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Six Solutions to Battery Mineral Challenges

Copper Crisis: Inequality and Conflict Put Global Decarbonization at Risk

Deserts, Water and Lithium: Indigenous Rights in the Energy Transition

When Communities Oppose Large Solar and Wind Installations

Generating Virtually Unlimited Solar Power Year-Round

By Maurice White

We all know that one of the major ways to fight climate change is to replace utility-scale power generation using fossil fuels with solar power. Wind and photovoltaics are cost-competitive, but their intermittent nature and the high cost of energy storage are major limitations. Concentrated solar power (CSP) has more than six GW of partially dispatchable solar power installed,[1] but it is not yet cost-effective.

I have been working on a new CSP approach that can provide fully dispatchable baseload power year-round. This article introduces a novel Stirling Innovations, LLC CSP Stirling power generator. It is integrated with low-cost phase-change salt thermal-energy storage to create a comprehensive system.[2] This system is maintenance-free.

The Difference Between This Technology and Similar Systems

The Stirling Innovations CSP system is far simpler than existing CSP. The schematic comparison between a typical central-receiver system and this central-receiver system makes that abundantly clear. Both have heliostat mirrors focused on a tower receiver with a heat transfer fluid that transports the heat to ground-based thermal-energy storage, which then drives the generator. The similarity ends there.

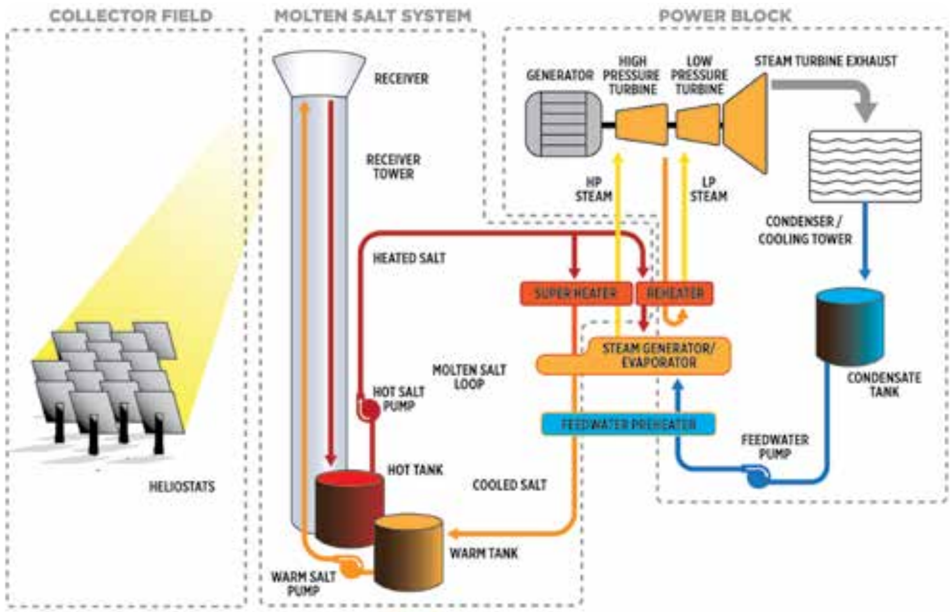


Figure 1. This schematic shows a typical central-receiver CSP plant operating with molten-salt thermal-energy storage.

The two key elements of this CSP system are delta Stirling engines and GREAT™ (GReen Energy at All Times) phase-change salt thermal-energy storage. These subsystems are hermetically sealed independently and when integrated, so no maintenance is needed or possible. Operating data from closely related components supports the expectation that they will operate for decades with high reliability and no degradation.

How a Typical Central-Receiver Power-Generation System Works

In the typical system schematic (Figure 1), salt from the warm salt tank is pumped to the receiver, where it is heated and transported to the hot tank. Hot salt is pumped to the superheater, reheater and steam generator before returning to the warm tank. High-pressure superheated steam drives the high-pressure turbine wheel. From there, it is reheated to drive the low-pressure turbine wheel and exits to the condenser.

Water from the condensate tank is pumped through the preheater to the steam generator, where it converts to high-pressure steam to drive the two turbine wheels. The exiting steam is condensed in the condenser and flows back to the condensate tank. A separate water loop is vaporized in the condenser and dumped into the air to condense the steam from the turbine.

The heliostat field is sized to deliver more heat than needed to operate the turbine generator, so more hot salt is pumped into the hot tank during the day than is pumped out. That excess is sized to provide the desired operating time after sundown. The hot tank typically ends the day full and the warm tank begins the day full.

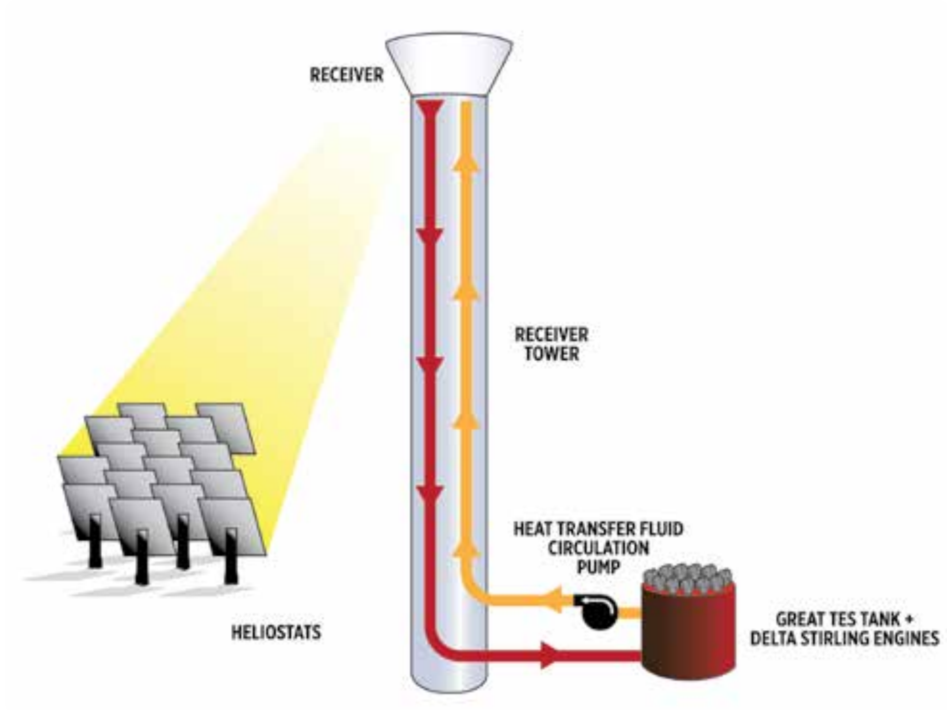


Figure 2. This schematic shows a Stirling Innovations central-receiver CSP plant operating with phase-change salt thermal-energy storage.

How the Stirling Innovations System Works

For the comparable Stirling Innovations system in Figure 2, the heat transfer fluid heats the salt in the tank and is pumped back to the receiver. All the additional functions described for the typical system are passively completed within the tank/engine system. The salt is melted during the day by the excess mirror area and operates the engines all night as it freezes.

The heat transfer fluid can be the state-of-the-art molten-salt loop used for existing central-receiver systems. The preferred approach is a two-phase pumped-loop liquid-metal heat-transport system. A liquid metal such as sodium is vaporized in the receiver to fill an insulated duct and condenses on the tank exterior to heat the salt. The liquid sodium is then pumped back to the receiver through a smaller liquid conduit.

The History of the Stirling Engine

The Stirling engine was invented in 1816 by Robert Stirling. Externally heated Stirling engines can use any heat source: liquid, gaseous or solid fuels; solar power; nuclear power; etc. The inventor John Ericsson spent the last decades of his life in an obsessive quest to perfect solar-dish Stirling engines, building several operating prototypes.[3]

Stirling engines were greatly improved beginning in the 1940s by Philips, using modern materials and engineering. In 1962, a free-piston Stirling version was conceived. Unlike kinematic engines that mechanically connect the pistons to an oil lubricated crankshaft, free-piston Stirling engines with no rubbing parts can provide extremely long life and high reliability.

Significant efforts to develop modern dish Stirling systems were documented in a 1994 comprehensive overview of seven complete systems and 19 critical component developments.[4] Two 1.5-MW dish Stirling projects were installed by Stirling Energy Systems in Arizona using 60 25-kW kinematic Stirling dish systems in 2010 and by Infinia in Utah using 429 3.5-kW free-piston Stirling dish systems in 2013.

Infinia assets were acquired by Qnergy from Israel, which has very successfully transitioned the Infinia solar engine technology and production line in Ogden, Utah to the manufacture of fuel-fired free-piston Stirling engines for harsh remote-power applications.[5]

The dish Stirling efforts showed they cannot directly compete with PV. As with other CSP, their value-add is to provide dispatchable power using thermal-energy storage. Using two of our technology advancements introduced in this article, a grand vision to provide virtually unlimited cost-competitive baseload solar power year-round becomes a feasible objective.

How Stirling Engines Work

Traditional Stirling engines use three basic configurations: alpha, beta and

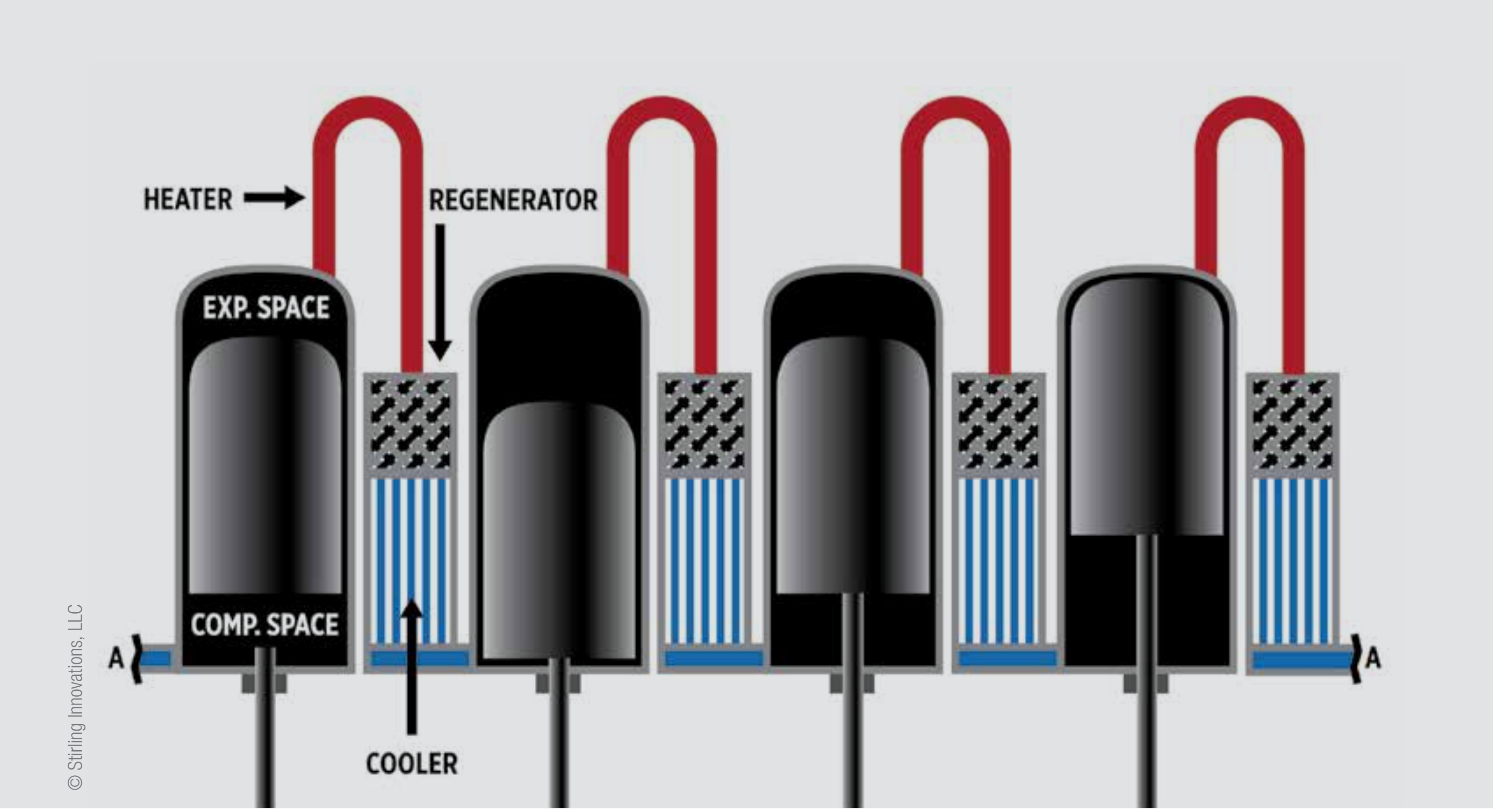


Figure 3. This schematic shows a generic four-cylinder double-acting alpha Stirling engine with heat exchangers identified.

gamma. Alpha engines use multiple power pistons while beta and gamma engines use a displacer piston and a power piston. The displacer piston shuttles working gas back and forth through heat exchangers. Kinematic Stirling engines establish piston and displacer motions using crankshafts and mechanical linkages. They can use all three configurations.

Free-piston Stirling engines were limited to beta and gamma configurations until the 2006 invention of double-acting alpha (DAA) versions.[6] The generic four-cylinder DAA engine schematic in Figure 3 is kinematic if the four piston rods are connected to a crankshaft and is a DAA free-piston Stirling engine if each rod is connected to an independent linear alternator.

All DAA Stirling engines before the delta configuration use these parallel piston axes with hot ends close together. The fine wire mesh regenerator absorbs heat when the working gas moves through it from hot to cold, then returns about 99% of that heat to the gas as it flows back a half cycle later. The regenerator is a key element of the engineer and clergyman Robert Stirling's initial invention.

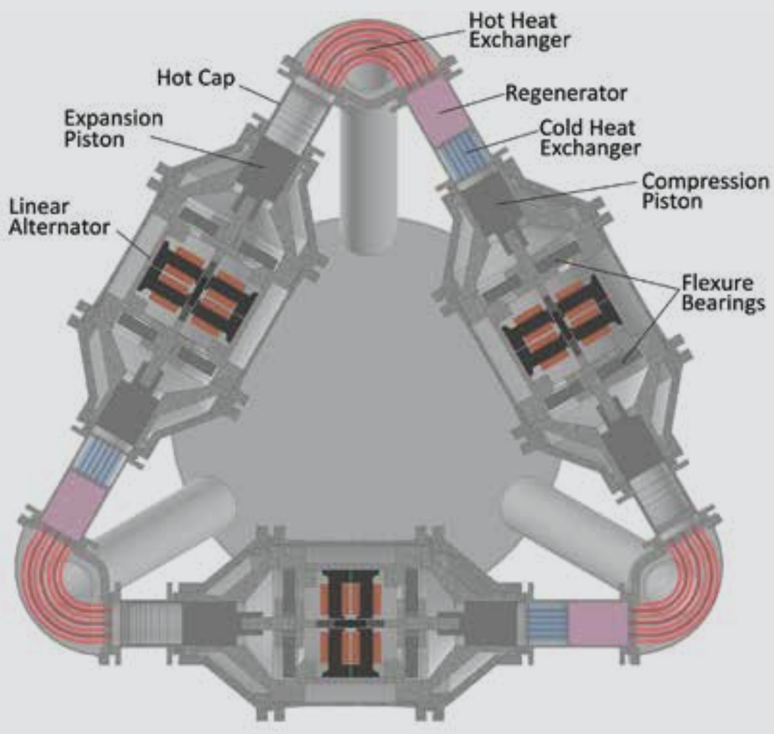
This configuration of heat exchangers results in significant flow losses and thermal losses where the heat exchangers connect to the hot and cold ends of the pistons. Rod seals are also problematic. Leakage past the pistons with clearance or rubbing seals is driven by large instantaneous pressure differences. Delta engines change that.

How a Delta Stirling Engine Works

A delta Stirling engine with piston axes in a unique equilateral triangle layout is illustrated in Figure 4. Minor issues with this configuration are that heater heads are separated and the design is not compact. Major advantages include optimally symmetric piston/heat exchanger configurations, no rod seals, and lower piston-pressure drops. These simplify the engine and improve efficiency.

Figure 4 shows a piston with a clearance seal on each end of each linear-alternator moving-magnet assembly, which is supported by flexure bearings. This configuration is identical to the production-line approach used by Infinia/Qnergy for over a thousand commercial free-piston engines, except for there being a piston on each end of the alternator instead of one end.

This basic delta Stirling configuration enables the simplest design, lightest weight, lowest cost and highest efficiency possible for Stirling machines. Several Stirling experts who have seen the delta configuration concur with this perspective. The major efficiency improvements were confirmed by Barry Penswick, a master practitioner of the



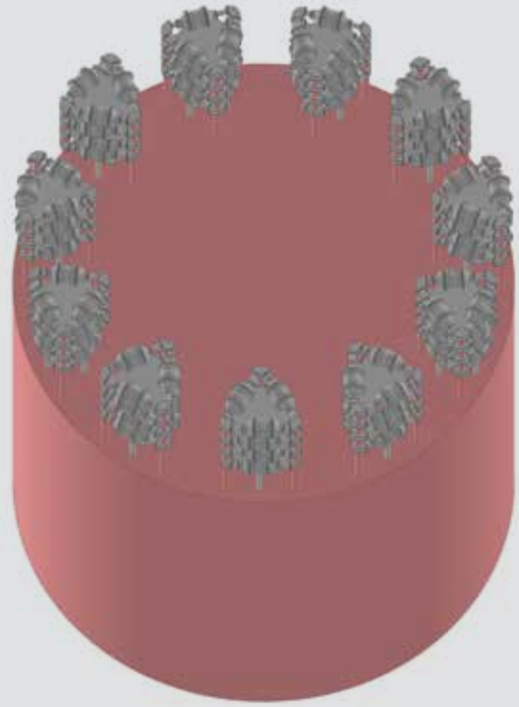


Figure 4. This diagram shows a delta Stirling engine cross-section and its components.

Figure 5. This diagram shows a 1-MW GREAT thermal-energy storage tank with delta Stirling generators and 12 hours of storage.

gold standard Sage design analysis code for Stirling engines.

A shroud around the heater contains sodium vapor that condenses on the heater tubes to provide engine heat input with uniform temperature. This avoids heater-head hot spots that were a major problem with earlier directly heated solar and flame-fired Stirling engines. GREAT thermal-energy storage inherently provides the sodium vapor to the welded-in engine-heater shroud.

Delta Stirling engines are simpler and more robust than Infinia/Qnergy free-piston engines, including ones for National Aeronautics and Space Administration (NASA) deep-space missions requiring up to 20 years of continuous operation with extreme reliability. Three Infinia space power engines continue operating flawlessly after more than 16 years at NASA Glenn Research Center. This shows their uniquely long life, zero maintenance and degradation, and high reliability characteristics.

How the GREAT Thermal-Energy Storage System Works

An analogy to phase-change vs. molten-salt energy storage is the familiar water/ice system. Heat removed from water creates ice. As that heat is returned to the ice, it melts. This energy storage process all occurs at 32˚F and stores the same amount of energy as it would take to heat water from 32˚F to 176˚F.

Similar salt properties enable one GREAT thermal-energy storage tank to replace two larger molten-salt tanks. Solid salt is about 30% more dense than the liquid, so it sinks to the bottom. Sodium is less dense than liquid salt, so it floats on the liquid-salt surface. At the sodium/salt interface, the salt solidifies, and the sodium vaporizes to fill the insulated vapor space above the thin sodium layer.

A 3-kW free-piston engine has proven itself to work well when welded into a GREAT thermal-energy storage container. The engine-heater head extracts heat, making it the coolest part, so the sodium condenses there to function as the engine heat source. The condensed liquid returns by gravity to the sodium pool.

One issue was that a crystalline salt layer can form on the liquid salt surface and attach to the wall during cooldown. That isolates the remaining molten salt below that level from the sodium layer. That issue was eliminated by trace heating to maintain the tank above the salt melt temperature in the region that can have a liquid salt surface during the heat-extraction mode.

One small phase-change salt thermal-energy storage module operated for seven years with no issues before being retired. Another was exposed to continuous melt/freeze cycles for

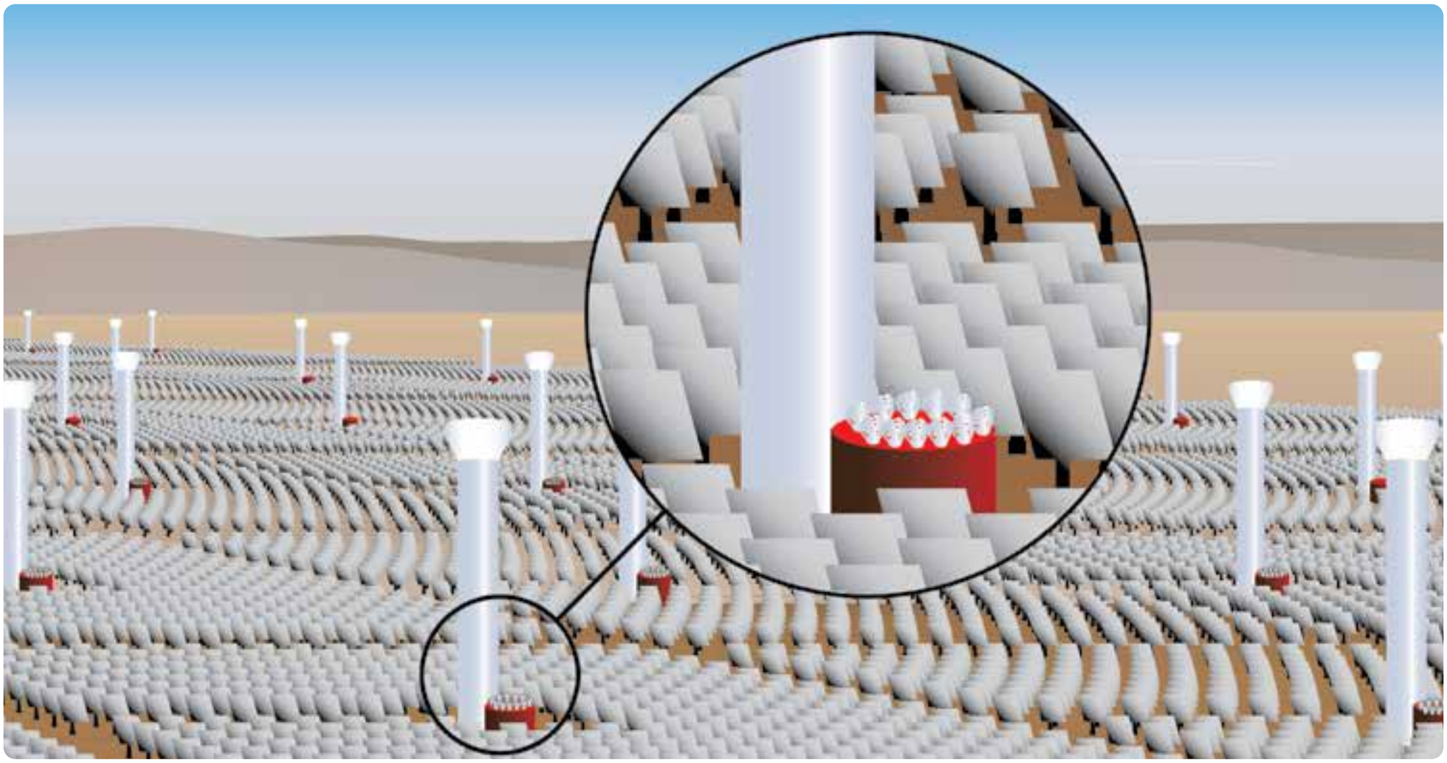


Figure 6. This conceptual drawing shows a potential utility-scale mini-central receiver installation.

more than four years, after which a detailed micro-analysis showed negligible impact on its stainless-steel container.

A 1-MW thermal-energy storage tank module design with 12 hours of storage is 20' in diameter by 18' high with 22 48-kW delta engines installed on top. This engine capacity uses commercial Qnergy 8-kW alternators to minimize early system cost. Future versions will use fewer engines with higher capacity to reduce manufacturing cost and simplify installation.

A utility-scale field of thermal-energy storage tanks with delta engine generators is illustrated in Figure 6. The modular array of heliostats associated with one tower receiver and adjacent GREAT thermal-energy storage tank can be replicated to achieve any given plant capacity. Each module is an independent CSP system. In practice, each heliostat will normally serve three or more receivers as the sun transits.

Advantages for Utilities

The modularity of this system eliminates the need to ever shut a plant down. There is no maintenance for the hermetically sealed thermal-energy storage or power generator. Closed loop heat rejection consumes no water. Positive revenue generation begins early and increases through plant buildout. The thermal storage capital cost at about $40/kW (electric equivalent) is about 80% less than lithium battery storage. And the technology is eco-friendly throughout its lifecycle.

Goals

This innovative CSP approach offers excellent potential for dramatic improvements in utility-scale CSP practicality. After modest incremental validation-stage costs, it can be rapidly expanded with automotive-scale production levels. Stirling Innovations is seeking a development partner with the resources and will to fully validate performance and establish manufacturing capability. ■

About the Author

Maurice White founded Stirling Technology Company, renamed Infinia and now Qnergy. He formed Stirling Innovations, LLC to commercialize delta Stirling machines and thermal-energy storage. He holds a bachelor's degree in physics from Harvey Mudd College and a master's degree in physics from UCLA. He is an American Solar Energy Society professional member.

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