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Hype Cycle for Disruptive Energy Technologies, 2023

Published 14 July 2023 - ID G00791596 - 86 min read

By Analyst(s): Simon Cushing

Initiatives: Energy and Utilities Digital Transformation and Innovation

Continued innovation in new and developing energy technologies will deeply disrupt future energy systems. This Hype Cycle provides energy company CIOs with the current state of key disruptive energy technology innovations, helping guide technology roadmaps in alignment with business strategy.

More on This Topic

This is part of an in-depth collection of research. See the collection:

- 2023 Hype Cycles: Deglobalization, AI at the Cusp and Operational Sustainability

Analysis

What You Need to Know

Profound structural change is taking place in global energy systems. Disruptive forces, including the decentralization and democratization of power generation, digitalization and energy decarbonization, are reshaping infrastructure and markets. Economic uncertainty and geopolitics have increased market volatility and shifted consumer and provider priorities. Energy companies are being compelled to redesign business and operating models, or face escalating social and operational challenges.

Continued advances and innovation across a wide range of energy technologies will increasingly and rapidly be needed to achieve ubiquitous, affordable, available and low-carbon acceptable energy provision in the future. Sustainable fuels, zero-carbon power generation, an efficient and safe hydrogen economy, the scaling up of carbon capture utilization and storage (CCUS), and renewable energy intermittency mitigation are among many such advances needed.

Energy producers, policymakers, and industrial energy consumers must further commit to technology development, directing investment and regulation toward enhancing the technology economic viability of these promising energy technologies. This Hype Cycle can help inform prioritization and investment decisions, helping energy company CIOs and their stakeholders understand the current maturity level of these innovations with consequent impact and associated risk.

The Hype Cycle

In the near term, the imperatives of affordable, secure and low-carbon energy may be conflicting, even mutually exclusive. Today, stark trade-off decisions are required, sacrificing progress in one area (for example, low carbon energy) for gains in another, such as affordability. Energy providers and consumers face costly choices in mitigating energy risk, and governments face — and may evade — unpopular policy decisions. Energy providers must therefore ensure continued progress to enable a commercially viable, secure and reliable lower-carbon energy future.

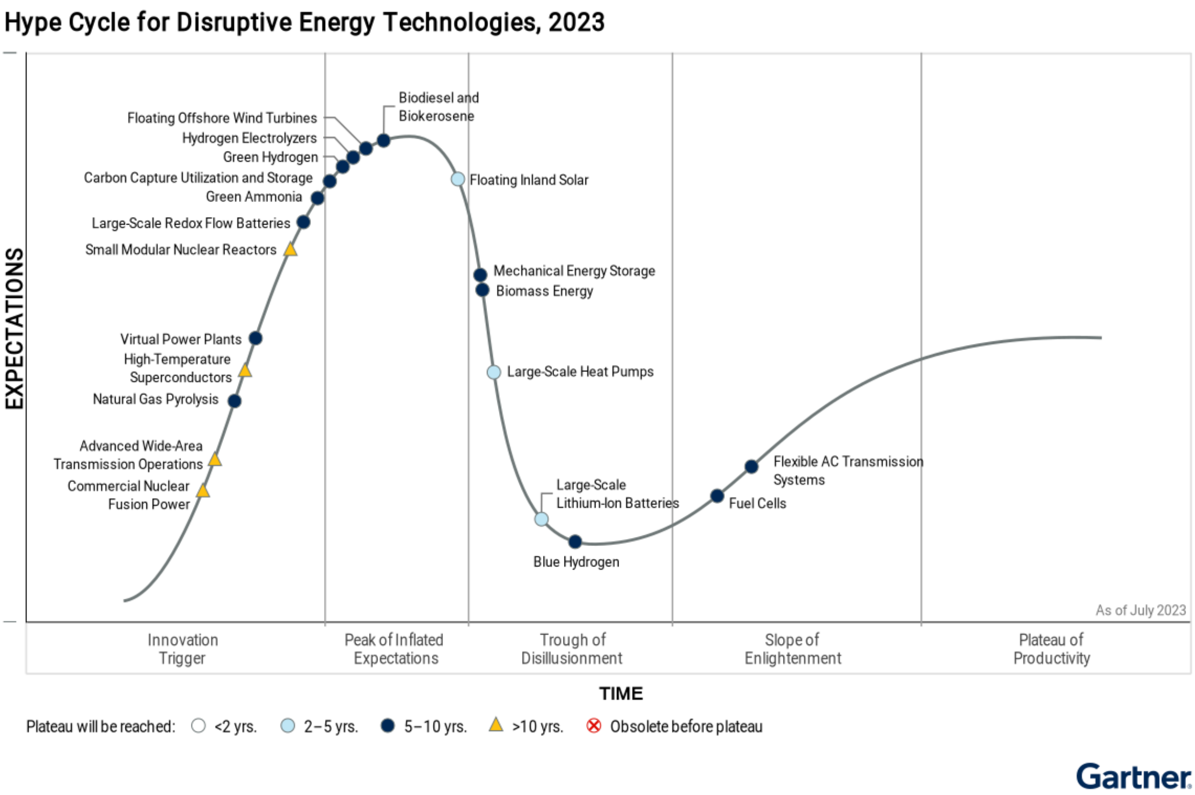
This Hype Cycle profiles 21 energy-related technologies. Successful development of these technologies could be critical in enabling transformed energy provisioning systems. Significant advances in the technical feasibility, commercial viability or scaling potential of these technologies could unlock rapid progress in meeting global energy needs and energy security challenges.

The pace of maturity of technologies in this Hype Cycle is mixed. Some, such as heat pumps and utility scale Li-ion batteries, are technologically relatively mature and need incremental innovation. Many, however, are moving more slowly, and commercial viability will require sustained investment and technological development. Other technologies, especially some early on the Hype Cycle, such as nuclear fusion, small modular fission reactors or high-temperature superconductivity, are typically making incremental progress, but still face major developmental challenges. These technologies should be tracked, or invested in as part of higher-risk, longer-term venturing or sustainability commitment strategies.

Technologies at and over the Peak of Inflated Expectations are typically more technically proven. Many in this group, such as biofuels and carbon capture, directly address the challenge of reducing atmospheric greenhouse gasses. Transformative claims for these technologies should be treated cautiously, but the technical barriers they face are lower than the economic or commercial ones. These technologies should be assessed for use where conditions are favorable and tested for commercial viability.

None of the technologies on this Hype Cycle are yet close to the Plateau of Productivity, either because of technological immaturity or lack of commercial feasibility. However, several, including utility scale lithium-ion batteries, blue hydrogen and fuel cells are reaching the bottom of the Trough of Disillusionment or the Slope of Enlightenment. Here, remaining challenges mean that the early potential of the technology looks unlikely to be fulfilled without advances elsewhere (for example, in carbon capture utilization and storage in the case of blue hydrogen). Otherwise, realism about usage makes investment or adoption decisions clearer, such as for fuel cells.

Figure 1: Hype Cycle for Disruptive Energy Technologies, 2023



The Priority Matrix

Many of the technologies included could be transformative for the world's energy systems. Commercial nuclear fusion and high-temperature superconductivity could reshape energy systems beyond recognition but are still enormously technologically challenging. Lithium-ion batteries, hydrogen electrolysers and biofuels are technically established, but need to scale. Other transformational technologies, including green hydrogen, green ammonia and small modular nuclear fission reactors are among the few with the potential to fully underpin new non-fossil-fueled economies. The increasing urgency for decarbonization makes it critical that at least some of these technologies progress.

Several of this Hype Cycle's technologies depend on cost-effective CCUS. CCUS is increasingly promoted as key to near-term atmospheric CO2 reduction but itself requires continued innovation to become cost-effective at scale. Others, such as biodiesel and biokerosene, are technically feasible, but commercially disadvantaged compared to typical fossil fuel energy costs.

This highlights a significant challenge for many of the technologies on the Hype Cycle — continued or accelerated commercial investment, policy action, government funding, and/or regulator action will be required to realize their benefits and potential. Carbon pricing and globally significant carbon markets, for example, could radically change their comparative commercial viability. It is unclear whether this action or investment will happen at the pace or scale needed to effectively address climate challenges.

The Hype Cycle also includes a number of technologies with moderate potential benefits, including flexible AC transmission and fuel cells. While not transformative, these could still play important roles in parts of energy systems, certain geographies or as building blocks for more widespread change in combination with other technologies.

Table 1: Priority Matrix for Disruptive Energy Technologies, 2023

(Enlarged table in Appendix)

Benefit	*Years to Mainstream Adoption*			
↓	*Less Than 2 Years* ↓	*2 - 5 Years* ↓	*5 - 10 Years* ↓	*More Than 10 Years* ↓
Transformational		Large-Scale Lithium-Ion Batteries	Biodiesel and Biokerosene Carbon Capture Utilization and Storage Green Ammonia Green Hydrogen Hydrogen Electrolyzers	Commercial Nuclear Fusion Power High-Temperature Superconductors Small Modular Nuclear Reactors
High		Large-Scale Heat Pumps	Biomass Energy Blue Hydrogen Floating Offshore Wind Turbines Large-Scale Redox Flow Batteries Mechanical Energy Storage Natural Gas Pyrolysis Virtual Power Plants	
Moderate		Floating Inland Solar	Flexible AC Transmission Systems Fuel Cells	Advanced Wide-Area Transmission Operations
Low				

Source: Gartner (July 2023)

Off the Hype Cycle

The fastest maturing technologies on Hype Cycle are still likely to mature in more than two years and up to five. Most will take between five and 10 years. Considering these time scales, likely disruptive energy technologies have not changed significantly since 2022, and there is high continuity with this year's Hype Cycle. However, a change has been made to reflect the rising promotion of CCUS. Increasing numbers of energy companies, and oil and gas companies especially, are increasing investment in CCUS infrastructure and signing commercial storage agreements.

As such, CCUS has been added as a distinct technology and low-carbon coal and low-carbon natural gas have been removed. Both depend entirely for their disruptive potential on carbon capture, which is now represented in its own right.

Blue hydrogen also depends on carbon capture, but its place in supporting a potential hydrogen economy sees it retained as a distinct technology.

On the Rise

Commercial Nuclear Fusion Power

Analysis By: Simon Cushing

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Energy is released when light atomic nuclei fuse together. The fusion of hydrogen into helium is the main process that releases energy in the sun. Nuclear fusion power generation seeks to produce electricity using heat from nuclear fusion reactions. The vision for commercial nuclear fusion power is cost-effective, large-scale, reliable and clean energy generation from nuclear fusion.

Why This Is Important

One source of fuel for fusion reactions can be extracted from water. Very small amounts of fuel can provide very large amounts of energy, meaning fuel supplies are effectively unlimited. The only byproduct of fusion reactions is helium, which is inert and harmless to the environment. Unlike fission reactors, fusion reactors cannot suffer meltdown or runaway reactions. Fusion offers the promise of clean, safe and nearly unlimited energy if remaining engineering and cost challenges can be met.

Business Impact

If realized, commercial cost-comparative nuclear fusion would be transformational. Viable fusion power could supply utility scale amounts of energy comparatively safely and with very little environmental impact. Energy availability and security would be achieved, and consumers could significantly reduce their own environmental impact with abundant and affordable energy.

Drivers

- The transformational promise of fusion power, along with the scientific and technical challenge, has driven research for many decades. Theoretical challenges have been addressed and future progress is largely now dependent on solving engineering problems.

- To address the challenges of creating the immense temperatures and pressures required to maintain fusion reactions, two main lines of research have developed: magnetic confinement and newer inertial methods. In magnetic confinement, strong magnetic fields contain high-temperature plasmas. Inertial methods involve extreme compression of small fuel pellets using lasers or projectiles.
- The potential availability, environmental and safety advantages over nuclear fission, fossil fuel generation, and many other energy supply methods continue to drive research. Climate concerns and the need for a successful energy transition are adding momentum.
- Fusion generation at significant scale has been demonstrated in short bursts, firstly by the Princeton Plasma Physics Laboratory (10 MW, no longer in operation) and by the Joint European Torus (JET, 16 MW).
- In 2021, the JET generated 11 MW of power in a five-second burst, a notable achievement adding momentum to the ongoing research.
- In November 2022, the Lawrence Livermore National Laboratory (LLNL) in California achieved a net energy positive fusion reaction using lasers for the first time, which is a significant achievement.
- In recent years, several countries (notably China and the U.S.) have renewed investment in fusion research. An increasing number of private companies are now also conducting research in a range of established and alternative approaches, with some claiming break-even operation before the end of this decade. In May 2023, fusion startup Helion announced an agreement to provide Microsoft with electricity from its fusion plant in 2028.
- ITER, the first reactor to produce self-sustaining and energy positive fusion, is under construction by an international consortium in France and scheduled to begin operation by 2026.

Obstacles

- Fusion has been researched for many decades, but progress has been highly incremental. Moreover, working reactors remain in the domain of research and experimentation.
- Energy production in magnetic confinement reactors requires immense temperatures and is currently limited to very short bursts.

- Fusion reactions' temperatures pose major engineering challenges. Only the LLNL has so far succeeded in generating a net energy positive reaction. Plasma containment, reactor materials and fuel production require further advances to enable cost-competitive fusion power to the grid.
- While notable, the LLNL experiments briefly produced only a tiny fraction of the energy required from utility scale fusion power. Given the slow pace of past fusion research, Helion's timeline for operational fusion power seems aggressive.
- Recent advances, progress with ITER and greater investment in alternative reactors may achieve net energy positive sustained reactions within a few years. However, without further demonstrable major breakthroughs, commercial operation is still uncertain and likely remains considerably more than a decade away.

User Recommendations

- Track developments in fusion research, incorporating it into long-term scenario planning efforts — recommended for CIOs in energy enterprises.
- Be cautious about current hype. Fusion power will be transformative if it ever achieves commercial operation. However, the time scale over which this may happen means the impact for businesses and CIOs is well into the future.

Sample Vendors

Commonwealth Fusion Systems; General Fusion; Helion; ITER; National Ignition Facility (NIF)

Advanced Wide-Area Transmission Operations

Analysis By: Lloyd Jones

Benefit Rating: Moderate

Market Penetration: 1% to 5% of target audience

Maturity: Embryonic

Definition:

Advanced wide-area transmission operations (AWTO) is a collection of analytics and operational capabilities, addressing the increased complexity of managing long-range energy transmission in systems with rapidly rising renewable sources. Improved system resilience is achieved by measuring, analyzing and managing the grid in subsecond intervals to maintain stability.

Why This Is Important

As utility large-scale renewable penetration levels rise, renewables are displacing legacy fossil-fueled generators. The residual mechanical inertia of the grid drops, thus requiring new capabilities to measure and manage the grid in subsecond intervals to maintain grid stability. AWTO is an emerging capability spanning several technologies, using several levers to measure and maintain system frequency to retain operational resilience.

Business Impact

System operators have deployed synchrophasors and wide-area control systems to measure and manage grid stability. AWTO has the capability to collect real-time data with low latency. AWTO provides the event processing capability to analyze the data, making real-time recommendations and future operational decisions. AWTO helps avoid under and overfrequency incidents by mitigating disturbances and ensuring the return to stable operating states through monitoring and control.

Drivers

- System operator zones are commonly interconnected with both AC and HVDC interties, operators need to coordinate across multiple zones, owners and participants. This is facilitated by AWTO.

- Large thermal plants are retiring, replaced by low-inertia renewable energy resources, such as wind and solar. Renewables are reducing the overall system's mechanical inertia and limiting the power system's ability to smoothly ride through disturbances created by supply-demand imbalances.

- AWTO provides advanced learning and computational models (AI & ML) to support high-speed intelligent operations using prescriptive modes of operation based on observations, to generate lookahead windows for system operators, so they can avoid disturbances.

- Independent system operators (ISO) need insight into current system performance to predict upcoming disturbances, along with control capabilities to maintain stability. AWTO capabilities are based on high-speed event processing to address disturbances from abnormal incidents that impact stability parameters, such as frequency, voltage, system stability and power swings.

- AWTO control strategies could include signal injection and propagation measurements to develop topology-sensitive, transient transfer models. State and topology-based configurations are used to train static and recursive models that can supervise or take control action (including islanding and synchronization). The models consume synchrophasor data from phasor measurement units (PMUs) to create an observable picture of grid behavior during disturbances, enabling faster rebalancing and synchronization.

- Control algorithms already issue automated commands and in the future will become capable of learning to improve automation choices. Provided high-speed processing is in place, operational commands can be issued to a wide range of levers (from flexible AC transmission systems [FACTS] devices to switches and resource control loops), while acknowledging market and physical constraints.

Obstacles

- AWTO is enabled by fast-response FACTS devices.
- System observability needs to be improved, and this can be addressed by improving PMU deployment and synchrophasor fast signal processing.
- The cost of ultralow-latency signal measurement and acquisition across wide areas.
- The management of operational wide-area data networks that manage and share low-latency IP traffic to balance measurement and control signals.
- Within an ISO system, computational power is required to compute wide-area event streams. This suggests quantum computing capabilities are needed to prescribe control signals.
- Dispatch of smart inverters' operational setpoints to create clusters of virtual synchronous condensers.

User Recommendations

- Leverage industry associations to build analytics capabilities to parse high-speed event data, and find and monitor event flags to alert operators of angular separation, oscillatory stability, voltage stability and islanding detection.
- Improve data handling for OT devices.
- Add PMUs to the network to increase synchrophasor data volumes, creating large volumes of temporal data with high velocity (low latency) that needs to be acquired, processed as event streams and persisted for postevent analysis.
- Align IT and OT cross-teams, as advanced data management capabilities do not reside in OT and processing complex algorithms requires domain expertise that does not exist in IT.
- Pilot advanced wide-area measurements with your OT vendors to understand and model inertia zones that could be leveraged to control the rate of frequency change.
- Plan to invest in fast response resources such as batteries and or switch curve reconfiguration.

Sample Vendors

General Electric (GE); Hitachi Energy; Reactive Technologies; Siemens

Gartner Recommended Reading

The Impacts of Exponential Renewable Generation Growth Across the Energy Ecosystem

Essential Patterns for Event-Driven and Streaming Architectures

Research Roundup: Top 10 Trends Shaping the Utility Sector in 2023

Natural Gas Pyrolysis

Analysis By: Simon Cushing

Benefit Rating: High

Market Penetration: Less than 1% of target audience

Maturity: Emerging

Definition:

Pyrolysis is the process of high-temperature heating (typically more than 500 degrees Celsius) of organic materials in the absence of oxygen, causing their decomposition. Pyrolysis of methane, the main constituent of natural gas, emits no CO2, creating only solid carbon waste and hydrogen. Hydrogen from pyrolysis is also called “turquoise” hydrogen.

Why This Is Important

Hydrogen is a promising energy carrier for a future low-carbon energy system. Pyrolysis is a potential bridge technology for accelerating the production of clean hydrogen in the short term. However, viable green hydrogen will need low-cost renewable energy and massive investment in production infrastructure, along with new uses for hydrogen to raise demand. Establishing a hydrogen economy will take time. Pyrolysis offers a clean alternative to current hydrogen production methods using existing natural gas infrastructure.

Business Impact

Most hydrogen is produced by steam methane reforming (SMR), an economic but CO2 emitting process. Almost all other methods are more costly and require global investment and regulatory action to drive adoption. Pyrolysis is an established method with anticipated competitive costs. Widespread adoption, and in particular installations at the point of use leveraging natural gas via existing infrastructure, could supplant SMR, reducing emissions rapidly at a modest cost compared to other approaches.

Drivers

- The International Energy Agency's (IEA's) net zero scenario calls for a doubling of hydrogen demand by 2030 to 180 mt, half of which is from low-carbon emission methods. In this scenario, electrolysis accounts for two-thirds of low-carbon production, requiring a global electrolyzer capacity of around 700 gigawatts (GW). In 2022, if all the planned projects are realized, the IEA estimated global demand could face a 66% shortfall in capacity.

- Planned electrolyzer capacity is likely to continue to grow (IEA estimates in 2021 were for only 90 GW capacity in 2030); however, additional alternative methods are also likely to be needed to fill the gap if net zero targets are to stay within reach.

- Methane pyrolysis produces only hydrogen and solid carbon waste, which can be sold commercially or stored. Pyrolysis eliminates the need to add carbon capture and storage (CCS) to existing facilities.

- The infrastructure for producing, transporting and storing natural gas (made up mostly of methane) is well-established and globally widespread. In July 2022, the EU Commission backed the inclusion of natural gas from 2023 in the EU's green taxonomy, a rulebook for climate-friendly investment. This could spur investment in natural gas as an energy transition fuel in Europe.

- Methane pyrolysis can be colocated to make use of natural gas infrastructure, making it attractive as a distributed hydrogen generator optimized for on-site production with negligible hydrogen transport or storage requirements. Gas distributors, industrial hydrogen and biogas producers could get a useful life extension.

- Interest in pyrolysis is rising and is an active field of research seeking greater energy efficiency and improved catalysts. Methane pyrolysis at an industrial scale has also recently begun, for example at BASF's methane pyrolysis Ludwigshafen test facility, which has been in operation since 2020.

- Pyrolysis can be applied to a wide range of hydrocarbon-based feedstocks, including biogas and waste plastics, to produce hydrogen and other commercial products. Pyrolysis is likely to feature at some scale in future sustainable energy and industrial systems, encouraging continued research and investment.

Obstacles

- Pyrolysis itself is not new. There are several established pathways, including thermal, plasma and catalytic decomposition. However, these depend on high temperatures or specifically engineered catalysts. Thermal pyrolysis has higher energy requirements than SMR, though lower than water electrolysis. Nonemitting energy sources (for e.g.,renewable electricity or waste heat) must be used for pyrolysis to have zero life cycle emissions.
- Natural gas is not pure methane and as a pyrolysis feedstock produces additional byproducts. Feedstock gas must either be purified or the byproducts need to be managed, adding technical complexity and cost.
- Industrial pyrolysis at scale remains commercially unproven. BASF anticipates commercially industrialized methane pyrolysis by around 2030. Competing hydrogen production methods have greater momentum and investment. Even when pyrolysis is commercialized, the competitive landscape may present significant barriers to entry, especially if hydrogen demand grows more slowly than hoped.

User Recommendations

- Decarbonise production and add methane pyrolysis as a possible near-term future option in order to locally generate hydrogen.
- Investigate the state of maturity and likely short-term future availability of methane pyrolysis from available providers.
- Engage with pyrolysis researchers, startups and/or promising providers and commit resources to supporting and accelerating commercialisation.

Sample Vendors

BASF; Modern Hydrogen; Monolith

High-Temperature Superconductors

Analysis By: Simon Cushing

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Emerging

Definition:

Superconductors are materials with zero electrical resistance. They can sustain intense magnetic fields and transmit electricity with no loss. High-temperature superconductors (HTSs) are materials that conduct with little or no resistance loss, without the need to achieve very low and commercially unfeasible temperatures.

Why This Is Important

Superconductors are used in magnets needing high-field intensities, such as in MRI machines. With zero loss, they could transform power transmission and many other electrical applications. However, most superconductors must be cooled down to about absolute zero, thereby limiting their use. In recent decades, materials have been found that superconduct at relatively high temperatures. These hold the promise of commercially feasible and more widespread application of superconductivity.

Business Impact

HTSs have the potential to be cost-effective in commercial applications in the electric power sector. Superconductivity can produce substantial environmental improvements by significantly reducing transmission losses and saving energy, and enabling more economical underground power transmission. According to the U.S. Department of Energy, practical HTSs could save the U.S. hundreds of billions of dollars a year in energy distribution costs.

Drivers

- Concerns about energy sustainability and global growth in energy consumption, particularly increased electrification, are driving utility companies to look closely at technologies that address the reduction of technical losses in the power utility sector. Transmission-resistive losses (depending on the transition voltage level) typically range from 5% to 10% and are the main contributor to technical losses.
- In addition, HTSs can reduce losses in motor/generation and storage application effectively, resulting in up to 10% more electricity being delivered to consumers without investment in additional generation capacity.
- Superconductors have a number of technological applications, from magnetic resonance imaging machines to mobile phone towers, and researchers are beginning to experiment with them in high-performance generators for wind turbines.
- The frontier of superconductor research is harnessing computational methods to calculate the crystal structures of combinations of multiple elements that could superconduct at near-room temperature and pressure.
- Superconductors that work at, or near, ambient conditions could have enormous impact in, for example, electronics that run faster without overheating.

Obstacles

- Common superconductors work only if they are kept very cold. Even the most sophisticated ones — copper-oxide-based ceramic materials — work only below 133 Kelvin (–140 degrees Celsius) and their usefulness is limited by the need for bulky and costly cryogenics.
- More recent research has found materials that superconduct at near-room temperatures, but only under extreme pressures, which again limits their usefulness.
- AC power transmission evaluation projects have not reached further than eight kilometers. Therefore, DC applications are being considered.
- In addition to superconductivity, materials for use in grid-scale energy transmission need properties, such as malleability and corrosion resistance. Even if high- or ambient-temperature superconductor materials can be cheaply produced and maintained, they may not have these properties.
- As of now, there is also no guarantee that ambient-temperature and pressure superconductivity is attainable in usable materials.

User Recommendations

Although high-temperature superconductivity does not directly impact energy and utility IT organizations yet, it is expected to be combined with advanced control and processing software to optimize/minimize energy losses and dampen volatile energy markets through advanced energy storage. Consequently, users must:

- Research HTSs not only for electricity transmission and distribution, but for use cases that require low technical losses.
- Explore options for using HTSs in motors, storage and electronics to reduce resistive heating and the need for cooling, and consequently, reduce energy consumption.

Sample Vendors

ABB; American Superconductor (AMSC); Bruker; Hitachi Group; Nexans

Gartner Recommended Reading

Research Roundup: Top 10 Trends Shaping the Utility Sector in 2023

Technologies to Watch April 2023: ChatGPT Writes Robot Code, Ultra-Fast Optical Switch, Superconductors and Unclonable Labels

Virtual Power Plants

Analysis By: Lloyd Jones, Lauren Wheatley

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

Virtual power plants (VPP) manage distributed energy resources (DER) to flex contracted load and energy resources. VPPs trade across electricity markets, from capacity to energy and ancillary services, to provide system operators with additional controllable resources that offer similar reliability and economic value as traditional dispatchable power plants. Resources can include batteries, electric vehicles, smart appliances, flexible heating/cooling loads, and on-site generators.

Why This Is Important

Balancing the grid becomes harder with the adoption of renewable energy (RE). RE can be curtailed in periods of low demand but at a considerable cost. The alternative is to leverage customer-owned resources to manage energy volatility. VPPs can flex energy resources, both load and generators, beyond the meter and trade these resources on energy markets. VPPs provide the capabilities to enroll, measure and manage energy beyond the meter, making it tradable on the wholesale markets.

Business Impact

VPPs balance DER production and consumption with per-customer forecasts to predict and trigger customer behavior. VPPs orchestrate and flex resources against global and local constraints with automated interactions. Utilities can use VPPs to address energy volatility and grid issues. VPPs trade energy resources across markets, optimize energy generation and schedule consumption to defer capacity investments. VPPs democratize the grid by utilizing available capacity and sharing the benefits.

Drivers

- Rising volumes of intermittent renewable energy, at the grid center and beyond the meter, are creating balancing challenges for system operators.

- There is growing recognition by regulators of the need to incentivize consumer load flexing to ensure energy availability and stabilize the grid. Energy-intensive devices such as batteries, inverters and chargers are becoming software-defined, allowing the assets operating envelope to be orchestrated across customers and asset classes.

- As the energy transition matures, so does the need for an independent balancing services market. Legacy electricity markets, such as day-ahead markets, are still relevant but cannot solve the balancing problem. The balancing market will need to interoperate and coexist alongside other markets, leveraging price and capacity data and extending current settlement services. Mandates, such as EU-SysFlex and FERC Order No. 2222, require electricity markets to treat loads as dispatchable resources on the wholesale market.

- Older power plants need heavy investment for management and construction. VPPs package resources into a dispatchable energy package that can be used by system operators across markets, but with low capital investment needed to control numerous DERs.

- Technology is accelerating the adoption of VPPs. There is increasing acceptance of enhanced technologies in the power industry, including cloud platforms and the Internet of Things, increasing concentration on cost-effectiveness in power generation, ease of accessibility of power through VPPs, and rising knowledge about the advantages of renewable power.

Obstacles

- Enertechs and energy management providers are disintermediating utility companies with product offerings beyond the meter, offering loads as a dispatchable resource to the intraday and balancing markets. Utilities need to choose to either compete or cooperate.
- Successful operation means investment in new systems and processes, notably management and trading systems. There is a lack of standardization in the ecosystem, making it challenging for VPPs to communicate with DERs and control systems. This means that composable architecture with an API integration platform for managing API-based DER assets is needed.
- Utilities may need to offer rebates, credits or other incentives to drive prosumer adoption.
- Managing large volumes of data effectively to ensure that VPPs are running optimally and delivering the precise ancillary services required by the market to keep the grid in balance in real time will be critical. Privacy and security risks must be identified and addressed.

User Recommendations

VPPs are needed to manage customers:

- Monitor the rate of RE penetration, by the time RE reaches 40%, utilities must initiate investment in energy orchestration to balance the grid.
- Develop event-driven business capabilities by expanding digital products to influence and orchestrate transactive electricity in conjunction with the markets. Acquire or build a digital platform business that will orchestrate diverse flexible resources across external participants, such as virtual power plants, aggregators and customers.
- Agree on mutual processes and data exchanges with retailers, aggregators and VPP operators to guarantee reliable, efficient and affordable operation of the electricity system and grid.
- Maximize the impact of VPPs by enhancing capabilities in the metering, billing and consumer engagement areas.
- Drive industry standardization by requiring open protocols from hardware manufacturers and software platform providers.

Sample Vendors

AGL; Hitachi Group; Mitsubishi Electric Group; Next-Kraftwerke (NEMOCS); Plexigrid; Schneider Electric (Autogrid Systems); SwitchDin; Siemens; VIVAVIS

Gartner Recommended Reading

2022 Sustainability Survey: Energy CIOs Can Help to Retain C&I Enterprises as Customers

Quick Answer: How Are Electricity Markets Changing as the Energy Transition Accelerates?

Quick Answer: How Electric Utility CIOs Can Respond to Changing Customer Expectations

2023 Utility Trend: Utility Business Models Are Evolving From 'Ego-Centric' to Eco-Centric

System Operators Must Adapt to Embrace Flexibility Markets

Small Modular Nuclear Reactors

Analysis By: Simon Cushing

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Emerging

Definition:

Small modular nuclear reactors (SMR) are advanced nuclear fission reactors with components that can be factory-made and transported for assembly on site. They are typically designed for a capacity of up to 300 or 400 MW, around a third of the capacity of traditional nuclear power reactors.

Why This Is Important

Nuclear fission power plants produce emissions-free, stable, base load electricity over decades with low operational costs. However, build costs are very high, and they experience very long construction times. They have highly restrictive siting requirements and produce radioactive waste. SMRs could radically reduce reactor cost, lead time and carbon footprint using factory-based modular construction. They have greater location flexibility and potentially reduced construction risk.

Business Impact

Nuclear energy offers secure, reliable power at predictable prices. SMRs promise these benefits, with advantages of shorter approval and construction times, lower build and operating costs, and more siting options. They could contribute significantly to improving energy security and managing energy costs, while eliminating energy purchase emissions and enterprise carbon footprint — especially for power hungry and energy intensive industries.

Drivers

- The intermittency and uncertainty inherent in renewable energy sources makes predictable, stable, dispatchable, good quality, base-load electricity highly desirable. Cost-competitive onshore renewable energy at scale also uses a lot of land.

- Nuclear power provides stable, high-quality, low carbon power over a long period and with much less land use per MW.

- The cost, scale and regulatory approval process for conventional nuclear power plant construction means they typically need long-term state support and financing to be viable. These challenges, along with raised safety concerns, have deterred widespread investment in new generations of nuclear plants. SMRs potentially address these with lower cost, faster approval cycles and build times, and reduced risk.

- The increasing urgency of climate change mitigation, along with heightened energy security concerns, has renewed interest in nuclear energy. SMRs could provide a route to more widespread provision of nuclear power with less state financing and higher security. The possibility of using brownfield sites also allows the generation to be located nearer to load centers.

- Favorable stances from some governments are reflected in SMR projects underway in Argentina, China and Russia. The U.S. Department of Energy initiated an Advanced SMR R&D Program in 2019, with demonstration projects slated for operation by 2030. The U.K. Government's 2020 Ten Point Plan and Energy White Papers announced the intention and early funding to deploy an SMR by the early 2030s. Demonstration projects have also started in Canada, and Poland announced projects in 2021.

- Nuclear technology has advanced considerably since early conventional plants were commissioned. A number of commercial companies are bringing forward SMR active designs. Several are based on proven third-generation technology, while some incorporate nontraditional coolants, novel fuels and other advanced concepts, promising greater efficiency and safety advantages.

Obstacles

- The SMR concept is unproven and under research. Projects in construction are located at nuclear power sites, rather than widespread locations. No construction of SMR serial fleets is underway, although Poland has announced plans for 10 plants.
- The cost-benefit of SMRs against modern renewables is uncertain. SMRs cost advantages need to be significant. The scale of investment makes nuclear electricity expensive. The U.S. Nuclear Economics Consulting Group believes no nuclear plant of any design is feasible in the U.S. today.
- The IEEFA think tank cast doubt on construction cost, time and performance claims.
- Following disastrous accidents, and with concerns of carbon intensity and radioactive waste, nuclear energy is controversial. SMRs face the same societal objections as conventional nuclear power plants, with likely stiff resistance from activists and communities to neighborhood SMRs.
- Uncertainties mean early projects will need long-term continued government commitment. The spread of commercially self-financing SMR, if it occurs, is years away.

User Recommendations

- Appraise SMR technology readiness by monitoring status and progress, with special attention to national investment strategies or regional project proposals.
- Incorporate SMRs in strategic technology assessment and create a clear timing position for SMR realization by monitoring provider company development activities and government regulatory progress.
- Identify potential or actual developers and suppliers of SMRs in the power ecosystem and engage with them to evaluate SMR potential for meeting planned future power requirements.

Sample Vendors

GE Hitachi Nuclear Energy; NuScale Power; Rolls-Royce; Westinghouse

Gartner Recommended Reading

Small Modular Reactors Will Provide Reliable Green Alternatives to Power Data Centers of the Future

Large-Scale Redox Flow Batteries

Analysis By: Lloyd Jones

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Adolescent

Definition:

A redox flow battery (RFB) is an electrochemical cell where reduction and oxidation ion exchange reactions occur across a membrane that separates two circulating liquid electrolytes to generate an electric current. Common electrolytes are vanadium and iron. RFBs are scalable, with almost unlimited longevity, able to tolerate deep discharge and unlimited cycling, making them ideal for long-duration energy storage at scale, improving system resilience at low operating costs.

Why This Is Important

RFBs at large scale provide dispatchable resources to support energy arbitrage use cases from short-term peak power to long-duration storage. This means the grid can host more renewable energy sources while still delivering resilient services. RFBs are stackable with long-duration storage. Capacity is increased by adding tanks. RFBs tolerate deep discharge, and have a long life cycle and “unlimited” energy capacity, though at a lower energy density compared to lithium ion batteries.

Business Impact

Traditionally, the intermittency gap has been covered by gas peakers. Storage is starting to displace gas generators in several markets. RFBs at large scale provide longer-duration storage (more than four hours) with a potential life span of decades and are tolerant of deep discharge cycles with low-maintenance requirements. RFBs are scalable with electrolytes stored in tanks adjacent to the cell. Flow batteries with their liquid electrolytes are inherently safer than lithium-ion technologies.

Drivers

- Estimates of large-scale storage needed by 2030 exceed 600 GW in the IEA Net Zero by 2050 scenario.
- RFBs are commercially available for two to 10 hours of storage.
- RFBs are tolerant across multiple temperatures; sustainable, providing an alternative to rare earth batteries with recyclable electrolytes. RFBs have a low toxicity; with low-cost extensible modular electrolyte tanks. RFBs have a strong safety record.
- Vanadium is commonly used with a proven track record of thousands of cycles delivering high reliability. Vanadium is used for cathode and anode electrolyzers reducing cross-contamination risks.
- RFBs are available with a widening range of electrolytes, such as iron, bromine or sodium solutions, with an ever-widening array of electrolytes and alternative metal air flow batteries.
- RFBs have a demonstrated life span of more than 10 years in commercial operation with no performance degradation.
- Easy recycling of the electrolyte.
- BloombergNEF forecasts the static energy storage market to double to 28 GW/69 GWh in 2030, across all storage technologies.
- The current largest redox flow vanadium battery has a current capacity of 100 MW/400 MWh with expansion underway to reach 200 MW/800 MWh in Dalian, China.

Obstacles

- Electrolyte solutions have tended to use rare materials, some of them such as vanadium are toxic.
- RFBs have a relatively low energy density requiring a large physically installed footprint, which, along with the volume of the electrolyte tanks, is a significant weight.
- At a large scale, round-trip efficiency is typically in the 65% to 75% range; however, with small single cells in labs, round-trip efficiency of 85% to 90% has been reported in the literature.
- A pivot toward inexpensive unlimited materials is needed, along with improved round-trip efficiencies and a reduced degradation rate by avoiding metal plating.
- Upfront capital costs exceed those of the more popular Li-Ion batteries.

User Recommendations

- Incentivize deployment of large-scale storage through direct support for storage through mandates and policies, the most common option.
- Keep the regulations transparent and open to developing markets for capacity, flexibility and ancillary services so that storage can compete with other technologies and measures.
- Examine alternative energy storage technologies such as Li-Ion for short-duration (less than four hours) storage.
- Invest in API interfaces to integrate flow storage control and management systems into large IT and OT domains.
- Invest in AI to optimize physical flow storage dispatch and charging operating cycles against the behavior of the wholesale market.

Sample Vendors

CellCube; ESS; Lockheed Martin; Primus Power Solutions; Sumitomo Electric Industries; ViZn Energy Systems

Gartner Recommended Reading

Research Roundup: Top 10 Trends Shaping the Utility Sector in 2023

Green Ammonia

Analysis By: Simon Cushing

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Green ammonia can be made using green or blue hydrogen with zero or low CO2 emissions. Ammonia has significant potential as a zero-carbon energy store and fuel.

Why This Is Important

Ammonia has a potentially pivotal role in low-carbon energy systems. It can be used as a hydrogen storage medium, and has potential as a fuel for transport and power generation as well as storage for heat. Current ammonia production emits CO_2 amounting to around 1.5% of global emissions. Around 70% of global ammonia is currently used to make fertilizers. Growth in global food production will increase its demand in future. Green ammonia production would contribute significantly to emissions reduction.

Business Impact

As an energy store, green ammonia is also a potential enabler of scaling reliable renewable power, providing businesses with another cost-effective means to reach emissions reduction and environmental goals. Commercially viable green ammonia could be transformative for shipping, providing a least-cost route to zero-carbon fueling and lessening the cost impact of decarbonization on supply chains for many industries. It could have a central role in decarbonizing agriculture.

Drivers

- Storage and transport of useful amounts of pure hydrogen requires cryogenic temperatures and high compression. Ammonia is easily stored as a liquid at much higher temperatures (around -30°C) and modest pressures. Ammonia transportation and storage technologies are mature, and distribution infrastructure is widespread and relatively evenly distributed.
- Ammonia can be used as zero-carbon emissions fuel in fuel cells, producing electricity, and in internal combustion engines, combined-cycle gas turbines and mixed with coal, producing nitrogen and water. It can potentially displace fossil fuels in energy production and act as an energy carrier.
- Ammonia's properties also make it an attractive store for renewable energy in chemical form, which can be released by direct reaction with air or by decomposition to release hydrogen. Demonstration projects in the U.K. and Japan are studying the feasibility, and clarifying the energy efficiency of ammonia synthesis, storage and combustion in a single site based on electrochemical reactions.
- Ammonia transport and distribution technologies, and infrastructure are mature, though are likely to need extension to cover renewable energy storage uses.
- In particular, ammonia may play a critical role in decarbonizing long distance shipping where electrification is considerably harder to achieve than in road or rail transport.
- The International Maritime Organization has committed to emission reduction goals. The International Energy Agency (IEA) identifies ammonia bunkering (fuel storage and loading) as potentially transformative in achieving targeted emissions reductions. One analysis suggests that ammonia is the least-cost pathway for shipping decarbonization and could supply at least 75% of the energy demand of the shipping industry by 2050. A group of companies has begun studying the development of a supply chain for ammonia fuel in Singapore, a major bunkering hub.

Obstacles

- Ammonia production is energy intensive, and recovering hydrogen from it also consumes energy. To be emissions-free, these processes require green hydrogen and renewable electricity. Lowering the cost of green ammonia is tied to continued reduction of the price of renewables relative to fossil fuels.
- The long working lifetimes of existing facilities may delay or impede investment in the new infrastructure needed to shift to low-emission production. Retrofitting CCS and switching to renewable energy sources will add cost.
- For use in today's combustion engines or turbines, ammonia must be mixed with other fuels, diluting its decarbonization effect. Investment and innovation are required to develop cost-effective and efficient pure ammonia combustion technologies for engines and turbines.
- Government action, state investment, and proactive engagement from existing producers and consumers are needed to incentivize and progress ammonia decarbonization and foster new uses for rapid adoption.

User Recommendations

- Engage with peers, stakeholders and transport providers to encourage research and investment to progress green ammonia production and fueling infrastructure. This is recommended for users with supply chains heavily reliant on global shipping.
- Engage with producers and suppliers to encourage proactive investment in decarbonized ammonia production. This is recommended for users in food production where fertilizers are important in the value chain.
- Track green ammonia as a strategic disruptive energy in relation to the development of hydrogen economies and the ability to source reliable renewable energy.

Gartner Recommended Reading

2023 Utility Trend: Green Hydrogen Expectations Are High, but So Are Challenges

At the Peak

Carbon Capture Utilization and Storage

Analysis By: Simon Cushing

Benefit Rating: Transformational

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

Carbon capture, utilization and storage (CCUS) technologies enable the trapping of carbon dioxide (CO2) produced by burning hydrocarbons or during other industrial processes and storing it so that it cannot enter the atmosphere. Captured CO2 can be stored indefinitely, or reused as a commercial byproduct and the process can be referred to as carbon capture and sequestration or carbon capture, utilization and storage.

Why This Is Important

According to the IPCC, emissions from current and planned fossil-fueled infrastructure over its lifetimes, mostly in power generation, exceed those consistent with 1.5 degrees Celsius global warming. Replacing current or planned infrastructure with low-carbon energy will require capacity growth at levels well above any so far achieved. Removing fossil fuel energy without alternatives would significantly disrupt most societies. CCS can reduce fossil fuel-based emissions in the short term, particularly in the absence of a rapid acceleration of alternatives.

Business Impact

CCS technologies can accelerate a balanced energy transition. Carbon sequestration offers opportunities for oil and gas companies to earn from depleted fossil fuel assets, for example through carbon capture and storage as a service (CCSaaS). Captured CO2 reuse offers industrial emitters an opportunity to monetize captured carbon by selling it onwards, offsetting costs, or generating new earnings. Potential new revenue streams and business models can add momentum to CCS deployment.

Drivers

- Since 2010, global greenhouse gas (GHG) emissions reductions have been more than offset by increasing energy, industrial, and transport activities. On current emissions reduction trends, the world remains likely to exceed the 1.5 degrees Celsius Paris Agreement global warming target.
- CCS can help accelerate emissions reduction. The probable scale of economic and societal disruption resulting from an unbalanced removal of fossil fuel energy strongly incentivizes governments against rapid fossil fuel elimination. CCS at scale potentially allows a more balanced transition away from fossil fuels while accelerating emissions reduction.
- According to the International Energy Agency (IEA), currently there are around 35 industrial, power generation and fuel transformation CCS facilities in operation, capturing 45 mt of CO2 per year. Plans have been announced for around 200 more projects by 2030, raising the captured yearly total to 220 mt CO2.
- CCS offers emitters a choice of pathways to direct emissions reduction or to offset them. Companies can fit capture technology to plants, or they can pay for carbon-capture-as-service, receiving carbon credits or recognized offsets from specialist companies who trap, transport and sequester CO2 directly.
- A number of startup ventures have started offering, or plan to offer, CCSaaS in the near future.
- While post- and pre-combustion technologies are well established, research is ongoing into novel capture routes and recent advances, particularly in direct air capture (DAC), that hold promise of improvement in CCS practicality and economics.
- Research is also advancing the range of possible CO2 uses, including to produce synthetic fuels, chemicals, plastics and building aggregates.

Obstacles

- CCS facilities add cost. Energy and products with CCS are less competitive than those without, disincentivizing investment.
- The performance of CCS technologies is mixed. As per a 2022 IEEFA report, the majority of 13 major CCS projects in power generation underperformed or failed. Continued innovation proves feasibility, reduces costs and improves scalability.
- Carbon capture does not fully eliminate emissions and costs escalate with the percentage of CO2 captured. DAC is currently land-intensive.

- CO_2 sequestration involves geological storage sites such as depleted oil and gas reservoirs, and salt caverns, requiring significant and long-term investment.
- Captured CO_2 reuse may not lower CO_2 emissions, depending on the source, displaced use, consumed energy and duration of retention, among other variables. CO_2 reuse is unlikely to contribute to reaching climate targets in desired timeframes.
- Cost-effective CCS at scale needs major investment and research advances. Policy and regulatory action including pricing-in carbon emissions from fossil-fueled processes accelerate CCS adoption.

User Recommendations

- Create a roadmap for CCS as mitigation or as a source of value based on ranking and prioritization of potential available pathways benchmarked against the current state.
- Engage with regulators, investors, startup providers and research bodies to improve CCS feasibility and economics improvement and create novel captured CO_2 uses.
- Explore opportunities for business model innovation based on CCS-relevant assets or resources and in the context of local regulatory frameworks.

Sample Vendors

Aker Carbon Capture; Baker Hughes; Batelle; Carbon Clean Solutions; Carbon Engineering; CGG; Climeworks; Northern Lights JV; Occidental Petroleum; Talos Energy

Gartner Recommended Reading

Market Guide for Gas Emissions Management Solutions

Green Hydrogen

Analysis By: Simon Cushing

Benefit Rating: Transformational

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

As a fuel, the only product from hydrogen combustion is water. It is one of the most promising zero-emissions fuels and energy stores. Green hydrogen is produced from water by electrolysis, where the electricity required comes from emissions-free renewable sources or nuclear energy.

Why This Is Important

Interest in green hydrogen is driven by its promise to deliver a clean energy future. Powering fuel cells, turbines and boilers, it possesses versatility to provide mobility, power system, domestic heat, and industrial services with no greenhouse gas emissions. It can be a fuel and a long-term storage medium to offset renewables' intermittency and seasonal variation. Existing gas distribution infrastructure can be repurposed to transport hydrogen blends or, in some cases, pure hydrogen, easing a transition to clean energy systems.

Business Impact

Green hydrogen is likely to eliminate fossil fuel usage in certain energy systems. In particular, it may be the only viable carbon-free energy source where electrification is not workable; for example, steel making, glass making and long-haul heavy transport. In power generation, it may act as a storage medium to mitigate renewable intermittency and as a clean fuel in retrofitted gas turbines. In the delivery domain, it will be an energy transport medium, while in retail, it may be delivered to customers directly or blended with natural gas.

Drivers

- Power generation accounts for about 40% of global CO2 emissions, which can be eliminated by replacing hydrocarbons with renewable energy supported by hydrogen or other energy storage. The remaining 60% come from industry, transport and other sources. Green hydrogen can act as a zero-emission energy carrier, displacing hydrocarbons in these sectors and, in effect, transferring renewable energy to all energy users.

- The International Energy Agency (IEA) reports that by the end of 2022, 26 countries had hydrogen strategies, up from 17 the previous year.

- Global hydrogen demand now exceeds prepandemic levels, and uses outside refining and fertilizer production (for example, as fuel) are growing rapidly (though these are still a negligible fraction of established uses).

- According to BloombergNEF (BNEF), there are over $90 billion of hydrogen projects in their global pipeline and dozens of hydrogen electrolyzer projects with more than 50 GW capacity. The U.S. infrastructure bill, passed in November of 2021, has designated $9.5 billion for clean hydrogen, while a part of $130 trillion, available through Glasgow Financial Alliance for Net Zero, will also accelerate R&D and deployment of green hydrogen in particular.

- Five new green hydrogen projects are slated to begin operation in the U.S. in 2023. Several new steel projects have been announced, following a demonstration project using pure hydrogen in iron reduction, and the first fleet of hydrogen trains has begun operation in Germany.

- Construction of the world's largest hydrogen project has begun at Ordos in China. The project is designed to produce around 30,000 tons of hydrogen a year for use in nearby refining and chemical plants, replacing coal-derived hydrogen.

- The EU Hydrogen Strategy projects hydrogen share in the energy mix to grow from less than 2% to 14% by 2050, and the IEA projects demand of around 115 million tonnes by 2030, an increase of 22% above 2020.

Obstacles

- Planned or projected hydrogen production falls short of the volumes needed to meet net-zero ambitions. The IEA Net Zero Scenario requires around 180 million tonnes of demand by 2030, with nearly half from new applications.
- Hydrogen is not available in its pure form. Separating it requires energy and adds cost. Green hydrogen is currently several times more expensive than gray or blue hydrogen.
- Unless other feasible methods are found, lowering green hydrogen's cost will require large-scale, high-capacity electrolysers using plentiful cheap renewable energy. The scale required is enormous. For example, The European Green Deal assumes an electrolyser capacity of around 500 GW by 2050, roughly double of today's entire European power supply.
- Hydrogen's round-trip efficiency is much lower than batteries. Hydrogen fuel cells and turbines are only about 60% efficient, far worse than electric motors. Electricity is likely to continue to be more efficient and cost-effective than hydrogen, green or otherwise, in areas where it can be used directly or via batteries.

User Recommendations

- Include hydrogen to your strategic disruptors list by monitoring developments in hydrogen markets, regulation policies and production/storage technologies, and setting scenario flags.
- Start forming partnerships across energy sectors to leverage unique skills and resources to advance corporate starting positions in the hydrogen economy.
- Explore the readiness of your IT and operational technology (OT) portfolios to address green hydrogen and hydrogen economy requirements.
- Accelerate buildup of new storage capacity for green hydrogen by accessing funds created by policymakers to promote hydrogen-based storage.

Sample Vendors

Enapter; Giner Labs; GTT (Areva H2Gen); Nel

Gartner Recommended Reading

Research Roundup: Top 10 Trends Shaping the Utility Sector in 2023

Hydrogen Electrolyzers

Analysis By: Lloyd Jones

Benefit Rating: Transformational

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

Electrolyzers are a technology that uses electricity to break water into hydrogen and oxygen in a process called electrolysis, which separates hydrogen by using electrodes to induce ion flow across a membrane. Electrolyzers are key for producing green hydrogen which could accelerate the transition to a low-carbon energy future.

Why This Is Important

Electrolysis powered by renewable energy creates zero-emissions hydrogen, providing a sustainable fuel for a decarbonized economy across all energy sectors. Today's hydrogen electrolyzers are mostly small with low efficiency. Reducing the barriers of performance and scale of hydrogen electrolyzers will unlock the hydrogen economy, displacing fossil fuels in generation, storage, heating, manufacturing and some transport use cases, enabling the market to pivot to lower emissions.

Business Impact

Hydrogen electrolyzers are a bottleneck for green hydrogen. Renewable energy at scale can provide a low, marginal cost power source for hydrogen electrolyzers, thus improving the economics. Current hydrogen electrolyzers operate with 60% to 75% process efficiency. High-efficiency, scalable hydrogen electrolyzers will unlock hydrogen as an alternative resource for energy storage and establish hydrogen as a low-cost fuel across industries, from transport to manufacturing.

Drivers

- Globally, policymakers are pinning a lot of optimism on hydrogen as an alternative energy resource for economies, with specific policy-funded intervention opportunities for green hydrogen across multiple industries.

- Fundamentally hydrogen electrolyzers allow energy production to be decoupled from demand, creating opportunities across the hydrogen value chain, from production, storage to distribution.
- The acceleration of the energy transition is adding intermittent renewable energy to the grid at an exponential rate, creating periods of oversupply of clean energy, which dramatically improves the economics of electrolysis. Coupled with expected lower wholesale prices over the medium term, this is a powerful driver of the hydrogen value proposition.
- Policy-driven research funding is driving results with innovations in electrolyzers, from membranes to anodes and cathodes and balance of plant, with a learning rate similar to wind, around 20% per doubling of capacity.
- Electrolyzer technologies are clustered around three technologies, each with its own limitations. Alkaline uses a liquid electrolyte solution of sodium hydroxide and water. When a current is applied to it, hydrogen is formed at the cathode — a technology that has been scaled in China (see China's Nascent Green Hydrogen Sector: How Policy, Research and Business Are Forging a New Industry, Mercator Institute for China Studies).
- Proton exchange membrane (PEM) combines electrons and water at the anode, splitting into hydrogen and oxygen. Hydrogen protons pass through the solid polymer membranes to release hydrogen gas on the cathode side. This technology is favored in Europe (see PEM Electrolyser Technology Gaining Favour, PE Media Network).
- Solid oxide electrolyzer (SOEC) combines electrons and water at the cathode forming hydrogen gas and negative ions. Oxygen passes through the ceramic membrane and reacts at the anode to release oxygen and electrons.
- Industrial electrolyzers can achieve unit efficiencies of up to 85% with the literature reporting lab results of 95% efficiency — approaching battery efficiency.

Obstacles

- Electrolyzers have a negative energy balance, consuming energy to produce hydrogen at an energy deficit. This drives poor economics, forcing a reliance on surplus renewable energy to improve the economics.
- Renewable energy is curtailed because of network constraints. This is forcing the colocation of the electrolyzer alongside the energy source, requiring "greenfield" infrastructure, and driving up costs.
- Electrolyzers are still in early development, current commercial unit costs in the range of 1.2M Euro per MW as of 2022.
- Research is needed to improve the price performance point to justify conventional business cases for wide-scale adoption. Policy and research are targeting cost pathways of $2/kgH2 by 2025 and $1/kgH2 by 2030.
- Innovations are needed to improve the energy efficiency of the electrolysis process. Materials modeling and chemistry could improve electrolyzer cell and stack degradation processes, along with novel materials for anode and cathode and membranes.

User Recommendations

- Leverage government innovation and research grant funding such as EU Hydrogen or U.S. Infrastructure Investment and Jobs Act (IIJA) to deploy electrolyzers.
- Build corporate knowledge and operational expertise now by starting with small-scale pilots.
- Watch industry press for case study results of early innovations and scale-outs.

Sample Vendors

AFC Energy; Cummins; Hydrox Holdings; Hysata; ITM Power; Nel; Plug Power; Topsoe; Verdagy

Gartner Recommended Reading

Research Roundup: Top 10 Trends Shaping the Utility Sector in 2023

2023 Utility Trend: Green Hydrogen Expectations Are High, but So Are Challenges

Floating Offshore Wind Turbines

Analysis By: Lauren Wheatley

Benefit Rating: High

Market Penetration: 5% to 20% of target audience

Maturity: Adolescent

Definition:

Floating offshore wind (FOW) turbines are offshore wind turbines mounted on a floating platform. They are stabilized by moorings and anchors. The force of the wind turns the blades and the turbine converts the kinetic energy into electricity, which is generally transported by underwater cables to an offshore substation and from there to an onshore substation on the coast and finally to consumers via the power lines.

Why This Is Important

An additional 70 GW of offshore wind power installation is needed every year between 2030 and 2050 to remain on the pathway to carbon neutrality. The ability to install FOW turbines in deeper waters, where winds tend to be stronger, opens up vast amounts of the ocean to generate renewable wind power: close to 80% of potential offshore wind power is found in waters where installing bottom-fixed turbines is infeasible.

Business Impact

FOW technology can deliver scale and more reliable availability of renewable power to facilitate the energy transition. However, due to a maturing market, contingency planning and risk management is paramount. Strategic alliances are a common approach to developing and operating FOW assets, leveraging the use of existing solutions from other sectors, transferable skills and technologies in the offshore oil and gas to derisk the development of FOW turbines.

Drivers

- FOW technology opens offshore areas with suitable water depths and high mean wind speeds (leading to greater asset efficiency) for offshore wind generation. There are transferable skills and technologies from fixed foundation offshore wind, onshore wind and oil and gas markets to catalyze innovation and industrialization.
- Offshore locations may be less politically divisive as sites for major infrastructure. In some regions there are already supportive offshore wind policy frameworks in place.
- Electrical power generated from offshore wind farms is expected to grow exponentially in the next few years and FOW turbines cost parity with fixed foundation technology is expected within a decade. Floating turbines can be built on land, assembled in port and towed to their site using standard tugs, leading to significant cost savings compared to fixed foundation turbine installations. For maintenance, they can be towed back to port where engineers can work on them in safe conditions.
- FOW turbines may be a key driver in helping to establish a green hydrogen economy, converting sea water into green hydrogen for export. Offshore wind power generation is constrained by the need to access the power grid. A move to hydrogen could resolve this problem, with electrolyzers located next to the turbines of an offshore wind farm. This could be an alternative business model, avoiding expensive grid connection costs and losses, or as an additional revenue stream when wind generation capacity exceeds demand, and the curtailed power can be directed into producing green hydrogen.
- FOW turbines can economically provide power for offshore oil and gas operations as an alternative to installation of gas turbines, offering a means to decarbonize oil and gas production.
- Electricity suppliers’ are complying with decarbonization obligations coupled with enabling business models such as corporate PPAs.

Obstacles

- Cost is a significant obstacle in this decade, although these are expected to fall as technology advances and supply chains improve.
- There are currently no key FOW design principles or standards for turbines or platforms that will support commercial deployment at scale, in different geographies, and cost-effectively with local adaptability to the supply chain.
- Capacity within the supply chain for equipment parts, including FOW platforms, personnel and specialist ships for the construction work.
- Capacity of the transmission network to bring the power onshore both in terms of connections to shore and capacity within the onshore transmission network is limited. These are also sensitive to supply chain constraints and regulatory processes for approvals for the upgrade expenditure and planning permission.

User Recommendations

- Enable your organization to reach improved performance and outcomes by using strategic roadmaps to articulate current-state renewable energy generation capabilities, the future desired state and the gaps that must be filled.
- Maximize the value of strategic alliances by implementing modeling, document and data management systems that will improve data sharing and access.
- Support the management of FOW resources by developing event-driven systems that provide access to appropriate analytical tools.

Sample Vendors

GE; Mitsubishi Heavy Industries (MHI) Group; Siemens Gamesa Renewable Energy; Vestas; Ørsted

Gartner Recommended Reading

Market Guide for Renewable Energy Management Systems

The Impacts of Exponential Renewable Generation Growth Across the Energy Ecosystem

Innovation Insight: Power Purchase Agreement Management Solutions for Energy and Utilities

Biodiesel and Biokerosene

Analysis By: Simon Cushing

Benefit Rating: Transformational

Market Penetration: 1% to 5% of target audience

Maturity: Early mainstream

Definition:

Biofuels are liquid or gas fuels, typically for transport, produced using renewable biomass resources. Biodiesel and biokerosene are biofuels with the same uses as hydrocarbon-based diesel and kerosene (jet fuel). Biofuels are commonly made from vegetable oils, used cooking oils or animal fats, used grease and farm waste. More experimentally, biofuels can also be made from tank-cultivated microalgae.

Why This Is Important

Plant or waste-based biofuels emit CO_2 when burnt but with no new net emissions. Transport is extremely reliant on fossil fuels and produces 20% of all CO_2 emissions. Road transport generates roughly three-quarters of transport emissions, and aviation around 10%. Decarbonized transport is essential to meaningfully reduce global CO_2 emissions. Biodiesel and biokerosene are “drop in” fossil fuel replacements, typically requiring minimal existing engine modification.

Business Impact

Diesel and gasoline are major drivers of global demand for oil. Large-scale adoption of biofuels would significantly reduce global oil demand. Diesel is widely used in freight transport, farm machinery and for other uses that are harder to electrify than passenger cars and motorized cycles. Transport is critical to many businesses, and low carbon fuels would significantly advance business emissions reduction efforts.

Drivers

- Much road and rail transport can be electrified, or potentially powered by hydrogen. With renewable electricity sources, electric or hydrogen vehicles are emissions-free. However, the scale of renewables installation makes timings uncertain, and hydrogen infrastructure has barely begun to be constructed, presenting an opportunity for biofuel adoption.
- In addition, it will take a long time to entirely replace the global fleet of ICE vehicles. Biofuels could help reduce emissions quickly in the remaining ICE fleet, or where renewable electricity is not available. Low carbon fuels that can be used with existing internal combustion engines (ICE) offer a potential route to rapid, meaningful transport emissions reduction.
- Aviation in particular is hard to decarbonize. Research is ongoing, but the comparatively low energy density (and composition) of batteries likely excludes the full electrification of larger commercial aircraft without significant technology breakthroughs. Airliners are expensive, long-lived assets. Replacement and retrofit costs are very high, moderating the pace of new technology adoption. Drop-in replacement fuels could significantly reduce the emissions of current airline fleets with minimal upgrade or consequent operational costs.
- In 2021, members of the International Air Transport Association (IATA), the airlines' trade association, committed to achieving net-zero operations by 2050 adding impetus to the development of sustainable aviation fuels (SAF). More governments, airlines, fuel producers and military air forces are announcing trials, targets and investment in SAF. Sourced sustainably, biokerosene can be a major SAF.
- According to IATA, 38 countries have SAF policies and 450,000 flights have taken place using SAF. Several proven production pathways exist and 300 million liters were produced in 2022.

Obstacles

- Biodiesel and biokerosene production still sees low volume. Biodiesel prices are double those of fossil fuel.
- Current technologies allow for biofuel-kerosene mixtures of up to 50%. Globally, biofuel is incorporated around 0.1% into kerosene. Greater blending alleviates some price differential, but production needs to scale up to close the gap.
- While plant-based biofuel growth and combustion are roughly net-zero, CO_2may be emitted during the production cycle. The highest full-life cycle emissions reduction is less than 80%.
- Recycled nonvegetable oils are significant feedstock for biodiesel and biokerosene production but may be net-carbon emitters. New technologies are needed to commercialize production from nonplant raw materials.
- Biodiesel and biokerosene aren't identical to their fossil fuel counterparts. Existing engines may need modification to use them, reducing benefit as drop-in replacements.
- Planting for fuel may displace food crops and raise food prices. Sustainable production may slow availability and price reduction.

User Recommendations

- Collaborate with transport service providers to source sustainably produced biofuels as a fuel alongside fossil fuel equivalents, where feasible.
- Seek investment and encourage research in biofuel research, testing, development and adoption by engaging with relevant industry associations and regulators.
- Include biofuels as part of enterprise sustainability roadmaps and closely monitor biofuel technology development, regulation, pricing and availability with a view to adoption as soon as favorable.

Gartner Recommended Reading

Sustainability Opportunities for Oil and Gas Vendors: A Gartner Trend Insight Report

3 Transformative Partnerships to Accelerate Transportation Emissions Reduction

Floating Inland Solar

Analysis By: Lauren Wheatley, Auria Asadsangabi

Benefit Rating: Moderate

Market Penetration: 1% to 5% of target audience

Maturity: Adolescent

Definition:

Floating solar photovoltaic (FPV) panels are power production installations that are mounted on structures or platforms and designed to float on water bodies. All solar PV technology uses cells, consisting of several layers of a semiconducting material, to convert sunlight into direct current electricity. The electricity is collected at a central inverter, converting it into AC electricity through a transformer and transmitting it to consumers via power lines.

Why This Is Important

PV deployment must grow from an installed capacity of 892 GW in 2021 to 5,052 GW in 2030, to remain on the pathway to carbon neutrality. Utility-scale PV requires significant use of suitable land, but it is not available everywhere. Land-constrained countries may prioritize land use for agricultural, forestry or other needs. FPV systems scale up renewables and reduce potential competing land-use pressures by colocating PV systems on water bodies, such as reservoirs or hydroelectric dams.

Business Impact

Rapid acceleration of large-scale renewable energy technologies is needed to facilitate the energy transition. FPV is a fast-emerging renewable energy technology that opens up new geographical markets to energy and utility companies for solar development, in regions where there is limited space on land for producing renewable energy. Growing levels of government support and investor appetite will help reach 10 GW of installed capacity by 2025.

Drivers

- Solar PV dominates renewable energy capacity additions, despite increasing capex costs since 2020. In several countries, utility-scale solar PV is the least costly option for adding new electricity capacity. Rising oil, natural gas and coal prices improve the cost advantage and add incentive for solar PV installation.
- The key drivers of the floating solar industry include lack of available land for projects, high land costs and high population density, coupled with aggressive national and citywide renewable energy and greenhouse gas emission targets.
- FPV allows for greater panel density for a given area, which makes developments more compact than land-based plants, their management simpler, and their construction and decommissioning straightforward. Moreover, installation is completely reversible, as there are no fixed structures like the foundations used for a land-based plant. .
- Deployed on inland bodies of water, FPV may be favorably sited near demand centers, reducing transmission losses.
- Colocation with hydroelectric sites brings power system benefits and reduced capital costs, especially for large hydroelectric plants to manage periods of low water availability.
- FPV systems can help avoid land-energy conflicts, lower site acquisition and preparation costs, gain potential system efficiency and production, improve solar PV performance, and convert underused space into areas that allow for revenue-generating use.
- FPV systems can combine projects with aquaculture operations, where fish cultivation is conducted in the waters below the PV panels.
- The modular nature of FPV allows for scalability and asset redeployment.
- Algal bloom, a serious problem in industrialized countries, may be reduced with FPV systems.

Obstacles

- Supply chain disruptions, including rising material and labor costs, supply of raw materials, and ESG concerns, threaten to derail FPV near-term projects. Rising shipping and equipment costs are threatening to postpone or cancel planned utility-scale solar projects. Given these items represent as much as one-third of project costs, small price increases can result in negative returns on investment for marginal projects.
- Factors such as system performance, topographic limitations and environmental constraints determine the technical potential and deployment of FPV systems.
- While FPV can be deployed in the ocean, ideally in sheltered bays, at present they must be protected from large waves and harsh weather conditions, which limits viable location options.
- Currently standards are lacking and FPV presents several design challenges that must be overcome, including electrical safety and long-term reliability of system components, anchoring and mooring, and maintenance complexity.

User Recommendations

- Consider deploying FPVs to help diversify power generation mixes, strengthen energy security and lessen land-use constraints.
- Support the management of FPV through development of event-driven systems that provide access to appropriate analytical tools.
- Drive an event-driven business model through deployment of low-cost Internet of Things (IoT) to detect contextual events in the wider environment. Identify IoT tools, and platform strengths and weaknesses. Prioritize investments in projects that connect IoT edge, platform and enterprise, and then link these together at scale.

Sample Vendors

AE Solar; Ciel & Terre; LONGi Green Energy Technology; Mibet Energy; Ocean Sun; Sembcorp Industries; Trina Solar

Gartner Recommended Reading

The Impacts of Exponential Renewable Generation Growth Across the Energy Ecosystem

Market Guide for Renewable Energy Management Systems

Sliding into the Trough

Biomass Energy

Analysis By: Ethan Cohen

Benefit Rating: High

Market Penetration: 5% to 20% of target audience

Maturity: Emerging

Definition:

Biomass is a renewable organic material that comes from plants and animals. The energy from these organisms can be burned to create heat or converted into electricity. The use of biomass fuels for transportation and electricity generation is increasing in many developed countries as a means to avoid carbon dioxide emissions from fossil fuel use. Sources of biomass include wood, agricultural crops and waste materials, municipal solid waste, animal manure and human sewage.

Why This Is Important

Biomass is converted to energy through various processes. The diversity of biomass production is mirrored in its application as an energy source and its broad applicability to decarbonization in the energy transition. Direct combustion is the most common method for converting biomass to useful energy. All biomass can be burned directly for heating buildings and water, for industrial processes and for generating electricity in steam turbines.

Business Impact

Demand for renewable energy makes biomass energy an important focus in energy transition. Biomass has the discrete advantage of being plentiful, easy to transport, and increasingly efficient to directly convert into electricity or to produce biofuels and hydrogen. Biomass energy can aid decarbonization because it utilizes organic material that would otherwise decompose into greenhouse gasses. As biomass fuel is sequestered carbon, the offset of carbon production versus fossil fuels is attractive.

Drivers

- Biomass is competitive, if not lower, in cost compared to fossil fuels.

- Biomass is both a renewable resource, and a byproduct of natural cycles and of plant and animal cycles and activity. It is available almost everywhere on the planet.
- Biomass energy potential can be transformed into energy via burning, bacterial decay, fermentation and conversion to gas/liquid fuel. It is usable across diverse use cases and optimizable for specific contexts, such as human waste bioreactors situated in urban wastewater treatment facilities.
- Biomass research is producing renewable jet fuel from industrial waste gasses, such as carbon monoxide from steel production into fuel for airplanes.
- Algal turf scrubbers are now able to fuel cars and clean up pollution. Algal turf scrubbers are long, thread-like algae that can be deployed near storm water and agricultural wastewater runoff to absorb excess phosphorus and nitrogen. The algae itself can then be converted into biofuel.
- Biofuel and hydrogen from sludge waste is now being produced at scale. The cost avoidance of sludge disposal plus the savings in self-provisioned energy makes biofuel use at water treatment plants a true progression toward water resource recovery and regeneration.

Obstacles

- Due to decentralized capital, poor profitability, frequent fluctuations of international crude oil prices and high market risk, investors seldom invest in power generation.
- It is difficult to get long-term contracts for consistent feedstock biomass supply at a reasonable price except where systematic concentration, such as in the case of human waste at water treatment plants, is possible.
- There is no special mechanism or governance to manage the development of the biomass resources industry, and no specialized department to manage the implementation of relevant national standards and policies. Bulk and energy density are different for the types of biomass and present various economic and environmental challenges and regulations.
- Biomass plantations deplete nutrients from the soil, promote aesthetic degradation, increase the loss of biodiversity and compete with agriculture for land use.

User Recommendations

- Seek to develop appropriate supply chain and related compliance business processes and technology enablement capability; the economic viability of biomass energy production could depend on this.
- Develop or purchase biomass forecasting and availability models. Advanced energy modeling solutions are a focus for energy and utility industry vertical vendors seeking to add insight and value to AI and IoT.
- Create analytics heuristics for modeling agro-forestry residues and pretreatment operating procedures to understand the feasibility and sustainability of blending biomass feedstocks to contract for suitable average composition of resources.

Sample Vendors

Fulcrum; Hexas; Ørsted; Renewable Energy Group; South East Water

Gartner Recommended Reading

2022 Sustainability Survey: Energy CIOs Can Help to Retain C&I Enterprises as Customers

Mechanical Energy Storage

Analysis By: Ethan Cohen

Benefit Rating: High

Market Penetration: 20% to 50% of target audience

Maturity: Early mainstream

Definition:

Mechanical energy storage systems convert energy into and from kinetic energy. There are several types, including pumped water storage, liquid air storage, compressed air storage and flywheels. Pumped hydro storage is the most widely used. The flywheel is generally used with site- or application-specific rotary equipment, such as in hybrid and electric cars. Compressed air energy storage is in a maturing stage of development and is typically sought in industrial applications.

Why This Is Important

Mechanical storage is the increasing demand for a clean source of stored energy to pair with renewable generation. Mechanical energy storage is more versatile in comparison to other storage technologies, such as battery storage, because it offers better reliability and resilience. Mechanical energy storage is disruptive in that it delivers a trifecta of key benefits to utilities and energy end users alike. It provides a broad swath of low-cost use cases, applicable in most operating contexts.

Business Impact

As more energy is provisioned by renewables, the need for energy storage grows. Having decarbonized energy production, storage without similarly low environmental impact is less valuable, particularly in the context of United Nations and international climate policy and agreement goals. The reliability, resilience and sustainability, and economics of decarbonized energy provisioning without complementary storage would be unfeasibly expensive and impractical to develop and operate.

Drivers

- Economics and scalability, both at utility scale and commercial and industrial customer scale, as well as the benefits to EV charging operators are the key drivers for mechanical energy storage.
- The current full cost of lithium-ion battery storage is about $300 per kilowatt hour (kWh), which is at least tenfold higher than for 12 hours of pumped hydro storage. The energy installation cost per kWh of mechanical energy storage systems is low relative to other types of energy storage method. For instance, installation costs of PHS and CAES types of mechanical energy storage are roughly $21 per kWh and $53 per kWh, respectively; whereas, other types of energy storage cost in the range of $100 to $1000 per kWh.
- Even developing technologies such as Brayton turbines, which are adiabatic compressors and expanders, can deliver meaningfully lower costs better than battery storage due to their high conversion efficiency, in the 92% to 98% range.
- The large and expanding number of utility services used to reduce the network congestion during peak hours not only extends the life of grid assets and improves resilience, but also boosts the demand for grid-connected mechanical energy storage systems. Utility services include bulk energy services, ancillary services, grid support services and renewable energy integration.
- Mechanical energy storage developed and owned by commercial and industrial organizations represents the largest disruption factor in the mechanical storage domain. As organizations seek to mitigate energy-related risks — particularly cost and carbon acceptability — mechanical storage, like microgrids, changes the balance of relationship in energy value chains from linear to circular.
- This means that mechanical energy storage prosumers can take agency over their performance and outcomes beyond commodity and arbitrage for risk and cost balance, and even potentially create new high-margin revenue.

Obstacles

- Mechanical energy storage is widely proven technology that can meet a wider array of utility needs. However, mechanical energy storage remains less visible and popular than battery storage because of: The physical footprint and size of systems; the emphasis of venture capital and other speculative investment being focused on battery technologies; and concern over asset workforce availability and maintenance of these systems.

- The growth of the mechanical energy storage market is being hindered by the availability of alternatives or substitutes in the form of chemical energy storage systems, such as Li-Ion battery, lead-acid battery, and molten salt energy storage.

User Recommendations

Form partnerships across energy sectors to leverage unique skills and resources to advance the starting position in mechanical energy storage, according to the strategy and ambition.

- Accelerate buildup of new mechanical storage capacity by accessing funds from investors as well as governments to promote mechanical storage.
- Explore the readiness of the technology portfolios energy technologies, operational technology (OT) and IT to address requirements for long- and short-term mechanical energy storage. Many domains of mechanical energy storage are still not yet mature including: cycle and system analysis and optimization, materials engineering, site feasibility and system integration.

Sample Vendors

Amber Kinetics; ENERGIESTRO; Hydrostor; LightSail Energy; OXTO Energy; Stantec; Stornetic; SUSTAINX; Voith Group

Gartner Recommended Reading

Market Guide for Electric Vehicle Charging Solutions

Large-Scale Heat Pumps

Analysis By: Simon Cushing

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Adolescent

Definition:

Heat pumps transfer thermal energy from warm areas to cool areas, typically taking energy from natural sources — air, ground or water. Their heat sources can also include heat captured from industrial exhaust data centers or other waste heat. Large-scale heat pumps operate at high outputs suitable for industrial uses or for heating of residential and industrial districts.

Why This Is Important

Industrial heating accounts for around 25% of all energy consumption, almost entirely provided using fossil fuels. Replacing fossil-fuel-burning boilers and heaters with heat pumps powered by renewable electricity could radically reduce the CO_2 emissions from industrial heating. Use of a thermal source enables heat pumps to generate more heat than direct use of the electricity that they are powered by. Large-scale heat pumps are needed to achieve the high temperatures required by industrial processes.

Business Impact

Cost-effective large-scale heat pumps could enable a decisive shift away from fossil fuel heat sources for many industries and district heating, helping businesses and communities reach decarbonization goals. Industrial heat pump operating costs depend mostly on electricity costs and the efficiency of output heat usage. Under suitable conditions, for example with high fossil fuel energy costs, operating costs can be favorable. Heat pumps can have long lifetimes and offer potential safety reliability benefits over combustion-based systems.

Drivers

- Achieving decarbonization targets will require a large-scale shift away from fossil fuel heating across the industry. Heat pump technology is not new, and a range of mature technologies, including ground, air, water and waste heat source pumps, are available from suppliers.
- Higher conventional energy prices will drive adoption of heat pumps as a non-fossil-fuel energy source. The Russian invasion of Ukraine has elevated the importance of energy security for many enterprises, whether directly affected or not, adding momentum for uptake since heat pumps reduce enterprise fossil fuel dependence. The International Energy Agency (IEA) found that global heat pump sales increased by 11% in 2022, though mostly in Europe.
- Large heat pumps typically have a short ramp rate, meaning that heating and cooling can be done quickly. Recent innovations include refrigerant-free units that promise increased efficiency, reduced cost and lower environmental impact.
- Next-generation heat pumps are in development with expected outputs nearly double those of today's largest commercially available units.
- Large-scale heat pumps can provide power grid stabilization by lowering the need for peak power generators, peak shaving and the efficient use of surplus power from an area to be converted into heat.
- As suppliers of district heat and similar applications, large-scale heat pumps could foster increased consumerization of energy with consequent impact on utility business models and revenue, depending on where the required electricity is sourced from. For utilities, they could provide a demand-side pathway for localized energy provision and decarbonization.
- Large-scale heat pump projects are operational, with more underway. Also, for industrial processes, large-scale heat pumps have been installed as a part of closed loop systems, including fleets of smaller pumps in district heating projects in the U.K., Norway and Germany.

Obstacles

- Today's large-scale heat pumps produce heat up to 150 degrees Celsius and approximately 70 MW maximum. Hence, they cannot meet high-temperature industrial requirements and do not offer a complete solution for decarbonizing industrial energy.
- Heat pumps remove direct CO_2 emissions from combustion on-site but require renewable electricity to be emission-free, which is a determining operational cost. In many places, government support will be needed to make heat pumps commercially competitive with fossil fuel heat.
- Some older heat pump designs use refrigerants that have an environmental impact.
- Purchase and installation costs for heat pumps are currently several times those of gas-fired boilers for equivalent use.
- Heat pump manufacturing is heavily focused in Asia/Pacific and, according to the IEA, supply chains are stretched. Growth at the scale required will need considerable investment in manufacturing capacity and secure supply chains. Incentives for adopters and direct support of manufacturers are likely needed to promote the investment required.

User Recommendations

Heat pumps can directly replace gas or oil-fired heating in a range of industrial applications. The economic rationale for doing so is highly dependent on the individual enterprise situation, including local electricity and conventional energy costs, as well as operational conditions on-site. Hence, before investing in heat pumps, enterprise should:

- Conduct a cost-benefit analysis of adopting large-scale heat pumps for equivalent applications, considering all variables and energy security over the likely lifetime of operation. This should be done at or before the end of existing fossil fuel heat sources.
- Examine innovations in large-scale heat pump technologies closely and engage with promising providers to assess the capabilities of promising innovations to address current heat pump challenges or economics.

Sample Vendors

European Centres for Outreach in Photonics; Mitsubishi Electric; Siemens; Star Refrigeration

Large-Scale Lithium-Ion Batteries

Analysis By: Lloyd Jones

Benefit Rating: Transformational

Market Penetration: 5% to 20% of target audience

Maturity: Early mainstream

Definition:

Lithium-ion (Li-Ion) solid-state batteries with energy density and delivery voltages per cell, make them ideal for high-power applications. Li-Ion cells are stacked to support short duration (less than four hours) storage at a MW scale. Large-scale storage addresses energy unbalance created by renewables' intermittency and improves system resilience while reducing operating costs.

Why This Is Important

Electrical peak demand is growing forcing faster ramp rates. Ramping was covered by gas peakers, however Li-Ion batteries at large scale are providing an affordable alternative. Li-Ion batteries can be reconfigured to cover use cases from short-term peak power, to ancillary services, such as operating reserve to frequency control. When deployed alongside renewable energy sources can smooth and stabilize energy production, creating production and price certainty.

Business Impact

Strategically sited large-scale storage is a valuable alternative to grid upgrades, at both centralized and decentralized locations. Solar is dominating the system profile — reducing midday net load and raising the ramp rate to the evening peak. Li-Ion battery technology accelerated by electric vehicle research has created a technology price performance sweet spot for short-duration (less than four hours) rapid response storage. Large-scale Li-Ion batteries currently exceed 300 MW/1200MWh.

Drivers

- Estimates of large-scale storage needed by 2030 exceed 600 GW in the IEA Net Zero by 2050 scenario.
- Li-Ion batteries are able to respond rapidly to the need for additional energy resources to meet the demand but for a limited period of time, typically less than four hours, but projects with upto eight hours are in the pipeline.
- Li-Ion battery costs dropped by 97% from $7,523/kWh in 1991 to $350/kWh in 2020, but supply chain issues saw the first price rise in 2023, strengthening the value proposition for energy arbitrage and deferring infrastructure upgrades.
- Lithium iron phosphate (LiFePO)-based batteries are gaining popularity as they do not need rare earth metals, such as cobalt and nickel, and have lower cost and toxicity, improved safety, and longer life cycle.
- Forward forecasts suggest technology innovation can drive costs toward $150/kWh for four-hour duration large-scale storage use cases by 2050.

Obstacles

- Storage plays a key role as an energy transition enabler. Storage can defer capacity upgrades but also competes with operational strategies such as demand response and voltage conservation.
- Li-Ion has a tendency to overheat, and can be damaged at high voltages. Li-Ion can experience thermal runaway and combustion, requiring safety mechanisms to limit voltage and internal pressures. Li-Ion performance degrades due to aging, losing capacity and then failure. Li-Ion has a limited life span compared to alternatives such as flow batteries.
- The emergence of new storage technologies, such as Nickel-Cadmium (Ni-Cd), and flow batteries, at significantly lower cost points may moderate or delay uptake of Li-Ion batteries.
- Sodium-ion batteries from CATL are a potential disruptor achieving 255Wh/kg in 2022 compared to the more expensive Li-Ion with a density of 260Wh/kg.

User Recommendations

- Incentivize deployment of large-scale storage with direct support for storage through mandates and policies.
- Participate in standards and regulations to ensure that regulations are transparent and open to develop markets for capacity, flexibility and ancillary services so that storage can compete with other technologies and measures.
- Ensure that any proposed Li-Ion energy management system includes temperature monitoring with fail-safe disconnects.
- Ensure Li-Ion energy management systems feature both passive and active cooling to dissipate heat gains.
- Research alternative storage technologies when examining longer-duration storage business toward 12 hours or more.
- Invest in API interfaces to integrate Li-Ion storage control and management systems into utility IT and OT domains.
- Invest in AI to optimize physical Li-Ion storage dispatch and charging operating cycles against the wholesale markets behavior.

Sample Vendors

AMP Energy; Contemporary Amperex Technology (CATL); General Electric; NGK Group; Panasonic; Samsung; Tesla

Gartner Recommended Reading

Research Roundup: Top 10 Trends Shaping the Utility Sector in 2023

Blue Hydrogen

Analysis By: Simon Cushing

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Adolescent

Definition:

Blue hydrogen is hydrogen produced from fossil fuels with carbon capture and storage to significantly reduce associated CO2 emissions. Costing less to produce than green hydrogen, blue hydrogen could act as a bridge to zero-emissions hydrogen and drive development of a hydrogen economy.

Why This Is Important

Current global demand for hydrogen (for petroleum refining and fertilizers) is met almost entirely by gray hydrogen, which is made from fossil fuels using processes which emit CO_2. Low-cost hydrogen is key to the creation of a hydrogen economy that can lead to a low-carbon energy future. Blue hydrogen, based on established processes and carbon capture technologies retrofitted to existing plants, can be produced more cheaply than green hydrogen and, in the best case, at similar cost to gray hydrogen.

Business Impact

For producers, competitively priced blue hydrogen offers a way to grow volumes and market share. It offers consumers a lower carbon alternative at minimal premium over gray hydrogen, and a way to reduce the carbon intensity of their hydrocarbon-based products. Blue hydrogen could quickly boost the growth of a hydrogen economy, involving a wider range of hydrogen uses in hard-to-abate energy-intensive uses. This would create new value chains and business models as a stepping stone to green hydrogen.

Drivers

- Recently, hydrogen has gained renewed interest and momentum as a potential key component of low-carbon energy systems globally. Hydrogen can serve as both a source and storer of energy, which is particularly useful in mitigating renewable intermittency or as clean fuel in generation. As of September 2022, the International Energy Agency (IEA) reports 26 countries committed to adopting hydrogen as a clean energy vector.
- The IEA reports that the pipeline of low-emissions hydrogen production is growing quickly, and estimates that if all current planned projects are realized blue hydrogen could provide over 40% of global hydrogen production by 2030.
- As a zero-emissions product, green hydrogen is preferred to meet environmental goals. However, green hydrogen today costs roughly two to three times more than blue. Major progress and investment in renewable generation and technology innovation are needed to bring these costs to competitive levels.
- Blue hydrogen is not zero-emission, but can be cost-effectively produced with meaningfully reduced emissions compared to gray hydrogen, and at a more competitive price than green. Newer alternative production technologies, such as autothermal reforming (ATR), show promise of reducing emissions and lowering blue hydrogen costs over established methods. Cost-competitive blue hydrogen could be a practical stepping stone toward a functioning hydrogen economy.
- In the near term, national and corporate emissions reduction targets are likely to drive increasing adoption of low-carbon solutions. Organizations will accept some price premium in these efforts. Blue hydrogen has the potential to be available more quickly and at less of a price premium than green hydrogen to meet these efforts.
- Increasing interest in blue hydrogen is illustrated by the 16 blue hydrogen projects currently operational around the world identified by the IEA, with around 50 under development.

Obstacles

- The large-scale investment needed in new hydrogen demand supply is an obstacle to implementation. Wood Mackenzie estimates that producers will need to invest around $600 billion in supply growth by 2050, and the IEA believes that $1.2 trillion is needed by 2030 to put the hydrogen sector on a path consistent with net-zero emissions.
- Economic blue hydrogen depends on cost-effective carbon capture and storage (CCS), and progress to date has been mixed. Without breakthroughs supporting greater scaling and cost-effectiveness of CCS, blue hydrogen may remain a marginal contributor to future energy system decarbonization.
- Commercially, blue hydrogen competes with other production methods. If renewable energy uptake and electrolyser innovation succeed in rapidly lowering green hydrogen costs significantly, the price advantage of blue hydrogen goes away.
- Blue hydrogen does not remove all CO_2 emissions and allows continued hydrocarbon production. Some influencers advocate placing investment in green hydrogen and other abatement technologies.

User Recommendations

- Assess blue hydrogen as a means to meet corporate emissions goals in the near term. If advantaged in terms of participation in the existing hydrogen economy, act now to assess the viability of investment in blue hydrogen production or infrastructure.
- Observe developments in CCS technology and projects, and in policymaker and investor activity, to assess the viability of investments in or use of blue hydrogen.
- Observe developments in the hydrogen economy, exploring possible partnerships and funding options to participate by assessing costs, risks and uncertainties, along with potential ecosystem partners.

Sample Vendors

Air Products and Chemicals; ExxonMobil, Shell

Gartner Recommended Reading

Research Roundup: Top 10 Trends Shaping the Utility Sector in 2023

Climbing the Slope

Fuel Cells

Analysis By: Simon Cushing

Benefit Rating: Moderate

Market Penetration: 1% to 5% of target audience

Maturity: Adolescent

Definition:

Fuel cells produce electricity through an electrochemical reaction between a fuel and an oxidizer. Most fuel cells use hydrogen; however, fuels can include methanol, ethanol and other hydrocarbons. Using hydrogen as a fuel, fuel cells produce only electricity, water and heat.

Why This Is Important

The output direct current (DC) from a fuel cell comes from chemical reactions rather than combustion. With hydrogen fuel, only electricity, water and heat result, providing an energy source with no greenhouse gas or pollutant emissions. Electricity can be used in a propulsion system, similar to electric vehicles, or converted into alternating current (AC) and supplied into conventional power systems.

Business Impact

Fuel cells are a viable form of distributed generation (DG) that is more reliable for consistent “base load” than variable wind or solar. Key applications include DG where a low environmental impact is desired (such as green data centers, small-scale utility-owned power plants, hospitals and universities). Fuel cells can power vehicle or other electric motors with zero emissions and avoiding the need for lengthy charging times.

Drivers

- The need for low-carbon energy solutions and emissions reduction in transportation are major drivers for fuel cell technology adoption.
- Fuel cells have potential as sources of power for vehicles. A fuel cell in isolation is more efficient and quieter than a combustion engine. Compared to battery electric vehicles (BEVs), fuel cell vehicles have a greater range, can be recharged/refueled much faster and are not significantly affected by cold weather.

- Fuel cells also have advantages over batteries for utility energy storage, including longer storage times, higher energy density and potentially greater operational charge/discharge flexibility supporting higher grid resiliency.
- Fuel cell technology is well established and has been in use for decades. Toyota and Hyundai launched commercially available hydrogen fuel cell cars in 2014 and 2015.
- Several major corporations are adopting fuel cells as a part of broader green data center strategies. Early adopters include Apple for the data center; FedEx and Staples for distribution facility power; Delmarva Power (Pepco Holdings) for distributed generation; Google for its headquarters; Coca-Cola for production facilities; and Walmart for retail locations.
- Japan, which has a long-standing, government-funded research program, is a leader in small-scale fuel cell commercialization, with more than 265,000 residential units installed by 2018, the majority being proton exchange membrane (PEM) fuel cells running on coal gas. More than 5.3 million are expected to be deployed by 2030.

Obstacles

- Fuel cell adoption remains relatively low due to high costs and reliability issues, as compared with other alternative energy sources like wind and solar.
- Cost, durability and reformer technology (hydrogen purification) continue to be the major challenges to fuel cell commercialization. In 2022, automaker Mercedes-Benz announced it was stopping production of its only hydrogen fuel cell model because of high manufacturing costs.
- Fuel cells have lower efficiency (significantly lower than Li-ion batteries, for example) with higher energy losses from fueling to energy delivery.
- In transport, fuel cells face significant competition from BEVs. For vehicles, a fuel cell’s efficiency is less than half of that of BEVs.
- Fuel cells are currently positioned as a niche power generation technology whose adoption is driven by its predictability and low environmental impact. A high installation cost per unit and ongoing durability issues continue to be obstacles to market adoption.
- Of the main types of fuel, hydrocarbons (natural gas or methanol) have the widest availability. Hydrogen availability remains limited with electrolysis (of water), the main pathway for creating hydrogen feedstock.

User Recommendations

- Prepare for increased fuel cell deployments by customers and anticipate effects through defined connection standards. Technical breakthroughs will be required for any sizable market penetration. However, there is a wave of early adoption as a green data center technology that warrants increased attention.
- Monitor the disruptive effect on traditional business models, operational technology (OT) and IT applications, because fuel cells will be deployed mostly as on-premises generation by consumers as a part of energy sector democratization (energy technology consumerization).

Sample Vendors

Acumentrics; Ballard Power Systems; Bloom Energy; Cummins; FuelCell Energy; Logan Energy; Panasonic; Plug Power; Toshiba

Gartner Recommended Reading

2023 Utility Trend: Green Hydrogen Expectations Are High, but So Are Challenges

Flexible AC Transmission Systems

Analysis By: Lloyd Jones

Benefit Rating: Moderate

Market Penetration: 20% to 50% of target audience

Maturity: Early mainstream

Definition:

Flexible AC transmission systems (FACTSs) are power electronic and other static equipment-based systems that provide rapid adjustment of AC transmission parameters to enhance controllability and increase power transfer capability. The flexible transmission allows for renewables integration, particularly from distant or offshore farms where underwater AC cabling is not economical or feasible.

Why This Is Important

A flexible alternating current transmission system (FACTS) is a type of power equipment with power electronics and fast (subcycle) control logic that enhances the flexibility, reliability and throughput (capacity) of power transmission systems. The device typically injects reactive power into the transmission and distribution network, or dynamically changes line impedance to mitigate power disturbances that would otherwise limit utility transmission and distribution capacity.

Business Impact

Transmission network operators will consider FACTS as an option for relieving transmission congestion and improving integration of renewable electricity sources onto the grid. Since FACTS implementations are relatively few, extensive consulting assistance and employee training will be needed at most utilities.

Drivers

- Growth in renewables (solar and wind farms), reliability concerns, network security, environmental issues and cost constraints are driving grid operators and owners to install FACTS to improve capacity and grid stability.
- FACTS enables utilities to push more power through transmission lines, where it is impractical to increase voltage or build new lines. FACTS is not always a lower-cost alternative to traditional transmission and distribution solutions, but it can be cost-effective as a retrofit to existing lines by avoiding servitude-permitting delays and improving the operational performance envelope with higher throughput and fast response to operational events.
- The main driver for FACTS is a need to interconnect large power systems to reduce renewable energy production volatility and support wide-area energy market arbitrage. For example, the proposed Tres Amigas Superstation (currently on hold) is designed to connect three U.S. primary interconnections (WECC, ERCOT and Eastern) and significantly improve overall system renewable hosting capacity.
- Future developments in FACTS include transformerless controllers, which will reduce costs and provide improved relocatability of equipment, as well as new silicon carbide and gallium-nitride-based switching devices.
- FACTS vendors are also combining energy storage with FACTS for improved integration of renewable energy sources onto the transmission grid. Some vendors are offering “containerized” FACTS solutions that can be more easily integrated into existing substation environments.
- The most common FACTS technologies include: (1) the first generation of FACTS — series compensation, static reactive power/volt-ampere reactive (VAR) compensators and thyristor-controlled series compensators (TCSCs), (2) the second generation — static synchronous compensators (STATCOMs), and (3) the third generation — unified power flow controllers (UPFCs).

Obstacles

- FACTS implementations are relatively few, consequently, extensive consulting assistance and employee training will be needed at most utilities. EMS enhancements may be required to address new operating requirements.
- Little more than 1,000 FACTS line projects were deployed globally since its inception-making access to resources, products and financing capital challenging.

- One of the obstacles to adoption is the emergence of an alternative means to address the challenge of the large-scale renewable generation transmission grid hosting capacity via advanced wide-area transmission operations (AWATO). While the FACTS approach focuses on hardware solutions such as use of power electronics and static equipment to improve grid controllability, AWATO focuses on using digital technologies to address the same issue. Although they can work in concert and complement each other. The competing approaches with AWATO are better positioned for faster and wider adoption.

User Recommendations

- Implement FACTS technologies to defer or eliminate more expensive transmission solutions. FACTS solutions can help mitigate rising VAR deficits and control issues due to the expansion of renewables on the grid.

- Consider the impact of FACTS deployment on traditional energy management systems (EMSs) and market operations.

- Evaluate the ongoing operations, maintenance requirements and workforce skills needed to keep the technology operating as intended. Outsourcing any maintenance and repair needs may be considered for the short term, until sufficient deployment justifies bringing the skills requirements in-house.

- Consider using HVDC as an alternative transmission technology with its larger power transfer characteristics.

Sample Vendors

General Electric (GE); Hitachi Energy; Mitsubishi Electric; Schneider Electric; Siemens Energy

Appendixes

See the previous Hype Cycle: Hype Cycle for Disruptive Energy Technologies, 2022

Hype Cycle Phases, Benefit Ratings and Maturity Levels

Table 2: Hype Cycle Phases

(Enlarged table in Appendix)

Phase ↓	Definition ↓
Innovation Trigger	A breakthrough, public demonstration, product launch or other event generates significant media and industry interest.
Peak of Inflated Expectations	During this phase of overenthusiasm and unrealistic projections, a flurry of well-publicized activity by technology leaders results in some successes, but more failures, as the innovation is pushed to its limits. The only enterprises making money are conference organizers and content publishers.
Trough of Disillusionment	Because the innovation does not live up to its overinflated expectations, it rapidly becomes unfashionable. Media interest wanes, except for a few cautionary tales.
Slope of Enlightenment	Focused experimentation and solid hard work by an increasingly diverse range of organizations lead to a true understanding of the innovation's applicability, risks and benefits. Commercial off-the-shelf methodologies and tools ease the development process.
Plateau of Productivity	The real-world benefits of the innovation are demonstrated and accepted. Tools and methodologies are increasingly stable as they enter their second and third generations. Growing numbers of organizations feel comfortable with the reduced level of risk; the rapid growth phase of adoption begins. Approximately 20% of the technology's target audience has adopted or is adopting the technology as it enters this phase.
Years to Mainstream Adoption	The time required for the innovation to reach the Plateau of Productivity.

Source: Gartner (July 2023)

Table 3: Benefit Ratings

Benefit Rating ↓	Definition ↓
Transformational	Enables new ways of doing business across industries that will result in major shifts in industry dynamics
High	Enables new ways of performing horizontal or vertical processes that will result in significantly increased revenue or cost savings for an enterprise
Moderate	Provides incremental improvements to established processes that will result in increased revenue or cost savings for an enterprise
Low	Slightly improves processes (for example, improved user experience) that will be difficult to translate into increased revenue or cost savings

Source: Gartner (July 2023)

Table 4: Maturity Levels

(Enlarged table in Appendix)

Maturity Levels ↓	Status ↓	Products/Vendors ↓
Embryonic	In labs	None
Emerging	Commercialization by vendors Pilots and deployments by industry leaders	First generation High price Much customization
Adolescent	Maturing technology capabilities and process understanding Uptake beyond early adopters	Second generation Less customization
Early mainstream	Proven technology Vendors, technology and adoption rapidly evolving	Third generation More out-of-box methodologies
Mature mainstream	Robust technology Not much evolution in vendors or technology	Several dominant vendors
Legacy	Not appropriate for new developments Cost of migration constrains replacement	Maintenance revenue focus
Obsolete	Rarely used	Used/resale market only

Source: Gartner (July 2023)

Document Revision History

Hype Cycle for Disruptive Energy Technologies, 2022 - 8 August 2022

Recommended by the Author

Some documents may not be available as part of your current Gartner subscription.

Understanding Gartner's Hype Cycles

Tool: Create Your Own Hype Cycle With Gartner's Hype Cycle Builder

Building a Low-Carbon Energy Strategy

Research Roundup: Top 10 Trends Shaping the Utility Sector in 2023

Research Roundup: Top Digital Trends Shaping the Oil and Gas Industry in 2023

Predicts 2023: Adapting to the Energy Transition

Predicts 2023: Oil and Gas — Navigating Constant Turbulence

Emerging Tech: The Future of Energy Storage

Table 1: Priority Matrix for Disruptive Energy Technologies, 2023

Benefit	*Years to Mainstream Adoption*			
↓	***Less Than 2 Years*** ↓	***2 - 5 Years*** ↓	***5 - 10 Years*** ↓	***More Than 10 Years*** ↓
Transformational		Large-Scale Lithium-Ion Batteries	Biodiesel and Biokerosene Carbon Capture Utilization and Storage Green Ammonia Green Hydrogen Hydrogen Electrolyzers	Commercial Nuclear Fusion Power High-Temperature Superconductors Small Modular Nuclear Reactors
High		Large-Scale Heat Pumps	Biomass Energy Blue Hydrogen Floating Offshore Wind Turbines Large-Scale Redox Flow Batteries Mechanical Energy Storage Natural Gas Pyrolysis Virtual Power Plants	
Moderate		Floating Inland Solar	Flexible AC Transmission Systems Fuel Cells	Advanced Wide-Area Transmission Operations
Low				

Benefit	*Years to Mainstream Adoption*			
↓	***Less Than 2 Years*** ↓	***2 - 5 Years*** ↓	***5 - 10 Years*** ↓	***More Than 10 Years*** ↓

Source: Gartner (July 2023)

Table 2: Hype Cycle Phases

Phase ↓	*Definition* ↓
Innovation Trigger	A breakthrough, public demonstration, product launch or other event generates significant media and industry interest.
Peak of Inflated Expectations	During this phase of overenthusiasm and unrealistic projections, a flurry of well-publicized activity by technology leaders results in some successes, but more failures, as the innovation is pushed to its limits. The only enterprises making money are conference organizers and content publishers.
Trough of Disillusionment	Because the innovation does not live up to its overinflated expectations, it rapidly becomes unfashionable. Media interest wanes, except for a few cautionary tales.
Slope of Enlightenment	Focused experimentation and solid hard work by an increasingly diverse range of organizations lead to a true understanding of the innovation's applicability, risks and benefits. Commercial off-the-shelf methodologies and tools ease the development process.
Plateau of Productivity	The real-world benefits of the innovation are demonstrated and accepted. Tools and methodologies are increasingly stable as they enter their second and third generations. Growing numbers of organizations feel comfortable with the reduced level of risk; the rapid growth phase of adoption begins. Approximately 20% of the technology's target audience has adopted or is adopting the technology as it enters this phase.
Years to Mainstream Adoption	The time required for the innovation to reach the Plateau of Productivity.

Phase	Definition

Source: Gartner (July 2023)

Table 3: Benefit Ratings

Benefit Rating	Definition
Transformational	Enables new ways of doing business across industries that will result in major shifts in industry dynamics
High	Enables new ways of performing horizontal or vertical processes that will result in significantly increased revenue or cost savings for an enterprise
Moderate	Provides incremental improvements to established processes that will result in increased revenue or cost savings for an enterprise
Low	Slightly improves processes (for example, improved user experience) that will be difficult to translate into increased revenue or cost savings

Source: Gartner (July 2023)

Table 4: Maturity Levels

Maturity Levels ↓	*Status* ↓	*Products/Vendors* ↓
Embryonic	In labs	None
Emerging	Commercialization by vendors Pilots and deployments by industry leaders	First generation High price Much customization
Adolescent	Maturing technology capabilities and process understanding Uptake beyond early adopters	Second generation Less customization
Early mainstream	Proven technology Vendors, technology and adoption rapidly evolving	Third generation More out-of-box methodologies
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