



Emerging Energy Generation & Storage Strategy Pathways

White Paper

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Introduction

Electricity Supply and Demand

Electricity is the lifeblood of the modern society. Most of the world's population is heavily dependent upon electricity as an energy source. Electric demand is growing rapidly, driven by accelerated electrification in the form of electric vehicles, transportation electrification, heat pumps, and other technologies, as well as surging data center and AI electric demand, especially with wide AI adoption. The International Energy Agency recently forecast that electricity “demand is set to rise 3.3% in 2025 and 3.7% in 2026 – more than twice as fast as total energy demand growth over the same period.”¹

Faced with unprecedented demand growth, new generation addition is not keeping up the pace. At the same time, traditional thermal generation, especially coal-fired plants, are increasingly being retired due to environmental regulations and economic viability

Currently, electricity is generated primarily from thermal generation (such as natural gas, coal, and oil), traditional nuclear generation, hydroelectric generation, wind energy, and solar energy. The power and energy industry is working on accelerating the integration of renewable energy sources and the development of emerging renewable generation technologies, such as geothermal energy, biomass, ocean energy, hydrogen, Small modular reactors (SMR) and space-based solar power, etc. Each form of generation technology holds unique potential to shape energy landscape.

Energy storage plays a vital role in enabling a sustainable future, facilitating seamless integration of renewable energy and transportation electrification. Energy storage is critical to ensuring grid reliability and resilience. Current storage technologies used in the power industry includes pumped storage hydro, battery storage, flywheels, and thermal storage. The industry is working on removing barriers for energy storage integration, as well as advancing storage technologies, such as increasing duration, reducing cost, increasing energy density, reducing weight, developing new method to charge, and creating new battery technologies for large- and small-scale applications.

The Alternative Energy Generation and Storage Initiative

IEEE Future Directions initiatives seek to identify and advance emerging technologies by creating forums for experts to collaborate on new areas. The Alternative Energy Generation and Storage initiative seeks to expand coverage of these areas, supplementing existing content and activities to raise the profile of these technologies and help reduce the imbalance between the soaring demand and struggling power generation supply.

¹ <https://www.iea.org/news/global-electricity-demand-to-keep-growing-robustly-through-2026-despite-economic-headwinds>

This initiative joins forces at IEEE level, promotes and supports emerging energy generation and storage technologies to meet the energy needs of terrestrial, ocean and space usages, and supports a sustainable energy future.

Approved in the first half of 2025, the initiative conducted a strategy workshop in July 2025, at the IEEE Power and Energy Society General Meeting. This document covers the workshop's output and provides a guide to the initiative's actions and technology focus.

Initiative Activities

Workshop participants reviewed the initiative's planned activities and provided feedback on these and other potential activities. Most suggestions fell within broad themes in the initiative's core plan, including a series of workshops, roadmap enhancements, and special issues in existing publications, all focused on the set of technologies included in the initiative's scope. Some suggestions were in new areas, or expanded the plans in areas in the initiative's proposal, such as educational content. This section summarizes the planned activities from the strategy workshop.

Workshops and Events

The initiative envisioned a series of workshops to bring speakers relevant to the focus technology areas into existing conferences and, where possible, share their content. The strategy workshop participants approved this plan and suggested a number of related additional activities, including:

- Panel sessions at upcoming conferences focused on initiative topics, including:
 - Pros/Cons of various energy generation technologies.
 - Storage options.
 - Energy Distribution.
- A periodic webinar series, potentially (bi-)monthly, covering a variety of relevant topics such as:
 - Storage: short- & long-term solutions, challenges, application- and environment-specific solutions. Synergy between generation and storage.
 - Ocean energy generation.
 - Integration of different generation technologies.
 - Space-based power technologies.
 - Reliability considerations in alternative energy generation & storage.
 - Abilene Christian University / Natura Small Modular Reactor webinar.²
 - An overview webinar framing the need and introducing the topic.
- Sponsor and/or attend the IEEE Cleantech summit³ for networking and volunteer recruiting.
- Join the IEEE Online Forum For Climate Change⁴ with initiative topics to leverage its audience and infrastructure.
- Organize panel sessions at UN and other external organizations. For example, conduct webinars for the Science Summit.⁵

² <https://acu.edu/2025/01/28/acu-partners-with-texas-tech-natura-to-advance-cutting-edge-technology/>

³ <https://techsummit.ieee.org/cleantech-2025/>

⁴ <https://ieee-ofcct.org/>

⁵ <https://sciencesummitnyc.org/>

Roadmap Updates

The initiative intends to work with existing roadmaps, primarily in the Power and Energy Society, to expand coverage of the focus technologies. Workshop participants widely supported this plan.

Publications

A core deliverable in its initial proposal, workshop participants were very supportive of adding special issues in existing publications to highlight focus technologies. Some IEEE areas they suggested for additional content included:

- IEEE Power and Energy Society.
- IEEE Reliability Society.
- IEEE Oceanic Engineering Society.
- IEEE Industry Applications Society

Workshop participants suggest a variety of other types of publications that the initiative plans to consider, including:

- Create overview white papers and articles.
- Create a case study on Alaska's micro-grids and unique challenges in partnership with the IEEE SusTech Initiative.
- Consider creating a multi-society journal if there is sufficient content.
- Use GenAI leading questions for topics and activities going on now and collate them into a knowledge base / presentation / publication.

Educational Content and Student Engagement

Mentioned among other deliverables in the initiative proposal, workshop participants suggested expanding educational content and student engagement to include several new activities:

- Produce educational content in partnership with IEEE Educational Activities and other IEEE societies, councils, regions, and initiatives.
- Create award / certificate programs related to the focus educational content.
- Hold student design competitions.
- Partner with existing conferences to have students show what they've done in relevant areas.
- Create new mentorship programs to energize young people and leveraging more senior people.

Partnerships

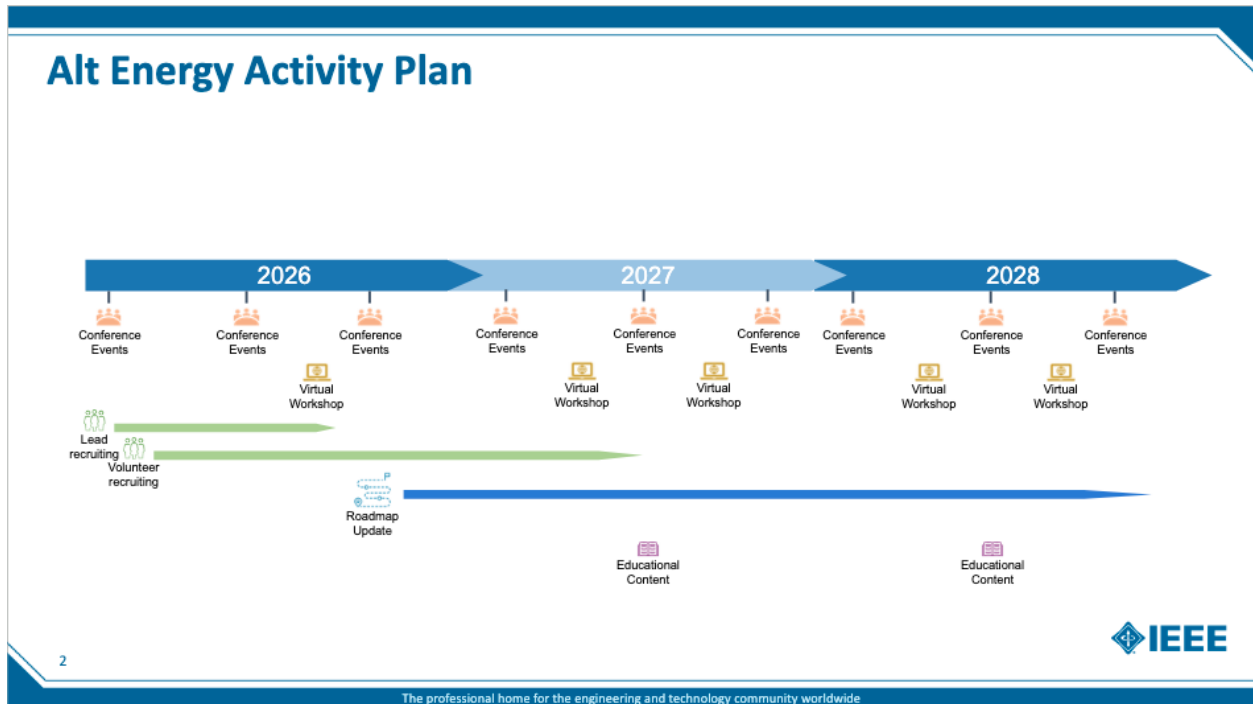
The initiative is already supported by the IEEE Power and Energy Society,

- Collaboration with a variety of technical societies, committees and standardization organizations, including several outside IEEE

- UN International Day of Clean Energy presentation
 - EU forums for collaboration
- Evaluate the various challenges already in place and consider adapting or launching a new one

Initial Work Plans

The above activities are incorporated into the initial work plan summarized below.



Volunteer Support

The Alternative Energy Generation and Storage Initiative needs volunteers to deliver its planned activities. There are opportunities for both functional work and leadership roles. Interested personnel should send an e-mail to aegs@ieee.org expressing the area(s) in which they are most willing and able to contribute.

Technology Focus

Mainstream power generation and even some forms of alternative energy generation such as terrestrial solar and wind power are covered well in existing IEEE publications and conferences. The Alternative Energy Generation and Storage initiative seeks to raise the profile of emerging and less-discussed technologies that have potential to meet the surging electricity demand. In some cases, this will be emerging technologies at lower levels of technology readiness. In other cases, more established technologies that are still not widely adopted may be addressed. This section lists many of the technologies on which the initiative will focus.

Renewable Baseload Energy Generation

Renewable energy sources may be continuously reliable, or “baseload power”, compared to other renewable sources such as solar and wind power that are intermittent and that cannot be always relied upon for continuous power generation. There are several baseload renewable energy sources that could be further developed to enhance energy supply.

Hydropower

Hydropower is a renewable energy source that generates electricity by harnessing the kinetic and potential energy of moving water, usually through dams, rivers, or diversion structures. It is one of the oldest and most widely used forms of renewable energy worldwide. This form of energy production is reliable and able to provide large-scale power.

Geothermal Energy

Geothermal energy production harnesses heat from beneath the Earth’s surface to generate electricity and provide direct heating. It taps into naturally occurring reservoirs of heat in the form of hot water, steam, and hot, dry rock. This makes it a clean and renewable source of power.

Enhanced Geothermal Systems (EGS)

A variant of geothermal energy, Enhanced Geothermal Systems use hydraulic stimulation to access geothermal heat in dry rock formations. This helps to expand geothermal viability beyond natural hotspots.

Biomass Energy

Biomass energy production is the process of converting organic materials—such as plants, agricultural residues, wood, and waste—into usable energy in the form of heat, electricity, or fuels. It taps into the chemical energy stored in biomass through photosynthesis.

This type of energy generation can use waste products to deliver energy and may be carbon-neutral if managed sustainably.

Marine Algae Bioenergy

Marine Algae Bioenergy is a variant of biomass energy production that uses algae grown in seawater to produce biofuels. Advantages include high yield and an ability to produce fuels without competing with food crops.

Artificial Photosynthesis

While not strictly a form of biomass energy, artificial photosynthesis is a technology that can be used to create biofuels similar to biomass fuels. This technology mimics natural photosynthesis to produce fuels from sunlight and water. As such, it has potential for carbon-neutral fuel production.

Renewable Intermittent Energy Generation

Intermittent renewable energy sources include sources that generate electricity in an inconsistent and variable way, such as solar power that cannot produce power at night and that produces variable output during the day based on weather conditions affecting the amount of sunlight the panels receive. These technologies represent challenges to grid stability and are most effective when coupled with battery storage solutions.

Ocean Energy

Ocean energy production (also called marine energy) is the process of generating electricity from the natural movement and properties of ocean water, including waves, tides, currents, temperature differences, and salinity gradients. It is a renewable energy source with vast potential, though most technologies are still in development.

Nuclear Power

Traditional nuclear power is an established energy source that the World Nuclear Association estimates 9% of power generation worldwide in 2025.⁶ While spent nuclear fuel represents a complex problem, nuclear power sources are considered “clean” energy generation because it produces very low greenhouse gas emissions during operation. In addition to widely established nuclear power plants, there are emerging and potentially new types of nuclear power with potential to greatly enhance energy production and distribution.

Small Modular Reactors

Small Modular Reactors (SMRs) are advanced nuclear fission reactors designed to be factory-built and transported as prefabricated modules. Their compact size and modular construction make them more flexible, safer, and potentially cheaper than traditional large-scale nuclear plants

⁶ <https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today>

Fusion Reactors

Fusion power is the process of generating energy by fusing light atomic nuclei (like hydrogen isotopes) into heavier ones, releasing enormous amounts of energy in the process. It's the same reaction that powers the Sun and stars, and scientists have been working for decades to replicate it on Earth as a practical energy source. While still futuristic, this technology promises low-carbon, high-output, and potentially safer energy production than traditional nuclear power.

Space-Based Power

Space-based power generation (SBSP) is the concept of collecting or generating energy in space and transmitting it wirelessly to Earth. It's an ambitious idea that could provide continuous, clean electricity without the limitations of weather, seasons, or nighttime.

Space-Based Solar Power (SBSP)

The most common concept for space-based power generation is space-based solar power. This form of energy generation relies on large solar arrays in orbit to collect sunlight and convert it into electricity, which is then transmitted wirelessly to Earth. Transmission to earth could be in the form of microwave or laser beaming. Potential advantages include continuous power generation unaffected by weather or night cycles that limit terrestrial solar power generation, and high solar intensity in space. This form of energy production also has significant challenges, including:

- High launch and assembly costs.
- Large ground receiving stations required.
- Safety and efficiency of wireless power transmission.

Modular Solar Power Satellites

A variant of space-based solar power, modular solar power satellites rely on smaller satellites working in a network to collect solar energy and beam it to Earth using infrared lasers or microwaves. This is potentially easier to deploy incrementally and maintain compared to one massive platform.

Reflector-Based Systems

Reflector-based systems rely on large mirrors in orbit to redirect sunlight to terrestrial solar farms at night or during cloudy conditions, boosting ground-based solar efficiency without direct energy transmission. This offers a solution that is simpler and potentially more cost-effective than solar-based power transmission.

Energy Storage Technologies

Energy storage technologies capture energy for later use, helping balance supply and demand, stabilize grids, and integrate renewable sources like solar and wind. They are essential for modern energy systems aiming for reliability and sustainability.

Emerging Battery Technologies

Lithium-ion batteries are a well-established solution widely used in electric vehicles and consumer devices. It is also by far the most used technology for new grid battery installations worldwide. There are, however, several battery storage technologies that aim to improve energy density, safety, cost, and sustainability compared to today's lithium-ion systems.

Solid-State Batteries

Solid-state batteries replace liquid electrolytes with solid materials for higher energy density and improved safety. Potential benefits include a longer lifespan, reduced fire risk.

Lithium-Sulfur Batteries

Lithium-sulfur batteries offer higher energy density than lithium-ion and may include life cycle improvements. Potential advantages include light weight and cost-effectiveness for large-scale storage.

Flow Batteries

Flow batteries are a type of rechargeable energy storage system that stores energy in liquid electrolytes contained in external tanks. Unlike conventional batteries (like lithium-ion), where energy is stored in solid electrodes, flow batteries separate the power-generating components from the energy-storing components, making them highly flexible and scalable. Not yet widely adopted, flow batteries offer many potential advantages over Li-ion batteries, including long-duration storage, scalability, long cycle lifetimes, low environmental impact, and flexible operation.

Organic Flow Batteries

A subset of flow batteries, Organic flow batteries differ from conventional flow batteries by using carbon-based (organic) molecules instead of metals like vanadium or zinc in their electrolytes. This makes them more sustainable, potentially cheaper, and environmentally friendlier, while still offering the long-duration storage benefits of flow battery systems.

Non-battery Electrical Storage Systems

Supercapacitors

Supercapacitors (also called ultracapacitors or electrochemical capacitors) are energy storage devices that store electricity through electrostatic and electrochemical processes. They are not batteries, but they bridge the gap between traditional capacitors and rechargeable batteries by offering very high-power density, rapid charge/discharge, and long cycle life.

Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy systems store energy in the magnetic field created by a superconducting coil. While there are engineering challenges associated with current superconducting materials, these systems offer extremely fast response times and high efficiency.

Mechanical, Thermal, and Other Energy Storage Systems

While batteries and electrical storage systems rely on electrochemical or electromagnetic processes, mechanical, thermal, *and other energy storage* systems use physical or heat-based forms of energy storage. Hydro storage, particularly pumped hydro storage (PHS), is a form of mechanical storage that is one of the most widely adopted large-scale energy storage technologies in the world. In addition to this type of storage, there are many other forms that are emerging or not widely adopted.

Gravity-Based Energy Storage

Gravity-based energy storage (GBES) is a mechanical energy storage technology that uses the principle of potential energy: lifting a heavy mass when excess electricity is available and then lowering it to generate electricity when demand is high. It's conceptually similar to pumped hydro storage, but instead of water, it relies on solid weights. It offers long lifespans, low environmental impact, scalability, safety, and other benefits.

Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) is a large-scale energy storage technology that stores electricity by compressing air into underground caverns or tanks, then releasing it later to generate power. It is one of the most promising alternatives to batteries and pumped hydro for balancing renewable energy supply and demand.

Liquid CO₂ Energy Storage

Liquid CO₂ Energy Storage (LCES) is an emerging energy storage technology that uses carbon dioxide as the working fluid, storing energy by liquefying CO₂ under pressure and releasing it later to generate electricity. It is being researched as an alternative to batteries and compressed air storage, with potential for large-scale, long-duration applications.

Molten Salt Storage

Molten Salt Storage is a thermal energy storage technology that stores heat in large tanks of molten salt, which can later be used to generate electricity or provide industrial heat. It is most commonly paired with concentrated solar power (CSP) plants but can also serve as a long-duration storage solution for other energy systems.

Sand-Based Thermal Storage

Sand-based thermal storage is a long-duration energy storage technology that uses heated sand as the storage medium. It captures excess electricity (often from renewables) by converting it into

heat, stores that heat in insulated sand silos, and later releases it for district heating, industrial processes, or electricity generation

Hydrogen Energy Storage

Hydrogen energy storage is a method of storing energy by converting electricity into hydrogen gas, which can later be used to generate electricity, heat, or fuel. It is considered one of the most promising long-duration and large-scale storage technologies because hydrogen can be stored for weeks or months and transported over long distances.

Energy Distribution

While not in the original initiative proposal, energy distribution is a key factor that ensures supply is available wherever there is demand. Some emerging technologies in this area were also suggested explicitly by workshop participants as areas to include in the initiative.

Wireless power grids

A wireless power grid is a system that transmits electricity over long distances without physical wires, using electromagnetic waves or beams to deliver power safely and efficiently. Instead of relying on traditional transmission lines, it uses wireless power transfer (WPT) technologies to move energy from generation sources to consumers. Advantages include the ability to deliver electricity into remote regions and elimination of the cost for extensive wiring and poles.

Micro-grids

Microgrids are localized energy systems that can operate independently or in conjunction with the main power grid. They integrate distributed energy resources (like solar panels, wind turbines, batteries, or small generators) with local loads (homes, businesses, or institutions) to provide reliable, resilient, and often cleaner power. The related concept of “Islanding” refers to the operation of a portion of the electrical grid when the main grid is disconnected or unavailable. Both cases represent methods to use energy generation and storage in ways that increase resilience and power availability.

Ultra high voltage power lines

Ultra high voltage (UHV) power lines are transmission lines that carry electricity at extremely high voltages — typically above 800 kilovolts (kV) — to move large amounts of power efficiently over long distances. They are part of the backbone of modern electrical grids, enabling renewable energy from remote areas to reach cities and industrial centers. While part of existing energy distribution systems, adoption of power lines varies substantially among different countries.



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