Two Breakthrough Innovations that Enable a Grand Vision to Provide Virtually Unlimited Generation of Clean, Green, Sustainable, Cost-Effective Solar Power 24/7/365

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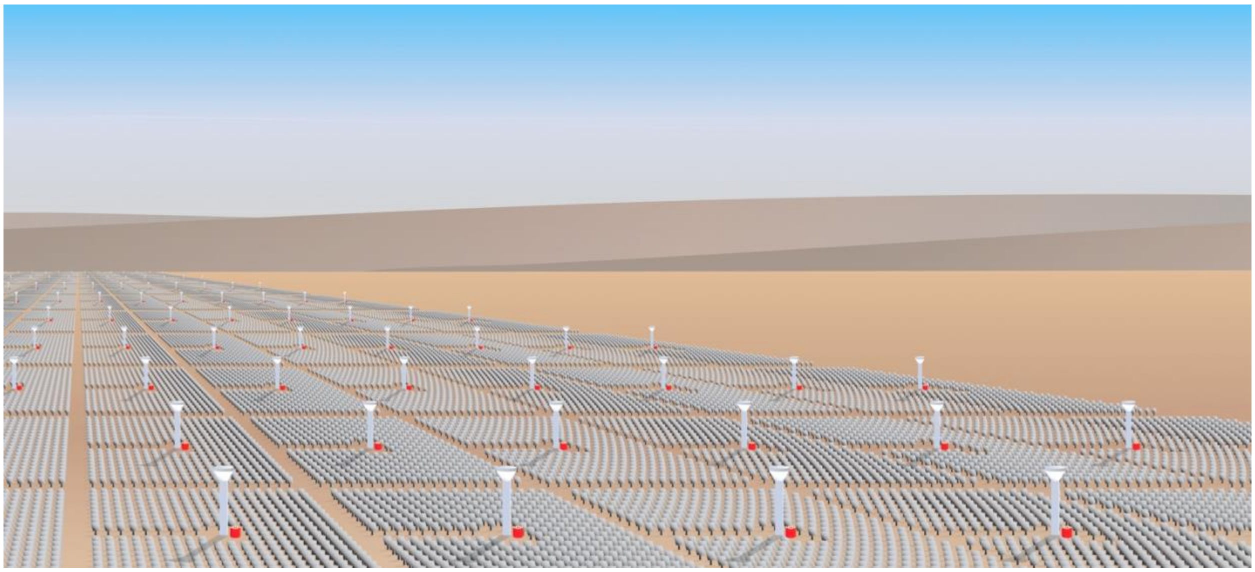
Stirling Innovations, LLC (SI)

Grand Vision White Paper – Revised Version June 2025

The Introduction of Delta Stirling Engines and GREAT™ (GReen Energy at All Times) TES (Thermal Energy Storage) with Potential Participation by an Entity that wants to Create the Future of Solar Power



Rendering of utility-scale mini-central receiver installation using GREAT TES and delta Stirling engines

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What Subject Experts are Saying about the SI Grand Vision

"*I really like the concept. It is an excellent thermodynamic match between concentrating solar power (a pure isothermal heat source), isothermal heat input to Stirling engines, and isothermal energy storage in low cost phase change materials. Thermodynamically, it doesn't get any better than your Clean Green Solar Power concept*." **Richard B. Diver, Ph.D., Solar Thermal Technology Department, Sandia National Laboratories (retired), co-author (Stine, 1994).**

"Maury White has pushed the envelope on free-piston Stirling machines and phase-change-salt thermal energy storage for decades. As my CTO when I was CEO at Infinia, he conceived, patented, and demonstrated both the world's first double-acting free-piston Stirling engine and his novel phase-change-salt thermal energy storage concept. He has now refined and combined those to create a green solar power solution that will be a total game changer if it even approaches projected operational parameters. It is clearly worth pursuing to prove or disprove his thesis." **J.D. Sitton, CTC Global CEO.**

"*I believe in the concept. It eliminates problematic heat exchangers between the concentrating solar power (heat source), input to Stirling engines, and energy storage in low cost phase change materials. Fewer components than any CSP alternative, components proven in other applications, excellent Thermodynamics. It is a real win-win for Concentrating Solar Power*." **Barry Lynn Butler, Ph.D., Solar Division VP, Science Applications International Corp. (retired), also SEIA CSP Division Chairman and Board of Directors,1996-2002.**

"I have personally known Maury White and his solar Stirling development work with STC and Infinia for decades. I have long been a strong supporter of solar Stirling systems, but earlier, they were not cost-effective as a direct competitor to wind and PV. The SI Grand Vision with 24/7/365 solar power totally changes that, and I agree with other solar experts who have endorsed it. The potential for this system approach is so important to our energy production that it requires research institutions and experts to step up to fully evaluate it." **Professor Scott Sklar, Sustainability Director - The George Washington University Environment & Energy Management I*nstitute (EEMI) & GWU's Solar Institute.***

"As Branch Chief of the Thermal Energy Conversion System Branch at Glenn Research Center for over 10 years, I was responsible for several free-piston Stirling terrestrial and space power technology and development contracts. Maury White and STC/Infinia made major breakthrough advancements in this period, including development of the free-piston Stirling convertors for future Radioisotope Space Power Systems. The free-piston Stirling convertors designed and manufactured by STC/Infinia currently hold the world record (over 18 years and continuing for each of three units in a laboratory environment) for dynamic power system life and reliability. The delta Stirling configuration is elegant and appears to verify all the boxes for simplicity, efficiency, cost, and light weight terrestrial power generation." **Richard K. Shaltens, NASA Glenn Research Center Branch Chief (retired).**

"As part of a research team at NREL, I tested an early free-piston Stirling engine from Maury White at STC on-sun at our high flux, high temperature solar test facility. This successful test helped to move the idea of a concentrating-solar driven Stirling forward. Scaling Maury's new CSP concept to larger size using solar towers as the energy source is a great match to the delta engine system. Indirectly heating the engine has numerous benefits including the incorporation of storage that could move this concept to an economically attractive, commercial scale." **Allan Lewandowski, Senior Researcher, Thermal Systems Center, National Renewable Energy Laboratory (retired).**

"A major contributor to carbon emissions that accelerate climate change is the generation of electricity with fossil fuels. Solar and wind power are making a real difference, but utility-scale energy storage is required to provide green power whenever needed. Many regions lack capacity for pumped hydro storage. Maury White's Grand Vision can be applied anywhere cost-effectively. I know Maury's dedication and commitment to making this a reality is intense and hope to see his approach aggressively evaluated in a timely manner." **Steven Ghan, Ph.D., Pacific Northwest National Laboratory Fellow (retired), Climate Scientist**

Comparison of Renewable Power Generation Alternatives

Overview of Primary Utility-Scale Renewable Power Generation Systems

Renewable Energy Type	Environmental Impacts	Cost	Reliability	Energy Storage Considerations
Wind Power	- Noise and visual impact - Threat to birds and bats - Recycling challenges	- High installation and maintenance costs	- Intermittent: depends on wind availability	- Moderate/high storage needs - Batteries are costly with environmental issues, limited life
Solar PV	- Mining impacts for silicon, rare earth metals, and lithium - Toxic waste from retired panels	- High upfront costs - Efficiency decreases over time	- Intermittent: no output at night or cloudy days	- High storage needs - Batteries are costly with environmental issues, limited life
Solar CSP (Concentrating Solar Power) state-of-the-art	- High water use for cooling	- High capital cost; viable mainly at large scale - Maintenance-intensive molten-salt storage system	- Partially dispatchable (typically 2–10 hours with molten-salt thermal storage)	- Integrated molten-salt storage - Can use hybrid systems (e.g., natural gas or hydrogen) for extended dispatchability
Solar CSP (Delta Stirling generator + GREAT TES)	- Minimal water use for mirror cleaning only - Low life cycle environmental impact - Fully sustainable - Rapidly scalable once validated	- High capital cost - Projected LCOE for generator + storage system of \$0.002–\$0.016/kWh is lowest of any alternative	- Fully dispatchable power 24/7/365 - Modular approach enables power plant to never shut down	- Integrated GREAT TES (passive phase-change salt thermal storage) - Hybrid use of green hydrogen or fossil fuels for extended storage

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Abbreviations and Acronyms

Abbreviation/Acronym	Meaning
AC	Alternating Current
AI	Atomics International
AMSC	American Superconductor Corp.
B	Boron
CAP	Compressed Air Pneumatics
CR	Central Receiver (Aka Power Tower)
CSP	Concentrating Solar Power
DAA	Double Acting Alpha
DC	Direct Current
DOE	Department of Energy
DWDL	Donald W. Douglas Laboratories
Fe	Iron
FPS	Free-Piston Stirling
GREAT	GReen Energy at All Times
GRC	Glenn Research Center
HTF	Heat Transfer Fluid
HTS	High Temperature Superconducting
IP	Intellectual Property
IRAD	Internal Research and Development
ITC	Infinia Technology Corporation
kW	Kilowatt
kWh	Kilowatt hour
LCOE	Levelized Cost Of Energy
MW	Megawatt
Na	Sodium
NaCl	Sodium chloride
NaF	Sodium fluoride
NaK	Sodium/potassium eutectic mixture
NASA	National Aeronautics and Space Administration
Nd	Neodymium
NEO	Fe/Nd/B magnets
ORNL	Oak Ridge National Laboratory
PV	Photovoltaics
RSG	Radioisotope Stirling Generator
SES	Stirling Energy Systems
SI	Stirling Innovations, LLC
STC	Stirling Technology Company
STPS	Solar Thermal Power Systems, LLC
TES	Thermal Energy Storage
UW	University of Washington

Executive Summary

It is generally accepted that one of the most effective ways to fight climate change is to replace utility-scale power generation using fossil fuels with solar and/or wind power. Wind and solar photovoltaic (PV) power generation are cost competitive, but their intermittent nature and the high cost of energy storage are major issues as these sources become a significant fraction of grid capacity. PV currently dominates the solar landscape with about 500 gigawatts (GW) of installed utility-scale solar power worldwide (IEA, 2022). Concentrating solar power (CSP) is making solid inroads with >6 GW of partially dispatchable solar power (typically two to ten hours after sunset) installed (Statista, 2022) but it is not yet cost effective.

This white paper describes a disruptive CSP technology improvement that uses a modular, maintenance-free power generator to reduce cost by quantity rather than capacity of power conversion units. When this is integrated with a similarly disruptive low cost, hermetically sealed, maintenance-free phase-change salt thermal energy storage (TES) module it produces a CSP system that can provide fully dispatchable baseload power 24/7/365. The functionality of this approach has been validated by laboratory testing and the scalability can be demonstrated in incremental steps with relatively modest investments. Once it is fully proven, capacity can be ramped up to high levels expeditiously by using straightforward automotive-scale production. It is feasible to rapidly increase the installation of fully dispatchable solar power at a significantly accelerated pace and reduced cost relative to conventionally accepted projections (NREL, 2023).

Stirling Innovations, LLC (SI) was established to commercialize delta Stirling machines and GREAT™ (GReen Energy at All Times) phase-change-salt TES. Delta Stirling machines are the culmination of 59 years of developing free-piston Stirling (FPS) engines and coolers. Earlier development prototypes addressed a wide range of focused applications on primarily government contracts with limited commercialization. Those efforts include three NASA space power engines that continue in operation after more than 18 years of operation at NASA Glenn Research Center (GRC) with no maintenance and no performance degradation, firmly establishing their uniquely long life, zero maintenance, and high reliability characteristics.

Delta Stirling machines retain those qualities in a new simplified topology that enables the lightest weight, lowest cost, and highest efficiency possible for Stirling machines. Several Stirling experts who have seen the delta configuration concur with this perspective. GREAT TES is also markedly superior to existing alternatives and derives from decades of phase change-salt TES experience. Both are sustainable and eco-friendly throughout their life cycle. This white paper shows how these can be integrated to enable a *Grand Vision* transition to virtually unlimited clean, green, sustainable, and cost-effective solar power production 24/7/365. Native 3-phase power generation simplifies power management and control. For those who would challenge these bold claims, please identify what basic topology change could be made to reduce weight, reduce cost, increase efficiency or otherwise simplify the approach presented herein.

Hybridization using fuels such as natural gas or green hydrogen enables seamless uninterruptible power generation through extended cloudy periods. This modular system is adaptable for applications ranging from tens of kilowatts to gigawatt-scale utility power. Major benefits for utilities include: 1) extensive plant modularity with independent 1-MW power and storage modules that eliminate the need to ever shut a plant down, 2) no maintenance for hermetically sealed TES or power generator (failed modules will be recycled and replaced), 3) the heat rejection system consists of a closed pumped loop antifreeze with an automotive style radiator, so no water is consumed other than for mirror cleaning, 4) positive revenue generation begins early and increases steadily during plant buildout, 5) GREAT TES capital cost at about $40/kW (electric equivalent) is at least 80% less than for Li battery storage, and 6) likely the lowest system levelized cost of energy (LCOE) of any dispatchable solar power generation. Basic patents are in place for both delta Stirling machines and GREAT TES. Additional patentable IP has been identified, with more expected as development progresses.

In an insightful book (Seba, 2010), Stanford Professor, entrepreneur, and visionary Tony Seba makes a compelling case for the inevitability of a solar power future for the U.S. and much of the world. This white paper provides details of delta engines and GREAT TES and outlines a development and demonstration approach to validate them in incremental stages. This approach offers a huge payoff potential with minimal investment at each validation stage of risk retirement and scalability increments. Implementation is described for the United States, but the model is readily extrapolated to other regions.

- Delta Stirling engines + GREAT TES enable an unlimited green power future 24/7/365.
- Both are sustainable and eco-friendly throughout their life cycle.
- These innovations require only minimal updates to proven technologies.
- Minimal investment will incrementally validate the system at each stage.
- Basic IP is in place; more has been identified.
- SI has access to the technical expertise needed and is seeking a development partner.
- The first delta Stirling engine will be close to a pre-production configuration because key components are already in production.
- Power generation + TES contribution to LCOE is bracketed at $0.002/kWh to $0.016/kWh for best case/worst case.
- Relevant experience supports the expectation that this system will operate for decades with no maintenance and high reliability.

The unique SI central receiver CSP system is schematically described and contrasted with the much more complex traditional CSP central receiver system below. After that, the SI system and subsystem innovations are described in more detail. The contribution of the power generation and energy storage systems to the total CSP system LCOE is projected to range from $0.002/kWh to $0.016/kWh for a best case/worst case spread.

SI is led by founder Maury White and VP Engineering Dr. Songgang Qiu, with more than 70 years of combined relevant experience. Fifteen former colleagues and competitors are enthused about the delta Stirling engine innovation and are anxious to support development as staff on demand when funding is available. This highly qualified team led by Dr. Qiu can efficiently develop and demonstrate the proposed full-scale 50-kW delta engine (20 of these will be used in the 1-MW modular system) with little or no management oversight. With support from Columbia Basin Consulting Group, Infinia and SI founder Maury White will similarly coordinate scale up from the 10-kWh laboratory demonstration version to a 300-kWh GREAT TES laboratory prototype. These will be integrated as a full-scale generator with subscale TES to document performance and scalability of the proposed power generation and storage subsystem. SI is seeking $6 million to complete this demonstration, with the next phase planned as a full-scale 1-MW modular system. The preferred approach is a joint venture with a development partner that has the resources and will to fully validate performance and establish manufacturing capability if warranted by results. Relevant contact information is at the end of this white paper. If the SI assessment proves to be anywhere near reality, this venture could truly lead a farsighted investor to Tony Seba's "Solar Trillions".

Characteristics of a Viable Grand Vision (Unlimited Solar Power 24/7/365)

The six essential elements of a successful Grand Vision, which no alternative approach to the one presented here can achieve without very unlikely breakthroughs, consist of the following:

1. Environmentally friendly and sustainable primary power source such as solar, wind or ocean waves/tides. (Seba, 2010) provides a strong argument that among these and other potential candidates, only solar is truly feasible.

2. Energy storage that provides reliable 24/7/365 baseload power and peaking power under most conditions.

3. Hybridization to enable seamless transition to a fossil fuel or green fuel backup in instances where the energy storage is depleted and the primary power source is unavailable, e.g., extended cloudy conditions for solar.

4. Reliable operation to provide baseload power without interruption. This is achieved with the proposed system by a combination of inherent reliability and extensive power generation and storage modularity.

5. Reliable transmission and distribution of the electric power produced from its source to the rest of the nation.

6. Provide all the above with a life-cycle cost that is comparable to current methods of power generation and distribution, with a modest margin for environmental benefits. This also implies avoiding significant utilization of any high cost or strategically limited resources.

7. Not essential but highly desirable is avoidance of adverse environmental impacts during manufacturing, operation, and decommissioning, with a bonus for extensive recycling at end of life.

The ultimate winner in the power generation plus storage arena will be the one that can deliver the above elements at the lowest market price. Based on favorable compliance with all the above criteria, the Grand Vision system approach presented here will likely emerge as the market leader.

The SI approach to achieve the Grand Vision incorporates a unique integration of four basic technologies:

1. Concentrating solar power (CSP) that uses parabolic dishes or heliostat fields to generate high temperatures for efficient power conversion. By using a small fraction of available remote areas with high annual solar insolation, mostly in the desert southwest, enough reliable power can be generated to supply virtually all U.S. electrical needs.

2. Free-piston Stirling (FPS) power generators. FPS technology is the primary focus of SI but is not necessarily essential for achieving the Grand Vision. Rankine or Brayton power conversion systems can also be integrated with the other three elements of the Grand Vision, but FPS offers many advantages.

3. Phase-change salt thermal energy storage (TES) with fossil fuel or green fuel hybridization. GREAT TES offers a paradigm-shift improvement over existing commercial molten-salt TES technology. A general salt TES advantage is that its energy storage cost is less than 10% of the cost for the best current electrochemical battery storage (Nilsen, 2022). Since GREAT TES is projected to have several times the operating life of any known batteries, the true comparative cost is even less. Comparable price drops for battery or other energy storage approaches are extremely unlikely.

4. High temperature superconductor (HTS) power transmission and distribution lines. This is a proven technology that will ultimately provide the lowest cost and highest reliability for extensive power transmission from generation sites to the rest of the country. HTS power lines can be buried in a 3-foot-wide trench using existing railroad and interstate highway rights-of-way, saving enormous land acquisition cost and disruption of existing property usage, while also hardening against weather and security threats. Conventional power transmission lines are clearly a feasible alternative, but siting costs will increase rapidly as capacity grows.

A further benefit is an option to use additional and/or off-peak excess solar power generation to produce green hydrogen from water using electrolysis. This can be used to fuel a hydrogen economy that, for example, meets clean transportation needs using fuel cells or clean internal or external combustion engines where the exhaust emissions consist primarily of pure water vapor. Hydrogen can also be stored at the CSP site to serve as a green fuel source for clean hybrid operation during cloudy periods.

Central Receiver CSP Power Generation System Comparisons

The SI CSP system is far simpler in concept and implementation than existing CSP systems. The schematic comparison between a typical central receiver (CR) system in Figure 1 and the SI CR system in Figure 2 makes that abundantly clear. Both have heliostat mirrors focused on a tower receiver with a heat transfer fluid that transports heat from the receiver to the ground located TES, which then drives the generator. The similarity ends there.

The two key elements of the SI CSP system are delta Stirling engines and GREAT TES. These subsystems are hermetically sealed independently, and also when integrated, so no maintenance is needed or possible. Description and operation of these critical subsystems is described in the sections that follow. Operating experience with closely related components supports the expectation that they will operate maintenance-free for decades with high reliability and no degradation of performance.

Typical CR Power Generation System Schematic

The heat transfer fluid for the conventional CR in the Figure 1 schematic is the same molten salt used for TES. In the morning when the system goes on sun the molten salt is essentially all in the warm storage tank where it ended up after the sensible heat was extracted to power the steam turbine after sundown the day before. The warm salt circulation pump delivers that salt to the receiver where its temperature is increased to the high temperature and delivered to the hot storage tank. Hot salt is pumped through the superheater, reheater, and steam generator before passing through the feedwater preheater and returning to the warm tank. The heliostat field is sized so that it delivers more heat than is needed to operate the turbine generator, so more hot salt is pumped into the hot tank during the day than is pumped out by the hot molten salt circulation pump to operate the turbine generator. That excess is sized to provide the desired operating time after sundown.

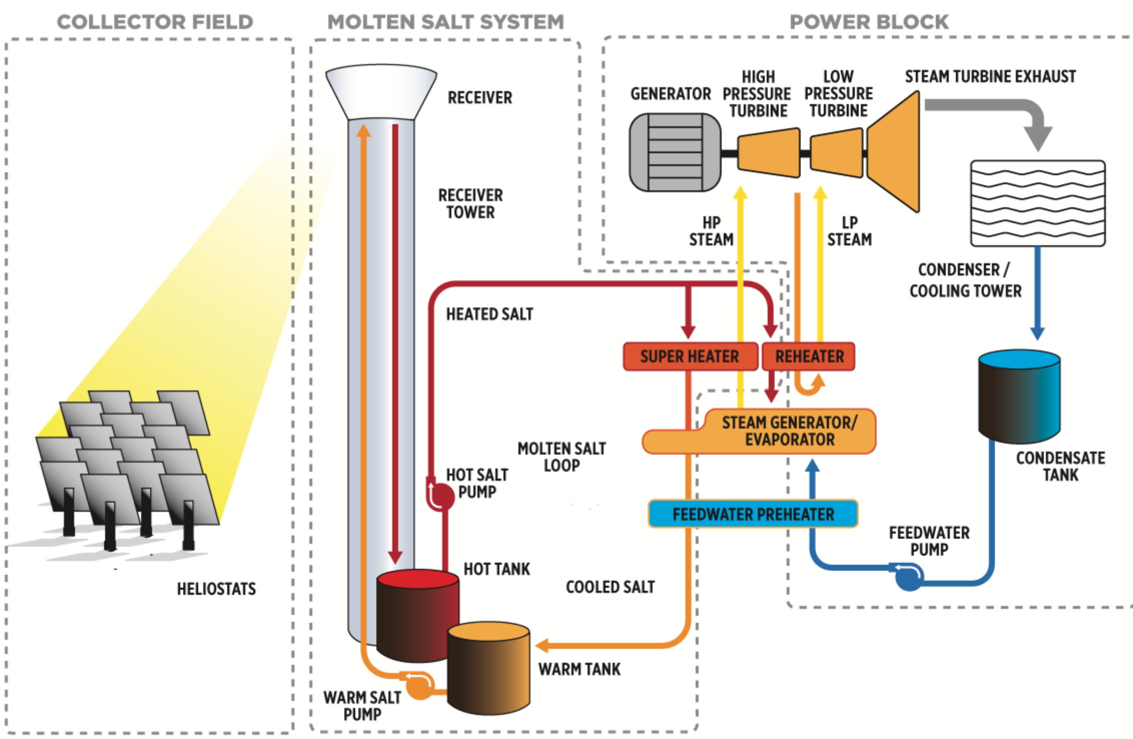

Figure 1. Schematic of typical central receiver CSP plant operation with molten salt thermal energy storage

Water from the condensate tank is pumped through the feedwater preheater to the steam generator where it converts to high pressure steam that passes through the superheater before expanding to drive the high-pressure turbine wheel. From there it is reheated to drive the low-pressure turbine wheel and exits to the condenser and then back to the condensate tank. The turbine axis is connected to a generator that feeds electricity into the grid. A separate water loop is vaporized in the condenser to condense the steam that exits the turbine. The resulting ambient pressure steam is released into the air by a cooling tower, consuming a substantial quantity of water. Another complication is that all the molten salt components must be heat traced to ensure that the salt never freezes out anywhere. This has both a capital cost impact and is a parasitic consumer of electrical power.

Stirling Innovations CR Power Generation System Schematic

For the comparable delta Stirling and GREAT TES CR installation in Figure 2, the heat transfer fluid delivers heat from the receiver to the salt across the tank interface, melting the salt. The heat transfer fluid is then pumped back to the receiver to be reheated. A conventional molten salt heat transfer fluid can be used, but ultimately a simpler and more efficient two-phase liquid metal heat transport system is anticipated. As with the conventional CR, the heliostat field is sized to power the generator through the day and fully melt the salt in the tank by the end of the day. As the salt freezes during the night, it supplies enough stored heat to maintain power generation all night. The balance-of-plant functionality described for the typical CR is entirely carried out passively (no moving parts) within the hermetically sealed tank/engine system, with the engine heater heads hermetically ducted to the Na vapor space at the top of the tank. Linear alternators in the delta Stirling engine produce three-phase power to feed the grid. The only non-hermetic item that requires occasional maintenance is the external cooling loop on the engines, where an anti-freeze coolant is circulated through the external engine heat rejector to transfer Stirling cycle waste heat to ambient by a closed loop automotive style radiator that consumes no water.

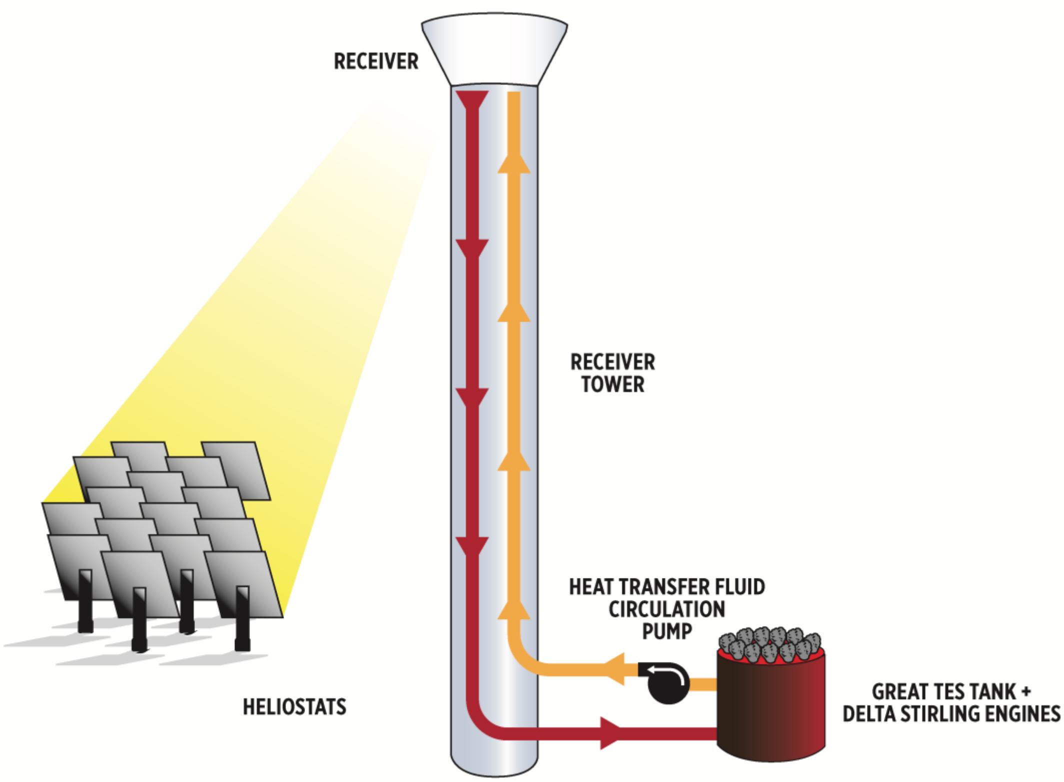

Figure 2. Schematic of SI **central receiver CSP plant operation with phase-change salt thermal energy storage**

SI CSP System Implementation with Delta Stirling Engines and GREAT TES

The SI system can be utilized with either parabolic dish concentrators or small central receivers. Each has unique advantages as described below. The dish approach is appropriate for installations of tens of kW to a few hundred kW. For utility-scale power levels it is anticipated that the CR approach will prove to be most cost effective. A variety of factors, including practical experience levels with each, will determine the best approach for specific applications.

SI Central Receiver Approach

The GREAT TES and delta Stirling engine concept schematically described above is intended for use with a small heliostat field and CR. Such small heliostat fields have been successfully used by Heliogen and others so no basic development is required. The most direct approach for heating the tank is to place it on the tower. A proprietary approach for that will be disclosed to potential investors under a nondisclosure agreement. The alternative illustrated schematically above and here is to place the tank on the ground near the tower and use a heat transfer loop to transport the heat from the tower to the TES salt in the tank. The heat transport can be implemented using a molten salt loop, as is generally done with current central receivers, but the preferred approach is to use a two-phase pumped loop thermosyphon with Na or NaK as the heat transport medium. System assessments of competing factors indicate that a module size of 1-MW electric output is near optimum so that is used for all discussion herein.

A conceptual perspective view of a utility scale field with ground mounted TES tanks and integral delta engine generator systems is illustrated in Figure 3. The modular square array of heliostats, principally associated with one central tower receiver and adjacent GREAT TES tank with delta engines located on top, can be replicated as needed to achieve any given plant capacity. Each module is in principle an independent standalone CSP generating system, but in practice each heliostat will serve three or more receivers as the sun transits from morning to evening to minimize heliostat cosine losses due to non-optimal sun/tower viewing angles.

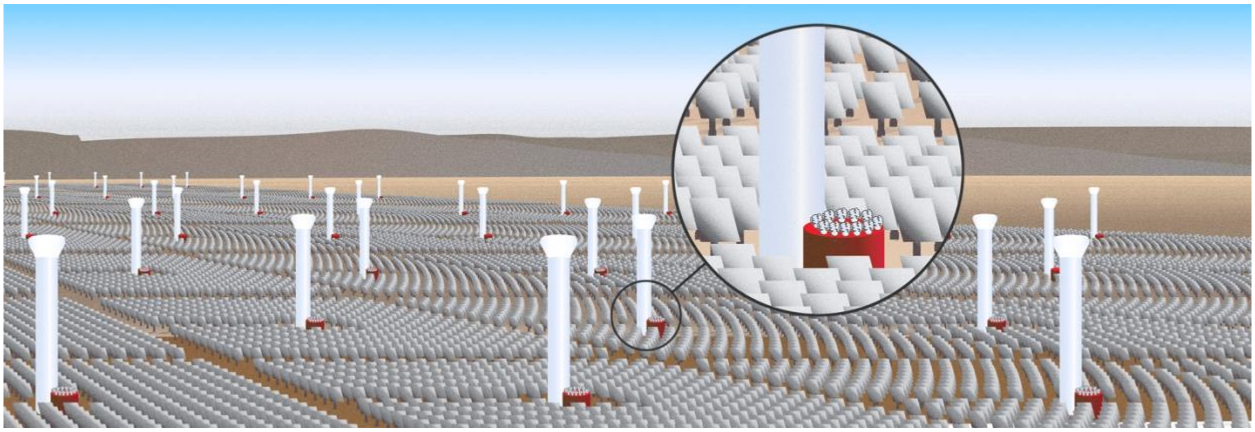

Figure 3. Depiction of a utility-scale central receiver field of GREAT TES and delta Stirling engine generating systems

There are five major advantages to using many small towers rather than one large one.

1. The extensive redundancy means that if a tower system is shut down for any reason it has a negligible impact on the total output rather than shutting down the entire solar plant.
2. The cosine losses, where each heliostat mirror has large changes in its effective area as the sun moves through the day, are substantially reduced by having any given heliostat, for example, serve tower A in the morning, tower B midday, and tower C in the afternoon.

3. The heat rejection system consists of a closed pumped loop using water and/or antifreeze with an automotive style radiator, so no water is consumed other than for mirror cleaning.
4. With modular construction, each tower can begin generating positive revenue as it comes online rather than waiting until the conclusion of a typical multi-year construction project.
5. No heliostats are at far distances from the tower where their effectiveness is diminished.

SI Dish Concentrator Approach

No dish engine systems to date have included TES, so any SI parabolic dish implementation will be unique. While dish Stirling systems have had far fewer field installations than trough or tower CSP systems, they have desirable characteristics that make them a strong contender for long-term commercial market success when using the improvements described herein. Significant efforts to develop modern dish Stirling systems have been made by many developers throughout the world. A comprehensive overview of seven complete dish Stirling systems and 19 programs for developing critical components is provided in (Stine, 1994). Two more recent installations of 1.5 MW dish Stirling projects were implemented by Stirling Energy Systems (SES) in Peoria Arizona using 60 25-kW kinematic Stirling dish systems in 2010 and by Infinia Corporation at the Tooele Army Depot in Utah using 429 3.5-kW FPS dish systems in 2013. A photo showing about one-third of the Infinia installation is shown in Figure 4.

Figure 4. A portion of the Infinia 1.5 MW dish Stirling installation at Tooele Army Depot

The delta FPS engine is well-suited for parabolic dish systems as well as for small-scale CR systems when integrated with GREAT TES. Dish size and modularity make installations much more flexible than for existing CSP systems. Dish engine systems have been successfully demonstrated with dishes as large as 17 meters in diameter (Stine, 1994), which is adequate to power about a 35-kW delta engine with 12 hours of TES. Even larger dishes are feasible.

General dish Stirling advantages include:

- Dish Stirling has demonstrated the highest conversion efficiency of incoming solar energy (insolation) to grid-quality power output of any technology: 31.25% set in 2008 by an SES engine at Sandia National Laboratories and increased to 32% in 2013 by Swedish Stirling (aka Ripasso Energy) in South Africa. It is anticipated that this record can be increased to more than 35% with a delta engine.
- Parabolic dish systems always point directly at the sun to optimize solar insolation capture with no cosine factor losses as inherently experienced by heliostat mirrors, which minimizes the required mirror area and cost.
- Dish engines can be installed on uneven terrain as shown in Figure 5, expanding the potential for many new locations not suitable for other CSP approaches.
- For generally-south-facing slopes dish systems can be installed even more densely while still minimizing the shadowing of other dishes.

- The above factors result in dish engines requiring less land area per MW than any other CSP technology.
- The approach of using many relatively low-capacity modules to achieve grid levels of output means that individual units can be taken offline for any reason with negligible change in power generated.
- A closed loop heat rejector means no water supply is needed except for periodic concentrator mirror cleaning, making dish Stirling systems consume far less water than existing CSP systems.
- They can potentially be economically viable for installations ranging from tens of kilowatts to utility scale fields with hundreds of megawatts or even gigawatts.
- The modularity enables revenue generation from power production as the buildout progresses rather than waiting years for completion as with existing CSP options.
- Dish Stirling systems are composed primarily of steel, with some copper and aluminum, and glass for the concentrator. The only exotic material is 250 g or less (about a half pound) of rare earth magnets per kilowatt of power generated.

Figure 5. Example of an Infinia dish Stirling installation on uneven ground

- Minimal environmental impact for both manufacture and ultimate decommissioning relative to other renewable energy sources.
- They can be manufactured using automotive-scale processes to achieve low-cost scaling by quantities of units rather than capacity of units.
- Avoids bird kills experienced by wind turbines and central receiver CSP.

SI has collaborated with two groups that have dish systems, one in Europe and one in the U.S., seeking to obtain funding for integration of GREAT TES and delta Stirling engines with their dishes. In the U.S., Solar Thermal Power Systems, LLC (STPS) has an advanced solar concentrator shown in Figure 6 that employs a new breakthrough focusing technology that enables high-precision temperature control and passive emergency defocusing. This approach mitigates the major issue of focal plane overheating often experienced by earlier systems and offers a low-cost approach oriented toward autonomous operation. Since a 12-hour TES module is too heavy to be supported by the solar receiver boom on this dish, the delta engine and TES module will be incorporated into, or adjacent to, the dish support base. A two-phase liquid metal pumped loop thermosyphon transports heat energy from the receiver to the TES unit as a vapor, with the condensed liquid metal pumped back to the receiver by an electromagnetic pump. The ground-mounted engine/TES module requires flexibility in the liquid and vapor heat transport conduits to accommodate dish tracking.

Figure 6. STPS prototype dish concentrator

Thalis Engineering Co Ltd www.thalisgroup.com is a renewable energy company in Cyprus. They have a proposal under evaluation by a European green energy fund for their SolarDish® system that includes a 4-kW Qnergy FPS engine integrated with 12 hours of GREAT TES by SI as conceptualized in Figure 7. Thalis is also eager to upgrade to a larger dish with a delta Stirling engine and 12 hours of TES whenever funding becomes available. The Thalis approach uses a dish with the tracking system pivot point behind the dish, so a large counterweight is required to balance the cantilevered dish. This is an ideal approach that enables the full engine/TES module to be located where it provides an optimal counterbalance function. The engine/TES module is oriented to enable tracking to any point in the sky without having the heater head contact the salt. A two-phase liquid metal pumped loop thermosyphon transports heat energy from the receiver to the TES unit as a vapor, with the condensed liquid pumped back to the receiver by an electromagnetic pump. In this case, both the liquid and vapor lines are fixed with respect to the dish tracking system.

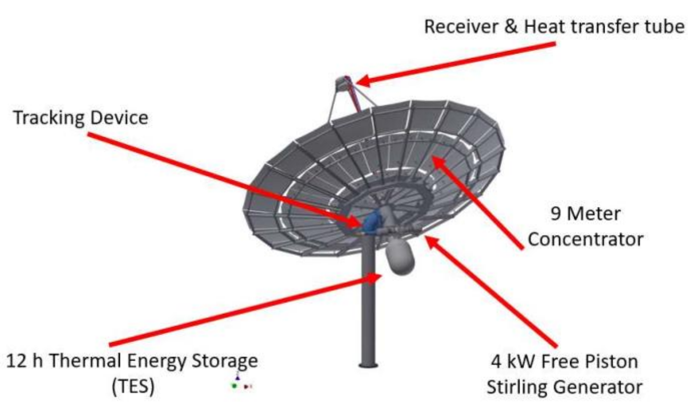

Figure 7. Thalis SolarDish conceptual configuration with GREAT TES

Delta Stirling Engines

Delta Stirling machines are a recent innovation that adapts proven maintenance-free long-life FPS hardware components to a new topology with many advantages. SI owns the basic delta Stirling machine patents (Emigh 2012, Emigh 2014). Traditional Stirling engines use three basic topologies:

alpha, beta and gamma. Alpha engines use multiple power pistons while beta and gamma engines use a displacer piston (shuttles working gas back and forth through heat exchangers) and a power piston. Alpha engines can be either single acting (two pistons) or double acting (three or more pistons). Kinematic Stirling engines in all three configurations dictate piston and displacer motions using crankshafts and mechanical linkages. They have inherent life and reliability limitations due to oil vapors from a lubricated crankcase eventually leaking past seals and fouling heat exchangers.

FPS engines were limited to single-acting beta or gamma configurations until a double-acting alpha (DAA) FPS topology was identified in (White M. A., Combining the Best in Free Piston and Kinematic Stirling Machines: The Multi Cylinder Free Piston Stirling Engine, 2005) and (USA Patent No. 7,134,279 B2, 2006). Multiple protypes have been successfully demonstrated by at least three organizations since then, but complex heat exchanger configurations and convoluted interconnecting flow passages that resulted from conventional parallel piston axes and a piston on only one end of the linear alternators, limited performance. What an Infinia 3-cylinder 12-kW DAA FPS engine definitively demonstrated was that the key concern about whether the thermodynamic forces would stably operate with the desired 120-degree phasing between pistons is not an issue. When cooling down after test runs, the proper phasing was locked in as the engine coasted down all the way to the 10-watt range.

The generic 4-cylinder DAA engine schematic in Figure 8 is kinematic if the four piston rods are connected to a crankshaft and is a DAA FPS engine with inherently correct phasing if the rods are connected to individual linear alternators. Points A are connected, usually with piston axes in a square pattern. All prior DAA engines use this basic topology with parallel piston axes and heater/regenerator/cooler heat exchangers daisy-chained together as shown with all hot ends adjacent. The fine wire mesh regenerator absorbs heat when the working gas moves through it from hot to cold, then returns typically 99% of that heat to the gas as it flows back a half cycle later. The regenerator is a key element of Robert Stirling's original 1816 invention.

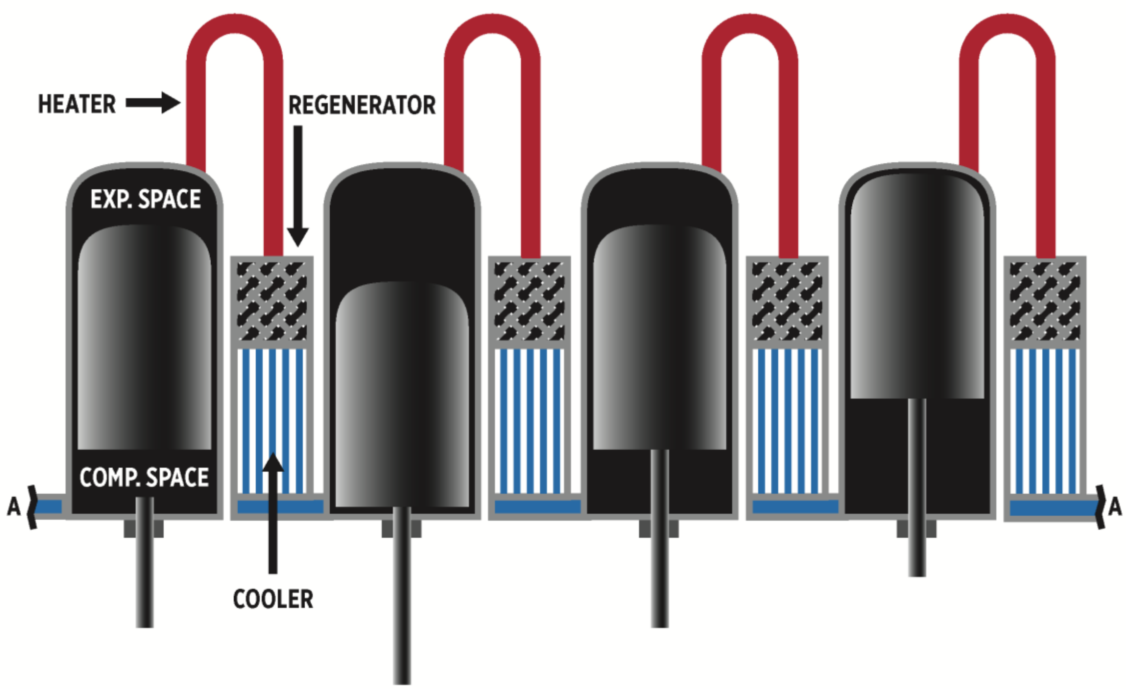

Figure 8. Schematic of generic 4-cylinder double-acting alpha Stirling engine

The physical implementation of this configuration of heat exchangers results in significant flow losses and asymmetries where the heat exchangers interface with 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 between adjacent helium working cycles. Delta engines change all of that. The delta configuration is an optimized subset of DAA FPS machines. It is the culmination of 59 years of experience developing FPS engines and coolers at Infinia and related organizations. It provides higher efficiency, lighter weight, ability to scale to much higher power levels, lower cost, and reduced operational sensitivity relative to conventional FPS engines, without compromising any of the proven FPS life and reliability. One example of that reliability is three Infinia FPS engines that NASA Glenn Research Center (GRC) continues to operate after more than 18 years with no maintenance and no degradation of performance.

- Delta Stirling engines are optimized to a level that can't be fundamentally improved upon.
- Offers unprecedented Stirling efficiency and low cost with zero maintenance.
- Uses commercially proven extreme life and reliability components.
- The first prototype will be close to a pre-production configuration.
- Scales to far greater power levels than existing Stirling machines.

Like all Infinia-derived FPS engines, the delta Stirling engine configuration presented here uses flexure bearings and clearance seals in a maintenance-free system that is hermetically sealed with no rubbing or wearing parts. Unlike the earlier Infinia DAA FPS engine with parallel piston axes, the delta Stirling topology illustrated in Figure 9 has the three piston/cylinder axes located in a plane on the legs of an equilateral triangle. This circumvents the prior asymmetric flow issues .

The 3-cylinder delta Stirling topology reduces what a Stirling engine is to its essential elements. Nothing can be removed without losing basic functionality. Heat exchanger packaging and manifolding cannot be simpler or more direct. These factors make it possible to achieve the lowest cost, highest efficiency, and lightest weight relative to any other Stirling engine configuration. This efficiency assertion was confirmed by engaging Barry Penswick, a master practitioner of the gold standard Sage Stirling analysis code, to conduct a delta engine analysis using Qnergy linear alternator specifications. He evaluated two cases: a generalized optimization and a constrained optimization where the pistons and the regenerators were forced to have the same diameters. The unconstrained case had 62% of ideal Carnot efficiency and the constrained case 58%. This is exceptional for the first cut at a new configuration. With few exceptions, well designed Stirling engines fall in the range of 50% to 55% of Carnot efficiency. The significance of this is emphasized by the fact that Philips demonstrated engines with over 50% of Carnot efficiency in the 1950s, with no real change since. Power output is easily modulated, and part-load efficiency is exceptional. Native 3-phase power generation by either 3-cylinder or 6-cylinder delta engines adds stability and simplifies power management and control relative to existing FPS engines.

The only downsides to delta engines are the three distributed heater heads and relatively large footprint. Also, the degree of piston bias mitigation (present with all FPS machines) that will be needed cannot be definitively determined until a prototype engine is operational. Intuitively, it is projected that the delta engine will have less bias than other FPS engines because leakage past all pistons is symmetric and is between cyclic pressure variations and the same average buffer pressure in the linear alternator region. All other DAA topologies have direct cycle-to-cycle pressure drops across the pistons. The delta Stirling configuration is the culmination of many topological iterations that sought to produce more symmetric flow patterns with simple heat exchangers and straightforward manifolding between them for DAA FPS machines.

As seen in Figure 9, a piston with a clearance seal is deployed on each end of each linear alternator, which has a central moving magnet assembly supported by flexure bearings. This piston/cylinder configuration is essentially identical to the production-line approach used very successfully by Infinia/Qnergy for thousands of commercial FPS engines, the basic difference being the implementation of a piston on each end of the linear alternator instead of one end. The cold heat exchanger/regenerator module is directly in line with the compression piston on one end of the alternator, with an expansion piston and integral hot cap on the other end.

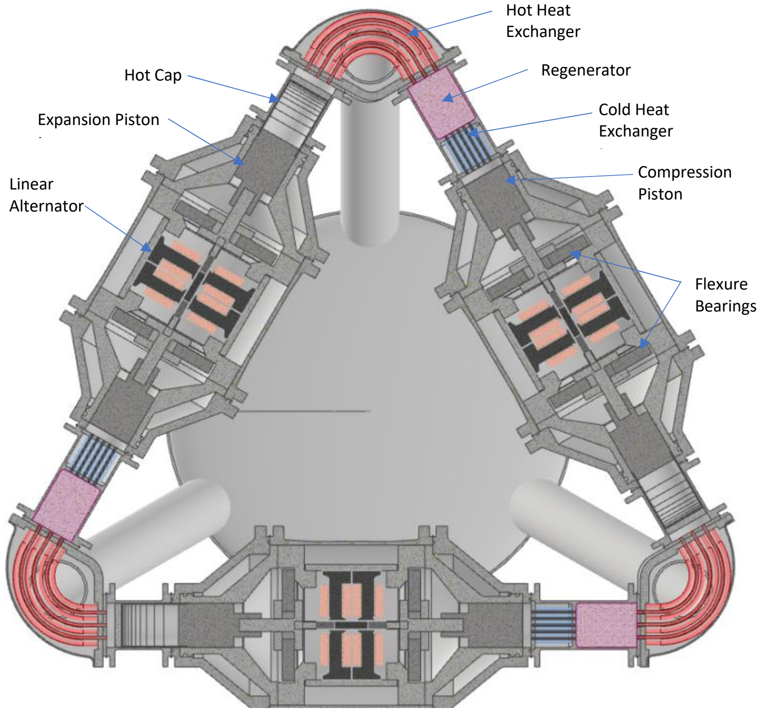

Figure 9. Cross-section drawing of delta Stirling engine conceptual design

The hot heat exchanger (or heater) is deployed between the regenerator associated with one alternator and the expansion piston hot cap from a second alternator. The thin wall hot cap with internal thermal radiation shields reciprocates with a relatively large clearance between it and a thin cylinder wall. This approach is thermally analogous to a displacer in a beta or gamma engine and is essentially identical to the hot cap used in all alpha engines. The function is to minimize the heat leak between the hot end and cold end in a similar manner to the thin-wall cylinder around the regenerator.

Dozens of heater tubes accept heat input on their exterior and transfer it to the helium working fluid as it shuttles back and forth between the hot cap in one Stirling cycle and the regenerator hot end in the adjacent cycle. For the solar/TES application, a shroud around the heater region contains sodium vapor that condenses on the heater tubes to provide engine heat input with uniform temperature and high thermal effectiveness. This avoids heater head hot spots that have been a major problem with earlier direct solar or combustion heating of Stirling engines.

The simplicity and low parts count of a delta Stirling engine is in stark contrast with any other prime mover power generator. With reference to Figure 9, there are only six distinct components/subassemblies.

1. Magnet mover assembly
2. Pistons on each end of the mover
3. Flexure bearings to support the mover and enable reciprocating motion
4. Copper and iron stators
5. Housing for the above including cylinders with clearance seals for the pistons
6. Heat exchanger assembly with inline heater, regenerator and cooler

A 3-D view of a fully balanced delta Stirling generator is shown in Figure 10. The imbalance in a delta machine does not occur as either a typical linear oscillation or rotational oscillation about an axis. Instead, the entire unit traces a small circle of a magnitude that depends on the moving masses, their amplitude, and the entire system mass. It has been demonstrated that over 90% of this motion can be eliminated with suitable passive balancers. The imbalance is projected to be fully eliminated with two properly coupled delta machines as illustrated in Figure 10. Not shown for this conceptual generator are mechanical couplings between alternator housings, a coolant pump, or a fan-cooled radiator to reject cycle waste heat to the environment.

To balance this generator, the upper delta engine is turned "upside down" relative to the lower engine. The heaters are aligned for convenience in fabricating the heat source vapor space ducting. The upper and lower engines are rigidly coupled together, and allowance is made to accommodate thermal expansion and contraction that occurs during heatup and cooldown.

The short cylinder below the balanced delta engine represents a laboratory liquid metal pool boiler. Radially disposed electric cartridge heaters embedded in a Na or NaK pool vaporize the liquid metal. The metal vapor condenses on the engine heater heads and returns to the pool by gravity through the vapor ducts that couple the heater heads with the pool boiler vapor space.

Current delta engine designs using commercially available Qnergy (successor to Infinia) production linear alternator/piston configurations, validated by millions of cumulative trouble-free operating hours, will generate 12.5, 25 or 50 kW of power at 60 Hz. A prototype at one of these power levels can be demonstrated relatively quickly and inexpensively. Newly developed linear alternators integrated with piston/cylinder modules will be needed for other power levels at 60 Hz. A moderate range of power variations using Qnergy components can be achieved by operating at other frequencies. For example, 50 Hz would produce 10, 20, or 40 kW with an increase in efficiency of two to three percentage points.

It needs to be emphasized that all the delta engine discussion herein is predicated on using existing commercial Qnergy 4-kW or 8-kW linear alternators. Those are indeed what early delta prototype development and demonstration systems should be based on. Once the proper vetting of the delta engine is completed the engine capacity should be scaled up to further decrease cost, size, and weight per kilowatt in pursuit of Grand Vision objectives. The Qnergy 8-kW linear alternator was produced very economically by essentially integrating two 4-kW alternators in tandem to double the output using the same flexure bearings and pressure vessel diameters. With a modest increase in length the output doubled and the cost per kW decreased substantially.

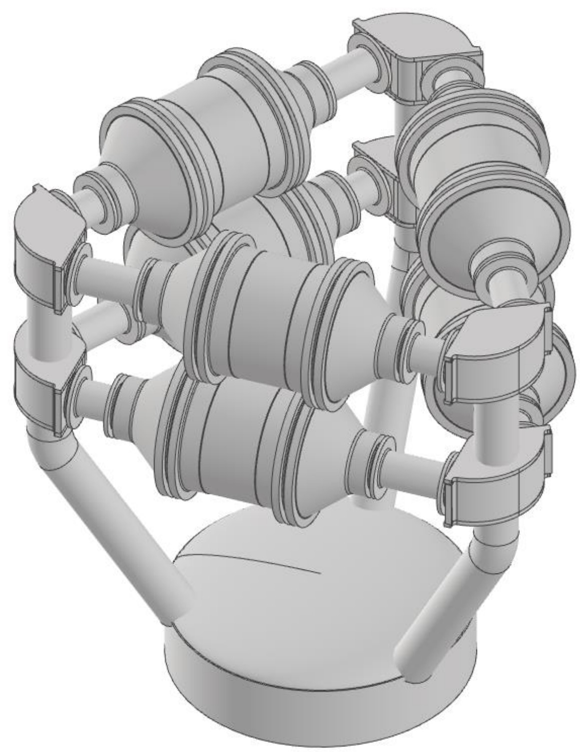

Figure 10. Perspective view of conceptual delta prototype lab generator with two delta engines integrated for full balancing and a sodium pool boiler with an electric heat source

While this is a good approach, an even better one is to increase diameter to enable increasing stroke length, which is limited by the flexure diameter. A combination of these can greatly increase output while further reducing cost, size, and weight per kilowatt for many of the components. Seven hundred kilowatt linear alternators were conceptualized in (White & et.al., 2007). Success at that capacity is not ensured but 50-kW and 100-kW alternators are relatively straightforward. Using 50-kW alternators results in a 300-kW balanced delta engine. Future assessments will determine the best engine sizes and whether significant scaling up or down from the nominal 1-MW GREAT TES CR module size described below is most cost effective.

The GREAT TES Innovation

The utilization of TES to avoid the major intermittency issues associated with PV power generation is the key differentiator for CSP systems. Molten salt TES systems that store sensible heat energy in multiple tanks, which is later extracted over a range of temperatures, are now standard with utility scale CSP. They are functionally practical but are costly and complex subsystems that require significant maintenance. Phase-change salt TES has many advantages, including a high latent heat of fusion energy storage at a single temperature. Several groups have attempted to implement phase-change TES, but the low thermal conductivity and large volume increase of the salt during melting have prevented practical solutions for all but very small capacity systems. GREAT TES eliminates those problems with a patented approach (White and Brehm 2013) that uses a liquid metal pool boiler directly integrated with the TES salt. This passive hermetically sealed system scales to many megawatt hours of energy storage and can be integrated with various power conversion systems. It is described further below.

GREAT TES Description

A schematic of an FPS engine integrated with GREAT TES is illustrated in Figure 11. The flat engine heater head is welded into the top of the TES containment vessel to always remain above the salt and sodium below. Since the solid salt is typically about 30% more dense than the liquid, any liquid salt will float above the solid. The Na is much less dense than the liquid salt, so it floats on the liquid salt surface. At the sodium/salt interface, the salt transfers its heat of fusion to the sodium, which solidifies the salt and vaporizes the sodium. In the insulated vapor space above the sodium layer, the engine heater head where heat is being extracted is the coolest part, so the sodium condenses on the heater head to function as the engine heat source. The liquid condensate then returns by gravity to the sodium pool. Once all the salt has solidified, the process stops, and the engine will cool down unless solar or combustion heating has resumed to begin re-melting the salt.

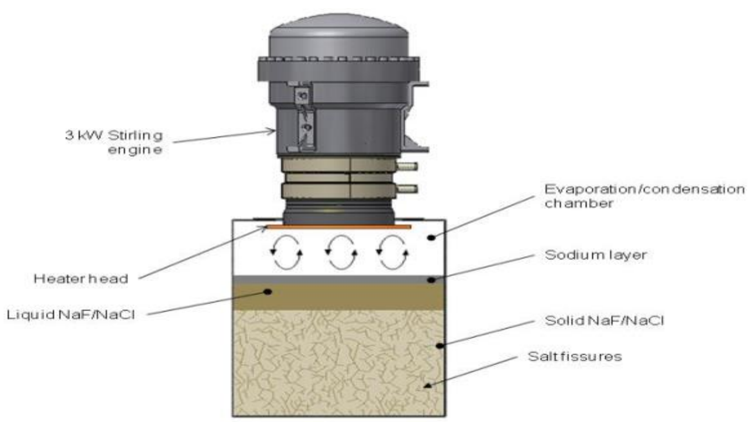

Figure 11. Schematic illustration of a Stirling engine integrated with GREAT TES

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The GREAT TES concept was successfully integrated with an Infinia 3.5-kW FPS engine and demonstrated in the lab. In the laboratory test module shown in Figure 12, a NaF/NaCl eutectic salt that melts at 680 C was used. One identified issue is the tendency for a crystalline salt surface layer to form and attach to the container wall during cooldown. This prevents the remaining molten salt below that level from properly interacting with the sodium layer. It was shown that problem could be eliminated by using trace heating to maintain the circumference of the TES vessel above the TES melt temperature in the region that can have a liquid/solid salt interface during the heat extraction mode.

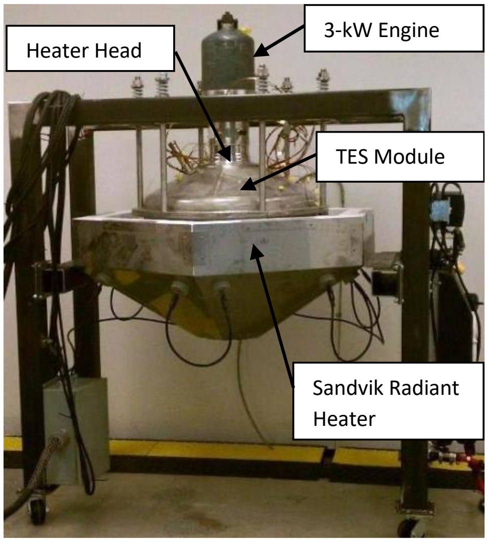

Figure 12. Laboratory test unit for GREAT TES demonstration

This approach can also be readily adapted to hybrid operation using hydrogen, natural gas, or other fuels to enable continuous power production during periods of extended cloudy conditions. Lithium salts generally have a significantly higher heat of fusion than other salts, but those are tentatively avoided for utility scale storage so Li cost or availability will not be an issue. The 680°C melting temperature of the salt used in the demonstration unit requires relatively high-temperature containment materials. There are many other salt eutectics available in the range of 550°C to 650°C that can use more common lower cost containment steels, with some compromise in system efficiency due to the lower operating temperature. Choices will be made based on overall system optimization and LCOE considerations.

Delta Stirling engines integrated with GREAT TES can be installed with parabolic dish concentrators or used in conjunction with small central receivers (aka power towers) as described schematically above. A conceptual TES tank configuration designed to be heated by a small CR with heliostat mirrors focused on the tower receiver is illustrated in Figure 13. A state-of-the-art molten salt receiver can be used with a molten salt heat transport system to melt the salt in a ground mounted TES tank, but the preferred approach is an advanced two-phase liquid metal receiver and heat transport system.

A wide range of capacity levels are feasible. A conceptual design for a 1-MW installation with 12 hours of TES was conducted. The TES tank is 20' in diameter by 18' high with 20 50-kW delta engines using current commercial Qnergy 8-kW alternators installed on top as 10 stacked pairs. This would be capable of producing 1-MW continuously by using fuel for heating during cloudy periods. Future versions are expected to use fewer engines with higher capacity to reach the desired power level while reducing manufacturing cost.

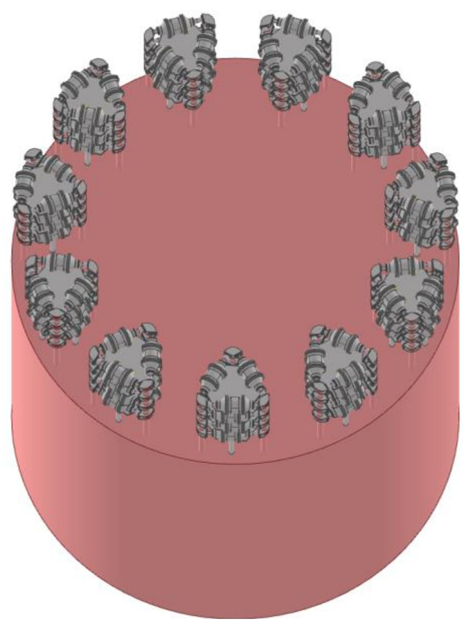

Figure 13. Conceptual layout of 1-MW solar generator with 12 hours of GREAT TES

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SI Experience that Validates Phase-Change Salt TES Life and Reliability Projections

SI experience with phase change salt TES helps to validate the expectation that GREAT TES will be a reliable long-life subsystem for the Grand Vision. The technology legacy discussion in a subsequent section of this white paper applies to phase change salt TES as well as FPS engines. The 25 years of fully implantable artificial heart power source development included phase change salt TES integrated with most of the eight generations of artificial heart engines. During most of that period TES was used to buffer between the fixed heat output of the radioisotope heat source and the wide variation of blood pump demand, and therefore heat input needs, that ranged from sleeping to vigorous exercise. Later, the use of an implantable radioisotope heat source became politically unacceptable. The program continued by transitioning to an electrically heated salt module that could be melted in one hour from an external power supply using a transcutaneous transformer, and then provide up to eight hours of fully autonomous operation as the salt solidified. Extensive experience with integrated TES in FPS engines is referenced by the following examples.

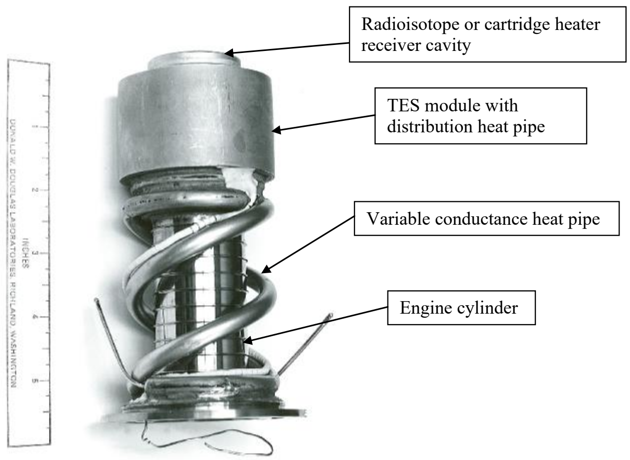

Figure 14. Artificial heart TES engine cylinder

Figure 14 shows an engine cylinder from the System 4 artificial heart engine without the vacuum insulation housing or heat source in place. The System 4 engine was operated successfully for seven years using both radioisotope and electrical heat sources and was fully functional when retired from service. This engine cylinder illustrates key components, including a TES module, a distribution heat pipe to transfer heat from the isotope to the engine heater head, and a variable conductance heat pipe that provides over-temperature protection by shunting excess heat directly from the hot end to the cold end.

Another relevant assembly from the heart program is the TES endurance demonstration unit pictured in Figure 15. This 304 stainless steel TES module was filled with a LiF/NaF eutectic salt that melts at 652°C and was cycled through 3 melt/freeze/cool cycles per day for over 4 years. After this, it was sectioned and evaluated by the Metallurgy Department at Exxon Nuclear. The Exxon evaluation report concluded that the salt attack on the steel was characterized by a slight roughening of all inside surfaces with slight intergranular attack at depths from 0.0002 in. to 0.0015 in. Decarburization of the steel to a depth of 0.003 in. was also observed, but this was concluded to be beneficial because the reduced carbon in the steel surface region desensitizes it to grain boundary corrosion. External oxidation of the vessel was substantially more severe than the effects of phase change salt exposure. The results of these and other TES tests provide a solid basis for projecting that a highly reliable and long-life GREAT TES system can be implemented using relatively common and cost-effective materials.

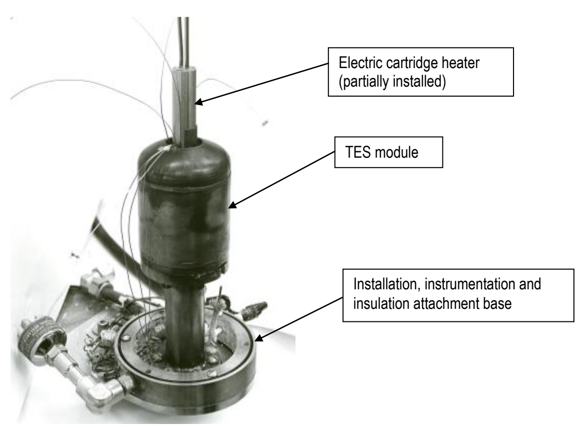

Figure 15. Artificial heart TES endurance test unit

In addition to the Infinia-related work described above, Oak Ridge National Laboratory (ORNL) conducted extensive containment material compatibility testing for salt mixtures in support of molten salt nuclear reactor development concepts in the 1960s and 1970s. In recent years, ORNL has conducted more such studies to evaluate higher temperature molten salt candidate compatibility with containment materials for both molten salt reactors and advanced CSP heat transport and molten salt TES systems. The overall conclusions confirm that salt TES is practical with no significant barriers to long term life and high reliability.

Delta Engine and GREAT TES Impact on Levelized Cost of Energy (LCOE)

- Delta Stirling engine and GREAT TES cost is projected to be very competitive.
- Bracketing production cost estimates used raw material costs with a manufacturing multiplier for the low end and Qnergy low-production Stirling engine prices with conservative learning rates for the high end, plus high/low power plant life projections.
- Results of $0.002/kWh to $0.016/kWh for the TES and generator best case/worst case contributions to LCOE are outstanding.

A critical factor in sorting out winners in the CSP arena is the LCOE, which is the average amortized cost of energy generated by a power plant over its lifetime. DOE regularly updates goals for LCOE in all solar technologies and has sponsored specific evaluations of it in many CSP programs using their standardized Solar Advisory Model (SAM). A recent comprehensive and consistent annual update (NREL, 2023) has a generic assessment of central receiver CSP LCOE at about $0.10/kWh. Under three scenarios of no, moderate or advanced technology innovation over the next decade they project 2030 LCOE to range from about $0.06/kWh to $0.10/kWh. DOE continues to use 2021 dollars for assessments.

It should be stressed that what we are providing in this section is <u>not</u> an LCOE assessment, but a best case/worst case bracketing analysis for GREAT TES and delta Stirling generator manufacturing and installation cost amortized over their operating life. That limited portion of their contributions to LCOE ranges from $0.002/kWh to $0.016/kWh. These numbers do not include any cost of money (interest) assessment or concentrator, receiver, and heat transport system balance-of-plant components that are common to all CSP systems. They do indicate that this system should be very cost competitive with any alternative renewable power generation and energy storage system.

Infinia conducted an LCOE task in 2012 for a complete dish Stirling system including four hours of phase-change salt TES (not the GREAT configuration) under DOE contract and results were slightly better than DOE CSP goals at that time. The delta Stirling configuration eliminates many expensive and complex components in existing FPS engines, such as the one used for that evaluation, to reduce engine cost by at least a factor of two. The GREAT TES approach also eliminates many expensive and complex components required by the earlier Infinia phase change salt TES system and by all molten salt TES systems. GREAT TES will accordingly have substantially lower cost than those. Operation and maintenance cost is projected by DOE to be a little less than $0.01/kWh for CSP but should be much lower when using GREAT TES and delta Stirling generators since they are hermetically sealed. Any failed units will simply be recycled and replaced, and that is expected to be rare.

A bracketing range of likely delta Stirling engine manufacturing cost can be estimated by considering two limiting extremes. The high end can be derived from Qnergy commercial Stirling engine sales price and the low end from raw materials cost. Qnergy currently sells only complete Stirling generator systems, but they formerly sold a 6-kW bare engine for about $25,000, or $4,167/kW when production was about 100 total units per year. The delta hardware simplification will reduce that by at least a factor of two and automotive scale automated manufacturing will provide dramatic reductions. A very conservative mass production cost reduction of only a factor of two would bring the engine cost to about $1000/kW.

A lower limit on capital cost of machines like the delta Stirling engine is the raw material cost times a manufacturing factor. A properly implemented delta Stirling engine will have the lightest weight and lowest cost possible for a Stirling engine. Scoping calculations using existing Qnergy components indicate that an existing technology delta version would weigh about 25 pounds per kilowatt. The dominant material is high-strength steel, with about 2% of the weight in magnets and about 12% in copper. Copper prices have been volatile over the past decade with about a $3/lb. average and near $4/lb. currently. Steel has also been volatile, but a reasonable value for high strength is about $5/lb. The only strategic and high-cost material in a delta engine is the Nd in the Fe/Nd/B magnets, often referred to as NEO magnets. The bulk raw material price for Nd was about $25/lb. in the 2000-2020 time frame. In 2022 it spiked to about $100/lb. and is currently (January 2025) around $40/lb. To assess the significance of that, current Qnergy linear alternators use about half a pound of NEO magnets per kW. Since Nd accounts for about 25% of the NEO magnet weight, at $100/lb. the Nd cost is about $12 per kW. Using the high levels for these ranges results in a material cost of about $130/kW. Doubling this to account for automotive-scale manufacturing and assembly of relatively simple components gives a ballpark estimate of $260/kW.

LCOE explicitly includes a plant operating life, for which DOE defaults are 20 and 30 years. Delta engines and GREAT TES are expected to have a very long life based on present anecdotal evidence. We will here bracket the range with 10-year and 50-year examples. Capacity factor is typically significantly less than 100% for CSP but we will assume 100% availability for the proposed utility scale system. That is reasonable due to the extreme modularity where any issue with one dish or mini-tower module will have negligible impact on the plant output and the failed module can be replaced in a short time. The bracketing range of $260/kW to $1000/kW over a 10-year life translates to an engine contribution to LCOE of $0.003/kWh to $0.011/kWh. For a feasible 50-year life this range drops to $0.0006/kWh to $0.0023/kWh. Applying a similar approach, but with 1.5 times the material cost to account for tank fabrication and salt processing, GREAT TES with 12 hours of NaF/NaCl storage results in a TES contribution to LCOE of about $0.005/kWh to $0.001/kWh for 10-year and 50-year life respectively. Combining these results gives a best case/worst case range of $0.002/kWh to $0.016/kWh for the portion of LCOE attributable to delta engines and GREAT TES.

Stirling Innovations, LLC Technology Legacy and Resources

SI is a small startup company, but it has access to extensive expertise and the ability to execute on its plan when suitable funding resources become available. SI was founded in 2021 for the express purpose of developing and commercializing delta Stirling machines and GREAT TES. The legacy technology timeline in Figure 16 provides context that supports the delta engine and TES assertions above. While the timeline is strictly accurate only for SI founder Maury White, the progress at every stage was totally a team effort. More than a dozen former Stirling engineer colleagues and competitors have expressed enthusiasm for the delta concept and a desire to support delta Stirling development effort as resources become available.

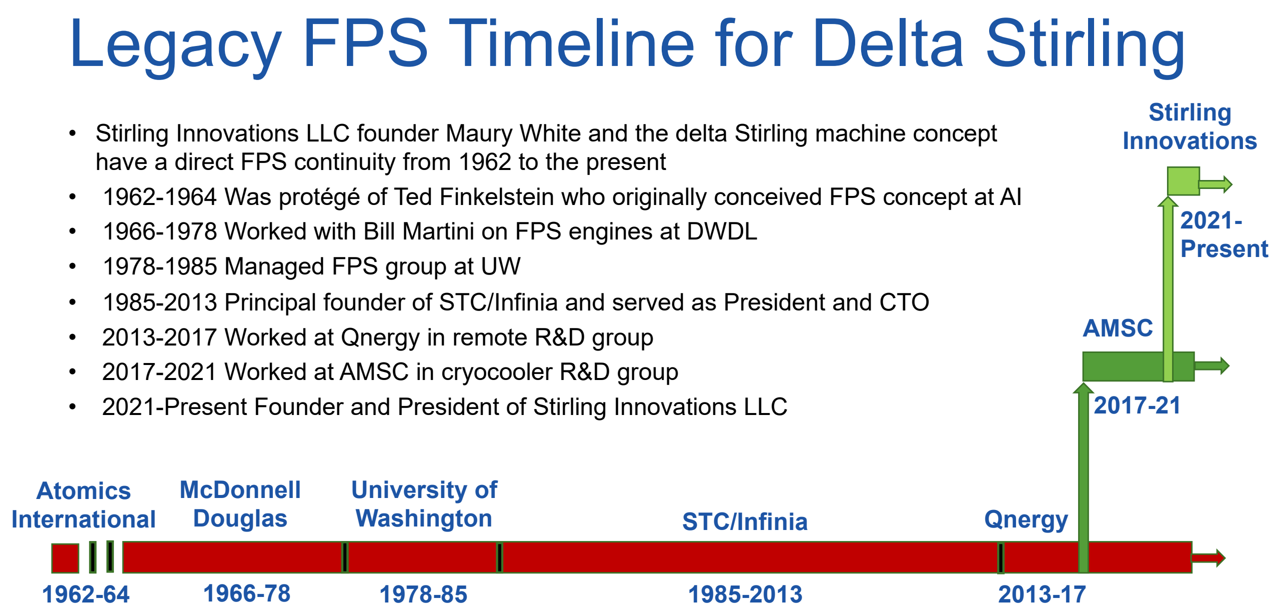

Figure 16. Legacy timeline for Stirling Innovations LLC and delta Stirling machines

The journey began in 1962 when Mr. White was assigned to work with Ted Finkelstein, who had just been hired by Atomics International (AI) to develop his concept for a free-piston Stirling engine with potential application as a power source for space nuclear power. Dr. Finkelstein and Mr. White analytically modeled and built crude models of a 4-cylinder DAA FPS demonstrator and a separate linear alternator. After a year and a half with good progress on both fronts, a Vice-President of AI parent company North American Rockwell became aware of this IRAD effort and asserted that linear alternators were not feasible because a crack engineering team he managed at Sundstrand had tried and failed to develop a linear alternator. The AI Stirling effort was terminated that day. Two years later, Dr. Bill Martini, who had worked on thermionic space power systems in the same group with Dr. Finkelstein and Mr. White, became a founding Manager at the newly established Donald W. Douglas Laboratories (DWDL) of Douglas Aircraft Co. (subsequently McDonnell Douglas) in Richland, WA. Dr. Martini had been intrigued with the FPS work at AI and convinced DWDL management to fund an internal FPS project. He then hired Maury White to initiate that effort. By this time, Dr. William Beale, to whom Dr. Finkelstein had described the AI FPS project, had reduced a beta FPS feasibility demonstrator to practice. All FPS work for four decades was limited to beta and gamma configurations.

In 1967, the DWDL group within McDonnell Douglas was awarded a contract with the National Heart, Lung, and Blood Institute to develop a fully implantable radioisotope fueled artificial heart FPS power source. While also conducting several other FPS development contracts, the artificial heart program became the primary funding source of the DWDL Stirling group for 25 years as it transitioned to the University of Washington (UW) and Stirling Technology Co. (STC). Many innovations, including flexure bearings integrated with clearance seals and phase-change salt TES integrated with FPS engines, emanated from the artificial heart program. STC was eventually renamed Infinia and went on to conduct numerous FPS and phase-change salt TES prototype development government contracts as well as to raise extensive capital for commercial solar dish engine development. The commercial effort installed over a hundred dish engine systems in fields of one to 35 units as the system iterated through four engine generations. This culminated in the installation of 429 3.5-kW dish systems as a 1.5-MW green power plant at the Tooele Army Depot in 2013. While the solar development was a technical success, and closely approached initial cost and performance goals, the much more rapid decline in PV prices than anticipated during the development period led to a non-competitive product and resulted in Infinia bankruptcy in 2013. An Israeli company Qnergy acquired the Infinia assets, including the production facility in Ogden, UT, and very successfully adapted the solar engines to serve the remote power market. An Infinia R&D and cryocooler group that remained in the Richland, WA area when the Board of Directors moved Infinia to Ogden, UT developed uniquely suitable cryocoolers that integrated with an AMSC high temperature superconductor (HTS) degaussing system for Navy ships. In 2017 AMSC acquired that group from Qnergy and continues to produce the Navy cryocoolers in Richland, WA. Mr. White left AMSC in 2021 to found SI. Infinia, Qnergy and AMSC have been very successful with the technologies developed for their respective application of FPS systems. Some relevant examples are briefly described below.

Infinia Engine Examples

One major Infinia project funded by DOE and NASA GRC was to develop Radioisotope Stirling Generator (RSG) engines for deep space power systems. About 25 FPS RSG engines were built with four of them designated for endurance testing. Those have all operated at GRC since about 2007 with no maintenance or performance degradation. One endurance test engine was taken offline and destructively evaluated after 105,616 hours (12 years) of operation (NASA, 2020). Some internal oxidation was observed, believed to have resulted from early operation when atmospheric oxygen permeated O-rings before recognition of the need for inert cover gas around the O-rings. The hot region of the regenerator showed some oxidative damage, but no incipient failure mode was identified. Next generation designs took measures to mitigate potential oxidation issues. The other three endurance engines continue on test with more than 18 years of operation. One continues to extend its world record for dynamic power systems on a daily basis, with the other two only a few hundred hours behind. The photo in Figure 17 shows the single RSG #13 on endurance test after its companion #14 in the normally balanced pair was shut down for the destructive evaluation noted above. The primary commercial installation by Infinia was the 1.5-MW dish-engine field at the Tooele Army Depot discussed above. About one-third of that installation was shown in Figure 4.

Figure 17. Infinia endurance test engine in operation at NASA GRC

Qnergy Engine Examples

Qnergy commercialization of the advanced Infinia solar engines was based on adapting them to meet identified remote power market needs. They have now installed thousands of their remote power generators that have accumulated millions of virtually trouble-free hours of operation in often harsh field conditions. Their PowerGen™ FPS generators (https://qnergy.com/powergen-series/) serve a wide range of remote power needs with power levels from 600W to 5650W offered. They have more recently been manufacturing and installing their Compressed Air Pneumatic (CAP) systems (https://qnergy.com/compressed-air-pneumatics/) that dramatically reduce methane emissions on gas pipelines, while also providing electric power and dry instrument air. A CAP installation, which also includes a PowerGen™ unit, is shown in Figure 18. A typical PowerGen™ field installation is shown in Figure 19. Much more detail can be found at www.qnergy.com.

Figure 18. Qnergy CAP field installation

Figure 19. Qnergy PowerGen field installation

AMSC Cryocooler Example

The AMSC-West FPS Stirling team in Richland, Washington developed and manufactures the best performing cryocoolers available to support AMSC Navy ship HTS degaussing systems. Installation of the first operational AMSC HTS degaussing system was recently completed on LPD 28, the USS Fort Lauderdale. Each ship uses 21 cryocoolers to enable functionality of the advanced HTS degaussing loops on board. Each cryocooler nominally lifts 300-W at 50°K with world-class efficiency and nearly silent operation. Firm orders are in place for production cryocoolers to support five more LPD ship installations and more than 100 of those have already been delivered from the AMSC-West facility in Richland, WA. Once the substantial operational benefits are confirmed many more orders are anticipated.

Concentrating Solar Power (CSP)

Some potential stakeholders know little about CSP, so this section is provided as a general overview of the current status for those who want more background context to better understand how delta Stirling engines and GREAT TES fit in. Modern CSP systems are utilized in three primary configurations: parabolic troughs, parabolic dishes, and heliostat central receivers (CR). Other CSP technologies such as Fresnel concentrators are not practical at Grand Vision scale. Trough systems use a relatively straightforward single axis tracking system, but dishes and heliostats require precision tracking of the sun on two axes. (Mehos & et.al., 2020) identifies 11.26 GW of operational CSP plants worldwide at the end of 2018. This figure includes some the 90 operating plants without TES as well as the 6 GW of partially dispatchable CSP noted earlier. Various DOE projections anticipate continuing increases in the deployment of CSP. An optimistic European perspective on current and future CSP is covered in (Blanco, 2016), with a 2024 updated second edition scheduled. These documents validate key elements of the Grand Vision as established mainstream CSP progress.

Parabolic Trough Systems

The generation of solar electric power from a parabolic trough CSP system was implemented in Egypt in 1912 by Frank Shuman and used to pump 6,000 gallons of water per minute from the Nile River to irrigate cotton fields (Seba, 2010). The first modern incarnation of a similar solar power plant is the Solar Electric Generating Systems (SEGS) installation in California. Luz Industries commissioned nine SEGS units between 1984 and 1990 that totaled 354 MW in Daggett, Kramer Junction and Harper Lake. Luz ended up in bankruptcy, but most of the SEGS units continue to produce solar power with new ownership. As of 2017, SEGS had produced a total of 18 million megawatt hours for California ratepayers. The first SEGS unit had an early hot oil TES that enabled it to operate for about three hours after sundown when peak loads often occur for much of California. SEGS can also operate in a hybrid mode to provide peaking power at any time by using natural gas to heat the heat transfer fluid. These attributes of CSP systems add significant value relative to PV systems.

The 280-MW Solana trough CSP plant with six hours of TES that went online near Gila Bend Arizona in 2013 was at that time the largest trough system with TES in the world. The Solana installation, (Power Technology, 2013) and (HelioCSP, 2013), includes 3200 parabolic troughs, each of which is 400 feet long, 18 feet wide and 19 feet high. The trough field covers 1757 acres out of the total site area of 1920 acres. Hot oil heat transfer fluid (HTF) is heated to 735°F by pumping it through the line focus tube of each trough. This heat is transferred both to a steam boiler that drives two 140-MW steam turbines and to the TES salt in six of the 12 thermal storage tanks. After sundown, the molten salt is pumped through the steam boiler from the hot tanks to the warm tanks at 530°F to utilize the sensible heat stored in the salt over the 205°F (114°C) temperature difference to drive the steam turbines.

> The Solana plant requires about five times more tank capacity than a similar capacity plant using GREAT TES and delta Stirling engines while providing only about half of the operating time using TES. This factor of ten difference would be only marginally smaller for current state-of-the-art CR CSP installations. The SI GREAT TES tank with integral delta Stirling power generators is also far simpler to fabricate and maintain than any other CSP approach.

Each of the 12 molten salt storage tanks is 140 feet in diameter and 45 feet high, leading to a total tank volume of 8.31 million cubic feet. 125,000 metric tons of solar salt (a mixture of potassium nitrate and sodium nitrate) is loaded into those tanks to provide the desired six hours of dispatchable power. More recent molten salt TES troughs and towers use molten salt rather than oil for the HTF, which enables higher temperature differences between hot and warm tanks to increase efficiency. Single-axis parabolic troughs have a line focus that is fundamentally limited to producing temperatures on the order of 565 °C or less, even with molten salt as the HTF. For Stirling or Brayton power generation to be efficient higher temperatures are needed, so they use two-axis parabolic dishes or heliostat systems as described below.

Dish Stirling Systems

Solar parabolic dish concentrators have also been around for a long time. In the 1860s French mathematician August Mouchet began developing parabolic dish concentrators for a variety of applications including a solar heated steam engine (DOE Energy Efficiency and Renewable Energy, ca 2002). Esteemed innovator John Ericsson (designer/builder of the Monitor during the Civil War) spent the last decades of his life in an obsessive quest to perfect solar dish Stirling engines and built several operating prototypes (Church, 1906). Significant efforts to develop modern dish Stirling systems have been made by many developers throughout the world. (Stine, 1994) provides a comprehensive overview of seven complete dish Stirling systems and 19 programs for developing critical components. Two more recent installations of 1.5 MW dish Stirling projects were implemented by Stirling Energy Systems (SES) in Peoria Arizona using 60 25-kW kinematic Stirling dish systems in 2010 and by Infinia Corporation at the Tooele Army Depot in Utah using 429 3.5-kW FPS dish systems in 2013. A photo of about one-third of the Infinia installation was shown in Figure 4.

SES went bankrupt in 2011. Their assets were acquired by a Chinese company and all physical and intellectual property was transferred to China. Infinia filed for bankruptcy in 2013 after investor funding was withdrawn and its assets were acquired by Qnergy in Israel. Qnergy adapted the next-generation Infinia 8-kW engine for use as remote power generators and is manufacturing them in Ogden Utah at the prior Infinia manufacturing plant. They are successfully marketing several variants to oil and gas producers and other clients who need extremely reliable low-maintenance power generation in difficult remote environments, with more than 2000 now in the field.

While dish Stirling systems have had far fewer field installations than trough or tower CSP systems they have desirable characteristics that make them a strong contender for long-term commercial market success as described above. The delta FPS engine integrated with GREAT TES is well-suited for both dish and mini-tower systems, where their modularity and scalability make installations much more flexible than for existing central receivers. Delta FPS engines are unique in offering reliable maintenance-free operation with high efficiency and low cost over a range from kilowatts to hundreds of kilowatts or even megawatts. With extensive modular installations, that can be extrapolated to hundreds of megawatts or gigawatts.

Central Receiver (CR) Systems

The name central receiver or power tower is descriptive of an arrangement of heliostat mirrors focused on a tower, which is more-or-less centrally located within the heliostat field. The receiver at or near the top of the tower absorbs the focused heat and transfers it to a ground-based TES and/or generator using a heat transfer fluid. The first modern CR system was the 1982 DOE-funded Solar One 10-MW demonstration system in California. Oil pumped through the receiver absorbed the heat that was transferred to storage tanks on the ground. As the oil was pumped from the hot tank to a cooler tank it generated steam to operate a steam turbine. After a successful demonstration period Solar One sat idle until it was upgraded by DOE in 1996 and re-designated as Solar Two. Solar Two included additional heliostats and changed to a molten salt heat transfer fluid and storage system that enabled higher temperatures and higher efficiencies. Successful demonstration of the Solar Two approach established the viability of the concept, but it was not until 2007 that the PS10 plant in Spain became the first commercial CR. That facility continues to produce 11 MW for the Spanish grid and has been followed up by several additional CR plants around the world.

Trough systems dominated CSP installations until around 2015 while a few CR installations further refined the concept and provided lessons learned. The higher CR temperatures enable higher efficiencies, and the cost has dropped below that for trough systems, so most recent and planned CSP installations are central receivers. The trend is also solidly in place for including TES to add dispatchability value to the solar power generation. The largest CR installation is the Ivanpah system that began operations in 2014 in California, just across the state line from Primm Nevada. This three-tower plant is unusual in that it does not include TES. It approximates the practical size limit for each of the central receivers based on the maximum distance a heliostat mirror can be usefully focused on the receiver near the top of the tower. Details from (California Energy Commission, n.d.) state that two of the units each generate a nominal 133 MW using 60,000 heliostats and occupying about 1100 and 1200 acres. The third unit on about 900 acres generates 120 MW with 53,500 heliostats. The tower-mounted receivers directly generate steam to drive steam turbine generators. Each plant also includes a natural-gas-fired steam boiler that assists the morning start-up cycle and can be used to maintain operation during cloud transients.

The key takeaway from this section is that solar concentrators for CSP systems have a solid track record in all three configurations. While they are a major cost element for all CSP systems, they will not be an impediment to widespread implementation of the Grand Vision.

High Temperature Superconducting (HTS) Transmission and Distribution

HTS transmission and distribution is independent from the purposes of this white paper. While it is not essential to the Grand Vision, particularly in the early years of development, we believe it is the most practical way of developing the transmission and distribution infrastructure necessary to accommodate large scale CSP generation in the southwest U.S. A major consideration is that it avoids the argument that it would not be practical to access all the necessary rights of way for conventional transmission. Several companies worldwide have developed the necessary HTS technology. Field installations have demonstrated the functionality and advantages. HTS cables have been demonstrated to transmit more than 5 GW, the practical limit for the highest capacity conventional transmission lines to date. HTS cables operate at very high current levels with relatively low voltages. Installations to date have been little more than a mile in length but there is no fundamental impediment to lines extending hundreds or thousands of miles. In general, AC HTS cables are used for short distribution lines and DC HTS cables for long transmission lines.

Figure 20. AMSC 3-phase AC HTS distribution line emerging from the ground to transition to conventional power lines (Courtesy of AMSC)

DOE funded significant HTS technology development and demonstration projects for several years until Secretary of Energy Steven Chu shut down all DOE HTS activity circa 2009. Commercial cable installations have been limited since then because the economics are currently viable only in special urban situations where conventional power line additions in congested areas are particularly problematic. AMSC is a premier U.S. provider of HTS cables and other superconducting systems. Figure 20 illustrates an AMSC AC installation where three separate cables emerge from the ground and transition to conventional 3-phase AC transmission lines. Figure 21, also courtesy of AMSC, provides a graphic comparison of conventional and HTS 5-GW transmission lines. The conventional lines are on towers that are 130 feet high and require a 600-foot right-of-way. By contrast, the HTS cable is buried in a three-foot-wide trench and requires only a 25-foot right-of-way for installation and maintenance. While costs are only marginally competitive now with only small companies and short installations directly involved, large multi-national corporations have signaled their intent to adopt HTS cable technology at scale that will reduce prices substantially once utilities and authorities embrace the approach.

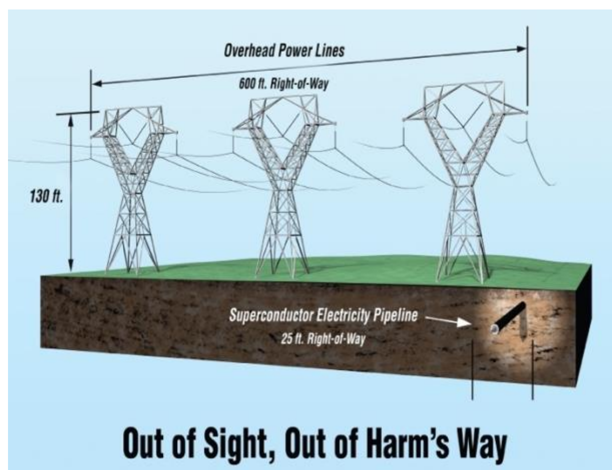

Figure 21. AMSC conceptual comparison between conventional transmission lines and DC HTS lines

STIRLING INNOVATIONS, LLC

Proposed Development, Demonstration and Validation Plan

The development and demonstration of delta Stirling engines and GREAT TES can be accomplished under a wide range of scenarios. A logical development approach is outlined below. Modifications to this plan are subject to negotiation as determined by specific objectives of the funding organization. SI has identified more than a dozen experienced Stirling engineers who are anxious to participate in the development of delta engines. Most of them are in a position where they can support this effort as independent contractors on a part-time basis, and some would be interested in a full-time role. Former Infinia VP Engineering, Dr. Songgang Qiu, has agreed to assume a similar role at SI and to function as future successor to SI Founder and CTO, Maury White. He is currently a tenured Mechanical Engineering Professor at West Virginia University and will coordinate the 50-kW delta engine development while maintaining a light teaching load or taking a sabbatical. In keeping with the SI embodiment of an Exponential Organization, he will select from the experienced Stirling engineers he knows well who have expressed a desire to participate in delta engine development as staff-on-demand contract engineers.

Maury White, GREAT TES inventor with decades of phase-change salt TES experience, will coordinate the GREAT TES scaled up system development. Most of the engineering implementation will be provided by the Columbia Basin Consulting Group (CBCG). CBCG has extensive experience with sodium and molten salt systems, primarily from development and operations at the Fast Flux Test Facility (FFTF) fast reactor plant at the DOE Hanford Engineering Works in Richland Washington. They are currently supporting development of the sodium coolant and molten salt TES subsystems for Bill Gates' TerraPower Natrium reactor. CBCG supported Infinia for the DOE contract that first demonstrated the GREAT TES concept. They also operate with staff on demand, accessing dozens of experienced engineers as needed for active projects.

Development Plan Overview

The planned approach is to design, fabricate and test a 50-kW fully balanced delta Stirling generator using two 3-cylinder engines as illustrated in Figure 10. This milestone will establish the functionality and baseline performance of the delta engine to validate the efficacy of moving forward. The first delta prototype engine will be essentially a pre-production engine rather than a laboratory demonstration because the most critical subsystems are already being commercially produced on the Qnergy production line. Other components use established Stirling engine heat exchanger configurations with an extensive history. Because of commercial component availability, a refined version of this 50-kW engine is anticipated for use in early 1-MW system implementations. Scaling to larger engines for production at scale will further reduce future cost. The delta engine demonstration will be managed by Songgang Qiu as noted above. Dr. Qiu managed several Infinia development programs including the engines that continue in operation at NASA GRC after more than 18 years and the commercial engines that evolved into the Qnergy production engines.

A parallel development will demonstrate and characterize a GREAT TES system scaled-up from the 10-kWh employed in the laboratory feasibility demonstration to 300-kWh. This is another key validation step to demonstrate that the concept functions as expected when scaled to a more relevant capacity. A key unanswered question is what salt purity and processing steps are required for successful operation. The laboratory demonstration unit used reagent grade salts but much lower grades are needed to maintain reasonable costs. Processing of the salt prior to adding the sodium layer includes melting to form the eutectic under a vacuum to extract volatiles. Most solid contaminates that don't react with the salt would sink to the bottom and stay there since the liquid salt is less dense than water. Because volatiles are actively removed it is likely that a very low-grade salt purity can be used. This thesis will be tested at the beginning of this project using small modules similar to ones used in the initial DOE project. They will include a heating source, salt processing, sodium fill and a calorimeter to document TES performance and will compare a range of salt purities. These results will guide the selection of salt purity to be used for the scaled-up module. CBCG has Richland and Pasco Washington facilites that include appropriate laboratory space designed for safe handling of liquid metal systems. GREAT TES development does not require the degree of specialized expertise that Stirling machines do, so building a long-term development team will not be difficult.

Development of the two units described above will be coordinated such that they can be integrated as a complete power generation and storage system after fully characterizing them as independent subsystems in a laboratory environment. Independent testing enables performance of each subsystem to be accurately quantified in a controlled setting. Documenting performance as a fully integrated subsystem is an important validation milestone to justify further scale up.

There are multiple options for how to implement the first full system demonstration on sun. A CR demonstration system can use any power generation capacity from the sub-hundred kW range to the MW range. The National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories is a CR specifically developed to support advanced CSP technology demonstrations. Alternatively, several small commercial heliostat systems have also been demonstrated and it may be possible to lease usage of one. The most advanced of these is Heliogen and they are the primary candidate for a long-term heliostat/tower team member.

For dish Stirling systems an ultimate commercial version will require an upgraded dish capacity with enough concentrator area to support on the order of a 25-kW delta engine with 12 hours of TES. The STPS dish size will support a 25-kW engine with about four hours of TES. A variant on that would be to operate the engine at 50 Hz to produce 20-kW with about three percentage points higher efficiency. That will enable about 8-9 hours of TES, needing only a modest addition of facets or further engine capacity reductions to provide 12 hours of TES. Larger dishes with a capacity that would support a 30 to 40-kW engine with 12 hours of TES have been successfully demonstrated and some scale-up beyond that is possible.

Examples of potential future development activities include the following:

- Endurance test delta engines to accumulate statistically significant long-term data.
- Establish procedures for level of salt purification and processing needed at scale.
- Scalability approach and manufacturing cost projections will be updated at each stage.
- Based on the initial demonstration system results the team will determine whether to go directly to a 1-MW demonstration plant or an intermediate level.
- Small utility-scale installations to power AI and other server farms are the initial target market.

Conclusions

Two technology innovations with the potential to dramatically reduce the level of harmful emissions associated with electric power generation using fossil fuels are described and a case is made for their commercial viability. Further scaling validation is required to increase the confidence level of a successful outcome. That can be done in an incremental manner with increasing levels of resource commitments only after success has been demonstrated at each stage. SI has access to the engineering and manufacturing resources needed to progress to an advanced system demonstration. We are seeking a joint venture or other collaborative arrangement with an entity that provides the financial resources necessary to conduct this effort and to support both the initial development and further development and commercialization, as warranted by results. Once the critical demonstration steps are completed there are many government, utility, and commercial opportunities to support increasing scale.

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