

The background is a vibrant pink color. On the left and right sides, there are large, abstract, wavy shapes that resemble liquid or smoke. These shapes are composed of many thin, curved lines that create a sense of depth and movement. The colors of these shapes range from light pink to a darker, almost black pink.

2025 TECH TRENDS REPORT • 18TH EDITION

ENERGY & CLIMATE

FTSG

Future Today Strategy Group's 2025 Tech Trend Report

Our 2025 edition includes 1000 pages, with hundreds of trends published individually in 15 volumes and as one comprehensive report. Download all sections of Future Today Strategy Group's 2025 Tech Trends report at www.ftsg.com/trends.





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**Mark Bryan**

Built Environment Lead

Exceed expectations or risk instability.

Climate change is no longer a distant challenge—it is an immediate force reshaping economies, industries, and the very infrastructure that businesses rely on. The past year has made this clear: Record-breaking heat has driven unprecedented energy demand, grid failures, and supply chain disruptions. The accelerating shifts in our planetary systems—melting ice caps slowing Earth’s rotation, heat waves, and the destabilization of the global water cycle—demand a response that extends beyond incremental change. The energy and ecological systems we depend on have stopped being static certainties, and without a fundamental shift in strategy, businesses will find themselves reacting to crises rather than leading through them.

The technologies in this report reflect where we stand today, but despite progress in areas like dispatchable energy and grid optimization, solutions remain incremental rather than systemic. Too often, corporate sustainability efforts are reactive, compliance-driven, and siloed, failing to recognize that climate risk is not a single-issue challenge—it is a structural transformation affecting the entire business ecosystem.

This shift will impact every aspect of enterprise strategy—from supply chain resilience and infrastructure investment to workforce planning and insurance costs. A company’s ability to operate in this changing world will be determined by its ability to build and invest for resilience, adaptability, and long-term value creation. Business leaders who fail to see this will not only face higher costs and increased regulatory scrutiny; they will risk losing competitive advantage to those who anticipate and design for the future.

This moment requires leadership that moves beyond expectations. It demands a shift from minimizing risk to maximizing opportunity: leveraging AI, biotechnology, advanced materials, and energy innovation not just for incremental efficiency gains but to redesign the systems that power industry itself. The leaders of the next decade will be those companies that recognize that sustainability is not an initiative—it is a strategy, a growth driver, and the foundation of competitive advantage in a rapidly changing world.



Innovations are redefining our ability to impact climate change and energy consumption.

1

Tech companies commit to largest renewable energy purchases

Major corporations sign record-breaking power purchase agreements to accelerate clean energy adoption.

2

Hybrid energy facilities link solar and storage

Renewable energy projects combining solar power with battery storage are coming online globally.

3

Data platforms boost transparency in sustainability reporting

New digital tools emerge to improve climate disclosure across private markets.

4

Breakthrough solar cells set new efficiency records

Scientists pushing the boundaries of solar cell technology are achieving world-leading performance.

5

Algae-based biofuels double output while capturing more carbon

Genetically engineered algae promise cleaner fuels and better environmental outcomes.



Accelerating changes are forcing a global shift—businesses can either lead or risk falling behind.

Last year was projected to be the warmest in human history. Greenhouse gas levels have reached record highs, intensifying the planet's heat retention and amplifying the effects of climate change. Across the globe, the impacts are visible and devastating—severe heat waves, catastrophic flooding, and prolonged droughts are displacing millions, jeopardizing food security, and disrupting economies. Oceans, which act as a buffer for much of the planet's heat, are warming at unprecedented rates, and polar ice continues to shrink rapidly. These are not distant concerns; they are pressing realities shaping the lives of billions.

In response, the global energy transition is gaining momentum. Investments in renewable energy are reaching new heights, with solar and wind energy leading the charge. Governments and corporations are making bold commitments to decarbonization, while advances continue in technologies such as clean hydrogen, carbon capture, and advanced battery storage. Renewable energy capacity is expected to more than double between 2024 and 2030, and collaborative international initiatives are driving advancements in nuclear power. These efforts are reshaping how energy is produced, stored, and consumed, underscoring the vital role of innovation in meeting climate targets.

Yet, the challenges ahead are significant. Fossil fuels still dominate the global energy mix, with critical sectors such as aviation, shipping, and heavy industry heavily reliant on nonrenewable resources. The demand for essential materials like lithium, cobalt, and nickel is surging, raising concerns about supply chain bottlenecks, environmental sustainability, and geopolitical risks. Furthermore, the uneven distribution of clean energy investments highlights the need for global equity in the transition, to ensure developing nations have access to technologies and resources.

At the same time, technological advancements are transforming how we address these challenges. Artificial intelligence can optimize energy systems, track emissions, and enhance energy efficiency. Blockchain is improving transparency in carbon markets, while breakthroughs in materials science are creating innovative solutions such as biodegradable plastics and advanced solar technologies. These developments demonstrate that the intersection of technology and policy holds enormous potential for accelerating progress.



Global shifts offer opportunities and threats for efficiency and established practices.

JANUARY 2024

AI-Driven E-Waste Recycling

Recycleye and SWEEEP Kuusakoski deploy AI-powered optical sorters to improve e-waste recycling in the UK.

APRIL 2024

University Achieves 190% Quantum Efficiency

Lehigh University researchers have developed a solar cell material with an unprecedented 190% external quantum efficiency.

NOVEMBER 2024

AI-Designed Turbine Boosts Urban Wind Power

EvoPhase and Kwik Fab unveil the Birmingham Blade in England, the first urban wind turbine designed by AI.

MARCH 2024

Melting Ice Caps Slow Earth's Spin

A study shows the melting polar ice caps are redistributing water mass, slowing Earth's rotation and lengthening days.

SEPTEMBER 2024

AI-Driven Tree Models for Urban Climate Adaptation

This technology from MIT, Google, and Purdue enhances urban climate adaptation by creating predictive 3D models of trees.

← PAST



The ocean and new materials hold deep promise for transforming our world for the better.

LATE 2030s

Enhanced Geothermal Systems Deploy in New Regions

EGS projects will be deployed in Germany and other low-enthalpy regions previously not considered for geothermal development.

MID-2035

Cities Build Carbon Oceans to Offset Emissions

These vast floating or submerged platforms are designed for electrochemical carbon dioxide removal or algae-based carbon capture.

END OF 2045

Terraforming Technologies for Climate Change Reversal

Breakthroughs in genetic and environmental engineering, as well as synthetic biology, will enable the first “terraforming” projects.

FUTURE >>

EARLY 2032

Ocean-Deep Geothermal Extraction Begins

Using floating platforms, offshore geothermal plants will begin extracting energy from beneath the ocean floor.

EARLY 2036

Synthetic Carbon Biomass for Carbon Trading

Beyond simply storing CO₂, the gas will be converted into synthetic carbon-based biomass that can be traded as a new type of asset.



The accelerating shift in climate and energy systems can give businesses access to new models and markets while avoiding liabilities.

New Business Models

The growing demand for climate-conscious solutions is creating new business models and revenue streams for companies that embrace energy efficiency, carbon reduction, and clean technologies. Early adopters will benefit, while those that delay may find themselves at a competitive disadvantage.

Energy Solutions Are Quickly Evolving

As energy tech—from carbon capture to renewable energy storage—matures and scales at an accelerated pace, businesses will need to adapt. The push for net-zero emissions goals and stricter regulations will make energy solutions faster, more affordable, and accessible to companies across all sectors.

New Technologies Are Creating New Markets

Advancements in climate-related technologies, from biodegradable plastics to AI-powered recycling, are opening up untapped markets and opportunities. Businesses that invest early can position themselves as sustainability leaders by capitalizing on global shifts toward environmental responsibility.

Resource Efficiency Is Becoming Key

As climate change intensifies resource scarcity, businesses that optimize consumption will not only reduce costs but also enhance their long-term viability. Companies can also explore untapped resources like waste—this circular approach both reduces disposal costs and can open new revenue streams.

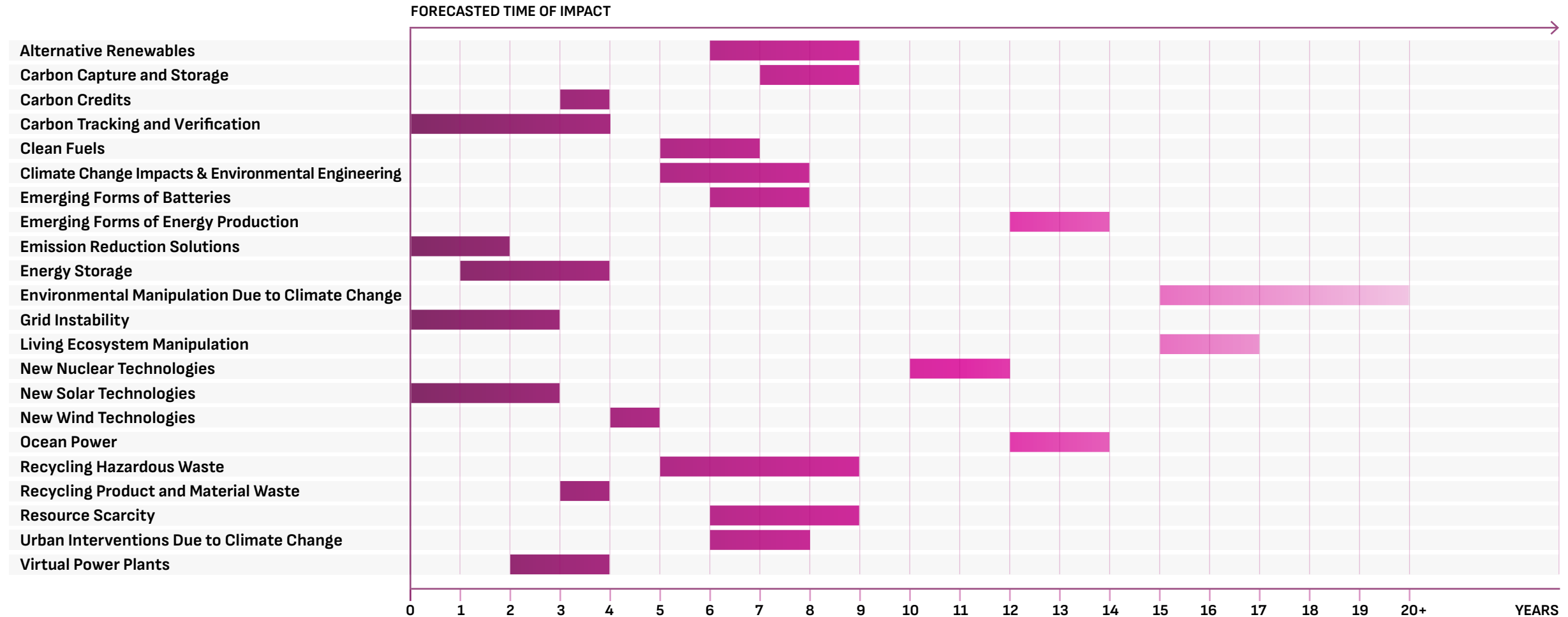
Access in Emerging Markets

Energy access is still a significant challenge in many emerging markets, where infrastructure can be unreliable and costly. For companies expanding into these regions, understanding climate and energy trends provides an edge in preparing for operational changes and identifying resilient strategies.

Melding Energy Storage and Smart Infrastructure

For businesses, investing in new storage technologies—such as the integration of gravity energy storage into buildings and advanced capacitors—could lead to smarter, energy-efficient buildings and facilities that optimize energy use and even become self-sustaining.

Renewable power reshapes short-term energy use and storage, while advanced fuels, batteries, and manipulation technologies redefine the long-term landscape.





The next decade will be defined by companies that don't just react to falling costs, regulatory shifts, and media hype but actively shape the transition.

SCALING

Scaling energy and climate technologies is both a strategic opportunity and a competitive necessity. Prioritize early adoption of cost-competitive energy solutions, and invest in low-carbon alternatives such as EV fleets and carbon capture to future-proof operations against regulatory and carbon pricing shifts.

COSTS

Anticipate falling costs for solar, wind, and energy storage as manufacturing scales, supply chains mature, and efficiency improves. To stay ahead, businesses should track cost trends, leverage incentives, and invest early in scalable solutions.

CONSTRAINTS ON ADOPTION

Permitting delays, grid modernization challenges, and slow policy harmonization can create uncertainty and slow deployment. High up-front costs, infrastructure gaps, financing barriers, and energy security concerns can all limit adoption of cleaner energy, especially in developing economies.

REGULATIONS

In the US and EU, stricter critical minerals regulations meant to reduce reliance on China could create supply bottlenecks. Nuclear energy may be hampered by outdated licensing processes and public resistance. Future regulations will focus on balancing security, safety, and scalability in key energy sectors.

MEDIA MENTIONS

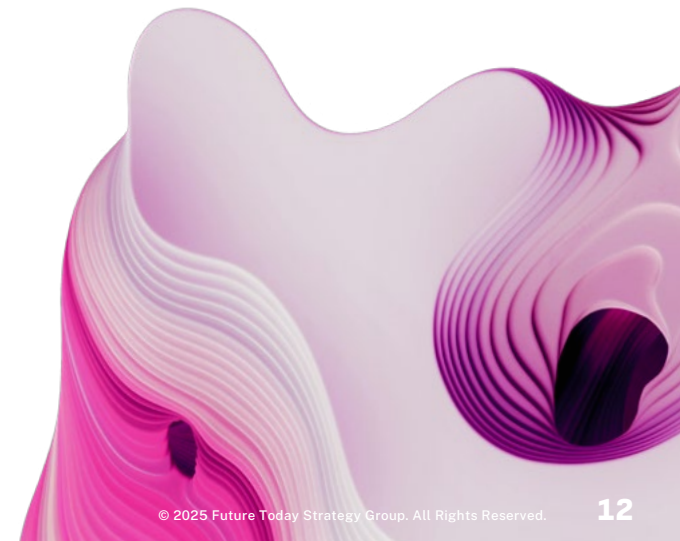
Expect media bursts around energy breakthroughs (next-gen battery storage, AI energy optimization, advanced nuclear), as well as grid modernization and policy shifts like carbon pricing or net-zero mandates. The rise of climate fintech and carbon credit transparency will further fuel industry buzz.

PUBLIC PERCEPTIONS

Expect a growing divide between those who see energy and climate innovations as empowering and skeptics who feel increasingly disconnected. Just as social media once promised democratization but fueled concerns over privacy and control, these technologies could spark debates about autonomy and fairness.

R&D DEVELOPMENTS

Brace for a seismic shift in energy and climate tech R&D, where AI-driven materials discovery, bioengineered carbon capture, and decentralized energy networks will upend traditional markets quickly. As policies lag, first movers will exploit regulatory loopholes, while stragglers risk being priced out altogether.





These individuals are at the forefront of development and transformation in the energy and climate industry.

- ◆ **Dr. Abdul Hai Alami**, professor at the **University of Sharjah**, for demonstrating the potential of compressed air energy storage to power AC devices as a viable alternative for domestic energy use.
- ◆ **Dr. Xiao-Ping Zhang**, professor at the **University of Birmingham**, for leading research on advanced smart grid technologies and their integration into existing wind turbine systems, to enhance efficiency and grid stability.
- ◆ **Parviz Sedigh and Mason Bichanich**, doctoral candidates at the **University of New Hampshire**, for developing an innovative underwater turbine to harness tidal energy.
- ◆ **Dr. Rawand Rasheed**, CEO of **Helix Earth Technologies**, for repurposing a NASA-developed air filtration technology for sustainable applications on Earth.
- ◆ **Dr. Seokheun Choi**, professor at **Binghamton University**, for leading research on bioelectricity, using bacterial spores to generate power from water molecules, as a novel alternative to traditional batteries and wireless energy transfer.
- ◆ **Dr. Connor Williams**, staff scientist at **Sandia National Laboratories**, for advancing fusion energy research by surpassing a critical threshold in energy generation, a key step toward burning plasmas and achieving ignition.
- ◆ **Dr. Avner Rothschild**, professor at **Technion—Israel Institute of Technology**, for leading the development of a new green technology for hydrogen production.
- ◆ **Dr. Zishan Akhter**, researcher at **Technology Innovation Institute**, for his work inventing the patented self-adaptive tip-sweep wind turbine.
- ◆ **Andrei Leonard Nicusan**, CTO of **EvoPhase**, for leading the development of the **AI-designed Birmingham Blade**, the world's first urban wind turbine optimized for low-wind urban environments.
- ◆ **Dr. Olga Malinkiewicz**, co-founder and CTO of **Saule Technologies**, for pioneering flexible, printed perovskite solar cells.
- ◆ **Vaibhav Bahadur**, professor at **The University of Texas at Austin**, for working on a groundbreaking solution to trap carbon dioxide in the ocean and mitigate atmospheric emissions.
- ◆ **Andrew Ng**, founder of **DeepLearning.AI**, for creating an accessible online tool that enables users to explore the impacts of solar geoengineering.



The race to reinvent energy and address climate change is accelerating...

OPPORTUNITIES

Advancements in Continuous Solar Power

Technologies that enable solar energy to provide electricity beyond daylight hours are gaining traction, improving grid reliability and positioning solar as a viable baseload power source.

Rewriting the Relationship Between Water and Energy

New technologies are unlocking energy stored in water's motion, temperature, and chemistry—transforming it into an active force in electricity generation, thermal management, and fuel production.

Reclaiming Wasted Heat for a Second Life

Lost energy from industrial systems is being revisited as a potential resource, offering new efficiencies through heat-to-electricity conversion technologies.

AI as a Societal Compass in Climate Resiliency

Intelligent systems are reshaping how communities anticipate and allocate critical resources, optimizing crop yields, emergency responses, and water distribution in regions facing prolonged climate stress.

...but without modern infrastructure and economic clarity, companies risk being trapped.

THREATS

Grid Infrastructure Bottlenecks

As new forms of energy come online they're outpacing grid upgrades, leading to curtailments and bottlenecks. Without modernized transmission networks, surplus energy from large-scale projects may go unused.

The Elusive Economic Equation

Cost models for next-generation energy sources remain uncertain, with financial unpredictability potentially limiting their scalability and long-term viability.

Digital Weakness in Physical Strength

As energy infrastructure becomes more intelligent, it also becomes more susceptible to interference, with cyber vulnerabilities presenting new risks to critical power networks.

Water's Hidden Vulnerabilities in Energy Systems

As water becomes a central element in climate mitigation, reliance on its availability for energy, cooling, and agriculture may introduce new systemic risks when droughts or contamination occur.

Invest in long-term strategies that reuse assets and protect future interests.



The convergence of AI and quantum computing is beginning to reshape energy forecasting and climate risk modeling. Consider partnering with quantum-AI labs to anticipate supply chain disruptions, optimize grid demand, and design novel materials for next-gen energy storage and transmission.



AI-driven recycling and emerging closed-loop material innovations are shifting waste to a revenue stream. Companies should assess their waste's value—especially in industries like electronics, energy, and automotive—and explore investments in automated material recovery or resale partnerships.



Amid climate disruptions, securing operational resilience will become a bottom-line imperative. Businesses should acquire strategic land with access to stable water sources, invest in atmospheric water harvesting, and integrate microgrid technology to insulate against infrastructure failures.



Businesses with large buildings, parking lots, or industrial sites should explore converting existing infrastructure into grid-supporting energy storage hubs. Investing in bidirectional EV charging or demand response programs could create new revenue streams while improving energy resilience.



Climate shifts will affect not just supply chains but also workforce productivity, office locations, and real estate values. Businesses should stay on top of city planning trends and invest in climate-resilient real estate, flexible work hubs, and AI-powered environmental planning tools.



The internet's energy consumption is growing exponentially, driven by high-res content and inefficient data centers. Companies should invest in AI-generated, ultra-personalized digital experiences that use adaptive rendering, edge computing, and lightweight file formats to reduce energy use while enhancing engagement.





Important terms to know before reading.

AMMONIA

A compound of nitrogen and hydrogen. It can be used directly as a fuel in direct combustion processes, as well as in fuel cells or as a hydrogen carrier. To be a low emissions fuel, ammonia must be produced from low-carbon hydrogen and nitrogen, then separated through the Haber process using electricity generated from low-carbon sources.

BIOENERGY

Energy content derived from biomass feedstocks and biogas. It comes in solid, liquid, and gaseous form. Its liquid form is often labeled biofuel.

BIOFUELS

Low-emission liquid fuels made from renewable sources.

BIOGAS

A mixture of methane, carbon dioxide, and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment.

CARBON CAPTURE (CC)

The process of trapping CO2 emissions from industrial sources, power plants, or directly from the atmosphere before they are released.

CARBON STORAGE (CS)

The long-term containment of captured CO2 in geological formations, materials, or biological systems to prevent its release into the atmosphere.

CARBON CAPTURE AND STORAGE (CCS)

The combination of carbon capture and carbon storage technologies to reduce CO2 emissions from industrial activities and energy production. CCS helps prevent atmospheric buildup of greenhouse gases, playing a critical role in climate mitigation.

CARBON TRACKING

The process of monitoring, measuring, and reporting CO2 emissions across supply chains, industries, and organizations. It enables businesses, governments, and individuals to assess their carbon footprint and identify opportunities for emission reductions.

CARBON VERIFICATION

The process of independently assessing and certifying the accuracy of reported CO2 emissions, offsets, or reductions to ensure compliance with climate regulations and carbon markets.

COMPRESSED AIR ENERGY STORAGE (CAES)

Stores excess electricity by compressing air in underground reservoirs and later releasing it.

CONCENTRATED SOLAR POWER (CSP)

A solar technology using mirrors to concentrate sunlight for heat-based power generation.

DIRECT AIR CAPTURE

Captures CO2 directly from the atmosphere.

DISPATCHABLE GENERATION

A source of electricity that can be turned on or off, such as nuclear, meaning it can be controlled. Non-dispatchable energy sources, such as wind and solar photovoltaics, cannot be controlled by operators.

ELECTROLYSIS

A process where electric current passes through a substance to effect a chemical change. In hydrogen production, electricity is used to split water into hydrogen and oxygen. If the power used for the process comes from sustainable energy sources, the process does not produce greenhouse gas emissions.

GEOENGINEERING

Technologies aimed at altering Earth's climate to counteract global warming.

GEOHERMAL ENERGY

A baseload renewable energy source harnessing heat from Earth's core. Supercritical and closed-loop geothermal are expanding its feasibility.

GRAVITATIONAL ENERGY STORAGE (GES)

A long-duration energy storage technology that converts surplus electricity into potential energy by raising heavy objects and later releasing them to generate power when needed.

**HYDROGEN**

A clean fuel used in fuel cells, turbines, and industrial processes.

MULTITASKING SOLAR

The integration of solar photovoltaics with other technologies, such as agrivoltaics (solar panels over crops), floating solar (on reservoirs and offshore), and electro-agriculture (solar-powered carbon-to-food conversion).

NUCLEAR FISSION

The process of splitting heavy atomic nuclei, such as uranium-235 or plutonium-239, into smaller fragments, releasing a large amount of energy.

NUCLEAR FUSION

The process of combining light atomic nuclei, such as hydrogen isotopes (deuterium and tritium), to form a heavier nucleus, releasing an enormous amount of energy.

ORGANIC SOLAR MATERIALS

Flexible, lightweight photovoltaic materials made from conductive organic polymers.

PEROVSKITE SOLAR CELLS

Next-gen photovoltaics with higher efficiency and lower production costs than silicon panels.

PHOTOVOLTAICS (PV)

A technology that converts sunlight directly into electricity using semiconductor materials that exhibit the photoelectric effect.

SOLID-STATE BATTERIES

Replaces liquid electrolytes with solid materials, improving safety, lifespan, and energy density.

SUPERCONDUCTORS

Conduct electricity without resistance, enhancing grid efficiency and quantum computing.

SUPERCRITICAL GEOTHERMAL ENERGY

Utilizes ultra-high-temperature fluids for efficient, carbon-free power generation.

THERMAL ENERGY STORAGE (TES)

A technology that captures and stores excess heat for later use, enabling grid flexibility, industrial efficiency, and renewable energy integration.

THERMOELECTRIC GENERATORS (TEGS)

Convert waste heat into electricity for industrial and grid applications.

THERMOPHOTOVOLTAIC (TPV) BATTERIES

Store high-temperature heat and convert it into electricity using high-efficiency PV cells.

ULTRA-HIGH VOLTAGE (UHV) POWER LINES

Transmit electricity over long distances with minimal loss.

VIRTUAL POWER PLANTS (VPPS)

Networks of solar panels, home batteries, and electric vehicles that act as a single power plant.



ENERGY TRENDS



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Humanity's future, to say nothing of its prosperity, will depend on how the world tackles two central energy challenges: securing reliable supplies of affordable energy and switching to efficient low-carbon energy.

Fatih Birol, Executive Director, International Energy Agency (IEA)



SOLAR

Solar Energy Expansion

Solar energy production converts sunlight into electricity using photovoltaic (PV) panels or concentrated solar power (CSP) systems. Microsoft has signed a record-breaking 10.5 GW corporate power purchase agreement spanning the US and Europe that's nearly eight times larger than previous deals. The \$11.5 billion investment, set for deployment in 2026, will accelerate clean energy adoption. This move aligns with a broader corporate shift toward sustainability, as companies like Amazon, Google, and Walmart invest in solar projects to offset energy-intensive operations. In the US, domestic solar manufacturing surged in 2024, adding more than 9 GW of module production capacity in the third quarter alone, largely driven by the Inflation Reduction Act. Meanwhile, Saudi Arabia secured \$3.2 billion in financing for 5.5 GW of solar projects, with commercial operations expected by 2027. As demand for data centers grows, large-scale solar procurement will play a critical role in balancing energy needs with sustainability targets.

Concentrated Solar

Concentrated solar power uses parabolic mirrors or “heliostats” to focus sunlight and generate extremely high temperatures, to ultimately produce steam that drives turbines for electricity generation. Unlike PV panels, CSP can incorporate thermal energy storage (TES) to provide continuous power, even after sunset. The US Department of Energy has committed \$30 million to CSP research and deployment, signaling renewed interest in its potential. In Q1 of 2024, India allocated 50% of its renewable energy tender to CSP, addressing grid reliability challenges from intermittent PV and wind power. Emerging modular CSP systems, such as 247Solar's superheated air technology, offer cost-efficient alternatives to molten salt storage. AI-driven optimization is enhancing CSP performance, with studies showing near-perfect forecasting accuracy. SolStor Energy, a new US-based firm, aims to deploy CSP with TES, for nighttime solar power. As global decarbonization efforts intensify, CSP's ability to deliver 24/7 renewable en-

ergy makes it a crucial player in the future energy mix.

Multitasking Solar

Multitasking solar integrates photovoltaic technology with other renewable systems, maximizing efficiency and sustainability. The European Union is backing a groundbreaking floating solar project in the North Sea, where SolarDuck is combining offshore solar with wind energy to optimize power generation. Meanwhile, agrivoltaics research at University of California, Davis is demonstrating how solar panels can enhance crop yields by providing shade, reducing water usage, and improving soil health—offering a climate-resilient solution for agriculture. In urban settings, Dutch researchers have developed solar-integrated window blinds that increase energy efficiency in buildings by 25% on sunny days. Additionally, electro-agriculture is emerging as a radical innovation that uses solar power to convert CO2 into acetate, which could allow plants to grow without sunlight and drastically reduce land use. Even the hospitality sector is embracing multitask-

ing solar, with a floating hotel powered by vertical wind turbines and solar umbrellas. As demand for clean energy rises, hybrid solar solutions are shaping the future of renewable power.

Dispatchable Solar

Dispatchable solar integrates PV generation with energy storage, allowing power to scale up or down based on demand fluctuations. Cypress Creek Renewables' new Texas facility called Zier has 208 MW of solar and 80 MWh of battery storage, and has already helped stabilize the ERCOT grid during peak demand. In California, Arevon Energy's \$529 million Vikings Solar-plus-Storage Project pairs 157 MWDC of solar with 600 MWh of battery storage, making it one of the first utility-scale solar peaker plants designed to supply stored solar power when demand spikes. Meanwhile, startup Exowatt is pioneering modular dispatchable solar for AI data centers, using thermal batteries to store energy for up to 24 hours at under 4 cents per kWh—cheaper than traditional electrochemical batteries. With Texas energy



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consumption at record highs and data centers driving rapid growth, dispatchable solar is emerging as a critical solution for reliable, cost-effective, and sustainable power delivery.

Perovskite Cells

Perovskite is a crystalline compound that can be used as a semiconductor in solar cells, offering a cheaper, easier-to-manufacture, and more sustainable alternative to silicon. Researchers at the National University of Singapore have set a world record with a 27.1% efficiency perovskite-silicon tandem solar cell, using a cyanate-integrated structure that enhances stability. Machine learning is also driving breakthroughs, with scientists using AI to identify new hole-transport materials, pushing efficiencies close to 26.2%. Mass production is on the horizon, as Sekisui Chemical plans to commercialize lightweight, flexible perovskite solar cells by 2025. In the US, a Department of Energy-backed initiative is advancing tandem perovskite-silicon technology, aiming to exceed 50% efficiency. Meanwhile, re-

searchers at the University of Surrey have developed lead-tin perovskite cells with a 66% longer lifespan. With ongoing stability improvements and manufacturing innovations, perovskite solar cells are positioned to reshape the renewable energy market.

Dye-sensitized Solar Cells

Dye-sensitized solar cells (DSCs) use organic dyes to capture photons, offering a lightweight, flexible, and sustainable alternative to traditional silicon-based solar panels. Recently, breakthroughs in molecular engineering have pushed DSC efficiency to new heights. Researchers have developed novel triazatruxene-based sensitizers, MS-1 and MS-2, achieving power conversion efficiencies of 12.81% and 10.92%, respectively—far surpassing the conventional N719 dye's 7.60%. A parallel tandem DSC combining MS-1 and N719 reached a record-breaking 12.89% efficiency, showcasing the potential of multi-dye configurations. Meanwhile, G-Lyte is preparing to unveil high-efficiency DSC technology at CES 2025 that's positioned as an eco-friendly alternative to dispos-

able batteries. Advanced materials such as heteroatom-doped graphene quantum dots are also enhancing DSC performance by improving electron transport and charge separation. With ongoing advancements in efficiency, recyclability, and integration into consumer electronics, DSCs are emerging as a key player in the future of clean energy.

Organic Solar Materials

Organic solar materials are conductive organic polymers or small molecules that absorb light and generate electricity in organic solar cells (OSCs). Researchers at Hong Kong Polytechnic University have achieved a breakthrough 20% power conversion efficiency by designing non-fullerene acceptors with optimized photoelectric properties, enhancing both voltage and stability. Meanwhile, a University of Michigan study found that some OSCs exhibited no performance degradation after three years of proton radiation exposure, making them a promising alternative to silicon for space applications. Additionally, scientists from the University of Cambridge and

Imperial College London have demonstrated that molecular arrangements in OSCs significantly impact light absorption and efficiency. Unlike rigid silicon panels, OSCs offer flexibility, low-cost manufacturing, and lightweight properties, making them ideal for wearable tech, building-integrated photovoltaics, and even space-based solar power. With continued advancements in efficiency and durability, organic solar materials are emerging as a key contender in the next generation of renewable energy.

Breakthroughs in Light Absorption

New materials and technologies are pushing solar energy efficiency beyond conventional limits. Researchers at the University of British Columbia have developed Nxylon, a super-black wood that absorbs more than 99% of visible light, far exceeding standard black coatings. This ultra-absorptive material could be used as a solar panel coating to reduce stray light and increase energy conversion. Meanwhile, Princeton Plasma Physics Laboratory has advanced the understanding of black silicon, a material etched with nanoscale pits to enhance light absorp-



SOLAR

tion. Their research into fluorine gas etching could improve the scalability of black silicon for high-efficiency solar cells. In another breakthrough, Lehigh University scientists have achieved an unprecedented 190% external quantum efficiency with a novel material using copper atoms in germanium selenide layers. This innovation surpasses the theoretical efficiency limits of silicon, capturing photon energy typically lost as heat. With materials science unlocking new frontiers in light absorption, the future of solar energy looks brighter than ever.

Solar Energy Coatings

New solar coatings are transforming how energy is harvested, allowing surfaces beyond traditional panels to generate electricity. Mercedes-Benz is developing a solar paint capable of powering electric vehicles, with ultra-thin 20%-efficient solar modules embedded directly into the car's exterior. A midsize SUV covered in this paint could generate enough energy for more than 7,430 miles of driving per year. Meanwhile, Oxford University researchers

have created a power-generating material that can be coated onto buildings, vehicles, and even mobile phones, achieving more than 27% efficiency, with the potential to surpass 45%. This innovation reduces reliance on large solar farms and expands solar adoption to urban environments. In another breakthrough, researchers have developed a waterproof perovskite solar coating integrated with drop triboelectric nanogenerators, which capture energy from both sunlight and rain. With these advancements, solar coatings could soon revolutionize renewable energy by embedding power generation into everyday objects.





WIND



WIND

Offshore Wind Turbines

Offshore wind turbines generate electricity by harnessing wind energy over open water, where wind speeds are typically stronger and more consistent than on land. Brazil has enacted a new law permitting offshore wind farms to enhance energy security and attract investment, offering incentives for projects within its territorial waters. In the US, Maine has announced a new offshore wind port at Sears Island to support floating turbine assembly, aiming for 3 GW of offshore wind power by 2040. And the US Department of Energy and the National Oceanic and Atmospheric Administration have launched an offshore wind forecasting initiative, deploying advanced sensors to optimize turbine placement and mitigate environmental impacts. Meanwhile, Lloyd's Register has introduced a Recommended Practice for Floating Offshore Wind Turbines, providing comprehensive guidelines for design, transport, and installation, aligning with international standards. Norway's Wind Catching Systems is pioneering the Windcatcher, a wall

of small 1 MW turbines designed to capture 2.5 times more energy per square meter than traditional three-blade turbines. With global investments accelerating, offshore wind is emerging as a critical pillar of renewable energy expansion.

Vertical Wind Turbines

Vertical-axis wind turbines (VAWTs) generate electricity using blades that rotate around a vertical axis, allowing them to harness wind from any direction. Unlike traditional horizontal-axis wind turbines, VAWTs are quieter, more compact, and better suited for urban environments. Researchers have developed genetic learning algorithms to optimize blade pitch, leading to a 200% efficiency increase and a 77% reduction in vibrations, and progress in addressing key structural challenges. In Hawaii, Kanoa Winds is testing Japanese Vertical Coaxial Contra-rotating Twin Blades technology, which has been successfully deployed in Japan for more than 15 years in dense urban settings. Meanwhile, Airiva, a modular wind turbine wall

system, is preparing for customer trials in 2024, offering 2,200 kWh of annual energy output per unit for commercial and industrial sites like highways and campuses. In the UAE, a patented self-adaptive tip-sweep turbine promises further efficiency gains. With these advancements, VAWTs are emerging as a scalable solution for decentralized, urban wind power.

Bladeless Turbines

Bladeless wind turbines generate electricity using oscillation or aerodynamic structures instead of rotating blades, reducing noise, maintenance, and environmental impact. Vortex Bladeless' wind turbine uses controlled oscillation to capture wind energy, making it ideal for urban areas where turbulence limits traditional turbines. In Egypt, researchers at Pharos University have developed a cone-shaped bladeless turbine, addressing concerns about migratory bird safety. Meanwhile, Aeromine Technologies has created a rooftop bladeless wind unit capable of generating 5 kW per unit, producing 50% more energy than

rooftop solar while requiring just 10% of the space. The Birmingham Blade, designed by AI, is tailored for low urban wind speeds and is projected to be seven times more efficient than conventional designs. With growing commercial interest and 11,000+ inquiries for Aeromine's system, bladeless wind energy is rapidly emerging as a viable, scalable alternative for sustainable urban power generation.

Airborne Wind Energy

Airborne wind energy (AWE) systems use tethered kites or drones to capture wind energy at higher altitudes, where wind speeds are stronger and more consistent than near the ground. SkySails Group has validated the world's first performance curve for AWE, confirming the efficiency of its power kite technology. Its subsidiary SkySails Power GmbH is also advancing kite-based energy solutions with its PN-14 model, capable of generating 200 kW, using optimized flight paths for maximum power production. Meanwhile, RWE and Kitepower have expanded their AWE test



WIND

site in Ireland, increasing the Falcon kite's capacity to 100 kW, more than tripling the previous system's output. These systems require less material than traditional wind turbines, making them cheaper to manufacture, easier to deploy, and ideal for offshore applications. With increasing investment and performance validation, AWE is poised to become a scalable and efficient addition to the global renewable energy landscape.

Automating Wind Farms

Automating wind farms involves using AI, digital twins, and autonomous robotics to optimize wind energy production, reduce maintenance costs, and improve operational efficiency. Vind AI, an Oslo-based startup, has secured 3 million euros to fund development of an AI-driven platform that optimizes turbine placement and configurations before construction, to maximize energy output. In offshore wind, the UK's UNITE project is deploying autonomous underwater robots to inspect and repair turbines, reducing the need for human

divers and improving maintenance in harsh sea conditions. Meanwhile, the US National Science Foundation's NorthWind project is developing AI-powered digital twins to predict wind turbine motion during installation, enhancing safety and precision. Bitcoin miner MARA Holdings is also leveraging automation by using real-time wind data to power mining operations only when conditions are favorable. With AI optimizing layouts, robotics handling maintenance, and digital twins improving reliability, automation is shaping the future of wind energy.





ALTERNATIVE RENEWABLES



ALTERNATIVE RENEWABLES

Geothermal

Geothermal energy harnesses heat from the earth's interior to generate electricity and provide direct heating and cooling with minimal carbon emissions. The Eavor-Loop system in Germany, developed by Eavor GmbH, is pioneering a closed-loop geothermal technology that eliminates the need for pumps, offering a scalable solution for district heating and power. Meanwhile, Fervo Energy's project in Utah has significantly reduced drilling costs and time, bringing geothermal closer to cost parity with other renewables. In Saudi Arabia, Strataphy is deploying a cooling-as-a-service model, allowing clients to access geothermal cooling without upfront costs, a key innovation for energy-intensive regions. The GLADE project, supported by the US Department of Energy, is testing high-temperature downhole tools and real-time drilling optimization, targeting a 25% increase in drilling speed. Additionally, researchers are exploring offshore geothermal, with floating platform designs that could unlock vast new energy reserves. With breakthroughs in

drilling, closed-loop systems, and offshore exploration, geothermal is poised for global expansion beyond traditional hot spots.

Supercritical Geothermal

Supercritical geothermal energy taps into reservoirs where temperatures exceed 400 degrees Celsius, dramatically boosting power output compared to conventional geothermal plants. These extreme conditions create supercritical fluids, which carry 10 times more energy than standard geothermal sources, offering a high-density, carbon-free power solution. New Zealand is investing \$60 million in supercritical geothermal research and drilling deeper wells—up to 6 kilometers—in the Taupo Volcanic Zone to explore its vast energy potential. Meanwhile, the US House Committee on Science, Space, and Technology has advanced legislation to fund superhot rock energy research, including a dedicated Superhot FORGE test site. Scientists are also studying rock permeability at high temperatures, finding that granite permeability increases 30-fold at 800 degrees

Celsius, potentially improving fluid circulation and energy extraction. With advancements in deep drilling, enhanced geothermal systems, and federal investment, supercritical geothermal could become a global game-changer for baseload renewable power.

Using Geothermal for Energy Storage

Geothermal energy storage captures heat and pressure underground, storing energy for controlled release when demand peaks. Princeton University's research highlights how flexible geothermal power can function like a battery, enhancing grid reliability by complementing intermittent renewables like wind and solar. Fervo Energy's Project Red has successfully demonstrated geothermal storage lasting more than five days, proving its potential for long-duration energy storage. Meanwhile, Sage Geosystems' 3 MW EarthStore facility in Texas is pioneering its Geopressured Geothermal System, which can store energy for 6 to 10 hours with a round-trip efficiency of 70%–75%. The facility will participate

in the ERCOT market, showcasing geothermal's ability to provide grid-balancing services. With declining drilling costs and minimal infrastructure modifications required, geothermal energy storage is emerging as a cost-competitive, scalable solution for clean energy storage—and a natural alternative to lithium-ion batteries for long-duration applications.

Ocean Thermal Energy Conversion

Ocean thermal energy conversion (OTEC) generates electricity by harnessing the temperature difference between warm surface seawater and cold deep-sea water. Because ocean temperatures remain stable, OTEC provides a continuous, weather-independent source of renewable energy. Global OTEC has introduced the OTEC Power Module, designed to power offshore oil and gas platforms while cutting CO₂ and methane emissions and reducing capital costs by 20%–30%. Meanwhile, the PLOTEC project in the Canary Islands is constructing a storm-resistant floating OTEC structure to test survivability in



ALTERNATIVE RENEWABLES

harsh marine conditions, a key step toward expanding this technology to island nations reliant on diesel generators. In Hawaii, Makai Ocean Engineering's OTEC plant is delivering 100 kW of baseload power, demonstrating the viability of this closed-loop system for long-term energy security. As advancements improve efficiency and infrastructure costs, OTEC is turning into a scalable solution for offshore energy and island electrification.

Hydropower

Hydropower generates electricity by harnessing the energy of moving water, making it one of the most reliable and scalable renewable energy sources. As the grid modernizes, new technologies are transforming hydropower for greater efficiency and resilience. The National Renewable Energy Laboratory is developing CYSAT-Hydro, an AI-powered cybersecurity tool to protect hydropower plants from growing cyberthreats. Meanwhile, hydro-hybrids—which integrate utility-scale batteries with hydropower—are improving

grid stability by storing excess energy for peak demand periods. Additionally, digital twin technology is being deployed to create virtual models of turbines so operators can simulate different conditions, predict maintenance needs, and optimize efficiency. These advancements make hydropower more adaptable, secure, and cost-effective, ensuring its role as a key foundation for the clean energy transition.

Hydro as a Water Battery

Hydro storage, or pumped storage hydropower, stores energy by pumping water into uphill reservoirs when electricity is abundant and releasing it downhill to generate power when demand peaks. This long-duration storage solution is being modernized with new approaches. Sperra, with \$7.7 million in US and German funding, is developing a subsea pumped hydro system using 3D-printed concrete spheres placed on the ocean floor, leveraging deep-sea water pressure for storage. Meanwhile, RheEnergise's "high-density waterless hydro" project in the UK replaces traditional water

with a denser fluid, increasing energy output by 2.5 times while reducing infrastructure needs by 40%. In the US, the Lewis Ridge Pumped Storage Project in Kentucky is repurposing former coal mine land for a 287 MW pumped hydro facility, marking the first such conversion in more than 30 years. As lithium-ion battery costs rise, pumped storage remains the most scalable and cost-effective energy storage method, reinforcing grid reliability with storage durations ranging from hours to years.

New Hydro Turbine Design

New hydro turbine designs are improving efficiency, environmental impact, and manufacturing speed to modernize hydropower infrastructure. GE Vernova's aerating turbine technology, part of a Saluda Hydro power plant upgrade in South Carolina, enhances water quality by increasing dissolved oxygen levels, meeting new environmental regulations while extending the plant's lifespan. Natel Energy's fish-safe turbines, featuring curved blades that create a protective stagnation zone, allow

99% of American eels to survive turbine passage. They're helping balance hydropower generation with aquatic ecosystem protection. Meanwhile, the Oak Ridge National Laboratory is leading the \$15 million Rapid RUNNERS project, which 3D prints large metal turbine runners, to reduce lead times and lower production costs for US hydropower facilities. With innovations in additive manufacturing, fish-friendly design, and water quality improvements, hydro turbine technology is evolving to ensure greater sustainability and long-term viability of low-emission energy generation.



CLEAN FUELS



CLEAN FUELS

Hydrogen

Hydrogen fuel is a zero-emission energy source that can be used in fuel cells or combustion systems to generate electricity, offering a clean alternative to fossil fuels. As hydrogen adoption grows, new technologies are improving safety, storage, and production. South Korea's KRIS has developed the nation's first real-time hydrogen fuel quality monitor, addressing contamination risks that could damage fuel cells or cause overheating. Meanwhile, Toyota's lightweight hydrogen capsules provide a portable refueling solution, allowing fuel-cell vehicles to recharge without a fixed station while also serving as an emergency power source. In micro-scale hydrogen applications, a compact hydrogen generator for recreational vehicles converts methanol into hydrogen on demand, solving storage and transport challenges. On the production side, Japanese scientists are advancing photocatalytic hydrogen production by using sunlight to split water into hydrogen and oxygen for scalable

solar-to-chemical energy conversion. Additionally, a new retrofitted micro-turbine can operate on both hydrogen and natural gas, making power plants more adaptable for a hydrogen-based economy. With innovations spanning fuel safety, portable storage, solar-driven hydrogen production, and dual-fuel power generation, hydrogen is steadily evolving into a key player in the clean energy transition.

Reducing the Cost of Hydrogen Production

Green hydrogen, produced using renewable energy, is key to decarbonizing industries and replacing fossil fuels, but its high costs remain a challenge. Researchers at Technion have developed a new electrolysis method that separates hydrogen and oxygen into different cells, improving efficiency and lowering production costs by reducing reliance on expensive membranes. Meanwhile, UNIST scientists have scaled up perovskite-based photoelectrochemical water splitting, increasing photoelectrode size by 10,000 times and





CLEAN FUELS

achieving more than 10% solar hydrogen conversion efficiency, a major step toward cost-effective, commercial-scale solar hydrogen production. Another promising approach comes from Koloma, a startup that has raised \$350 million to discover and extract underground hydrogen reservoirs, potentially offering a naturally occurring, carbon-free fuel source. As research progresses in electrolysis efficiency, solar hydrogen scalability, and geologic hydrogen extraction, green hydrogen is moving closer to becoming an affordable and widespread clean energy solution.

Biofuels

Biofuels, derived from renewable organic materials, are advancing as low-emission alternatives to fossil fuels, with applications in aviation, transportation, and industrial energy. LanzaJet's commercial-scale alcohol-to-jet fuel facility is converting ethanol from corn, sugarcane, and municipal waste into jet fuel, potentially reducing aviation emissions by up to 66%. Meanwhile, Washington State University has developed a process to convert lig-

nin-based agricultural waste into jet fuel. It provides a sustainable alternative to fossil-derived aromatics while maintaining high fuel performance. Seaweed-based biofuels are also emerging, with researchers demonstrating a method to convert common marine biomass into aviation fuel, potentially cutting emissions by 82%. Additionally, an electro-biodiesel process from Washington University in St. Louis offers 45 times greater efficiency than traditional biodiesel, reducing land use while generating net-negative carbon emissions. As advanced biofuels scale, they could revolutionize multiple industries, making renewable fuels more accessible and decarbonizing hard-to-electrify sectors.

Syngas From the Sun

Solar syngas is a synthetic gas produced using concentrated solar energy to drive high-temperature chemical reactions that convert CO₂ and H₂O into hydrogen and carbon monoxide. This process provides a renewable alternative to fossil-based syngas, which is a key feedstock for synthetic fuels like jet fuel, gasoline, and

diesel. Synhelion's DAWN facility in Germany is the world's first industrial-scale plant to produce syngas using solar heat, with plans to scale production to 1 million metric tons annually over the next decade. A separate study has demonstrated an automated solar thermochemical system, using a ceria-based redox cycle to generate customizable syngas compositions for Fischer-Tropsch fuel synthesis. Researchers are also exploring photocatalytic syngas production, where a novel catalyst harnesses solar energy to convert CO₂ and methane into syngas, providing a high-efficiency, emissions-reducing alternative. With advancements in solar thermochemistry and automation, syngas from the sun is turning into a scalable, carbon-neutral pathway for producing sustainable transportation fuels.





FOSSIL FUEL INNOVATION



FOSSIL FUEL INNOVATION

Reducing Fossil Fuel Impact

Efforts to reduce fossil fuel dependency are being challenged by rising energy demands, particularly from data centers, AI computing, and industrial sectors. A surge in natural gas plant construction—with 80 new plants planned by 2030—risks delaying the transition to renewable energy. Many of these plants lack carbon capture systems, further undermining climate goals. Meanwhile, EPA regulations have tightened emissions standards, and coal plants are facing mandates to install carbon capture or shut down by 2032. In response, companies are adopting alternative fuels, such as Piramal Pharma's switch from coal to biomass briquettes, that reduce carbon emissions while maintaining industrial energy needs. Additionally, innovations like L-Mul, an energy-efficient AI computation algorithm, could significantly lower the power consumption of AI-driven data centers, reducing the need for new fossil-fuel infrastructure. Addressing both energy demand and supply is key to mini-

mizing fossil fuel reliance and accelerating clean energy adoption.

Methane Emissions Reductions

New advancements in methane tracking, conversion, and mitigation are accelerating efforts to reduce the gas' environmental impact. Methane is 28 times more potent than CO₂ in trapping heat, making its reduction critical for climate change mitigation. Satellites such as Methane-SAT and Tanager-1 now provide real-time, high-precision methane leak detection, while lidar-based aerial systems and drone-mounted sensors are enhancing on-the-ground monitoring. In industrial applications, LongPath Technologies, backed by a \$162 million DOE loan, is expanding its laser-based detection network to 20,000 square miles, identifying leaks down to parts per billion. At the same time, researchers at University of Central Florida have developed a breakthrough process that converts methane into green hydrogen and high-performance carbon materials, of-

fering a dual benefit of methane reduction and sustainable fuel production. Additionally, University of California, Davis studies show that seaweed-based cattle feed can cut methane emissions from grazing cattle by 40%, presenting a scalable agricultural solution. These emerging detection, capture, and conversion technologies provide a multi-sector approach to methane reduction, from energy and agriculture to industrial emissions tracking.



NUCLEAR



NUCLEAR

Nuclear

Nuclear power generation is the process of producing electricity through controlled nuclear reactions, primarily fission, where atomic nuclei split to release energy. Nuclear power is undergoing a wave of advancements, from new reactor deployments to breakthroughs in reactor design and fuel technology. The completion of Plant Vogtle Unit 4 in Georgia adds 1,114 megawatts of power, making Plant Vogtle the largest nuclear plant in the US at nearly 5 gigawatts. Meanwhile, Argonne National Laboratory is pioneering Generation IV reactor research, with a focus on sodium-cooled fast reactors that enhance safety, efficiency, and fuel sustainability. In fission research, CERN's n_TOF facility has conducted the first-ever high-energy measurement of uranium-235 fission, refining models of nuclear reactions. Scientists at University of Washington and Los Alamos National Laboratory have used the Summit supercomputer to simulate nuclear fission at an unprecedented level, improving understanding of scission neutron behavior.

Additionally, advancements in antineutrino detection technology are offering new ways to remotely monitor reactor operations, with potential implications for nuclear security and nonproliferation. These breakthroughs are shaping the next generation of nuclear power, reinforcing its role in a low-carbon energy future.

Fusion

Fusion power, the process of generating energy by fusing atomic nuclei, is advancing rapidly through AI-driven plasma control, new reactor materials, and large-scale projects. Researchers at Princeton University have developed an AI model that can predict and prevent plasma instabilities in fusion reactors, a breakthrough that enhances stability and efficiency. At the DIII-D National Fusion Facility, this AI successfully forecasted disruptions 300 milliseconds in advance, allowing for real-time corrections. Meanwhile, the WEST tokamak in France achieved a milestone by sustaining a 50-million-degree plasma for six minutes, demonstrating progress in using tungsten as a reactor material.

On the infrastructure front, Virginia is set to host the world's first grid-scale fusion power plant, aiming for commercialization by the early 2030s. In China, researchers have introduced Chixiao, a linear plasma device designed to test fusion materials under extreme conditions, reinforcing global efforts to make fusion a viable energy source. These advancements mark significant strides toward a future where fusion provides limitless, carbon-free energy.

Laser-Driven Fusion

Laser-driven fusion, a process that uses ultra-powerful lasers to compress and heat fuel to conditions required for nuclear fusion, is making significant strides toward commercialization. At the National Ignition Facility, scientists have achieved record-breaking energy outputs, including a 5.2 megajoule reaction in February 2024, more than double the input energy, proving that fusion ignition can be sustained. Meanwhile, Colorado State University's ATLAS Facility, set for completion in 2026, will drive laser fusion research through a \$150 million partnership with Marvel Fusion,

which has also secured \$70 million in Series B funding to advance inertial confinement fusion. The OMEGA laser system has demonstrated a direct-drive method that achieves fuel gain with far lower energy requirements than traditional approaches. In Australia, HB11 Energy has partnered with ELI ERIC, the world's largest high-power laser provider, to develop hydrogen-boron fusion, a fuel choice that eliminates neutron radiation risks. With major advancements in laser precision, fuel composition, and experimental efficiency, these breakthroughs are bringing laser-driven fusion closer to a viable, clean energy source.

Molten Salt Reactors

Molten salt reactors (MSRs) are an emerging nuclear technology that uses liquid salt as both a coolant and fuel carrier, offering higher efficiency, improved safety, and reduced nuclear waste compared to traditional reactors. Recent advancements are accelerating the commercialization and deployment of MSRs worldwide. At Oak Ridge National Laboratory, researchers have analyzed molten uranium trichloride (UCl₃)



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to better understand its chemical behavior, crucial for reactor fuel design. Meanwhile, North Carolina State University has introduced a novel plasma bubble spectroscopy technique to detect and monitor elements in molten salt, to improve reactor safety and fuel efficiency. Texas A&M University is collaborating on Natura MSR-1, the first liquid salt-fueled reactor licensed in the US, aiming to produce clean energy and medical isotopes. Dutch companies are developing small modular MSRs, and China is constructing the first thorium-based MSR, which will harness abundant thorium reserves for sustainable energy production. These advancements position molten salt reactors as a critical component of the global energy transition.

Small Modular Reactors

Small modular reactors (SMRs) are compact, factory-built nuclear reactors designed to provide flexible, scalable, and cost-effective clean energy. Unlike traditional large nuclear plants, SMRs can be deployed in smaller increments, making them attractive for industrial applications,

AI data centers, and regions with growing energy needs. Major tech companies are investing in SMRs, with Google partnering with Kairos Power for a potential 500 MW SMR project, while Amazon collaborates with X-energy on a 320 MW reactor for cloud infrastructure. Oracle is also exploring SMRs for powering its data centers. At the same time, Ghana has signed an agreement with NuScale Power to build a VOYGR-12 SMR, marking its first step into nuclear energy. In France, a new small reactor project aims to strengthen the nation's energy strategy. Advances in AI-driven reactor optimization at Purdue University are improving SMR efficiency, reducing power fluctuation errors to below 1%, and demonstrating digital twin capabilities for predictive modeling. Meanwhile, Energy Vault and NuCube Energy are working on nuclear microreactors to power AI-driven data centers by integrating energy storage solutions for reliability. SMRs are poised to revolutionize clean energy generation, through decarbonization, energy security, and adaptability for a rapidly evolving grid.





EMERGING FORMS OF ENERGY PRODUCTION



EMERGING FORMS OF ENERGY PRODUCTION

Hygroelectricity

Hygroelectricity is the process of generating electricity from moisture in the air, offering a renewable and scalable energy solution for various applications, including wearable electronics, HVAC systems, and carbon capture. New breakthroughs in moisture-electricity generation (MEG) and humidity-driven energy harvesting are pushing this technology forward. Binghamton University has developed a paper-based wearable device that extracts electricity from water molecules using bacterial spores, potentially powering sensors and medical devices. Meanwhile, Helix Earth Technologies' Helix Micra system, initially developed for NASA spacecraft, dramatically improves air conditioning efficiency by reducing energy use by 50% as it leverages moisture absorption for dehumidification. This technology is scalable via 3D printing, reducing production costs and environmental impact. Newcastle University researchers have created a synthetic membrane that

utilizes humidity differences to capture and remove carbon dioxide without external energy inputs, an alignment with climate mitigation goals. Additionally, Chinese scientists have developed ionic hydrogel-based MEG devices that generate record-breaking power density, demonstrating potential for self-powered electronics. These innovations signal a growing shift toward utilizing atmospheric moisture as a clean energy source as they pave the way for low-carbon, high-efficiency energy harvesting solutions.

Wave Power

Wave power is a form of renewable energy that captures the motion of ocean waves to generate electricity, offering a predictable and abundant source of clean energy. New developments in wave energy converter (WEC) technology and optimized farm layouts are accelerating wave power's commercial viability. Eco Wave Power's project in Porto, Portugal, in partnership with MOQ Engineering, is set to be the first megawatt-scale wave energy project in

the region, aligning with Portugal's goal of 85% renewable electricity by 2030. The company is also expanding into Taiwan and the Port of Los Angeles. Meanwhile, a pilot WEC project in Jaffa Port, Israel, developed in collaboration with EDF Renewables IL, marks the country's first wave energy initiative. Studies along the Pacific coast of Central America highlight wave energy's potential, estimating it could provide 35 times more energy than wind in some areas. Advanced oscillating water column turbine modeling and control co-design strategies are further optimizing WEC efficiency and farm layouts, increasing power output while minimizing environmental impact. As research progresses, wave energy is poised to become a key player in the global clean energy transition.

Tidal Turbines

Tidal turbines generate electricity by capturing the kinetic energy of ocean currents, offering a predictable and consistent renewable energy source compared to wind and solar power. New advancements in tid-

al stream technology are driving innovation in the sector. The Dragon 12 tidal energy kite, developed by Minesto, has successfully delivered 1.2 MW of electricity in the Faroe Islands, leveraging a unique gliding motion to enhance energy output. Inyanga Marine Energy Group is deploying a 20 MW HydroWing system in North Wales, utilizing modular Tocardo T-3 turbines to reduce costs and streamline installation. Meanwhile, the Cape Cod Canal's test site has received federal approval for tidal energy trials that aim to integrate generated power into the New England grid. In the US Pacific Northwest, the OPALCO Tidal Energy Pilot Project faces economic and environmental challenges, particularly concerns about Southern Resident killer whale habitats. Research efforts at the University of New Hampshire, supported by the Department of Energy, are testing compact tidal turbines under the nearby Memorial Bridge and could contribute to future scalable designs. With growing global investment, tidal turbines are becoming a key component of the marine renewable energy mix.



EMERGING FORMS OF ENERGY PRODUCTION

Mimicking Photosynthesis

Mimicking photosynthesis involves replicating the natural process plants use to convert sunlight into energy, with applications in renewable fuel production, tissue engineering, and biotechnology. Japanese researchers have successfully integrated chloroplasts from algae into hamster cells, creating photosynthetic animal cells that can survive and generate energy for at least two days. This breakthrough challenges the assumption that animal cells would digest chloroplasts and suggests future possibilities in tissue engineering and regenerative medicine by enhancing oxygen production in lab-grown tissues. Meanwhile, scientists at Daegu Gyeongbuk Institute of Science and Technology have developed a biohybrid system for solar hydrogen production that incorporates fluorescent nanocomposites and *Shewanella oneidensis* bacteria to improve photocatalytic efficiency. Their system achieved a hydrogen production rate of 18.4 mmol per hour per gram of catalyst, surpassing previous methods in artificial photosyn-

thesis. These developments highlight the potential for bioengineered solutions to address both energy generation and medical advancements, bridging the gap between plant and animal biology.

Thermophotovoltaic

Thermophotovoltaic (TPV) technology converts heat into electricity by using thermal emitters to generate infrared light, which is then captured by photovoltaic cells. This process enables efficient energy recovery from high-temperature sources, offering applications in industrial waste heat recovery, renewable energy storage, and off-grid power generation. Researchers at Rice University have developed a quantum-inspired thermal emitter that improves TPV efficiency, potentially exceeding 60% conversion rates. The emitter, composed of tungsten, silicon nanocylinders, and a spacer layer, allows for precise photon emission control, enhancing energy conversion. Meanwhile, Antora Energy has launched a 2 MW TPV manufacturing facility in California that's focused on high-efficiency grid-scale ther-

mal storage. Its III-V semiconductor-based TPV cells achieve more than 40% efficiency, generating 100 times more power than traditional solar cells. Another breakthrough, detailed in ScienceDaily, reports a 44% efficiency milestone at 1435 degrees Celsius, with potential advancements pushing limits beyond 50%. Innovations such as photon recycling and material flexibility position TPV as a promising battery-free alternative for energy storage that will help to decarbonize industrial processes and enhance renewable grid stability.

Thermoelectric Generators

Thermoelectric generators (TEGs) convert heat into electricity by exploiting temperature differences in materials. Recent breakthroughs in geometry and material flexibility are dramatically improving their efficiency and applications. Researchers have developed hourglass-shaped thermoelectric materials that boost energy conversion by 360% compared to conventional rectangular designs. Using 3D printing, they optimized microstructures to reduce

thermal conductivity and enhance power generation, achieving the highest thermoelectric performance index for 3D-printed materials. Meanwhile, new flexible thermoelectric films are emerging, capable of converting body heat into electricity. Made from bismuth telluride, these films are just one micron thick and maintain efficiency even after repeated bending. With potential uses in wearables, self-powered sensors, and electronics cooling, these innovations position TEGs as a key solution for sustainable energy harvesting in diverse industries.

**SCENARIO YEAR 2029**

RAINCHARGE: THE END OF DEAD PHONES

It started as a niche innovation—an experimental humidity generator capable of pulling electricity from the air. By 2029, this breakthrough has evolved beyond the lab, as a coalition of tech giants, energy companies, and materials science pioneers unveil RainCharge™—the world’s first moisture-powered consumer charging system. Now, phones, laptops, and wearables seamlessly harvest electricity from ambient humidity, fog, and rain, eliminating the need for traditional charging in wet and tropical climates.

The breakthrough was made possible by cross-industry collaboration. Samsung and Apple integrated IH-MEG technology into their RainCharge™-ready smartphones, embedding microscopic moisture-electricity layers beneath their glass screens to allow for passive charging. Ford and Siemens developed RainGrid, a moisture-activated urban energy network that powers public transit shelters, outdoor advertising screens, and emergency response infrastructure without reliance on traditional electricity grids. Meanwhile, outdoor brands like Adidas and Patagonia pioneered RainWeave™, a hydrogel-embedded fabric that enables clothing to generate electricity from sweat and humidity, making it ideal for extreme sports, emergency workers, and disaster response.

Looking ahead, RainCharge technology is poised to move beyond Earth. By 2040, NASA and SpaceX will be testing moisture-electricity generators on Mars to harness trace humidity from the planet’s thin atmosphere, while oceanic industries explore how RainCharge systems could provide backup power for offshore wind farms and cargo ships, reducing reliance on fuel-based generators. The once-radical idea that rain could be used as an energy source has now transformed global infrastructure, powering everything from personal devices to city-wide energy grids.





ENERGY STORAGE



ENERGY STORAGE

Emerging Forms of Batteries

Innovations in battery technology are moving beyond conventional lithium-ion designs, introducing sustainable and long-lasting alternatives. Swiss researchers have developed a fungal biobattery, a microbial fuel cell that generates electricity from nutrients rather than chemical reactions. Fully biodegradable and 3D printed, this battery offers a low-impact solution for powering sensors in agriculture and environmental monitoring. Meanwhile, quantum batteries are showing promise, with nonreciprocal energy transfer increasing charging efficiency by a factor of four. These designs, leveraging time-reversal symmetry breaking, could revolutionize quantum computing and energy storage. Another breakthrough comes from nuclear-powered diamond batteries, which harness carbon-14 from nuclear waste to generate continuous energy for up to 5,700 years. These batteries could power pacemakers, satellites, and remote sensors without ever needing replacement. As researchers push the boundaries of energy

storage, next-generation batteries promise to be more sustainable, efficient, and long-lasting, reshaping the future of power.

TPV Batteries

Thermophotovoltaic (TPV) batteries convert stored heat into electricity using high-efficiency photovoltaic cells, offering a promising alternative for grid-scale energy storage. US scientists have achieved a breakthrough in TPV efficiency by developing air-bridge thermophotovoltaic cells with 44% efficiency—a major improvement over previous designs. This innovation uses photon recycling via a nanophotonic air bridge, increasing energy capture and making TPV batteries more viable for high-temperature energy storage. Additionally, advancements in germanium-based TPV converters have reached 23.2% efficiency, improving cost-effectiveness for thermal battery applications. With scalable, low-cost, and sustainable designs, TPV batteries are emerging as a viable alternative to lithium-ion storage, particularly for renewable energy integration and industrial decarbonization.

Iron-Based Batteries

Iron-based batteries are emerging as a cost-effective, sustainable alternative to lithium-ion and vanadium-based storage systems. Researchers at Pacific Northwest National Laboratory have developed an iron flow battery using nitrogenous triphosphonate, achieving high cycling stability over 1,000 charge cycles while maintaining 98.7% capacity. Meanwhile, Worcester Polytechnic Institute scientists have enhanced alkaline iron batteries by adding silicate to suppress hydrogen gas generation in a move toward improving efficiency for grid storage. Iron cathodes are also being explored as a replacement for cobalt and nickel in lithium-ion batteries, potentially reducing costs and improving sustainability. Form Energy has secured \$405 million to scale its 100-hour iron-air battery, designed for long-duration energy storage. Additionally, Australia's first iron flow battery factory is under construction with a goal of providing grid-scale storage by 2025. With advancements in chemistry and manufacturing, iron-based batteries

are set to play a key role in decarbonizing energy storage.

Solid State Batteries

Solid-state batteries replace conventional liquid electrolytes with solid materials, improving safety, lifespan, and energy density for electric vehicles (EVs) and grid storage. A triple-layer lithium metal battery developed at DGIST enhances fire resistance and maintains 87.9% efficiency after 1,000 cycles, making it a safer alternative to traditional lithium-ion cells. Harvard researchers have designed a lithium metal battery that charges in 10 minutes and lasts for 6,000 cycles, solving dendrite formation issues with a micron-size silicon anode. Meanwhile, Toyota and Imec are leading commercialization efforts, with Toyota developing EV batteries capable of 621-mile ranges and 10-minute fast charging for release by 2027, while Imec's 1070 Wh/L lithium-metal battery surpasses current industry standards. Manufacturing innovations include polymerized ionic liquid electrolytes and compatibility with existing lithium-ion production lines, reducing costs.



ENERGY STORAGE

With faster charging, higher energy density, and improved safety, solid-state batteries are set to transform EVs and renewable energy storage.

Gravitational Energy Storage

Gravitational energy batteries store energy by raising heavy weights when surplus power is available and releasing them to generate electricity when needed. This emerging technology offers a long-lasting, low-maintenance alternative to conventional energy storage methods, particularly for integrating renewable energy into the grid. A Purdue University study assessed the feasibility of small-scale gravity batteries for residential use, but high costs and limited storage capacity proved prohibitive. In contrast, large-scale implementations are advancing globally. Skidmore, Owings & Merrill and Energy Vault are repurposing skyscrapers as vertical energy storage systems, using modular designs to integrate gravity-based storage into urban infrastructure. Meanwhile, Scottish startup Gravitricity is converting an abandoned Finnish mine into Europe's first underground gravity

battery, demonstrating the potential for repurposing disused mining sites. In China, Energy Vault has deployed a 100 MWh gravity battery, capable of powering 3,500 homes, as part of the country's strategy to lead in renewable energy storage. These innovations highlight gravity batteries as a durable, scalable, and geography-independent energy storage solution, with potential applications in cities, remote areas, and repurposed industrial sites.

Flow Batteries

Flow batteries store energy in liquid electrolytes, offering scalable, long-duration energy storage solutions ideal for integrating renewable energy into the grid. Unlike conventional batteries, they separate energy storage and power generation, allowing for flexible capacity expansion. Harvard's Aziz Group has made breakthroughs in aqueous organic redox flow batteries, developing a self-repairing molecule called "zombie quinone" that reduces capacity fade by 40 times, significantly improving battery lifespan. Meanwhile, researchers at the Korea Institute of Energy Research have

enhanced viologen redox flow batteries, achieving 99.4% efficiency and improved cycle life by adding functional groups that stabilize battery chemistry. At Pacific Northwest National Laboratory, scientists have boosted flow battery longevity by 60% using a starch-derived additive, β -cyclodextrin, which accelerates electrochemical reactions while maintaining stability. These advancements underscore the potential of low-cost, long-lasting flow batteries to revolutionize energy storage, reducing dependence on mined materials while enabling greater renewable energy adoption.

Capacitors

Capacitors are energy storage devices that rapidly charge and discharge electricity, playing a vital role in medical implants, electric vehicles, and consumer electronics. Recent breakthroughs are enhancing their efficiency, durability, and application range. Researchers at the University of Twente have developed a multilayer capacitor with more than 90% efficiency, capable of billions of charge cycles, significantly extending device lifespan. At the





ENERGY STORAGE

Indian Institute of Science, scientists have created a light-charged supercapacitor that achieves a 3,000% capacitance boost under UV light, with potential applications in self-powered sensors. Meanwhile, new heterostructures using barium titanate and molybdenum disulfide have demonstrated a record 191.7 J/cm^3 energy density, with minimized energy losses. These innovations are pushing capacitors beyond traditional roles, improving grid-scale storage, self-powered electronics, and sustainable energy solutions.

Compressed Air Energy Storage

Compressed air energy storage (CAES) systems store excess energy by compressing air and later releasing it to generate electricity. This method offers a scalable and cost-effective alternative to traditional batteries, supporting grid stability and renewable energy integration. Highview Power is constructing four cryogenic air storage facilities in the UK, each with 2.5 GWh capacity, utilizing liquid air energy storage to manage peak demand and store excess

renewable energy. Meanwhile, researchers at the Chinese Academy of Sciences have enhanced adiabatic CAES (A-CAES) by injecting heated water under pressure, improving air storage density by 15% and achieving 71.7% efficiency. Additionally, a buoyancy-based CAES system developed at the University of Sharjah demonstrates a 60% round-trip efficiency, with a projected energy cost significantly lower than conventional batteries. As innovations in temperature regulation, underground storage, and system integration advance, CAES is emerging as a key player in large-scale energy storage, enabling a more resilient and sustainable energy grid.





SCENARIO YEAR 2032

COATINGS TO KEEP THE LIGHTS ON

As the humid air settles over Singapore's Marina Bay at dusk, the city quietly illuminates itself. Building facades glow thanks to Solvion's latest innovation, SolvLux—a coating that combines dye-sensitized solar cells, fungal bio-batteries, and graphene-based conductivity to create seamless, self-powered surfaces. Singapore first tested the new coating on its public transit hubs, creating a new generation of self-powered bus shelters. Now street lights, traffic signals, and building facades use the power-generating coating to reduce energy demand both during the day and at night without pulling a single watt from the electrical grid. SolvLux absorbs diffuse sunlight during the day, storing excess energy in moisture-activated fungal bio-batteries and ensuring uninterrupted operation through Singapore's frequent evening downpours and humid nights. The city no longer "turns on" its lights; the lights simply exist as they're seamlessly woven into the fabric of infrastructure.

Beyond Singapore's urban core, SolvLux is changing lives in rural Malaysia, Indonesia, and Vietnam, where it is leapfrogging traditional electrification efforts. Instead of waiting for government-funded grid expansions, off-grid villages have begun installing SolvLux on fences, pathways, and community hubs. Bio-energy technicians—workers trained to monitor and optimize fungal bio-batteries—have aided in these locations. Mushroom farmers and biotech specialists are being retrained to cultivate and maintain fungal battery colonies, ensuring consistent electron production and long-term system health. These workers operate fungal energy labs, periodically replenishing and optimizing urban biofilms, much like gardeners tending to a city-wide ecosystem.





ENERGY TRANSPORT & THE GRID



ENERGY TRANSPORT & THE GRID

UHV Power Lines

Ultra-high voltage (UHV) power lines transmit electricity over long distances with minimal energy loss, supporting large-scale renewable energy integration and improving grid efficiency. These transmission systems, which include ultra-high voltage alternating current (UHVAC) and ultra-high voltage direct current (UHVDC), are critical for enabling the clean energy transition. China is at the forefront of UHV technology with several large-scale projects. The Gansu-Zhejiang ± 800 kV UHVDC transmission project will transport 36 billion kWh annually, with more than 50% from renewables, reducing 17 million tons of CO₂ emissions. The Zhangbei-Shengli 1,000-kV UHVAC project will transmit 70 billion kWh per year, supplying 19 million households and increasing wind energy integration. The Jinshang-Hubei ± 800 kV UHVDC project, the highest-altitude UHV transmission system, spans 1,901 kilometers and will deliver 40 billion kWh annually to central China. With billions in infrastructure investment, UHV power lines are reshaping global energy

grids, enabling the efficient transmission of renewable energy while reducing reliance on fossil fuels and meeting growing electricity demand.

Superconductors

Superconductors are materials that can conduct electricity without resistance when cooled below a critical temperature, enabling highly efficient power transmission, advanced computing, and next-generation energy storage. Recent breakthroughs in high-temperature superconductors (HTS) are expanding their real-world applications, from energy grids to medical imaging and quantum computing. MIT-backed startup VEIR is developing superconducting transmission lines that use a proprietary nitrogen-based cooling system, allowing for higher power capacity while minimizing grid expansion challenges. The technology could double US transmission capacity to meet 2035 decarbonization goals. Meanwhile, University at Buffalo researchers have created the highest-performing HTS wire

using rare-earth barium copper oxide, achieving record current densities and improving efficiency in power grids, fusion energy, and MRI technology. Josephson junction research is also advancing, with helium-ion beam techniques enhancing superconducting circuits for faster, more efficient electronics. These innovations in superconductors are set to revolutionize energy infrastructure, improving transmission efficiency, reducing power loss, and supporting the integration of renewable energy worldwide.



ENERGY TRANSPORT & THE GRID

Dynamic Line Rating Systems

Dynamic line rating (DLR) systems use real-time data, such as temperature, wind speed, and line conditions, to assess the actual capacity of transmission lines rather than relying on conservative static ratings. By maximizing grid efficiency, DLR enables greater integration of renewable energy while minimizing costly infrastructure expansion. The Federal Energy Regulatory Commission is considering a new rulemaking to enhance DLR adoption across the US, aiming to improve grid reliability and operational flexibility. A large-scale DLR deployment by AES and LineVision has demonstrated how real-time monitoring can increase transmission efficiency and reduce environmental impact. Meanwhile, Georgia Tech and Smart Wires are integrating DLR with advanced power flow control technology, using machine learning and localized weather predictions to optimize energy flow. Research in Estonia highlights how confidence intervals in DLR models can improve transmission capacity by accounting for terrain-specific weather variations.

These advancements position DLR as a key grid-enhancing technology that enables utilities to unlock additional capacity, integrate renewables more effectively, and modernize power infrastructure without extensive new transmission development.

Grid Management

Advanced AI models, blockchain technology, and grid-forming inverters (GFMs) are driving innovations in real-time grid management. A graph neural network model developed by the University of Virginia enhances power flow analysis, improving accuracy and efficiency while adapting to changing grid conditions. Powerledger and Energie Steiermark are using blockchain-based energy trading, allowing prosumers in Austria to buy and sell surplus electricity with greater transparency and flexibility. Digital twins and power hardware-in-the-loop testing methods are improving grid stability by modeling real-world power flow and restoration strategies. GFM inverters provide voltage, frequency, and inertia support, helping stabilize grids with high levels of wind and

solar power. By leveraging AI, blockchain, and real-time modeling, these advancements enable a more resilient and decentralized power system, ensuring grids can efficiently handle fluctuations in demand and renewable energy supply.

Grid Instability

As grids transition to renewable energy sources, challenges such as reduced inertia, extreme weather events, and increasing demand spikes make stability solutions more critical than ever. Reactive Technologies is addressing grid stability concerns through real-time inertia measurement with its GridMetrix technology, which is already deployed in the UK and expanding into the US and global markets. Climate change-related risks, including flash floods, droughts, and extreme heat, are further straining grids, requiring massive investment in modernized infrastructure—an estimated \$24.1 trillion by 2050. New technologies are emerging to enhance grid resilience. The Pacific Northwest National Laboratory has developed grid-forming inverters, which improve voltage and fre-





ENERGY TRANSPORT & THE GRID

quency stability when integrating wind and solar power. The University of Birmingham has designed smart control systems to prevent frequency dips and forced oscillations in wind farms. GE Vernova is deploying synchronous condensers in Chile to boost grid inertia and voltage regulation, reducing blackout risks. As renewable penetration increases, grid instability must be proactively managed using advanced analytics, real-time monitoring, and next-generation grid technologies to ensure a reliable and resilient energy future.

Virtual Power Plants

A virtual power plant (VPP) is a network of decentralized energy resources—such as solar panels, home batteries, electric vehicles (EVs), and smart appliances—that collectively act as a single power plant. VPPs enhance grid stability by intelligently managing energy supply and demand, reducing reliance on traditional fossil-fuel power plants and increasing renewable energy integration. Maryland became the first US state to pass legislation supporting

vehicle-to-grid integration, allowing EVs to supply electricity back to the grid. The 1 GW AI-powered VPP in Texas, a partnership between NRG Energy and Renew Home, will use smart thermostats and AI-driven energy optimization to manage power for 200,000 homes. Renew Home also launched America's largest residential VPP, managing 3 GW of energy use and planning to expand to 50 GW by 2030, potentially covering 10%–20% of peak US electricity demand. In Europe, Enpal's AI-based VPP is connecting solar-equipped homes, EVs, and heat pumps to create a decentralized energy network, with plans to expand to 80,000 customers. By aggregating distributed energy resources, VPPs improve grid resilience, lower costs, and accelerate the transition to renewable energy.



CLIMATE TRENDS



ADDRESSING CARBON EMISSIONS



ADDRESSING CARBON EMISSIONS

Carbon Capture and Storage

Carbon capture and storage (CCS) is a technology that captures CO₂ emissions from industrial sources or directly from the air and stores them underground to prevent release into the atmosphere. Recent breakthroughs are making CCS more efficient and scalable. Tech companies like Google and Salesforce are investing in CCS at paper mills and wastewater plants, converting CO₂ into bicarbonate for long-term ocean storage or injecting captured emissions underground. AI-driven research at Argonne National Laboratory is accelerating material discovery for CCS, generating 120,000 new metal-organic frameworks in minutes. As climate goals drive CCS adoption, these innovations are making carbon removal cheaper, more effective, and widely deployable.

Natural CSS

Natural carbon capture and storage (natural CSS) refers to processes that use biological or oceanic systems to absorb and store CO₂, differing from conventional CCS, which relies on industrial technologies for direct air capture and underground storage. Researchers are enhancing these natural methods to boost efficiency and scalability. Scientists have genetically modified algae to absorb CO₂ more effectively, doubling biofuel production while aiding wastewater treatment. Meanwhile, Equatic is building North America's first ocean-based carbon removal plant, using electrochemistry to trap CO₂ while producing green hydrogen. Captura, another startup, is piloting an electrochemical process to remove CO₂ from seawater, increasing ocean alkalinity for long-term carbon storage. Additionally, a newly discovered cyanobacteria strain, Chonkus, thrives in CO₂-rich waters, rapidly sinking to store carbon naturally. These innovations are making nature-based CCS scalable and commercially viable, aligning with global decarbonization goals.

Direct Air Capture

Direct air capture (DAC) is a technology that removes CO₂ directly from the atmosphere and stores it underground or repurposes it for industrial use. Unlike natural carbon sequestration, DAC provides a faster, scalable solution for reducing greenhouse gases. In Iceland, Climeworks has launched Mammoth, a large-scale DAC facility using 72 industrial fans powered by geothermal energy to capture CO₂ efficiently. In Wyoming, Spiritus is developing Orchard One, a "Carbon Orchard" set to sequester two megatons of CO₂ annually, aiming to cut costs below \$100 per ton through geological storage. University of California, Berkeley researchers developed covalent organic frameworks, lightweight materials designed to capture CO₂ from ambient air, with potential for large-scale deployment. At Rice University, a modular electrochemical reactor enhances direct air capture efficiency while enabling hydrogen co-production. These projects signal a shift toward industrial-scale DAC, increasing the feasibility of large-scale carbon removal as

a key climate mitigation tool. As DAC infrastructure expands, technological advancements and cost reductions will be crucial for achieving global net-zero targets.

CO₂ Storage

CO₂ storage is the process of securely trapping captured carbon dioxide in underground reservoirs, minerals, or ocean formations to prevent it from reentering the atmosphere. Unlike direct air capture, which removes CO₂ from ambient air, CO₂ storage focuses on long-term sequestration of emissions from industrial sources. In Texas, Oxy Low Carbon Ventures is leading a project to store 722,000 metric tons of CO₂ annually in underground wells, supporting Microsoft and Amazon's carbon removal goals. In Hungary, the Danube Removals Project marks the EU's first on-shore CO₂ storage initiative, using biogenic CO₂ from biofuels. Meanwhile, researchers at the University of Texas at Austin have developed a sixfold faster CO₂ storage method using hydrates, offering a chemical-free, ocean-based solution. As carbon



ADDRESSING CARBON EMISSIONS

storage expands, scalability, stability, and regulatory support will determine its role in global decarbonization efforts.

Carbon Tracking

Carbon tracking technology is evolving as businesses face rising regulatory and investor pressure to disclose and reduce emissions. MSCI's Private Company Data Connect streamlines sustainability reporting for private markets, integrating with Persefoni's carbon accounting tools to standardize emissions data. Hyundai and Kia's IGIS platform leverages blockchain and lifecycle assessment methods to track emissions across supply chains, ensuring compliance with international regulations. Workiva's new carbon solutions platform, bolstered by its Sustain.Life acquisition, automates emissions reporting and aligns data with frameworks like SEC and California climate disclosure rules. Meanwhile, Coforge ENZO, developed with Salesforce, consolidates emissions data for real-time carbon footprint tracking. As governments mandate audit-ready climate disclosures, AI-driven platforms and blockchain-se-

cured carbon tracking are becoming critical for corporate sustainability strategies.

Emission Reduction Solutions

AI-driven solutions and digital twin technology are reshaping emissions reduction strategies. IBM's Maximo Emissions Management integrates real-time monitoring with AI-powered incident tracking, optimizing sustainability in energy and transportation sectors. A Hexagon study found that digital twins reduce emissions by 15% and costs by 19%, yet only 16% of executives plan major investments, revealing an untapped opportunity. Meanwhile, AFEN, France's new carbon removal association, unites more than 30 members to advance negative emissions technologies, aligning with global carbon neutrality goals. The economic potential of carbon dioxide removal technologies exceeds a trillion dollars, driving interest in policy integration and private-sector collaboration. As AI enhances asset efficiency and digital twins provide predictive insights, companies face growing pressure to scale these innovations for both economic and environmental gains.

Reducing Digital Carbon Emissions

As data center energy demands surge, AI-driven optimization and liquid immersion cooling are cutting carbon footprints. AI models improve cooling efficiency, workload management, and dynamic resource allocation, reducing emissions from cloud computing. Refroid Technologies' liquid immersion cooling—India's first—lowers energy use by up to 40% and achieves a PUE as low as 1.05, aligning with India's growing 4 GW data center expansion. Meanwhile, structured pruning methods like MINI-LLM reduce GPU power consumption, making large AI models more energy-efficient. As hyperscale data centers expand, integrating AI, liquid cooling, and model efficiency techniques will be critical to reducing digital carbon emissions while supporting next-gen computing and sustainability mandates.

Carbon Credits

Carbon credits are tradable certificates that allow businesses to offset emissions by funding projects that remove or reduce CO₂. Google's new deal secures 100,000 tons of biochar-based carbon credits from Indian farms, highlighting biochar's role as a low-cost, scalable carbon removal solution. Meanwhile, FG Capital Advisors' 2025 Carbon Token is targeting institutional investors with nature-based projects and battery metals investments, reinforcing carbon credits as a high-value asset class. In Europe, the EU's carbon removal legislation is establishing clear methodologies for biochar, direct air capture, and Bio-CCS, aiming to standardize global markets. With corporate demand rising and new financial mechanisms emerging, carbon credits are evolving from voluntary offsets to regulated, investment-grade assets, driving climate action through market-based incentives.



ADDRESSING CARBON EMISSIONS

Carbon Verification

Carbon verification ensures the accuracy and credibility of carbon credits, unlike carbon tracking, which focuses on measuring emissions. Net Zero Co. secured \$5.5 million to develop blockchain-based carbon removal tokens, providing full traceability for sequestered CO₂. Meanwhile, Gold Standard's pilot program for digital Measurement, Reporting, and Verification (dMRV) is testing automated emissions reporting to enhance efficiency and transparency in carbon credit certification. A study in IEEE Xplore highlights game-theoretic blockchain models that improve MRV accuracy, reducing fraud and increasing compliance. With corporations and governments prioritizing verified climate action, advancements in blockchain, AI, and automation are making carbon markets more transparent and trustworthy, strengthening their role in global decarbonization efforts.



RECYCLING



RECYCLING

Recycling Product Waste

New technologies are revolutionizing the recycling of e-waste, textiles, and EV batteries, making waste recovery more efficient and scalable. Recycleye has deployed the first commercial AI-powered sorting system for electronic waste in the UK, using machine learning to identify and separate valuable components like circuit boards, metals, and batteries. Researchers at Iowa State University have developed a rare-earth metal extraction method using proteins, reducing reliance on mining for critical materials. Meanwhile, South Korean scientists have introduced an eco-friendly lithium-ion battery recycling technique that restores cathodes to full capacity without high heat or toxic chemicals. In textiles, a University of Delaware team is using a microwave-based process to break down blended fabrics, enabling better recycling of polyester and cotton. As AI and advanced chemistry optimize material recovery, waste recycling is shifting from costly, inefficient processes to high-precision, sustainable solutions.

Recycling Material Waste

Breakthroughs in recycling are transforming plastic, textiles, and industrial waste into reusable materials. University of California, San Diego researchers have developed a biodegradable thermoplastic polyurethane embedded with bacterial spores, enabling 90% degradation within five months. A UC Berkeley team has created a vaporization process that converts polyethylene and polypropylene plastics into reusable gases with 90% efficiency, supporting a circular economy. Meanwhile, University of Southern California scientists have pioneered a fungal-based method to recycle carbon fiber composites, preserving 97% of their strength for reuse in aviation and automotive industries. AI-driven textile sorting is also advancing, with a new autonomous system integrating robotics and spectral imaging to improve fiber recovery. In construction, RMIT University has strengthened concrete by 40% using waste carpet fibers, reducing early-age cracking and repurposing textile waste. These innovations are reshaping

material waste recycling, reducing landfill dependency, and creating new value chains across industries.

Recycling Hazardous Waste

New recycling technologies are redefining hazardous waste management. France is exploring a controversial plan to repurpose radioactive waste into consumer products like cutlery, pending public approval for a dedicated recycling facility. Meanwhile, AMG Critical Materials has launched New-MOX SAS to convert stored plutonium into mixed-oxide (MOX) fuel, addressing costly storage challenges while enhancing nuclear energy efficiency. MOX fuel recycling, already used in Europe and Japan, could recover 12%–22% more energy from uranium and reduce nuclear waste. These initiatives highlight a shift toward innovative waste reuse, but safety concerns and regulatory oversight remain critical to their success.



SCENARIO YEAR 2031

THE FINANCIALIZATION OF TRASH

In 2031, waste isn't just a sustainability concern—it's a trillion-dollar asset class, tracked, traded, and monetized in real-time digital waste markets. The old model of extraction and disposal has been replaced by AI-driven material circulation, where products are designed for reclamation from the start. Business leaders who once relied on raw material supply chains now invest in urban mining, smart biodegradables, and AI-powered waste arbitrage to secure competitive advantage.

Waste-backed assets (WBAs) have emerged as a dominant force in global markets, securitizing recyclable materials, carbon-negative plastics, and rare-earth metals recovered from urban mining. AI-driven waste audits, now mandated alongside financial audits, ensure that companies accurately report and offset their waste liabilities. Blockchain-secured waste verification systems prevent fraud, ensuring that every ton of traded material meets strict environmental and circular economy standards.

At the same time, AI-powered recycling infrastructure has reached unprecedented efficiency, with deep-learning models disassembling electronics at a component level to recover valuable materials with near-perfect precision. The rise of “virtual mines” has made landfills obsolete, turning e-waste into a key resource for the consumer tech industry. Meanwhile, biodegradable smart materials—embedded with bacterial spores, hydrolytic enzymes, and adaptive feedback systems—enable products to disassemble themselves when no longer needed. AI-driven carbon tracking platforms verify degradation rates in real time, ensuring compliance with increasingly strict circular economy laws.





CLIMATE CHANGE IMPACTS



CLIMATE CHANGE IMPACTS

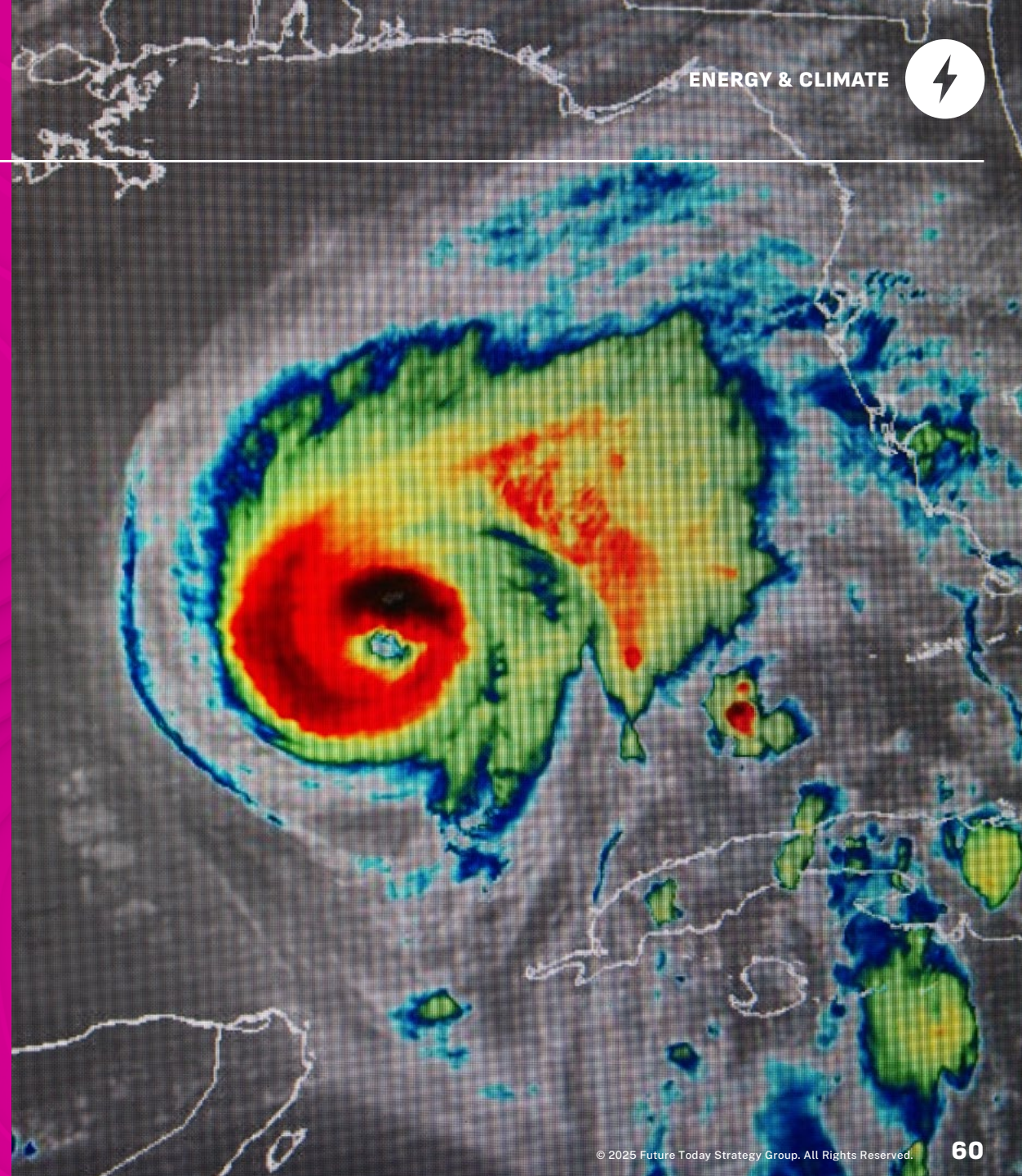
Intelligent Systems for Extreme Weather

Extreme weather events, driven by climate change, are intensifying in frequency and severity, prompting new technological solutions for disaster prediction and response. Nvidia's Earth-2 digital twin platform uses AI to simulate weather conditions, enhancing real-time forecasting for storms, flooding, and heat waves. Taiwan's Central Weather Administration is adopting Earth-2 to improve typhoon predictions, while the Weather Company integrates its APIs for global forecasting. The UN's new AI resilience initiative, led by the International Telecommunication Union and the UN Environment Programme, is developing global standards for AI-driven disaster response, addressing seismic and hydro-meteorological risks. 3D wireless networks combining terrestrial, aerial, and satellite systems are being explored for early warning systems and emergency coordination, with AI optimizing their efficiency. In New York City, drones with thermal imaging are now used in hurricane simulations to locate victims and assist first responders. As cli-

mate threats escalate, AI, digital twins, and wireless networks are shaping the future of disaster resilience.

Improving Water Security

Rising global water shortages are driving technological breakthroughs in atmospheric water harvesting and sustainable farming. Aquaria Technologies' solar-powered atmospheric water generators extract moisture from the air, producing up to 264 gallons daily with near-zero operational costs. Researchers in Singapore have developed an advanced aerogel that absorbs water at 5.5 times its weight, enabling 12 harvesting cycles per day. King Abdullah University of Science and Technology's mass transport bridge system extracts 23 liters per square meter per day, even in arid regions. Meanwhile, AirFarm's inflatable aeroponic farms reduce water use by 99%, optimizing agriculture in water-scarce areas. Osaka Metropolitan University has also improved water adsorption technology, lowering energy needs by 55%. These innovations are transforming water access,





CLIMATE CHANGE IMPACTS

reducing reliance on depleting freshwater sources, and enabling sustainable water management in drought-prone regions.

Community Resilience Interventions

As climate change intensifies, communities are developing new strategies to address its emotional, social, and physical impacts. Climate cafes, grassroots gatherings modeled after death cafes, are emerging worldwide to help individuals process climate anxiety and grief, with more than 350 facilitators trained in North America alone. In wildfire-prone regions in British Columbia, Rogers Communications has deployed AI-powered cameras, successfully detecting wildfires 16 minutes faster than existing systems. At MIT, students are turning anxiety into action through hands-on engineering projects, from hydrogen-powered vehicles to autonomous ocean research drones. Meanwhile, refugee resettlement programs are integrating AI-driven dynamic allocation systems, improving employment outcomes by up to 50% while balancing resource distribution. These initiatives

highlight how technology, innovation, and collective support networks are reshaping how communities prepare for and adapt to climate-related challenges.

Resource Scarcity Assistance

Climate change is intensifying resource shortages, prompting innovation in agriculture, water access, and emergency response. AI-driven tools like SOLACE-AI, funded by 4 million euros from Wellcome, aim to streamline decision-making in climate-related health emergencies, reducing evidence synthesis time from a year to near-instant. In agriculture, AI-powered weather forecasting is helping smallholder farmers in India cut debt and increase savings, while initiatives like AIM for Scale are expanding similar solutions across Asia, Africa, and Latin America. Meanwhile, Indian scientists are developing climate-resilient seeds to withstand rising temperatures, pests, and drought, with government support accelerating research. In Africa, the Nairobi Declaration seeks to triple fertilizer use and restore 30% of degraded farm-

land, though agroecology advocates push for bio-fertilizers over synthetic inputs. As climate pressures mount, AI, biotechnology, and regenerative farming are emerging as key solutions to global resource challenges.





ENVIRONMENTAL & ECOSYSTEM MANIPULATION



ENVIRONMENTAL & ECOSYSTEM MANIPULATION

Earth Engineering

As climate change accelerates ecosystem degradation, advanced restoration technologies are emerging to rebuild forests, coastlines, and wetlands. Continental and Land Life have developed an autonomous tree-seeding robot capable of planting one tree per minute, addressing deforestation in inaccessible terrains. In Canada, Flash Forest is deploying UAVs (unmanned aerial vehicles) to rapidly distribute seed pods in wildfire-damaged areas, using microbial enhancements to boost germination rates. Coastal restoration efforts are also advancing, with an environmental group repurposing recycled oyster shells to stabilize sinking shorelines. Meanwhile, WWF's ManglarIA initiative is integrating AI, drones, and sensors to monitor and protect mangroves, crucial for carbon sequestration and storm protection. These innovations highlight a shift toward automated, AI-driven, and nature-based interventions to restore ecosystems at scale, mitigating climate impacts while enhancing biodiversity.

Atmospheric Climate Engineering

As climate risks escalate, engineered interventions in the atmosphere are being explored to cool the planet and mitigate extreme weather. Marine cloud brightening could reduce summer heat exposure in the Western US by 55%, but its effectiveness may decline due to ocean circulation shifts. Stratospheric aerosol injection strategies show varying cooling efficiencies based on injection latitude, with subtropical releases yielding the highest impact. A proposed method for intentional stratospheric dehydration could reduce water vapor in the upper atmosphere, enhancing radiative cooling. AI-driven simulations like Andrew Ng's Planet Parasol are enabling public exploration of solar geoengineering's risks and trade-offs. Meanwhile, autonomous solar-powered catamarans are being tested to spray seawater into the atmosphere, enhancing cloud reflectivity. As these geoengineering methods advance, researchers warn of unpredictable regional impacts, underscoring the need for robust modeling and global oversight.

Water Infrastructure Engineering

As climate change intensifies coastal threats and freshwater scarcity, new engineering solutions are transforming water management. In Boston Harbor, North America's first living seawalls mimic natural habitats, enhancing biodiversity while strengthening flood resilience. MIT's architected reefs dissipate 95% of incoming wave energy, protecting shorelines from erosion. Hybrid dunes in the Netherlands combine engineered dykes with natural sand formations to mitigate storm damage. Meanwhile, desalination technology is advancing, with a solar-powered hydrogel boosting seawater evaporation rates by 18.8%, offering a low-energy solution for freshwater production. AI-driven drought prediction models are also improving accuracy, aiding policymakers in proactive water resource management. These innovations mark a shift toward nature-integrated and AI-enhanced approaches, ensuring long-term resilience against rising sea levels and water scarcity.





SCENARIO YEAR 2045

THE OCEAN TERRAFORMING WARS

In 2045, climate collapse is no longer a distant threat—it's here. The solution? Terraforming the oceans. Some nations are turning the seas into massive carbon sinks with engineered algae blooms, electrochemical CO₂ extraction, and deep-sea energy farms. Others call it a reckless gamble, fearing ecological disaster. The world is now divided, and the stakes couldn't be higher.

China and the EU lead the charge. China's genetically engineered coral reefs and deep-sea carbon vaults stretch across the South China Sea, while Europe's "Carbon Oceans"—floating CO₂ capture platforms—dot the Atlantic. Germany and Norway have merged geoengineering with offshore wind and geothermal grids, making climate control a trillion-dollar industry.

But nature isn't cooperating. Massive algae blooms are warping food chains, oxygen-depleted "dead zones" are spreading, and once-thriving fisheries in West Africa and South America have collapsed. Climate refugees flood into nations that had no say in these experiments.

Meanwhile, the Pacific Rim refuses to play along. Japan, Australia, and Indonesia have outright banned ocean terraforming, calling it "climate imperialism." They warn that tampering with the seas could trigger hyper-hurricanes, acidification, or worse. The US, after years on the sidelines, is jumping in—but in true American fashion, corporations, not governments, are running the show. Amazon Blue and Exxon-Terraform dominate the market, selling carbon credits while reshaping entire ecosystems.

Now, the world teeters on the edge. Terraforming supporters say it's the only way to save the planet. Opponents warn we're engineering our own destruction. The question is no longer should we control the oceans—but can we?





ENVIRONMENTAL & ECOSYSTEM MANIPULATION

Engineered Plant Ecosystems

As climate change disrupts ecosystems, scientists are enhancing plant resilience, optimizing crop yields, and accelerating ecological restoration. University of California, Riverside researchers have implanted a marine algae gene into land plants, enabling them to absorb a broader light spectrum for increased productivity. AI-driven autonomous seaweed farms are optimizing carbon capture and biofuel potential. In Maine, hemp is being tested for phytoremediation, absorbing toxic PFAS chemicals from contaminated soil. At the Center for Advanced Bioenergy and Bioproducts Innovation, researchers have genetically modified bioenergy crops like sorghum and sugarcane to use 10%–20% less water without reducing yield. Drone-monitored silvopasture systems are integrating trees with grazing land for more sustainable agriculture. These advancements highlight a future where plant ecosystems are strategically engineered to support food security, environmental clean-up, and climate adaptation.

Engineered Animal Ecosystems

Scientists are leveraging genetics, robotics, and AI to enhance animal resilience and ecosystem stability in response to climate change. Assisted sexual propagation in corals has increased thermal tolerance, with lab-grown recruits showing significantly lower bleaching rates during the 2023 Caribbean heat wave. In agriculture, Canadian researchers are breeding low-methane cattle to cut emissions, integrating genetic selection with carbon credit incentives. AI-powered bee monitoring is optimizing pollinator conservation, using real-time object recognition to track colony health. Meanwhile, autonomous underwater robots are revolutionizing aquaculture by detecting biofouling and net damage, reducing labor costs and improving fish farm efficiency. These innovations highlight how engineered animal ecosystems are becoming critical tools for biodiversity conservation, sustainable food production, and climate adaptation.





URBAN INTERVENTIONS



URBAN INTERVENTIONS

Hybrid Urban Systems

Cities are integrating floating infrastructure, climate-adaptive transit, and resource-efficient developments to enhance resilience and sustainability. Seoul's Great Han River Project will introduce floating offices, hotels, and food zones by 2030, with marina expansions and river transit to support economic growth and leisure. In New York, the Climate Resilience Roadmap dedicates \$6 billion to elevating transit infrastructure, installing flood defenses, and strengthening drainage systems to withstand extreme storms. Microsoft is launching zero-water AI data centers, eliminating more than 125 million liters of water use annually. In England, new town proposals emphasize walkability, green infrastructure, and car-free accessibility to lower emissions. These projects showcase a shift toward hybrid urban systems that merge climate adaptation with economic and environmental priorities.

Cooling & Green Infrastructure

Cities are deploying AI, ecological modeling, and green infrastructure to mitigate rising urban temperatures and enhance climate resilience. MIT, Google, and Purdue University's Tree-D Fusion technology uses AI-generated 3D tree models to optimize urban tree placement, predicting growth patterns and maximizing cooling effects. The system maps 600,000 urban trees, helping address environmental equity by guiding tree canopy distribution. Meanwhile, the Wayqecha Amazon Cloud Curtain Experiment explores how fog water supports ecosystems, providing insights into nature-based cooling strategies. By integrating AI-driven forestry management and climate-responsive ecological interventions, urban planners are creating smarter, greener cities that adapt to extreme heat while improving environmental sustainability.

Water Resilience & Flood Management

Cities are deploying AI, sensor networks, and nature-based solutions to manage stormwater and reduce flood risks in the face of climate change. Shanghai is expanding its sponge city initiative, aiming for 80% urban rainwater absorption by 2030 through green infrastructure, drainage upgrades, and digital monitoring. Meanwhile, AI-powered neural networks are improving flood prediction in sponge city systems, optimizing drainage performance and flood mitigation strategies. In India, researchers are developing an Arduino-based flood management system that uses real-time rainfall and soil moisture data to control reservoir gates and prevent downstream flooding. These innovations highlight a shift toward proactive, data-driven flood resilience strategies that blend smart infrastructure with ecological solutions.





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