Hype Cycle for Low-Carbon Energy Technologies, 2023

Published 25 July 2023 - ID G00798235 - 109 min read

By Analyst(s): Simon Cushing, Lauren Wheatley

Initiatives: Executive Leadership: Sustainability; CSP Digital Transformation and Innovation; Manufacturing Operations

Energy market volatility and innovation in energy technologies are transforming organizations' relationships with energy. This Hype Cycle details the current state of key low-carbon energy technologies to help executive leaders track technology maturity, associated impact and risk.

More on This Topic
This is part of 2 in-depth collections of research. See the collections:

- A Guide to Implementing a Low-Carbon Energy Strategy
- 2023 Hype Cycles: Deglobalization, AI at the Cusp and Operational Sustainability

Strategic Planning Assumption(s)

Analysis

What You Need to Know

Energy systems are undergoing profound change due to disruptive forces including the decentralization and democratization of power generation. While governments, industries and enterprises are focusing on reducing greenhouse gas emissions, economic uncertainty and geopolitics have increased market volatility. Hence, advances in sustainable fuels, low-carbon power generation, emerging green hydrogen technologies, carbon capture and renewable energy intermittency mitigation are needed.

Business models must account for the interdependent strategic, financial, political and social costs of energy consumption. Low-carbon energy strategies must tackle the current energy crises and advance toward net zero, removing the energy blind spot from corporate strategy.

This Hype Cycle empowers executive leaders and their stakeholders to understand the current maturity level of these energy innovations with consequent impact and associated risk. The innovations showcased here may be used to:

- Track future energy market challenges of affordability, availability and acceptability.
- Assess generation sources for future corporate power purchase agreements (CPPAs) or direct equity investments.
- Compensate for constricted availability of low-carbon energy from markets by identifying sources of self-generation.

All energy systems, like any other critical infrastructure, are potential targets for cyberthreats. Executive leaders must implement robust cybersecurity measures to protect the control systems, data networks and associated sensitive information.

The Hype Cycle

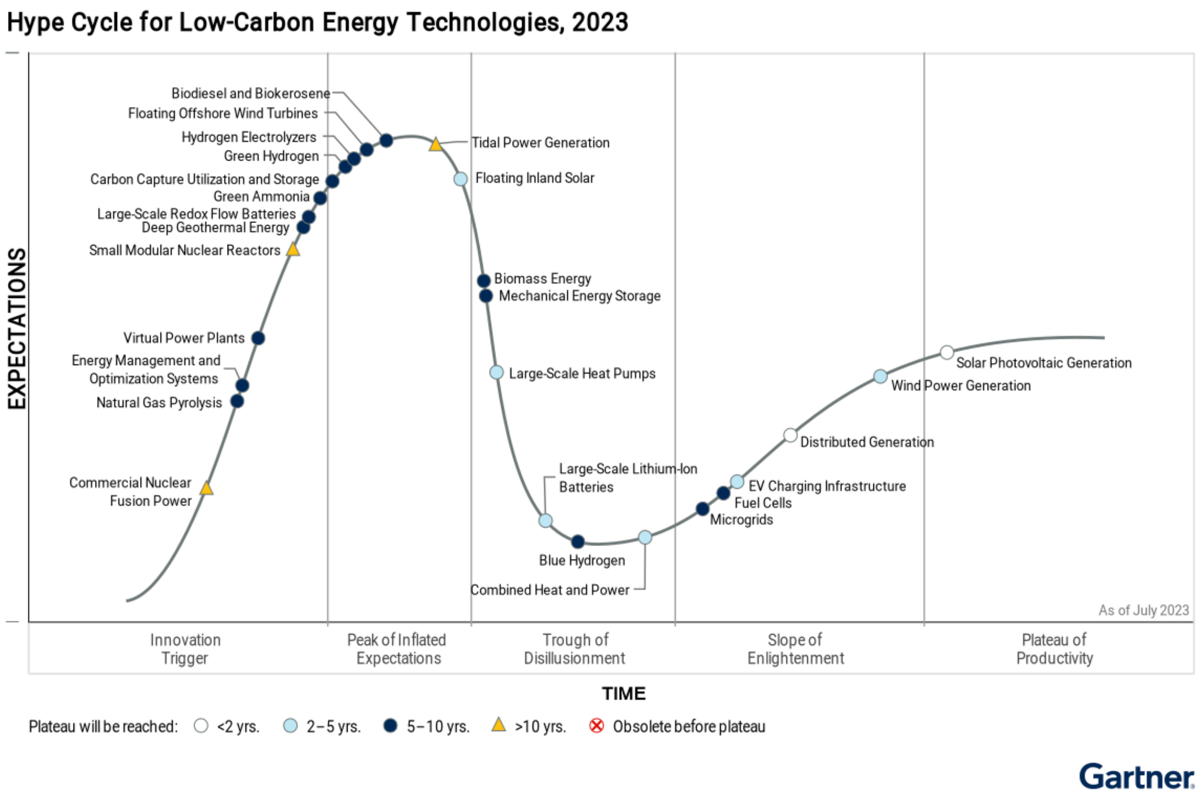
Some technologies within this Hype Cycle may be relatively immature, require significant investments or are more challenging to implement. Some will become industrial scale modern renewables and others will remain niche options. Executive leaders should adopt a portfolio view across low-carbon investment opportunities by reviewing technology adoption rate, cost, availability and skills needed for deployment.

This Hype Cycle profiles 27 energy-related technologies that may enable transformed energy provisioning systems. The pace of maturity of technologies in this Hype Cycle is mixed; some, such as large-scale heat pumps and large-scale Li-Ion batteries are relatively mature and need incremental innovation. Many, however, are moving slowly (for example, small modular nuclear reactors), and commercial viability will require sustained investment and technological development. Other technologies, especially at the start of the Hype Cycle, such as commercial nuclear fusion power and small modular nuclear reactors, are typically making incremental progress, but still face major developmental challenges. Hence, if energy is a core risk to the business, 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 but not necessarily scaled in the market. Many in this group, such as biodiesel and biokerosene, and carbon capture utilization and storage, 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.

Solar photovoltaic generation and wind power generation are close to the Plateau of Productivity, where industrialization is driving prices down and the technology has become mainstream. Several technologies including large-scale Li-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, carbon capture utilization and storage, and blue hydrogen). Otherwise, realism about usage makes investment or adoption decisions clearer, such as for fuel cells.

Figure 1: Hype Cycle for Low-Carbon Energy Technologies, 2023



The Priority Matrix

Many of the technologies included could become transformative — for example, distributed generation as it may invert the utility business model. Commercial nuclear fusion power could reshape energy systems beyond recognition but are technologically challenging. Large-scale Li-Ion batteries, hydrogen electrolyzers, and biodiesel and biokerosene are technically established, but must scale. Other transformational technologies including wind power generation, green hydrogen, green ammonia and small modular nuclear 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 technologies rely on cost-effective carbon capture utilization and storage (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 are currently commercially disadvantaged compared to typical fossil fuel energy costs.

A significant challenge for many of these technologies will be continued or accelerated commercial investment, policy action, government funding and/or regulator action 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. 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 Low-Carbon 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	Distributed Generation	Large-Scale Lithium-Ion Batteries Wind Power Generation	Biodiesel and Biokerosene Carbon Capture Utilization and Storage Green Ammonia Green Hydrogen Hydrogen Electrolyzers	Commercial Nuclear Fusion Power Small Modular Nuclear Reactors
High	Solar Photovoltaic Generation	Large-Scale Heat Pumps	Biomass Energy Blue Hydrogen Deep Geothermal Energy Energy Management and Optimization Systems Floating Offshore Wind Turbines Large-Scale Redox Flow Batteries Mechanical Energy Storage Microgrids Natural Gas Pyrolysis Virtual Power Plants	
Moderate		Combined Heat and Power EV Charging Infrastructure Floating Inland Solar	Fuel Cells	Tidal Power Generation
Low				

Source: Gartner

Off the Hype Cycle

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)

Energy Management and Optimization Systems

Analysis By: Lauren Wheatley

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

Energy management and optimization systems (EMOS) are modular platforms that allow commercial and industrial (C&I) customers to better manage their energy use. An EMOS combines a holistic view of the main energy consumption sources with advanced optimization capabilities to interact with automation systems and production goals. It consumes data from meters and sensors and communicates with an energy supplier, grid operator or market to orchestrate operational use cases.

Why This Is Important

Volatility in energy cost and supply is hurting business and driving inflation. Commercial and industrial (C&I) companies need to proactively mitigate immediate energy price and security concerns while still making meaningful progress toward emissions reduction goals, such as net zero. Managing energy costs will require C&I consumers to increase investment in energy management and optimization technologies.

Business Impact

C&I enterprises are prioritizing cost and environmental impact in their energy-related decision making and are looking to proactively control energy sourcing and consumption. This has resulted in growing markets for energy services by subscription. The move toward service-based models requires the rapid adoption of digitalized products by E&U companies such as offering EMOS capabilities to help customers conserve energy, save money, manage GHG emissions and comply with regulatory mandates.

Drivers

- C&I and community-entity energy customers are increasingly seeking greater control of their energy supply chains to control costs and build energy resiliency.
- There are growing markets for energy technology, energy services and energy-as-a-subscription services.
- Industrial digitalization is instrumenting the asset base, enabling EMOS platforms to proactively optimize energy loads.
- EMOSs require an ecosystem of partners, data, hardware and software that may be provided by multiple vendors. This gives energy company CIOs the opportunity to work with vendors to deploy a composable EMOS platform that aligns most closely with their energy and sustainability strategy.
- Increasing investments in smart grids and smart energy meters allows connection and coordination of all of an enterprise's equipment and devices, enabling continued advancement of EMOSs. By using IoT data and applying tools such as AI and predictive maintenance, EMOS products can provide intelligent operations capabilities, a strategy where physical systems are represented, configured and controlled by intelligent software.
- Volatility and rising energy prices mean that technologies, such as digital twins and AI to enable bidirectional coordination and automation that weren't financially feasible and lacked technical maturity just a few years ago, are now viable.
- The drive toward digital business is about rethinking what is possible, and for E&U companies, how their customers can engage with distributed energy resources in the future. This is particularly important where exponential innovation beyond the meter has delivered consumer energy technology and consequent grid parity, challenging existing energy supply assumptions creating new business models and new opportunities.

Obstacles

- C&I companies seek low-risk solutions that can be easily scaled with a limited management overhead and capital investment, allowing them to focus on critical business activities. However, EMOS system implementation and integration can require energy management expertise and a sophisticated understanding of the financial and risk implications of various purchasing options.
- When creating new business models and opportunities, be aware of the internal challenges faced by customers and align with C&I enterprises’ priorities such that they can execute at a lower cost point and unlock additional opportunities.
- C&I business leaders do not trust the data they have to support ROI calculations, agree on priorities or support the digital solutions.
- While there is a myriad of vendors entering the market, many have limited capabilities focused predominantly on dashboarding and reporting rather than insights and energy optimization.

User Recommendations

- Prepare to support an energy services business by factoring EMOS functionality and solutions into deployment roadmaps.
- Invest early to enable commercial success by establishing energy consumption data and information management strategies that will support an energy services business that delivers cost reduction programs and environmental management goals to C&I enterprises. Establish a roadmap to consolidate enterprise real-time data by integrating IoT infrastructure from edge to cloud.
- Align business and digital strategies with changing C&I enterprise drivers. For years, E&U customer engagement focus has been on customer service while managing a narrow scope of commodity transactions, but during this era of transition, customer experience will define the breakout enterprise. CIOs must design customer experience/total experience (CX/TX) that is fit for purpose across the energy transition.

Sample Vendors

C3 AI; Dametis; Energy21; EnergyCAP; GE; Honeywell; IMS Evolve; METRON; Schneider Electric; Siemens

Gartner Recommended Reading

Market Guide for Energy Management and Optimization Systems

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

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

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

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

Deep Geothermal Energy

Analysis By: Lauren Wheatley

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

Deep geothermal energy is ultimately derived from the heat of the earth's core by drilling deeper than about 1,200 feet (as opposed to shallow geothermal or hydrothermal resources above that). This energy is harnessed through a heat exchange process, either to be used as hot water or converted into electricity. It is a reliable low-emission energy source.

Why This Is Important

Deep geothermal energy is extracted from extended boreholes which are typically over 1,000 feet deep. It is capable of providing carbon-free heat and continuous baseload power to compensate for the intermittency of wind and solar technologies. It produces one-sixth of the CO2e produced by a natural gas plant, while consuming less water on a life-time basis compared to conventional electricity generation. It is a reliable source of power. It has a small land footprint and can be used for large and small-scale installations.

Business Impact

Geothermal energy can meet heating and cooling needs, reducing carbon emissions and helping businesses achieve sustainability targets. Geothermal projects offer consistent, long-term revenue due to reliable resources and low operating costs. However, high costs, limited installation locations, earthquake risk and uncertainty in resource scale limit adoption.

Drivers

There are five drivers for the adoption and growth of geothermal technologies:

- **Cost:** Capital costs for geothermal energy installation are high, but operational and running costs are low. This, in combination with geothermal resources being constant rather than intermittent, creates energy security. Future energy costs are not subject to market volatility and are known. Incentives such as the U.S. Inflation Reduction Act may drive and accelerate the adoption of geothermal technologies.

- **Energy transition:** Heating and cooling needs are typically derived from fossil fuels. Geothermal energy has the potential to expand its role in providing heating and cooling for industrial processes. For example, Janssen Beerse in Belgium has invested 40 million euros in a geothermal plant which reduced greenhouse gas (GHG) emission by 30% in 2021 (15,900 tons per year). Geothermal energy is also enabling the energy transition for local communities through district heating schemes.

- **Capability improvements:** Technological limitations around heat-to-electricity conversion have hampered deployment of geothermal energy in part. However, advances in organic Rankine cycle (ORC) technology is improving the conversion of thermal heat into electricity. This also enables existing geothermal plants to improve their capabilities without the need to drill additional wells. Emerging technologies such as superhot geothermal energy, energy storage and data science drill location modeling will expand the impact and viable use of geothermal energy.

- **Scalable:** Currently individual plants range from kilowatts to hundreds of megawatts of maximum capacity output, making geothermal energy solutions scalable to different operating contexts.

- **Reliable:** Power output from geothermal energy is predictable, unlike wind or solar technologies.

Obstacles

- **Location:** Geothermal plants need to be located where the resource is readily available, typically near tectonic plate boundaries or where the resource is close to the earth's surface.
- **Local depletion of heat:** At some sites, geothermal extraction rates must be managed to avoid reducing output because of local cooling effects.
- **Environmental impacts:** Although geothermal energy is a renewable resource, greenhouse gasses can be released from the drilling of wells. These GHGs are released naturally, but there is a rate of increase near geothermal plants. Overall, the emissions are still lower than fossil fuel technologies. Well injection of water and fluids to generate heat from wells is often under pressure. This can lead to localized earthquakes. For example, the Pohang earthquake in South Korea in 2017 was attributed to the development of a geothermal project.
- **Capital costs:** High capital cost of geothermal energy may mean that other types of renewable energy projects are more attractive.

User Recommendations

- **Assess:** Evaluate the geothermal resource potential in your region, and assess the technical, economic and regulatory feasibility of projects. Conduct risk assessments and develop risk mitigation strategies.
- **Finance:** Identify and pursue financing options suitable for geothermal projects, such as public-private partnerships, green bonds, international funds, or collaboration with financial institutions specializing in renewable energy. Seek out funding mechanisms that align with your organization's financial goals and risk appetite.
- **Partner:** Explore synergies with other industries or energy sources to maximize project value and optimize resource utilization.
- **Scale:** Collaborate with geothermal developers, technology providers, research institutions and government agencies to leverage their expertise, share knowledge and reduce project risks. Form strategic partnerships that can help navigate the complexities of geothermal development.

Sample Vendors

Eavor; GE Renewable Energy; Ormat Technologies; Quaise Energy; Toshiba Energy Systems & Solutions Corporation

Gartner Recommended Reading

Quick Answer: What Are the Corporate Renewable Energy Procurement Options in the Pathway to Net Zero?

3 Practical Actions to Address Uncertainties in Pathways for Reducing GHG Emissions

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.

- CO2 sequestration involves geological storage sites such as depleted oil and gas reservoirs, and salt caverns, requiring significant and long-term investment.
- Captured CO2 reuse may not lower CO2 emissions, depending on the source, displaced use, consumed energy and duration of retention, among other variables. CO2 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 CO2 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

Tidal Power Generation

Analysis By: Lauren Wheatley

Benefit Rating: Moderate

Market Penetration: Less than 1% of target audience

Maturity: Emerging

Definition:

Tidal power is a form of renewable energy that harnesses the power of ocean tides to generate electricity. It involves capturing the kinetic energy of the tides using technologies such as tidal turbines or barrages. As tides rise and fall, water flows through turbines, driving generators to produce clean and predictable electricity. It has the potential to provide a consistent and renewable energy source, leveraging the regular nature of tidal cycles.

Why This Is Important

Unlike wind and solar energy, which are intermittent and dependent on weather conditions, tidal power can be accurately forecast, offering stable and consistent power generation. The International Energy Agency suggests sustained annual growth of 33% through 2030 is needed to be on track to meet net zero, an average 1 GW of capacity additions annually (see Projects, Pipelines and Power: Around the World's Tidal Projects).

Business Impact

Tidal power generation offers consistent, long-term revenue due to reliable resources and low operating costs. It enables businesses to position themselves as leaders in the renewable energy transition and benefit from the growth of the tidal energy sector. However, high development costs and limited installation locations limit adoption.

Drivers

- The global shift toward renewable energy sources creates a favorable environment for the development of tidal power. Governments and utilities are increasingly focused on diversifying their energy mix and integrating more clean energy sources into their grids.

- Tidal power benefits from the predictability of tidal cycles, allowing accurate forecasting of energy generation. This stability makes tidal power an attractive option for grid integration, load balancing, and meeting base-load energy demand, as it provides a consistent and reliable energy supply.

- Collaboration among countries, research institutions and industry stakeholders plays a crucial role in driving the tidal power industry forward. Knowledge sharing, technology transfer, and collaboration on research and development efforts accelerate advancements in tidal energy technologies and improve project economics.

- Technological advancements in tidal power have improved the efficiency and reliability of tidal turbines, control systems and other associated equipment in a harsh operating environment. Innovations in materials, design and deployment techniques have increased the performance and cost-effectiveness of tidal energy systems, making them more attractive for commercial deployment.

- Advancements in tidal power technologies can have spillover effects, benefiting other sectors such as offshore engineering, marine resource monitoring and underwater infrastructure development. The knowledge and expertise gained from tidal energy projects can be applied to other marine-related industries such as offshore wind and wave energy, promoting cross-sectoral collaboration and innovation.

Obstacles

- Limited availability of suitable sites restricts the potential for widespread adoption and limits scalability of the industry.
- Upfront capital costs are relatively high and can pose a barrier to entry for developers and investors compared to conventional energy sources. Connecting to the electricity grid can be costly, especially for small-scale schemes.
- The technology is relatively nascent, and developing and deploying reliable and efficient turbines, moorings and control systems in harsh marine environments present technical challenges.
- Projects can have localized environmental impacts on marine ecosystems, including disruption of sediment transport, changes in water flow patterns and potential effects on marine life.
- The absence of standardized policies and regulations specific to tidal power in many jurisdictions can create uncertainty for project developers and investors.
- Projects may be perceived as higher-risk investments due to technology maturity, regulatory uncertainties and the limited track record of commercial-scale deployments.

User Recommendations

- Stay informed about international market developments and trends in tidal power. Monitor successful projects, technological breakthroughs and policy changes to identify potential opportunities for partnerships, technology transfer or market expansion.
- Conduct a thorough assessment of the feasibility and viability of tidal power projects in your region or relevant areas of operation. Projects are likely to be public-private partnership ventures.
- Foster collaboration with other industry players, research institutions and technology providers. Collaborative partnerships can accelerate project development, drive innovation, and share risks and costs.
- Prioritize environmental sustainability by conducting thorough environmental impact assessments and implementing mitigation measures. Engage with experts in marine ecology and ensure compliance with relevant regulations to minimize potential adverse effects.
- Work closely with financial institutions, investors, and development banks to explore project financing options for tidal power initiatives.

Sample Vendors

ANDRITZ Hydro Hammerfest; KIS-ORCA; MAKO Energy; MCT (MeyGen); Nova Innovation; Orbital Marine Power; Scotrenewables Tidal Power; SIMEC Atlantis Energy

Gartner Recommended Reading

Quick Answer: What Are the Corporate Renewable Energy Procurement Options in the Pathway to Net Zero?

3 Practical Actions to Address Uncertainties in Pathways for Reducing GHG Emissions

The Impacts of Exponential Renewable Generation Growth Across the Energy Ecosystem

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

Combined Heat and Power

Analysis By: Sarah Watt

Benefit Rating: Moderate

Market Penetration: 5% to 20% of target audience

Maturity: Early mainstream

Definition:

Combined heat and power (CHP), also known as cogeneration, is a highly efficient energy system that simultaneously generates electricity and useful heat. It maximizes the overall energy output by utilizing the waste heat that is typically lost in conventional power generation, providing both electricity and thermal energy for heating, cooling or industrial processes in a cost-effective and sustainable manner.

Why This Is Important

CHP is highly efficient, typically achieving fuel conversion efficiency levels of 80% or more. By utilizing the waste heat, CHP reduces energy waste and maximizes the utilization of fuel resources. Thermal energy can be used to meet heat requirements with hot water or passed through an absorption chiller to meet cooling needs. CHP reduces greenhouse gas (GHG) emissions and environmental impact compared to conventional separate heat and power generation. CHP may contribute to local air quality improvements by reducing the consumption of fossil fuels from duplicated systems.

Business Impact

CHP reduces energy bills and improves energy security by allowing facilities to continue to operate in the event of disruption to grid-supplied energy, as long as fuel sources are available (natural gas, oil, biogas, biomass) and capacity demands can be met by generation loads. CHP can reduce the reliance on the grid. It is particularly beneficial for critical infrastructure, such as hospitals, data centers and industrial facilities.

Drivers

- **Energy Resilience:** Businesses, particularly those with critical operations or sensitive processes, seek to ensure a reliable and uninterrupted energy supply. CHP systems can operate independently or in conjunction with the grid, providing a reliable on-site power source that can continue to operate during grid outages or disruptions, minimizing downtime.

- **Energy and Cost-Efficiency:** According to the U.S. Environmental Protection Agency, CHP systems can achieve high levels of efficiency, often surpassing 80%, allowing businesses to generate both electricity and thermal energy from the same fuel source (see CHP Benefits). By maximizing the utilization of fuel resources and capturing waste heat, businesses can significantly reduce energy waste and lower their energy expenses.

- **Agility:** CHP systems can be configured to operate with a variety of fuel sources, including renewable fuels such as biomass, biogas or waste heat recovery. Integrating renewable energy sources into the CHP system enables the efficient utilization of sustainable energy resources and facilitates the transition to a low-carbon energy system. CHPs also come in a variety of sizes from microscale to macroscale, increasing its scalability.

- **Thermal Demands:** Industries with high thermal energy demands, such as manufacturing, chemical processing or food production, are driven to adopt CHP to improve process efficiency. By utilizing waste heat for industrial processes, CHP systems can increase overall process efficiency, reduce energy costs and enhance the competitiveness of industrial operations.

- **Energy Transition:** Increasing concerns about climate change and environmental impact drive the adoption of CHP as part of the energy transition. By utilizing waste heat and achieving higher energy efficiency, CHP reduces GHG emissions and lowers carbon footprints.

Obstacles

- **Capital Costs:** Capital cost for CHPs can be significant, and ongoing maintenance and operational expenditure must also be accounted for.

- **Emissions Pathway:** Although CHP compared to fossil fuel technology reduces GHG emissions, it still locks enterprises into an emissions pathway over time, when compared to renewable energy technologies.

User Recommendations

- Define your organization's energy and sustainability goals. Determine how CHP aligns with these objectives and identify specific targets, such as reducing energy costs, improving energy efficiency, enhancing power reliability or reducing greenhouse gas emissions. Integrate CHP impacts to GHG reduction pathways.
- Involve key stakeholders, including facility managers, energy managers, engineers, finance teams and sustainability experts, in the decision-making process. Collaborate with internal teams and external consultants to ensure a comprehensive understanding of the technical, financial and operational aspects of CHP.
- Investigate funding options and financial mechanisms to support the implementation of CHP. This could include internal funding, external financing, grants, energy efficiency programs or partnerships with energy service companies (ESCOs). Assess the potential for cost savings, revenue generation and leveraging available financial incentives to make the project economically viable.

Gartner Recommended Reading

Quick Answer: What Are the Corporate Renewable Energy Procurement Options in the Pathway to Net Zero?

3 Practical Actions to Address Uncertainties in Pathways for Reducing GHG Emissions

The Impacts of Exponential Renewable Generation Growth Across the Energy Ecosystem

Climbing the Slope

Microgrids

Analysis By: Ethan Cohen

Benefit Rating: High

Market Penetration: 5% to 20% of target audience

Maturity: Early mainstream

Definition:

A microgrid is a self-sufficient group of interconnected electrical loads and distributed energy resources that can operate as a stand-alone power system or be connected to the grid to provide optimization optionality. Microgrids commonly range in size from 100 kilowatts (kW) to 10s of megawatts (MW) and can connect to and disconnect from the grid. Microgrids can operate in both grid-connected and island modes based on technical and economic criteria to optimize energy cost and availability.

Why This Is Important

Microgrid uses include rural electrification, residential or community power networks, commercial, industrial, municipal, hospital and military base power grids. Microgrids leverage traditional and renewable generation sources. Microgrids offer a compelling alternative to traditional energy generation and distribution, using Internet of Things (IoT) to enable integrated control of distributed power generation assets.

Business Impact

Microgrids impact utility generation, distribution and energy retailing domains. They are becoming more important as utilities create new energy ecosystems and expand energy services offerings. Microgrids are also examples of energy technology consumerization, challenging the traditional business model of utility-provisioned energy delivered as a cloud service. By facilitating consumer integration into the energy market, microgrids are contributing to consumer energy management and the energy delivery infrastructure's geodesic transformation.

Drivers

Microgrids offer advantages to utilities and customers by improving energy efficiency, reducing transmission and distribution losses, improving reliability, reducing environmental impact and providing a more cost-efficient electricity infrastructure compared to the traditional electricity distribution grid, as they also:

- Provide local options regarding the choice of electricity generation source and supply, such as distributed renewable energy sources (particularly those that are for energy storage).
- Enable energy customers to self-provision for operational resilience and collaborate or partner with utilities to achieve specific outcomes.
- Support renewable energy and energy efficiency through a viable approach to local grid modernization while incorporating local distributed energy supplies and storage technologies to meet the specific needs of their constituents while networking with the main grid.
- Deliver benefits to utilities by supporting the central grid in handling sensitive loads and the variability of renewables locally and supplying ancillary services to the bulk power system.

Obstacles

- Microgrids do not have the same economies of scale and the coincident load factor of the centralized grid.
- The commercial integration of microgrids into energy markets will require a platform for the energy-sharing, resource-sharing and market-sharing economy.
- Technical constraints inhibit the integration of microgrids into distribution grids, including specific elements like dual-mode switching functionality, reliability, power quality and protection.
- Central electricity network operation impacts for microgrids require new utility systems, such as distributed energy resource management systems and advanced distribution management systems, which can be costly and complex to deploy.
- Microgrids must have mechanisms to regulate voltage and frequency in response to changes in load and system disturbances. This is because all power in microgrids comes from distributed generation resources and controllable loads within the microgrid, which typically requires investment in operational technology (OT) to perform distributed control.

User Recommendations

As microgrids progress into mainstream utility, CIOs should:

- Observe market developments in microgrid use cases, and evaluate what kinds of offerings might be advanced to develop new revenue, enhance resilience and improve energy provisioning.
- Enable the utility to quickly and thoroughly evaluate microgrid development and/or operation by developing minimum viable products for microgrid cases. Despite the significant promise and industry excitement about the concept, relatively few fully commercialized state-of-the-art microgrids have been deployed by utilities in many regions.
- Advance computational capabilities by improving physical models that leverage machine learning and automation.
- Dedicate some investment to a microgrid design authority to improve microgrid operations reliability, security and self-healing capabilities in intelligent grid operation for electricity distribution.

Sample Vendors

Alencon Systems; Ameresco; Generac Power Systems; NRG Energy; PowerSecure; Schneider Electric; Siemens; Veritone; Yokogawa Electric Corporation (PXiSE Energy Solutions)

Gartner Recommended Reading

2023 Utility Trend: Orchestrate Flexible Resources to Maintain Power System Operational Integrity

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

EV Charging Infrastructure

Analysis By: Lauren Wheatley

Benefit Rating: Moderate

Market Penetration: 20% to 50% of target audience

Maturity: Early mainstream

Definition:

The EV charging infrastructure, or electric vehicle supply equipment (EVSE), is a component of the overall supply system for the recharging of EVs and plug-in hybrid EVs. Different means of providing electricity to charge EV batteries exist, including slow residential AC charging and fast commercial DC charging. Ownership models include private, publicly owned, municipal or commercial charging points, including those owned by EV manufacturers, fleet owners and individuals.

Why This Is Important

Current momentum in EV sales can only be sustained if the majority of the population have access to convenient and affordable charging infrastructure, both publicly available and private chargers at residences and workplaces, among other destinations. EV charging infrastructure has implications for utility companies, depending on the role they want to have in the electrification of transportation; there is significant benefit for those owning, managing and operating EV charging infrastructure.

Business Impact

The major areas of utility impact will be delivery (charging infrastructure life cycle management) and retail. Owners of the distribution network will have to ensure their infrastructure can handle additional load introduced by EV charging. The impact of EV charging on distribution networks can be mitigated with charging control to avoid periods of peak demand. Ownership of the EV charging infrastructure provides network operation benefits, in addition to increased electricity sales.

Drivers

- EV charging infrastructure needs to increase more than twelvefold by 2030 to support the growth of electric cars projected in the International Energy Agency's Global EV Outlook 2022, adding 22 million charging points per year. This will require a cumulative installed charger capacity of over 1.9 terrawatts, and have a significant impact on electricity supply and demand.

- Charging infrastructure is not yet ubiquitous. In the U.S., together the Inflation Reduction Act and the Infrastructure Investment and Jobs Act have earmarked nearly $11 billion for the establishment of a network of EV chargers. Many European countries still fall short of the Directive 2014/94/EU of the European Parliament and of the Council recommendations, while automotive companies are creating joint ventures, e.g., Daimler Truck, TRATON GROUP and Volvo Group, to install high power charging points near highways and logistics hubs.

- EVSE infrastructure continues to rapidly evolve, with some countries installing large-scale interconnected EV charging stations along main transport routes. Key considerations for developing charging networks include digitalization, interoperability and planning roadmaps.

- In markets where there is strong public and policymaker support for EV, the network operator may explore EV charging as an extension of energy delivery infrastructure, with a traditional investment recovery model. In other markets, utility organizations use this as an unregulated business opportunity. The ability to gather consumption patterns will help utilities mitigate the impact on the distribution grid and may result in additional future revenue growth as electricity displaces gasoline as the preferred transportation fuel.

- The electrification of heavy freight trucks is underway and long-term planning for megacharger infrastructure (1 MW or more) is required.

- The Open Charge Point Protocol (OCPP) allows EV chargers to expand their digital functionality, allowing advanced interoperability between charger and OS.

Obstacles

- Recharging EVs places a high load on the electrical grid when they are not scheduled for periods of reduced load or reduced electricity costs.
- Market fragmentation and lack of a common unifying platform slows maturation and adoption of EV charging infrastructure.
- EV charging technology evolves at a slower pace than EV technology due to longer product life cycles, limited R&D investments and because EV charger replacement rate is slow in relation to cars.
- Regulation is often an obstacle to the adoption of smart charging technology. For instance, Germany and some U.S. states have mandated the adoption of card payment terminals at public chargers, which indirectly discourages charge point operators from adopting "plug and charge," the most convenient technology.

User Recommendations

- Invest in electric charging infrastructure if you operate in markets where there is a significant government sponsorship for EV adoption. In those markets, utilities (mostly distribution network operators) can recover the investment in EV charging through regulated distribution tariffs where investments enable new business models that deliver convenience and price competitiveness to end customers.
- Leverage EV charging infrastructure to get better insight and some control over EV charging implications on existing distribution grid and improve asset utilization.
- Ensure your EV infrastructure strategy aligns with your jurisdiction's regulatory treatment of EV infrastructure investment. The regulatory structure has strong implications for the ownership structure and organizational arrangements of charging infrastructure.

Sample Vendors

ABB; Blink Charging; ChargePoint; EVBox; EVgo; General Electric; Schneider Electric; Siemens; Tesla

Gartner Recommended Reading

Market Guide for Electric Vehicle Charging Solutions

Emerging Tech Impact Radar: Electrified Vehicles, 2022

Distributed Generation

Analysis By: Lloyd Jones

Benefit Rating: Transformational

Market Penetration: More than 50% of target audience

Maturity: Mature mainstream

Definition:

Distributed generation (DG) is an energy supply method that situates generation at or near where it's used. DG may include a mini-hydro, diesel, biofuel, wind, solar or fuel cell, and may be customer-owned. DG is a subset of distributed energy resources (DERs) and includes on-site storage. Wider adoption transforms centrally managed, radial delivery networks to more complex networks requiring advanced hybrid engineering control and economic-incentive-based distribution network operating modes.

Why This Is Important

Utilities may deploy DG as part of a strategy to manage the timing of network upgrades. DG may be used temporarily or permanently to alleviate congestion and assure energy availability. Energy-intensive customers in industrial sectors seeking to secure energy availability have invested in DG. Commercial and groups of residential customers are investing in DG. DG adoption challenges legacy utility business models, raising questions about how the grid will be operated and monetized.

Business Impact

DG deployment has transformational impacts on utilities. DG gives energy customers more choices, and may increase the installed base of environmentally and economically sustainable generation — reducing greenhouse gasses — and may encourage improved energy efficiency. However, DG creates significant challenges to grid operations, even while improving energy resilience. DER in general, and DG in particular, are the main drivers of the energy transition.

Drivers

- According to the Bloomberg New Energy Outlook 2021 report, the cost of solar declined by 85% from 2010 to 2021 — close to low-triple-digit price performance improvement in less than a decade. However, costs are expected to rise in 2022 for the first time in 10 years due to supply chain and commodity price rises.
- The price performance improvement is the main driver behind rapid DG (renewable) adoption by consumers. Exponential technology advances at the grid edge are making it simpler, easier and less expensive for businesses and consumers to begin self-generation. They are also making it easier for consumers to actively manage their interaction with energy markets by controlling when to buy, store or sell energy back to the grid.
- Regulatory mandates, such as FERC 2222 of 2021, mandate equal treatment of smaller-scale DG on the wholesale markets.
- Jurisdictions that actively pursue renewable energy by supporting feed-in tariffs and net metering arrangements are more conducive to DG deployment. For example, California expects that one-fourth of new-generation resources will come on the customer's side of the meter (mostly rooftop solar). The International Energy Agency World Energy Outlook forecasts that incremental solar photovoltaic deployments will account for more than 70 GW of the combined future capacity additions through 2040 — the largest share of total additional capacity by type.
- Engine innovation is accelerating, with smaller, quieter units coming to market, including modular and linear engines that are multifueled.

Obstacles

- Integrating DG into electric distribution networks is a significant challenge requiring electric delivery operations knowledge, and expertise in software and hardware design.
- Integrating DG into utility business operations requires utilities to serve a more-dynamic, decentralized grid and respond to diverse prosumer and business partner ecosystems.
- Most utilities have had little incentive from regulators to pursue DG. Few utilities have an organizational structure ready to coordinate and facilitate a vast array of third parties with interests in DG expansion.
- DG interconnection standards are maturing in particular, following the release of the IEEE 2030.5 standard; however, regulatory oversight is still a patchwork of interconnection rules. Issues with sitting and permit costs still limit adoption.
- National grid codes need to be updated to support interconnection applications.

User Recommendations

- Watch out for transmission and distribution asset deferral benefits, but have backup plans if the DG technology has an unplanned outage.
- Propose incentives to regulators that would help them support cost-effective nonwire alternatives to traditional utility wire infrastructure upgrades while adhering to their service mandate.
- Review the information management and communication effects of DG growth, such as the need to expand communications networks and historian systems. Because a significant percentage of DG will be deployed by customers in the form of renewable generation, it will also enable consumer participation in carbon dioxide abatement.
- Treat DG as a part of overall DER strategy. That will require investment in distributed energy resources management systems or modification of advanced distribution management systems to address the needs of DG orchestration.

Sample Vendors

Ballard Power Systems; Bloom Energy; Capstone Green Energy; Caterpillar Energy Solutions; ITM Power; Plug Power; Rolls-Royce; Tesla; Wärtsilä

Gartner Recommended Reading

The Energy Transition Question: Do We Need the Grid?

Energy CIOs: Get Ready to Operate Under Multiple Energy Provisioning Business Models

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

Market Guide for Distributed Energy Resource Management Systems

Wind Power Generation

Analysis By: Lauren Wheatley

Benefit Rating: Transformational

Market Penetration: More than 50% of target audience

Maturity: Mature mainstream

Definition:

Wind power generation is the conversion of wind into usable electricity, principally using wind turbines. Wind turbines are a mature technology deployed worldwide to provide a sustainable and decentralized energy solution for residential, commercial and utility-scale applications. More nascent technologies include harvesting electricity from the wind by kites.

Why This Is Important

The International Energy Agency estimates it is necessary to increase wind power from 9% of the electricity mix in 2020 to 21% in 2030, with growth in on- and offshore markets. Wind power enhances energy independence and security, allowing individuals, communities and businesses to generate power locally.

Business Impact

Rapid acceleration of large-scale renewable energy technologies is needed for the energy transition. Wind power can be harnessed at different scales, offering flexibility, but is not a ubiquitous solution, and power generation is intermittent. Embracing wind energy demonstrates a commitment to sustainability.

Drivers

- While being location dependent and having a large land footprint, wind power has a vast global potential to provide clean electricity to society.
- Wind power helps enhance energy security by diversifying the energy mix and reducing dependence on imported fossil fuels. It can provide renewable electricity that reduces vulnerability to geopolitical tensions and price volatility in the global power markets.
- The wind power sector creates job opportunities in manufacturing, installation, maintenance and research, promoting economic growth.
- The cost of wind power has been declining significantly over the past decade, making it increasingly competitive with conventional energy sources. Technological advancements, economies of scale, and streamlined project development have contributed to cost reductions, driving the adoption of wind power as a cost-effective solution.
- Government policies and incentives play a crucial role in promoting wind power. These can include feed-in tariffs, tax incentives, renewable portfolio standards, carbon pricing and grants. Supportive policies provide certainty and financial benefits to wind power projects, encouraging investment and growth.
- Many enterprises have set sustainability goals to reduce their carbon footprints and demonstrate environmental responsibility. Incorporating wind power into their operations helps to achieve these targets and align with stakeholder expectations.
- Advances in energy storage technologies and grid integration solutions are enabling higher levels of wind energy penetration. The ability to integrate wind power effectively with the existing grid infrastructure and balance supply and demand has contributed to the growth of wind power.

Obstacles

- Connecting wind farms to the electricity grid and ensuring efficient transmission of electricity can be complex and costly. There are over 1,350 gigawatts (GW) of generator capacity actively seeking interconnection in the U.S., and 80 GW of wind energy projects stuck in a permitting process across Europe.
- Integrating a high penetration of wind power into the grid can pose technical challenges, including grid stability, voltage regulation and frequency control. Ensuring grid flexibility, adequate transmission capacity, and smart grid solutions are important for seamless integration.
- The upfront investment required for installing wind turbines and high end-of-life costs can be a significant barrier, and access to financing options can also be a hurdle to adoption.
- Supply chain disruptions, including rising material and labor costs, supply of raw materials, and environmental, social and governance (ESG) concerns, threaten to derail near-term projects.
- Wind power is a low embodied carbon alternative to fossil fuels. However, fossil fuels are generally required to manufacture the equipment and construct the projects.

User Recommendations

- Enable your organization to achieve 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. Review feasibility of wind power against that of other renewable energy technologies.
- Collaborate with financial institutions, energy service companies or renewable energy developers to explore innovative financing models that align with financial goals and constraints. Consider options such as power purchase agreements and leasing arrangements, and what phase of a project you may wish to invest in.
- Implement sustainable asset management practices, such as recycling turbine components and engaging in biodiversity protection, to demonstrate a holistic approach to wind power.
- Conduct a thorough financial analysis, including return-on-investment (ROI) assessments and life cycle cost evaluations, against business objectives.

Sample Vendors

ENERCON; GE; Mitsubishi Heavy Industries; Siemens Gamesa; Vestas

Gartner Recommended Reading

Quick Answer: What Are the Corporate Renewable Energy Procurement Options in the Pathway to Net Zero?

3 Practical Actions to Address Uncertainties in Pathways for Reducing GHG Emissions

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

Entering the Plateau

Solar Photovoltaic Generation

Analysis By: Lauren Wheatley

Benefit Rating: High

Market Penetration: More than 50% of target audience

Maturity: Mature mainstream

Definition:

Solar photovoltaic (PV) generation produces electricity using a collection of electronic devices or solar cells added to large panels. It is a renewable energy source that harnesses the power of the sun to generate electricity without emissions. Solar PV generation systems are widely deployed worldwide, providing a sustainable and decentralized energy solution for residential, commercial and utility-scale applications.

Why This Is Important

Solar PV systems are key for meeting net-zero emissions targets by 2030. Solar PV generation systems enhance energy independence and security, allowing individuals, communities and businesses to generate electricity locally. Solar PV generation can be deployed in various other applications, including heating, cooling and water pumping.

Business Impact

Rapid acceleration of large-scale renewable energy technologies is needed to facilitate the transition from fossil-based energy systems. Also, beyond-the-meter solar PV systems offer long-term cost savings for businesses by reducing electricity bills and improving the resilience of electricity supplies. Embracing solar PV generation demonstrates a commitment to sustainability and impacts carbon footprint positively.

Drivers

- Solar PV generation still dominates renewable energy capacity additions. In many countries, utility-scale solar PV generation is the least costly option for adding new electricity capacity.
- Governments worldwide have implemented supportive policies to encourage the adoption of solar PV generation. These policies include feed-in tariffs, net metering, tax incentives, renewable portfolio standards and streamlined permitting processes.

- Solar PV generation enables a level of energy independence by generating electricity on-site and reducing reliance on the grid and imported fossil fuels. This appeals to individuals, businesses and countries seeking to enhance their energy security, reduce energy price volatility and diversify their energy sources.

- The maturity of energy storage technologies, such as batteries, has advanced significantly. This has enabled the storage of solar energy excess for later use, although this capability adds to solar PV generation's overall cost. This storage capability addresses the intermittent nature of solar PV technologies. It allows for self-consumption of solar power when sunlight is unavailable.

- Continued technological advancements have expanded the range of solar PV generation applications, making solar PV systems more appealing to a broader market. Examples of advancements include increased energy efficiency, improved aesthetics, flexible and lightweight designs, and integration with smart grid systems.

- Many businesses have set sustainability goals and adopted renewable energy targets as part of their corporate social responsibility strategies. Solar PV generation systems help businesses achieve these goals by purchasing renewable energy generators, green tariffs — or power purchase agreements — and self-generation.

Obstacles

- Despite declining costs, the upfront investment required for installing solar PV systems can still be a significant barrier to adoption. Also, access to affordable financing options can be a hurdle for adopting solar PV systems.

- Grid infrastructure may need upgrades to handle variable solar power generation and bidirectional energy flows.

- Supply chain disruptions, including rising material and labor costs, supply of raw materials and environmental, social and governance (ESG) concerns, threaten to derail solar PV generation near-term projects.

- Rising costs are threatening planned utility-scale solar projects. Small price increases can result in negative investment returns for marginal projects.

- Unfavorable regulatory environments and policies, complex grid connection procedures, uncertain net metering and tariff regulations can hinder the adoption of solar PV systems.

- As solar panels reach their end of life, custom-made recycling solutions are necessary to deal with large volumes of e-waste.

User Recommendations

- Improve performance and outcomes by using strategic roadmaps to articulate current and desired future states of renewable energy generation and the gaps that must be filled.
- Stay updated on local, regional and national incentives, as well as government programs to maximize the benefits of available incentives and partnerships.
- Consider collocating energy storage solutions to enhance the reliability and flexibility of solar PV generation. Explore smart grid integration options and advanced monitoring systems to optimize energy production, consumption and grid interaction.
- Collaborate with financial institutions, energy service companies and renewable energy developers to explore innovative financing models that align with financial goals and constraints. Consider options like power purchase agreements and leasing arrangements.
- Optimize system performance by implementing a robust energy management system to analyze and control performance.

Sample Vendors

Canadian Solar; First Solar; Hanwha Q CELLS; Jinko Solar; LG; LONGi; REC Group; SunPower; Suntech; Trina Solar

Gartner Recommended Reading

Quick Answer: What Are the Corporate Renewable Energy Procurement Options in the Pathway to Net Zero?

3 Practical Actions to Address Uncertainties in Pathways for Reducing GHG Emissions

The Impacts of Exponential Renewable Generation Growth Across the Energy Ecosystem

Appendixes

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)

Acronym Key and Glossary Terms

Evidence

Notes

Recommended by the Authors

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

20 Strategic Cost Optimization and Sustainability Opportunities

How to Set Strategic Ambition for Sustainability

Use-Case Prism: Tactical Energy Conservation Solutions

3 Practical Actions to Address Uncertainties in Pathways for Reducing GHG Emissions

Quick Answer: What Are the Corporate Renewable Energy Procurement Options in the Pathway to Net Zero?

Quick Answer: Key Considerations Before Sourcing a Corporate Power Purchase Agreement

Table 1: Priority Matrix for Low-Carbon Energy Technologies, 2023

Benefit	*Years to Mainstream Adoption*			
↓	***Less Than 2 Years*** ↓	***2 - 5 Years*** ↓	***5 - 10 Years*** ↓	***More Than 10 Years*** ↓
Transformational	Distributed Generation	Large-Scale Lithium-Ion Batteries Wind Power Generation	Biodiesel and Biokerosene Carbon Capture Utilization and Storage Green Ammonia Green Hydrogen Hydrogen Electrolyzers	Commercial Nuclear Fusion Power Small Modular Nuclear Reactors
High	Solar Photovoltaic Generation	Large-Scale Heat Pumps	Biomass Energy Blue Hydrogen Deep Geothermal Energy Energy Management and Optimization Systems Floating Offshore Wind Turbines Large-Scale Redox Flow Batteries Mechanical Energy Storage Microgrids Natural Gas Pyrolysis Virtual Power Plants	

Benefit	*Years to Mainstream Adoption*			
↓	***Less Than 2 Years*** ↓	***2 - 5 Years*** ↓	***5 - 10 Years*** ↓	***More Than 10 Years*** ↓
Moderate		Combined Heat and Power EV Charging Infrastructure Floating Inland Solar	Fuel Cells	Tidal Power Generation
Low				

Source: Gartner

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
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)