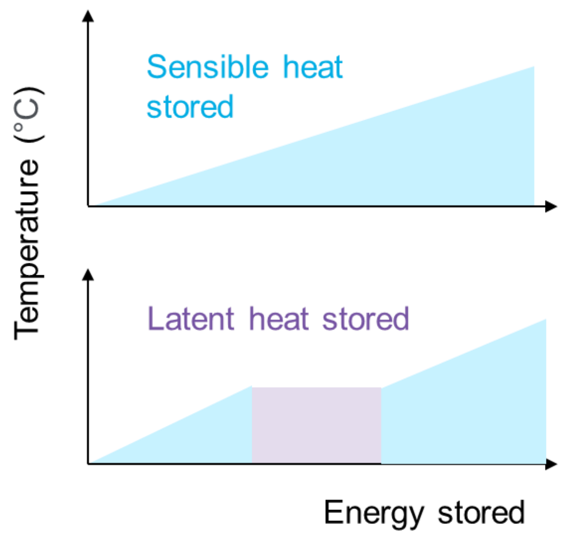
Compressed-air energy storage (CAES) and **liquid-air energy storage** share some characteristics. Both could be classified as either thermal or mechanical energy storage as they incorporate elements of both. Adiabatic CAES storage, mentioned previously, actually uses thermal storage as a component of its process to improve efficiency.

Low-round trip efficiency: When used exclusively for power generation, thermal energy storage tends to have a low round-trip efficiency (about 50%) compared with other technologies discussed in this section.

Potential solutions

Combined heat and power: Thermal energy storage could co-locate with centers of industrial heat demand or district heating networks to boost round trip efficiency. This, however, may constrain how much the system will be able to take advantage of power pricing arbitrage as it will have to discharge during hours of heat demand, rather than just hours of high-power prices.

Sensible versus latent heat storage



Source: BloombergNEF

Thermal energy storage

How does it work?

Maturity

Sensible thermal storage

VAST SOLAR

Vast Solar uses sodium as the heat transfer medium in its novel concentrated solar power plant design, rather than the molten salt used in typical plants. The use of sodium makes heat storage in the plant more modular and less prone to failure. While Vast is focused on solar, molten sodium could be applied generally for energy storage. Sodium as a heat transfer medium has a much larger operating temperature range than molten salt, making it particularly flexible and suitable for solar thermal, where the energy resource is intermittent.

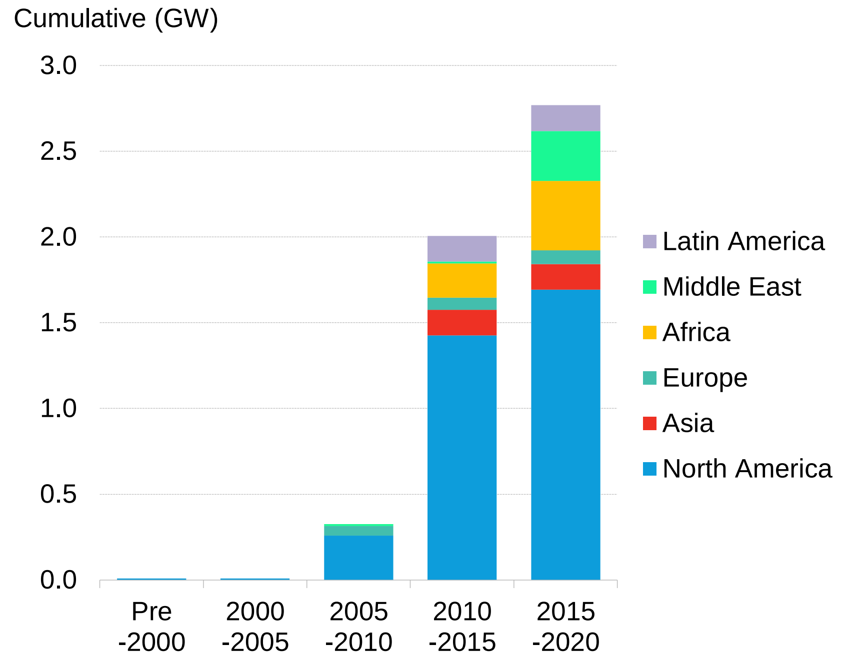
Vast Solar has developed a 1.1MW pilot plant in New South Wales, Australia and is developing a further 50MW plant in Northwest Queensland.

MALTA

Malta uses electricity to run a heat pump that simultaneously heats up molten salt and cools down a liquid coolant. To discharge the energy, the salt and coolant are used to create a temperature differential that dries a heat engine by creating an air vortex. Malta says its process has a round-trip efficiency of 50% for power, but it also produces waste heat that could power district heating networks. Malta says its technology can store energy for 200 hours, but it is initially targeting 10-12 durations.

Malta spun out of Google's X incubator group in 2018. Since then, it has raised $87 million at a reported valuation of $138 million. Investors include Breakthrough Energy and Piva Capital. Malta has signed a co-development partnership with Siemens to make turbomachinery. It is currently developing a 100MW/1,000MWh energy storage site in Spain with funding from the European Innovation Fund. And a similarly sized project in Canada. It will break ground on the first project this year and estimates sites can be built in 18 months.

Sensible heat storage capacity



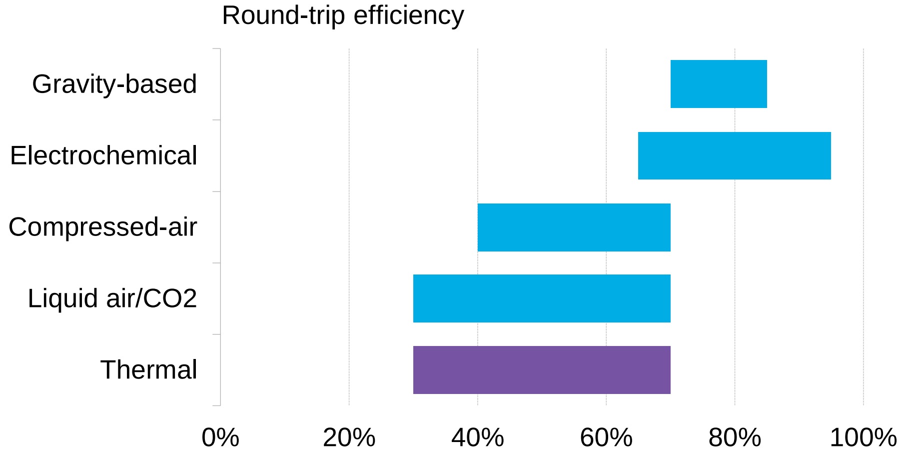
Source: BloombergNEF

Thermal energy storage

Latent: Liquid-air

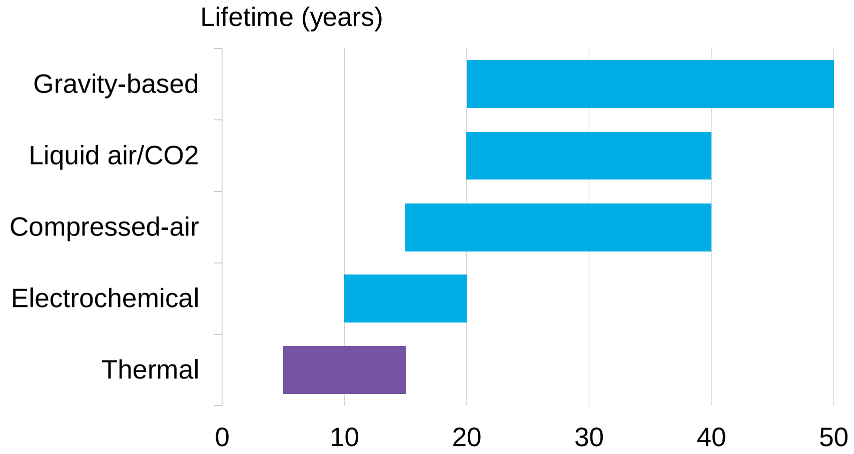
	How does it work?	Maturity
Highview Power	Highview power uses air as a thermal storage medium. The air is cooled down to -196°C using electricity and then stored in low-pressure tanks as liquid. Once exposed to ambient air temperature, the liquid air rapidly turns to gas. This expansion in volume is used to drive a turbine and generate power.	Highview Power is a veteran of thermal energy storage. It commissioned a 350kW/2.5MWh pilot plant in the early 2010s. The company is currently developing another two projects, with total capacity over 100MW/650MWh in Europe. While progress over the last decade has been slow, it is quickening with Highview having raised $83 million since February 2020.
EnergyDome (Ground-breaking energy storage)	EnergyDome uses electricity to cool CO_2 until it liquefies. The liquid CO_2 is then stored in an ambient temperature tank at 70 bar to keep it in a liquid state. To discharge energy, the system heats the liquid CO_2, turning it back into a gaseous state, and that high-pressure gas flows at speed through a turbine generating electricity. The technology has favorable characteristics relative to competing storage technologies including high energy density, flexible siting, no cryogenic temperature requirements and the ability to provide inertia to the grid. It is targeting a storage duration of 4-24 hours.	Founded in 2019, the company has raised $11 million. It has yet to develop a commercial project. The company aims to start building its first power plants based on the technology by 2023.

Round-trip efficiency of energy storage technologies



Source: BloombergNEF, National Renewable Energy Laboratory

Lifetime of different energy storage technologies



Source: BloombergNEF, National Renewable Energy Laboratory

Chemical energy storage

Excess renewable power in future could generate large amounts of hydrogen (H_2) acting as seasonal energy store, making up for weeks to months of low renewables output. Innovation in green H_2 production is needed, but H_2 innovations specific to energy storage for the power industry should focus on power conversion (turbines) and storage (ammonia). Turbines are not an efficient way to convert H_2 to power, but economies of scale mean they will likely be the cheapest path. Turbines need to be adapted to better manage H_2 combustion and reduce NO_x emissions. For countries without natural caverns or depleted gas fields to store H_2, technologies for the production and direct use of ammonia, a H_2 derivative that is easier to store will be important.

New approaches and technologies

Turbines: Fuel cells are more efficient at producing power from H_2 than turbines, but turbines are currently up to an order of magnitude cheaper at utility scale, because they have greater economies of scale.

Ammonia: Countries with suitable geological resources can use depleted gas fields and salt/rock caverns to store H_2. Without these resources, it is likely more economic to convert H_2 to ammonia, which is cheaper to store. Ammonia, however, will need its own turbines for power generation. Another innovation to make ammonia use more competitive could be the direct electrochemical production of ammonia – rather than producing H_2 as an intermediary step. This is, however, extremely early stage.

Limitations

Higher levels of NO_x: Combusted H_2 burns hotter than natural gas resulting in NO_x production, a pollutant and GHG. NO_x can be captured with selective catalytic reduction (SCR) equipment but these add to both the opex and capex of a plant. While ammonia burns at a lower temperature than gas – an entirely separate challenge – it also produces NO_x when combusted.

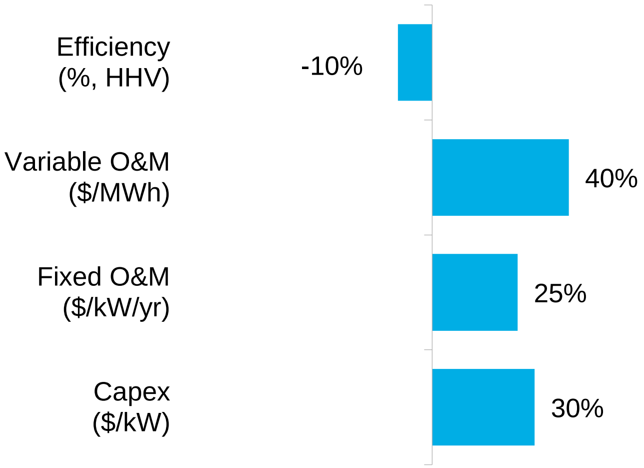
H_2 is leakier and combusts differently: H_2 is difficult to handle because it is such a small molecule and prone to leaking. It will require higher specification equipment than natural gas turbines to manage. Flames also propagate through hydrogen six times faster than natural gas, increasing the risk that flames flow upstream to the H_2 source, damaging hardware. Ammonia on the other hand burns much slower than natural gas.

Water consumption: Some turbines are capable of burning 100% pure H2 today but consume large amounts of water to control combustion temperature. This adds to the cost, corrodes equipment and wastes water.

Potential solutions

Selective catalytic reduction: Lowering the cost and improving the performance of SCR equipment would make hydrogen-fired turbines more competitive. Current SCR equipment can add 20% to the capex of a gas turbine and the parasitic load of running the equipment can reduce the efficiency by 10%.

Impacts of full hydrogen upgrades on natural gas-fired turbine power plant, 2021



Source: BloombergNEF

New power capacity

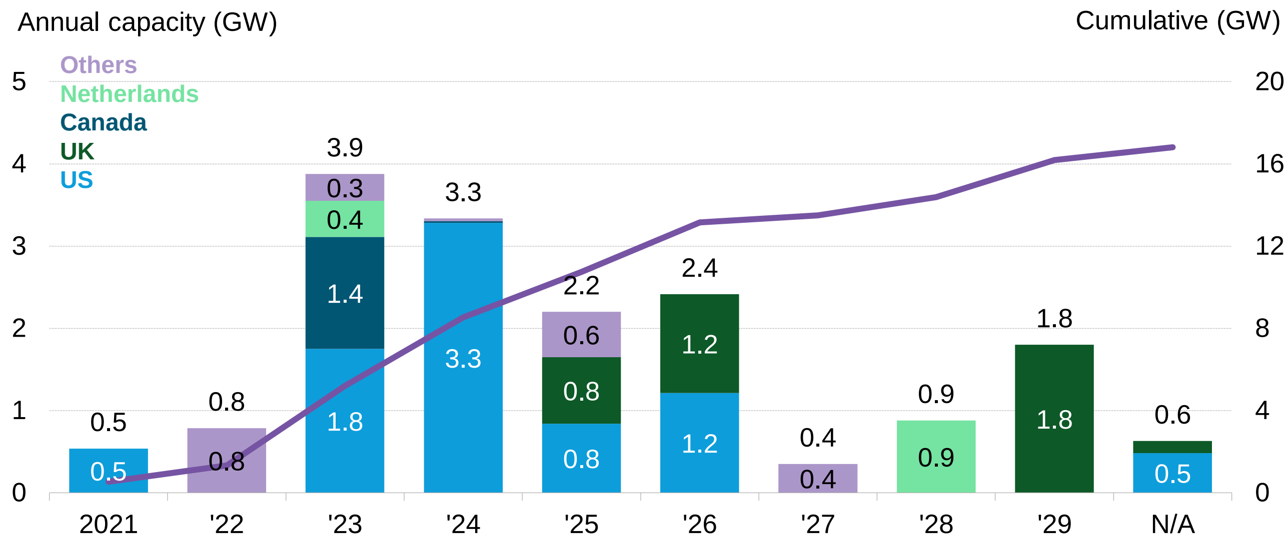
Chemical energy storage

Hydrogen turbines

	How does it work?	Maturity
SIEMENS	Siemens announced in 2020 that some of its smaller auto-derivative turbines (about 30-60MW) were already capable of producing power using exclusively H_2. These turbines, however, could only consume pure H_2 by using 20,000 liters of water per hour to control the temperature of combustion. This water is an added expense, corrodes equipment and is a scare resource. Siemens is focused on reducing the water consumption in the process.	In 2020, Siemens published a white paper saying that it was aiming to transition all its turbines to be capable of producing power using 100% pure H_2 by 2030.
MITSUBISHI	In 2018, Mitsubishi Power developed a turbine capable of blending up to 30% H_2 by volume, which reduces the emissions of the plant by 10%. It is also working to develop a 100% H_2-fired turbine. Innovation is largely focused on developing a new fuel nozzle to prevent flashback towards the fuel source, which could result in catastrophic failure.	Mitsubishi wants to commercialize its H_2 turbine by 2025. Mitsubishi has partnered with Vattenfall to retrofit a gas turbine at one of Vattenfall's power plants in the Netherlands by 2027. Each turbine at the site has 440MW of capacity. Mitsubishi has also secured contracts to sell two M501JAC turbines (each with 330-430MW) to Utah, US and another pair to Alberta, Canada.

BNEF did not profile startups for this section because BNEF believes that – except for reducing the cost of hydrogen/ammonia production – turbines are the most economic approach to making chemical energy storage more competitive. These innovations are driven by turbine makers such as Mitsubishi Power, Siemens and GE.

Announced pipeline of H_2-ready power projects by country



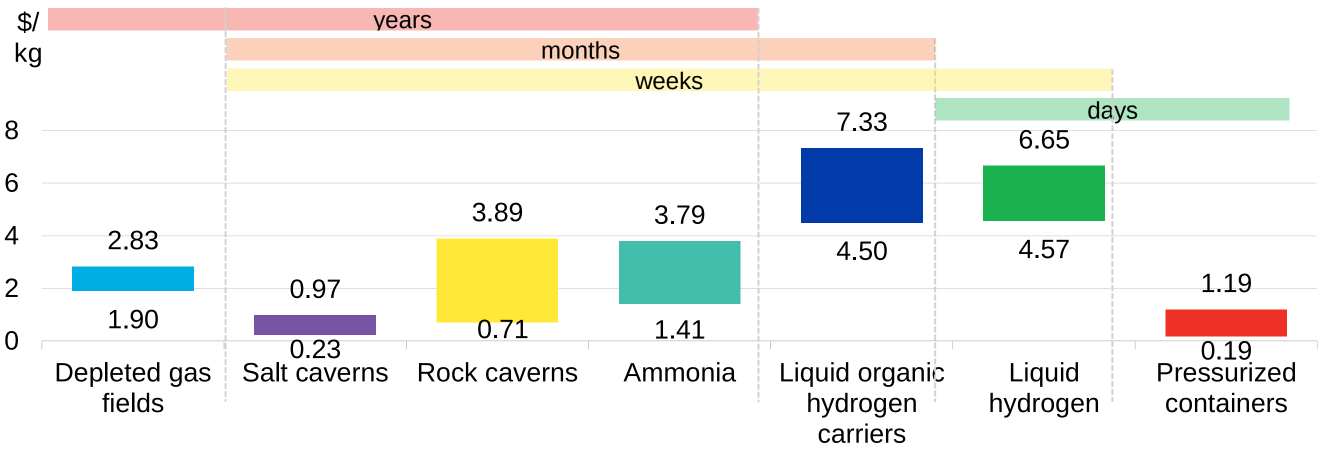
Source: BloombergNEF

Chemical energy storage

		How does it work?	Maturity
Ammonia	MITSUBISHI	Mitsubishi Power is also developing a 40MW turbine that can combust 100% ammonia. The turbine will be an adaptation of its H-25 gas turbine series. In 2017, Mitsubishi initially looked at an ammonia turbine that cracked ammonia (NH3) into hydrogen and nitrogen, and subsequently combusted the hydrogen while capturing the nitrogen. This was to prevent the production of NOx during ammonia combustion. The more recent development of a 100% ammonia turbine suggests that Mitsubishi may view this as a more viable technology route.	Mitsubishi is aiming to commercialize its ammonia turbine 'in or around' 2025. Mitsubishi's activity in ammonia turbines is largely driven by Japan's affinity for ammonia as a zero-carbon fuel – due largely to poor H2 storage resources and expensive renewable power.
	IHI	IHI announced in March 2021 that it had achieved a 70% blending of ammonia into a 2kW class turbine as part of the development.	Like Mitsubishi, IHI is also targeting a 2025 launch date for an ammonia turbine.
	MONASH University	Researchers at Monash University in Australia are attempting to address the two main challenges with direct electrochemical production of ammonia: low production rates and depletion of the reaction cell. In June 2021, they announced results stating that the use of phosphonium salt as a proton source slowed the depletion of the reaction cell. The production rate, however, remained far lower than would be needed to generate at an industrial scale.	This technology is a lab project that has yet to demonstrate any real commercial benefits. Researchers are exploring the idea because direct production of ammonia could theoretically be more flexible, use less pure feedstock, and have greater efficiency than producing ammonia with hydrogen via a Haber-Bosch process – how green ammonia is currently produced.

Storing H_2 is more expensive than natural gas because it takes up three to four times more volume and is more energy intensive to liquefy. For weeks long storage, salt/rock caverns and depleted gas fields will the best option in regions that have favorable geographies (Europe, North America, Middle East, Russia, Australia). Ammonia could be the cheapest option where natural storage is not available.

Levelized cost of hydrogen storage and typical storage duration, 2019



Source: BloombergNEF

Power grid technology

Power grid technology

Grid and demand-side technologies that improve efficiency and reduce the curtailment of variable renewables are key technologies in helping to deliver a least-cost zero-carbon power system. These technologies must help grid operators optimize power flow, manage inertia, integrate distributed solar, storage and EVs, and build more efficient power lines and grid equipment. In the near term, sensors and software can reduce grid congestion, through managing power flow control and bi-directional power. Longer-term we need to invent new electronics and materials.

What do we need?

Decarbonizing the power system will result in more power generation on the distribution grid, two-way power flows, location and time mismatches between clean power generation and demand, and increased grid congestion. Some of this congestion can be avoided by re-dispatching generation but this comes at a significant cost. In 2020, grid congestion cost Texas's system operator (ERCOT) $1.4 billion. To improve performance and limit cost increases, the grid will need innovation in three key areas:

1. **Power-flow optimization** such as the use of real-time grid data to model and optimize power flows
2. **Distributed energy resource (DER) integration** such as technologies that support two-way power flows
3. **Next-generation components** such as upgrading decades-old cables and grid equipment to newer technologies.

What should we tackle first?

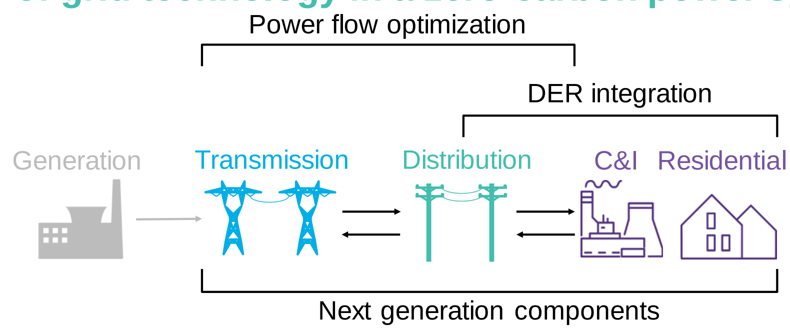
First, grid operators should enhance the capacity of current transmission and distribution grids with sensors, optimization software and grid controls. In parallel, software platforms can help to integrate DERs to support grid balancing and decarbonization. Physical infrastructure change will take longer but is as important as optimizing today's grids. New electrical equipment, such as smart electric panels, can support flexibility services using DERs, and improve efficiency. In the long term, grid material innovations may bring power losses down to negligible levels.

Why is it hard?

Most technologies discussed in this section are already developed, but face adoption risks and regulatory hurdles. Some grid constraints introduced by decarbonization can be mitigated by continued expansion of legacy grids, making it hard to wean off traditional investment patterns even though they are characterized by long installation times and the possibility of higher system costs. Long turnover times also slow the adoption of new technologies, as grid assets last about 40 years. There is also a misalignment between utility investment incentives and market participants, leading to inadequate rewards for new technologies. Grid regulation often provides returns on capital assets such as wires and poles, and not grid efficiency.

Innovation requires partnerships with manufacturers and grid operators, known to be risk-averse, and may inhibit scaling technologies. New line materials, such as superconductors, can cut power loss but need to be at very low temperatures, so are costly.

The role of grid technology in a zero-carbon power system



Source: BloombergNEF. Note: C&I (Commercial & Industrial), DER (Distributed Energy Resource). Two-way arrows indicate a bi-directional flow of power.

Power-flow optimization

Over 1,260GW of zero-carbon resources, such as solar, wind and battery storage, are backlogged in US interconnection queues as of 2021, according to a study by the Berkeley Lab. This is more than the entire US generation fleet. We could – and need to – build out grid infrastructure. But often a cheaper near-term solution is to use the existing grid more intelligently (i.e. power-flow optimization). Innovations here include using sensors, software and power electronics to control and transport more power on existing grid assets. New technologies can also help ensure system stability using fast frequency response, avoiding potential blackouts. As the collected grid data and number of variables increases, high-performance computing (HPC) may be useful for analytics. The scope of fully scaled optimization technologies are limited by a lack of incentives for efficiency in countries. Performance-based revenue mechanisms, versus rate-basing capital assets, may better support efficiency.

New approaches and technologies

Modeling power flow: Grid capacity is usually rated statically, using conservative estimates. Technologies including sensors, dynamic line rating (DLR) and topology optimization software, allow grid operators to optimize power flow using real-time data to maximize grid use. DLR finds line capacity based on ambient factors and line conditions.

Controlling power flow: Optimization models need hardware to alter power flow. Smart switches, feeder automation and static compensators can control voltage and circuit feeders to maximize grid capacity.

Managing inertia: Inertia, the energy stored in spinning generators, helps stabilize frequency if a power plant fails. Most renewables do not inherently provide inertia. To solve this problem, in a zero-emissions grid, operators must be able to accurately track the amount of inertia present in their system versus making conservative estimates. Grid-forming inverters can regulate voltage and frequency providing synthetic inertia. Ultracapacitors, fast-response and power-intense storage devices, also create synthetic inertia.

Limitations

Computational intensity: As utilities collect more data and data variables increase, grid analytics will need more computing power.

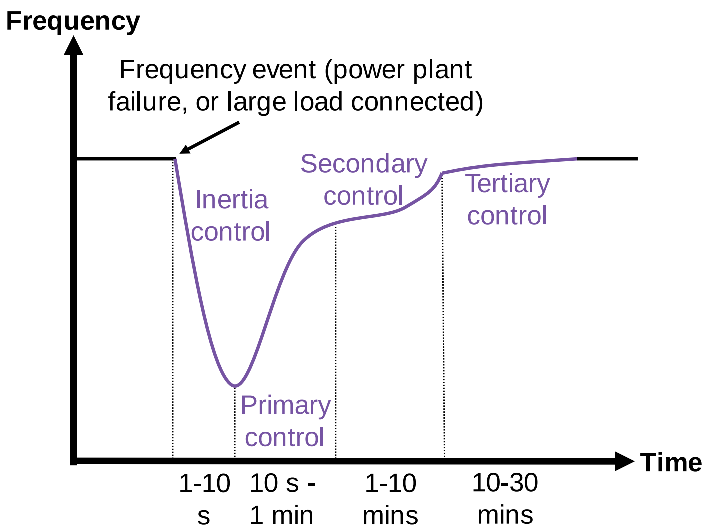
Revenue mechanisms: In countries with cost-plus grid revenue mechanisms, grid operators make a return on capital assets such as lines. This can fail to recognize the role of digital technologies due to their lower capital costs.

Potential solutions

HPC: As more data is collected, high-performance computing (HPC) could support the need for multi-variable, dynamic grid optimization. HPC is faster than regular computers by processing equations in parallel.

Efficiency incentives: Regulations allowing grid operators to rate-base software spending and make a return on operational savings can incentivize more efficient grid operations.

Role of inertia in frequency response



Source: BloombergNEF. Notes: This is a conceptual diagram and dimensions are not to scale. Mins (minutes), s (seconds).

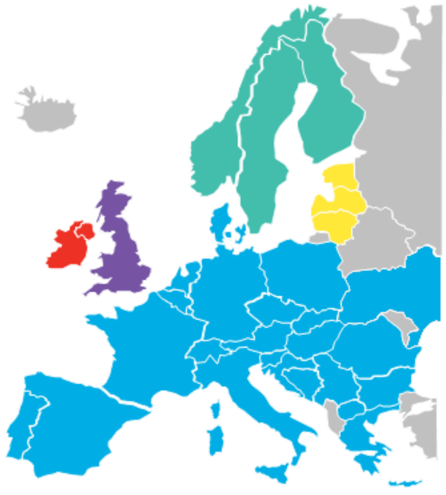
Power-flow optimization

BNEF pioneers

Managing inertia

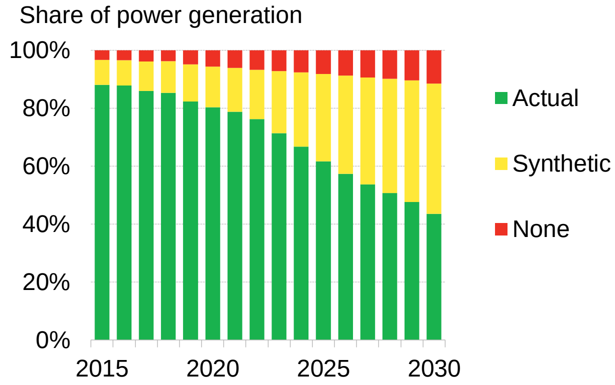
		How does it work?	Maturity
Measurement	reactive technologies	Reactive's service is providing real-time inertia data on the transmission and distribution grid. The startup uses hardware and software to measure grid inertia, as opposed to grid operators' usual method of using models to estimate it. Reactive claims the distribution grid provides up to 30% of grid inertia, such as from pumps. With data on distribution-side inertia, grid operators can avoid curtailing renewables and call on less thermal power for frequency response. Reactive will reportedly enable savings of £72 million ($94 million) for the UK's National Grid over five years by cutting curtailment and thermal backup costs.	Reactive's technology is protected by over 150 patents. In its latest investment round in 2021, it raised $15 million in Series C funding with investors including Breakthrough Energy Ventures. Reactive's biggest customer today is National Grid, with which it signed a six-year, £6-million contract. It wants to sell a new technology to a risk-averse power sector. The coming year will show Reactive's ability to sign deals and scale pilots to commercial projects.
Synthetic inertia	SYNVERTEC	Synvertec developed a control algorithm, Sychronverter, that mimics the properties of a spinning generator. The software integrates with inverters used for renewable energy, storage and EVs. This turns the inverters into grid-stabilizing devices that provide synthetic inertia, and support voltage and frequency regulation.	The control algorithm was developed at the Tel Aviv University and patented in 2014. Since then, it has received interest in Europe, Asia and the US. Synvertec received a 2.67 million euro grant from Horizon 2020 in 2016, and in 2020 it raised $1.5 million from China Light & Power – OSEG to support research and expansion in Asia. In 2021, it joined forces with the US company Rhombus Energy Solutions to develop the Sychronverter using Synvertec's algorithm and Rhombus's smart inverter. The software requires no inverter design or infrastructure changes, which may encourage grid operators to pilot.

Synchronous regions of Europe



Source: ENTSO-E, BloombergNEF. Notes: Synchronous regions operate at a synchronized grid frequency, and have interconnected transmission grid operators.

Percentage of inertia-providing generation in Europe



Source: BloombergNEF European Energy Transition Outlook 2021, Ambitious Policy Scenario

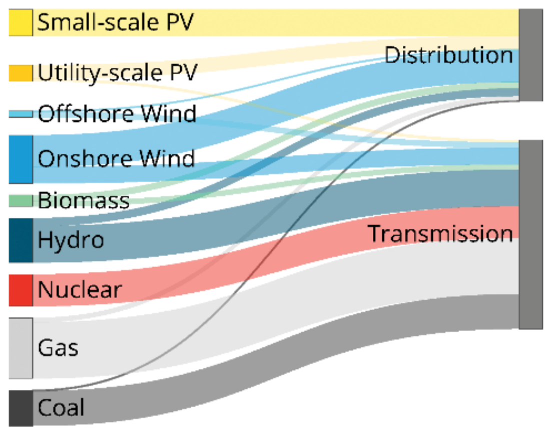
Power grid technology

Power-flow optimization

BNEF pioneers

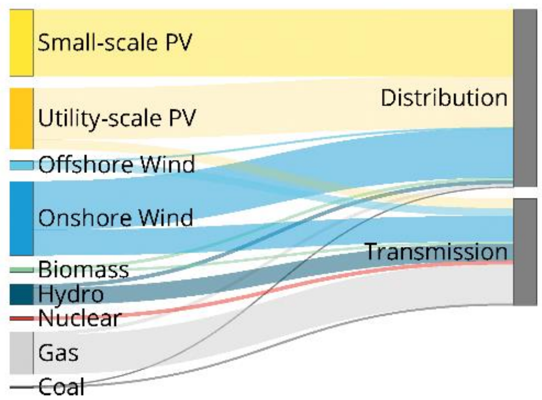
			How does it work?	Maturity
Managing inertia	Synthetic inertia	SKELETON TECHNOLOGIES	Skeleton Technologies develops and manufactures ultracapacitors based on a curved graphene design. Its technology can be used to stabilize grid frequency and provide synthetic inertia. The ultracapacitor reportedly supports seven times higher conductivity than regular ultracapacitors (that use activated carbons), and a four-fold increase in power density.	In January 2022, Skeleton Technologies closed a 37.6 million euro Series D financing round. It has raised a total of 205.3 million euros over 10 rounds, with investors such as InnoEnergy and Marubeni Corporation. The startup will use the funds to ramp up manufacturing, using its patented curved graphene design.
Modeling power flow	Dynamic line rating	LINEVISION	LineVision makes a device that collects overhead line data, such as movement and temperature. It collects the data using lidar and an electromagnetic field, and helps grid operators see where there is untapped grid capacity. It is placed at the bottom of transmission towers, making it cheaper and safer than installing devices on the line itself, which requires planned downtime or live-line work. Linevision says this can unlock 15-40% more grid capacity versus static ratings.	LineVision was founded in 2018. It raised $12.5 million in a 2021 Series B, with investors including National Grid Partners, Clean Energy Ventures and UP Partners. It has secured deals with US utilities, including National Grid, Dominion Energy and Xcel Energy, and works with European utilities in the Farcross Project, which aims to support cross-border grids in Europe.
		Ampacimon	Ampacimon develops DLR sensors and software for the transmission and distribution grid. Using real-time data from its sensors attached to power lines, the startup's software monitors and forecasts grid capacity. For example, it helped a European system operator tap 50% more grid capacity.	Ampacimon secured one funding round of 4 million euros in August 2020, which it is using to develop its system for distribution grids. It has contracts with utilities including Enel, NYPA and Tepco. The startup's sensor technology is patented, based on research carried out since 2003 at the University of Liège.

Connection voltage of generation resources in Europe in 2020



Source: BloombergNEF

Connection voltage of generation resources in Europe, 2050

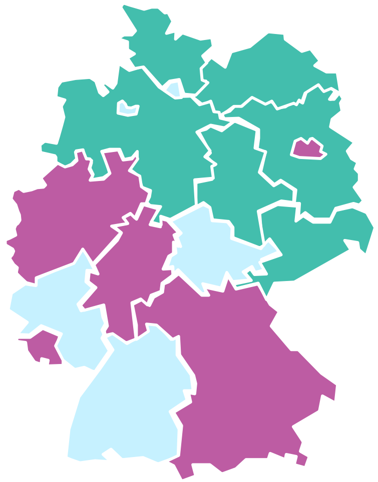


Source: BloombergNEF

Power-flow optimization

			How does it work?	Maturity
Modeling power flow	Topology optimization	newgrid	NewGrid’s software optimizes transmission topology. Grids have thousands of circuit-breakers, but they are usually not controlled based on real-time data. Doing so is a complex mathematical problem. For example, the US Mid-Atlantic regional transmission operator’s (PJM) circuit breakers add up to trillions of possible combinations. NewGrid’s software uses mixed-integer programing to optimize circuit-breaker controls. This can reportedly cut congestion by 50% and wind curtailment by 75%.	The startup was founded in 2015, raising $0.8 million as of August 2021. It has demonstrated its system in simulations using grid data from partners including PJM, the US Midcontinent Independent System Operator, and National Grid. NewGrid is a member of the US incubator Greentown Labs, and the US Working for Advanced Transmission Technologies (WATT) Coalition. A growing focus in the US government on high-capacity transmission may support NewGrid’s pipeline. Its software sales may benefit from the expansion of grid hardware, such as LineVision’s and SmartWires’, that support data collection and power-flow control.
	Controlling power flow	SMART WIRES	Smart Wires uses power electronics hardware and software to control power flow to maximize transmission grid capacity. Its technology, SmartValve, is a static synchronous series compensator that alters line voltage. It pushes power from overloaded lines, and pulls power to lines with spare capacity.	In early 2021 National Grid installed 48 SmartValves in the UK, creating 1.5GW extra capacity – enough to power one million homes with renewable energy. The utility scaled up its deployment at the end of 2021 to unlock an additional 500MW. In Smart Wires’ latest funding round in 2019, the startup raised $75 million in Series E funding, and in 2021 it became a listed company on Nasdaq First North Growth.
		SWITCHED SOURCE	Switched Source makes a device to control power flow on the distribution grid. It routes power between circuit feeders to capture more distribution grid capacity. The startup says this can reduce capex on transformers and new lines, and increase solar hosting capacity up to two-fold.	The startup was founded in 2015. It has received grants, of which the largest has been $8.56 million as part of the US Advanced Research Projects Agency-Energy’s (ARPA-E) Scaleup Launch Pad program in 2019. Switched Source is also a 2021 alumni of 35 Mules, an innovation incubator run by Florida Power & Light (FPL).

Expected energy balance in Germany, 2030



- Generation surplus
- Balance
- Load surplus

Source: BloombergNEF, German Grid Development Plan.

In Germany, there is a north-south divide in generation-rich areas and demand-rich areas, which constrains the transmission system.

Distributed energy resource integration

A key challenge in grid decarbonization is integrating distributed energy resources (DERs), such as rooftop solar and electric vehicles (EVs), while maintaining grid reliability. In BNEF's New Energy Outlook, global cumulative capacity of small-scale PV triples between 2021-2030, reaching 823GW. New software platforms, such as vehicle-to-grid (V2G) and virtual power plants (VPPs), help coordinate DERs and provide grid services. In addition to software, smart electric panels can support load flexibility by controlling electrical circuits. Integrating DERs involves using data from devices, raising data security and privacy concerns. Encryption and quantum cryptography may help avoid unauthorized access.

New approaches and technologies

EV charging: Smart charging, the ability to control when EVs charge, can be used to charge EVs outside of peak demand times to support the grid, and coincide with low power costs and emissions. Bi-directional charging (V2G) can be used to discharge an EV's battery to the grid to further limit peak loads and participate in grid services.

DER software: Innovations today are in distributed energy resource management systems (Derms) and in DR. Derms use AI to monitor and integrate DERs to provide flexibility services. DR software tailors load to power supply. DR is not new, but AI innovations can optimize and automate DR for zero-carbon power uptake. VPPs help to aggregate and remotely manage multiple DERs on one platform, to provide grid services. In the future, peer-to-peer (P2P) trading platforms may support transactive energy, a potential market model in which prosumers – producers and consumers – provide grid services and trade power.

Smart panels: Electric panels route power from the grid to a building's circuits. Smart panels collect data on individual circuits, such as rooms in a home, and use digital circuit breakers to control their power flow. With this circuit-level control, smart panels can support load flexibility.

Limitations

Digital security: Cyber-attack threats and privacy issues grow as more devices connect to the grid. Privacy of data, such as billing, power use, location and identity comes into question with EV and DER software. For example, 25 Tesla vehicles were hacked in January 2022.

Communication: Communication protocols and links (channels for data transfer) need to be standardized for efficient control of assets.

V2G costs: The high costs of EVs and two-way chargers, and added costs of EV battery degradation, may deter consumers taking part in V2G programs when returns are unclear.

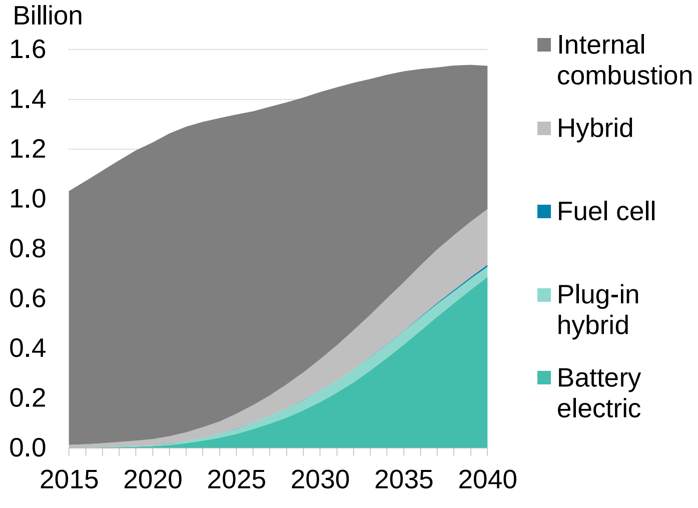
Potential solutions

Encryption: Encryption, such as on a blockchain, can help leverage more data while retaining privacy. Encryption means encoding data to avoid unauthorized access.

Quantum security: Quantum cryptography leverages quantum mechanical properties to protect data. For example, ID Quantique provides quantum key distribution (secure communications), and network encryption.

Battery data: More real-world EV battery data is needed to understand degradation impacts from driving, grid services and other factors. This can be used to create a clear proposition to track degradation and replace batteries.

Global passenger vehicle fleet by drivetrain

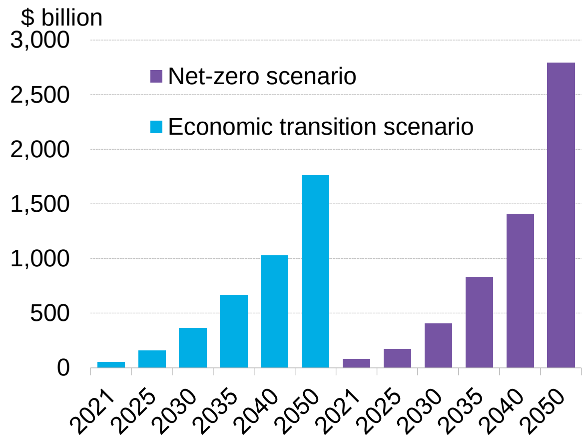


Source: BloombergNEF. See: Electric Vehicle Outlook 2022

Distributed energy resource integration

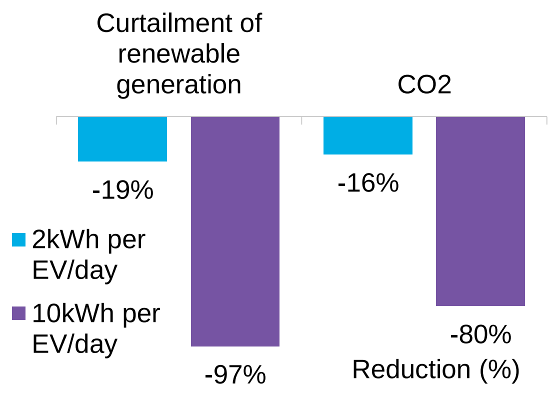
EV charging		Company	How does it work?	Maturity
BNEF pioneers	V2G	Nuvve	Nuvve develops a V2G platform to use EV batteries for grid services. It estimates that its system can annually offset 250kg carbon emissions per car. If the system is used on 10% of the passenger EVs sold in 2025 alone (BNEF projects 14 million), this could cut emissions by nearly 400,000 tons a year – the emissions of about 50,000 US households.	Nuvve raised about $62 million going public in a 2021 reverse merger. It has a range of partnerships, including charging manufacturers (Wallbox), OEM partners (BYD, Bluebird) and utilities (SDG&E, ConEd). It has a joint venture with EDF called Dreev to develop V2G services, and with Stonepeak called Levo, aimed at financing electric buses. To avoid added consumer costs for V2G functions two-way charger costs need to fall, or V2G tech needs to be integrated into EVs.
BNEF pioneers	V2G	WiTricity	Witricity develops wireless EV-charging based on magnetic resonance technology. This can be used with V2G systems, and may make V2G programs more convenient for EV owners.	WiTricity has raised $52 million as of February 2021. Its technology is patented, and it has licensing agreements with firms such as Toyota, Delphi and Daihen. In 2018, WiTricity and Honda co-launched a wireless V2G system, using WiTricity's charging and Honda's V2G software. While there is a lack of standardization for wireless charging, WiTricity is collaborating with carmakers to develop global standards.
	Smart-charging	ev.energy	ev.energy has created a smart-charging platform. It optimizes EV charging based on power prices and emissions. ev.energy licenses its platform to utilities and charging manufacturers as a flexibility resource.	The startup completed a $12.8 million Series A funding round in February 2022. Investors include ArcTern Ventures, Energy Impact Partners and E.ON's VC arm, Future Energy Ventures. In 2021, E.ON partnered with ev.energy to launch an off-peak EV tariff in the UK. The startup has over 50,000 platform users in the US, Europe and Australia. ev.energy licenses its platform to utilities and charging manufacturers as a flexibility resource.

Cumulative investment in EV charging hardware



Source: BloombergNEF

Reduction in renewables curtailment and CO2 emissions in Germany due to flexible charging, 2040

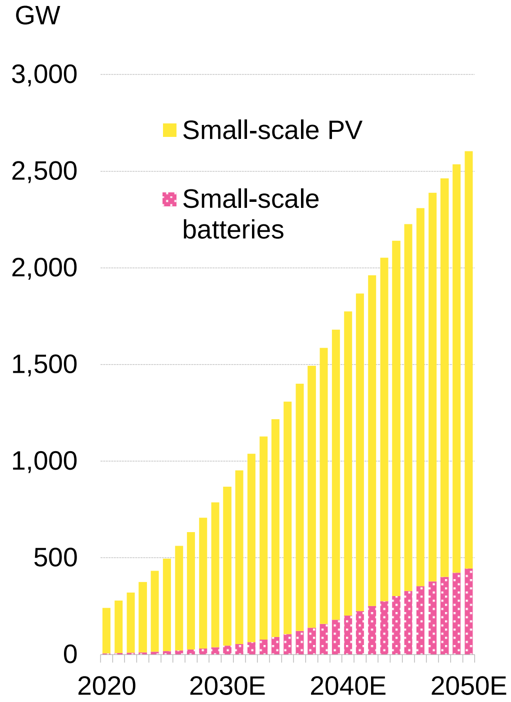


Source: BloombergNEF. Note: Assumes EVs are 76% of passenger vehicles, 58% of commercial vehicles.

Distributed energy resource integration

DER software		How does it work?	Maturity
Derms (BNEF pioneers)	AutoGrid	AutoGrid makes an AI-based software platform to manage DERs. It supports grid flexibility services with DER management, DR and storage management on one platform.	AutoGrid is set to be acquired by Schneider Electric by the end of Q3 2022. Its latest funding round was in in 2021, when it raised $85 million in Series D funding, with investors including SE Ventures, Microsoft and Climate Innovation Fund. AutoGrid has over 50 customers in more than 10 countries in the US, Europe and Asia.
P2P (BNEF pioneers)	LO3 ENERGY	LO3 Energy makes a P2P power-trading platform. It uses blockchain to create an audit trail, and can automate transactions.	LO3 has raised a total of $16.8 million in funding over three rounds. Most recently, in 2021 it raised $11 million in a Series B, from investors including Shell Ventures and Sumitomo Corporation. LO3 has done pilots with utilities, such as Green Mountain Power. In the long term, if decentralized energy growth leads to transactive energy markets, LO3's platform is well-positioned to help track and automate P2P trading.
DR	OhmConnect	OhmConnect develops a DR software platform. It aggregates flexible demand into a VPP.	OhmConnect has raised a total of $28.5 million since its founding in 2013, with investors including Sidewalk Infrastructure Partners (SIP), 500 Startups and Elemental Excelerator. In 2020, SIP partnered with OhmConnect to develop a 550MW VPP by 2023. The VPP will use flexible loads, such as smart thermostats, to provide grid services. SIP invested $80 million in the VPP, and $20 million in Series C funding in OhmConnect.
DR (BNEF pioneers)	BLUE FRONTIER	Blue Frontier makes air conditioning (AC) units for commercial buildings that support load-shifting. The unit reportedly cuts cooling power use by up to 90% by using liquid desiccant instead of a refrigerant vapor-compression cycle. Its efficiency, combined with its load-shifting capability, enables the unit to cut emissions by over 85%.	In 2021, Blue Frontier closed a $1.1 million seed-financing round led by VoLo Earth Ventures. The startup is in the pilot stage, but its unit will become more important as cooling demands grow. BNEF's Economic Transition Scenario forecasts global AC energy consumption to surpass 4,500TWh, or 12.8% of worldwide power demand, by 2050 based on current technologies.

Global cumulative installed capacity of small-scale solar PV and batteries



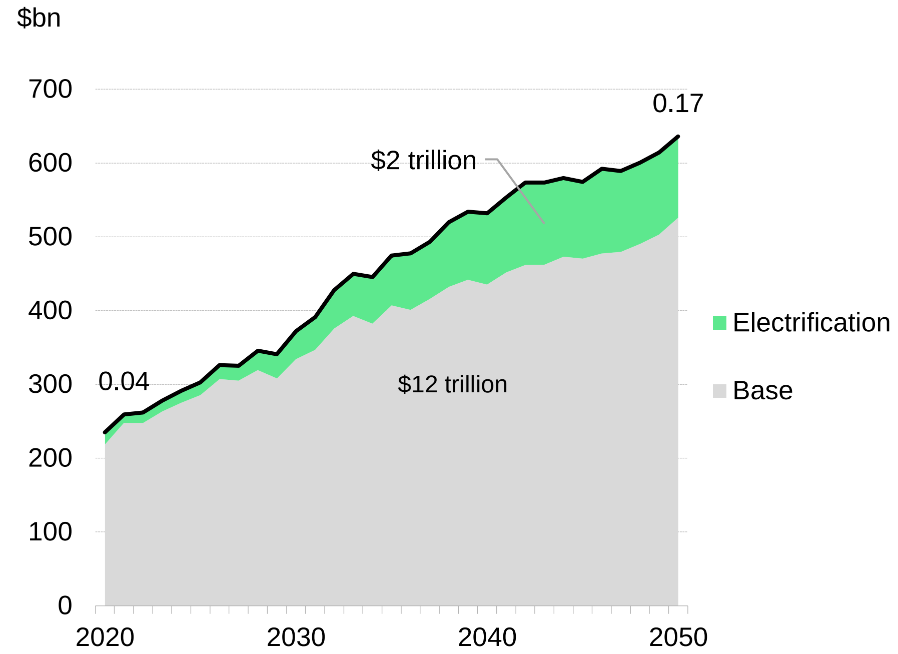
Source: BloombergNEF. Note: GW (Gigawatt), solar PV (Solar Photovoltaic)

As DERs grow, DER software platforms help monitor, analyze and integrate them on the grid. These platforms also track grid services provided DERs to accurately reward DER owners.

Distributed energy resource integration

Smart panels	How does it work?	Maturity
ATOM POWER	Atom Power makes smart panels for commercial, industrial and residential customers. Its digital circuit breakers control current flowing through a system, and when the circuit is disconnected.	Atom Power's most recent funding was a $17.8 million Series B round in June 2020, with investors including ABB Technology Ventures and Valor Equity Partners. In 2019, the startup's solid-state circuit breaker was the first to be listed by certification body Underwriters Laboratory, which boosts its credibility.
SPAN	Span develops a smart electric panel and products to go with it, such as EV chargers. The panel also supports whole-home DR.	Span raised $90 million in funding in March 2022. This will partially go to developing products that use the startup's panel. Coupling products with the panel may boost Span's sales. In 2021, Span partnered with Green Mountain Power (GMP) to launch a pilot program using its smart panels for DR. GMP offered 100 customers a free Span panel to support both DR and home electrification.

Global grid investment



Source: BloombergNEF. Note: Electrification includes connection costs and network reinforcement costs associated with new heating, cooling and transportation demand. For methodology see Section 5 here (or here on terminal).

By more efficiently managing devices, smart panels enable electrification, such as installing EV chargers, without panel-overloading. This may help utilities reduce grid costs related to electrification of energy consumption, including transport, heating and cooling,

Next-generation components

Wires and switches are the foundational components of the power system. The global power system consists of 74 million kilometers of power lines and 710,000 substations. New materials, including line coating and conductors, and advanced switches can help boost capacity and reduce power loss. Switch advancements are also important to allow grids to respond quickly to faults and renewable fluctuations, which improves system reliability. Coatings reduce cable losses by efficiently cooling them, and superconductors can be used to make new lines with no resistance. Superconductors operate at very low temperatures, which makes them impractical for commercial use today. But advancements in room-temperature superconductors may support future projects.

New approaches and technologies

New line materials: New coatings, such as photonic materials that control light, can help cool lines to reduce power loss. While new conductors move power with lower losses by reducing line resistance. Super-conductors are especially interesting as they can eliminate resistance. Entso-E says that high-temperature superconductors (HTS) can carry five times the current of a copper cable.

Advanced switches: Switches support fast reactions and electrical efficiency on the grid. Innovations include hybrid switches and micro electro-mechanical systems (MEMS). Hybrid switches use semiconductors and mechanical parts for fast response times and have lower losses than solid-state switches (which only use semiconductors). MEMS switches use new processing technology to make smaller, more efficient versions of today's switches.

Limitations

Cooling costs: HTS needs to be cooled with liquid nitrogen or gaseous helium. In 2019, scientists at the Max Planck Institute for Chemistry reportedly operated a HTS, based on the material lanthanum hydride, at a record high temperature of -23 degrees Celsius. But this is still too low for practical grid use.

Grid turnover: The adoption of new lines depends on turnover rates of power grids, and willingness of line manufacturers and grid operators to try new technologies. This may inhibit startup scaling.

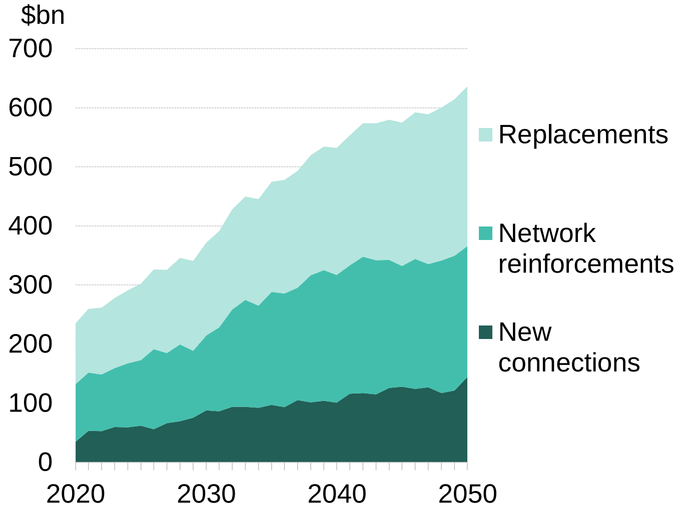
Potential solutions

Room-temperature superconductors: While still in the research phase, these would be able to reduce the need for line-cooling.

Researchers at the University of Rochester made a material using carbon, hydrogen and sulfur that reportedly superconducts at 58 degrees Fahrenheit (14.4 degrees Celsius). But the material still needs to be under very high pressure. Scientists continue to research materials that superconduct in ambient pressure and temperature.

Growing grid needs: Many grids are reaching end-of-life and need to be replaced, which is a potential opportunity for startups to sell and scale new grid materials. BNEF estimates that at least $14 trillion needs to be invested in the grid worldwide by 2050 to support an evolved power system. According to the American Society of Civil Engineers, most US lines were constructed in 1950-1970, with a 50-year lifetime.

Global annual grid investment

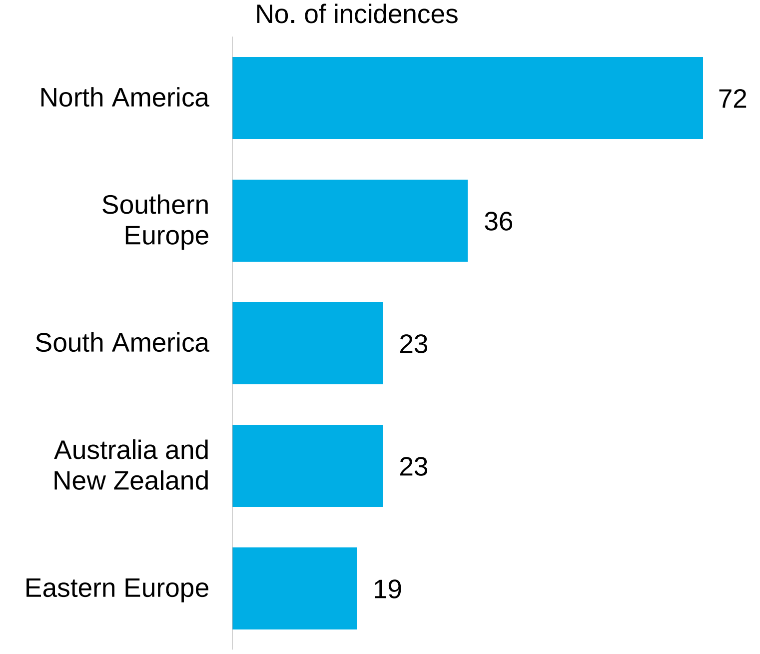


Source: BloombergNEF. See: Power Grid Long-term Outlook.

Next-generation components

New line materials	Conductors		How does it work?	Maturity
		VEIR	Veir develops superconducting transmission lines using HTS tape and evaporative cryogenic cooling. The technology can reportedly increase the amount of power transmitted on a line five-fold. It enhances grid capacity with higher ampacity (max current), lower losses and ultra-low heat insulation.	Veir raised $10 million in Series A funding in 2021, with investors including Breakthrough Energy Ventures, Congruent Ventures and The Engine. In 2021 it also received about $3.3 million in funding through ARPA-E's Open 2021 program. Veir is early-stage, demonstrating its technology in a lab. The founders are from ARPA, MIT and BP.
		TS CONDUCTOR	TS Conductor makes a high-efficiency conductor. It reportedly doubles a line's capacity by using a carbon core (instead of steel) and an aluminium encapsulation layer. The design reduces resistance and increases ampacity and resilience to high temperatures. The conductor can be installed without retrofitting utility poles.	The startup raised $25 million in Series A funding in 2021, with investors including Breakthrough Energy Ventures, National Grid Partners and a NextEra Energy subsidiary. The capital will be used to build a US manufacturing facility. The technology's resilience to heat and ability to improve line capacity are both key selling points, as utilities are looking to improve physical grid resilience. For example, PG&E chose TS Conductor for fire remediation on its distribution grid.

Top regions with wildfire risks, 2001-2021



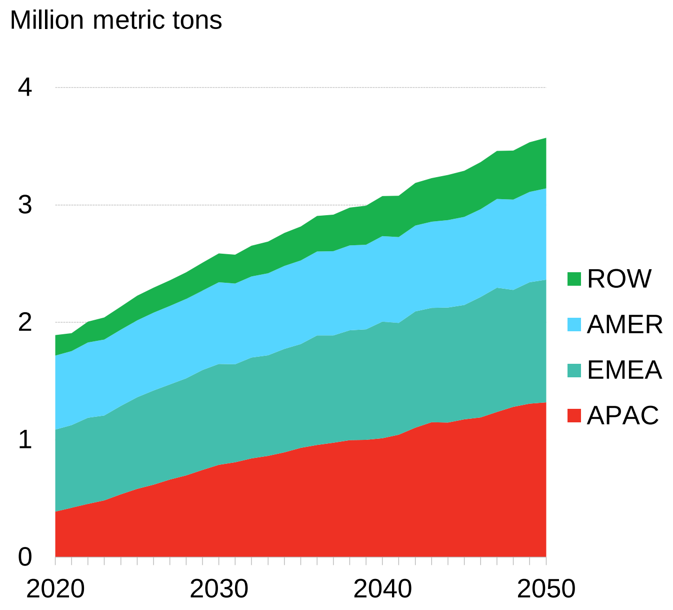
Source: BloombergNEF, EM-DAT

New materials that increase resilience to heat can help utilities both cut power loss and build physical grid resilience to climate risks. Power grids are exposed to climate risks, such as wildfires and extreme hot temperatures, that lead to economic losses. For example, US utilities project an annual loss of up to $4.1 billion due to hurricanes and wildfires.

Next-generation components

			How does it work?	Maturity
New line materials	Line coating	ASSETCOOL THERMAL METAPHOTONICS	AssetCool develops photonic coatings to cool overhead power lines. This can reduce power loss and reportedly increase ampacity (max current) by at least 20%. The coating interacts with wavelengths of light to cool grids by dissipating more infrared heat and decreasing solar heat absorption.	AssetCool raised $1.18 million in 2021, with investors including Kero, Enterprise Ventures and Mercia Asset Management. The startup was founded in 2016, and its material is patented. Depending on how the coating is applied, such as a spray or integrated into lines, it will need to partner with line manufacturers to scale.
	Advanced switches	menlo micro	Menlo develops MEMS switches. Menlo's switch can reportedly make circuits up to 99% more efficient than traditional, solid-state switches. While a typical mechanical switch reacts in milliseconds, Menlo's switch reacts in microseconds (1,000 times faster). The switch is based on heat-resistant alloys and micro-actuators (tiny devices that make the switch move) between a glass coating. The alloys reduce heat loss due to negligible resistance.	Menlo was spun out from GE Ventures in 2016 after a decade of internal research. In March 2022, Menlo raised $150 million in Series C funding, bringing total funding to $225 million. The round was led by Vertical Venture Partners and Future Shape. In 2018, Menlo partnered with Corning to provide specialized glass, and with Silex Microsystems (a MEMS foundry) to manufacture its switch. The switch can be made with the same processes as semiconductors. The key issue that may inhibit commercial projects is that circuits need to be redesigned to reap Menlo's full efficiency and circuit down-sizing potential.

Copper demand from power lines



Source: BloombergNEF

New line materials and line-cooling technologies can help cut power losses, downsize grids and reduce capex. In China, the world's largest grid market, annual grid investment will double to $122 billion by 2050 from 2020. Most of this will go to overhead lines, and improving the efficiency of these lines may help limit China's added grid costs.

Further reading

Relevant research content

Research note	Links
Still Distant Fusion Emerging As a Net-Zero Option	web | terminal
Nuclear 2H 2021 Market Outlook	web | terminal
Climate-Tech Innovation: Next-Generation Geothermal	web | terminal
2021 CCUS Market Outlook	web | terminal
Beyond Lithium-Ion: Long-Duration Storage Technologies	web | terminal
Long-Duration Storage: Opportunities and Barriers	web | terminal
LCOE Highlights: Hydrogen, CCS, Small Nuclear	web | terminal
Hydrogen: The Economics of Power Generation	web | terminal
1H 2022 Hydrogen Market Outlook	web | terminal
Vehicle-to-Grid: Big Opportunities, Big Challenges	web | terminal
Get Paid to Charge with Vehicle-to-Grid	web | terminal
Virtual Power Plant 101	web | terminal
Distributed Energy Resource Management 101	web | terminal
Power Grid Long-Term Outlook 2021	web | terminal

Copyright and disclaimer

BloombergNEF (BNEF) is a leading provider of primary research on clean energy, advanced transport, digital industry, innovative materials, and commodities.

BNEF’s global team leverages the world’s most sophisticated data sets to create clear perspectives and in-depth forecasts that frame the financial, economic and policy implications of industry-transforming trends and technologies.

BNEF research and analysis is accessible via web and mobile platforms, as well as on the Bloomberg Terminal.

BloombergNEF

Coverage.

Clean energy
Advanced transport
Commodities
Digital industry

Get the app

On IOS + Android
about.bnef.com/mobile

Client enquiries:

Bloomberg Terminal: press <Help> key twice
Email: support.bnef@bloomberg.net

Learn more:

about.bnef.com | @BloombergNEF