Gen 3 Concentrating Solar Power

By John Benson

March 2023

1. Introduction

Many years ago, I felt the technology war for generating power had been won by photovoltaics (PVs). I was right, but I might have missed a few words in the above conclusion: "…the technology war for generating **electric** power… photovoltaics (PVs) **plus battery energy storage (BESS)**."

Lately I've been working on a non-consecutive series of posts on the "Industrial Decarbonization Roadmap." I posted the last of these for the major greenhouse gas (GHG) emitting industries on March 9th (summarized and linked below – Part 6 has links to the other parts of this series). All of these industries need energy in two forms: electricity and heat. Although electrification is a major pillar in reducing the amount of GHG each of these industries emit, each still needs large amount of thermal energy (heat). Yes, you can generate heat with electricity, but this is generally inefficient, especially for high-temperature heat.

Occasionally I come across a document that is overwhelming in scope and information-content. This requires me to adjust how I post papers based on this document if it falls within the scope of subjects that I normally write about and contains information my readers would want to read. The DOE Industrial Decarbonization Roadmap is one of those documents.

As I was skimming through the primary document, I decided pretty quickly that this would require multiple papers to cover, and thus a series. Part 6 is on Cement Manufacturing. In 2020, the United States produced 87 million metric tons (MT) of Portland cement and 2.3 million MT of masonry cement at 96 plants in 34 states. Of those, 86 plants employed the dry kiln process and nine used the wet kiln process. In 2020, sales of cement were around $12.7 billion and consumption was about 102 million MT. Texas, Missouri, California, and Florida have the highest cement production, in that order, and they account for about 45% of U.S. cement production.

https://energycentral.com/c/ec/industrial-decarbonization-roadmap-part-6-cement-manufacturing

The current U.S. Department of Energy understands the requirements for large amount of thermal energy. Thus, they have continued to plug away, reinventing concentrating solar power (CSP) and associated technologies. This paper will review their efforts, including a major CSP test facility that they just broke ground on in New Mexico.

2. Why CSP

In addition to CSP's ability to generate very high temperature thermal energy and store this energy for long periods, there are few other tricks it performs that are beyond PVs capabilities:

- By using thermal storage and advanced thermal generation technology (read: Brayton power cycle using supercritical carbon dioxide (sCO_2) as a heat-transfer fluid) can store and convert solar energy much more efficiently than PV plus BESS. This technology has a conversion efficiency upwards of 50 percent.

- Several different high-temperature heat transfer fluids can be stored for days to weeks, resulting in the ability to provide electric-energy (using the above described generation tech) during long-term peak demand periods.

Economically PV+BESS technology is hard to beat, but that assumes the land for the PV is very low cost or free. Currently we have lots of available land in the Western U.S., but environmentalists and utility-scale PV-developers are already starting to butt heads. In the Livermore Valley, California, where I live, recent significant PV projects have faced a major fight, and I really don't believe there will be more of these here in the future.

But there are many older existing projects that could be repurposed into CSP, especially out in the deserts of Southern California, which are ideal for concentrating solar power.

3. Current CSP Technology and Alternatives

Let's start by expanding on the points I made in the prior section. The most efficient technologies for PV arrays being currently deployed is around 20%. If this energy needs to be stored for use at the end of the end of the Summer peak demand period (near sunset or later), the most popular method is to use BESS based on LFP Lithium-Ion battery technology. The typical round trip efficiency for this storage[1] is around 80%. Thus we are now down to 16% efficiency, for late-peak energy, best-case.

You can now see why DOE decided to shoot for high-efficiency as their main metric for success. Of course that also means aiming their development far into the future (I would guess 3035 for first commercial deployment). Thus they mainly using bleeding-edge technology, many alternatives, and developing multiple alternatives of each major plant component. Each of these are described in the following subsections.

3.1. Heat Transfer Fluid

A few decades ago I was a member of the Livermore Jaycees. One of my fellow members was another engineer that worked for Sandia National Labs (their headquarters is near Albuquerque, NM. But they have a major facility in Livermore). He worked on a major CSP project in Southern California. If I remember correctly, their heat-transfer fluid was liquid sodium. Having earlier worked on several Liquid Metal Fast Breeder Reactors (which also used sodium), I know that this metal can be very problematic. Sometime in the intervening decades DOE / Sandia switched to molten salt (much more stable than sodium). That was still one of the candidates for the CSP heat transfer fluids until recently. The other (and now the only) candidate is a bit strange:

Over the course of two and a half years, the Generation 3 Concentrating Solar Power Systems (Gen3 CSP) funding program evaluated three technology pathways that could enable high temperatures and, thereby, highly efficient CSP plants. Each pathway was a phase of matter used to transfer heat: liquid, solid particle, or gaseous/supercritical fluid. On March 25, 2021, the U.S. Department of Energy (DOE) announced that Sandia National Laboratories (SNL) would be awarded $25 million to build a next-generation CSP plant using the solid-particle pathway, with the goal of de-risking commercial CSP systems operating above 700° Celsius (1,290°F).[2]

[1] Alex Mey, EIA.gov, "Utility-scale batteries and pumped storage return about 80% of the electricity they store," Feb 12, 2021, https://www.eia.gov/todayinenergy/detail.php?id=46756

[2] Energy.gov, Energy Efficiency and Renewable Energy, Solar Energy Technologies Office, "Generation 3 Concentrating Solar Power Systems (Gen3 CSP) Phase 3 Project Selection," March 21, 2021, https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp-phase-3-project-selection

DOE determined that particle-based systems require fewer components and are less complex to operate compared with liquid- and gas-based systems. Additionally, particle-based systems need relatively few high-cost materials to collect and transport thermal energy. These factors could increase plant availability and reliability and enable simpler plant construction and commissioning.

And unlike the other two pathways, ceramic, sand-like particles can withstand temperatures greater than 800° Celsius (1,470° F), making them useful in electricity production and other solar-thermal heat applications, including industrial process heat, thermochemical energy storage, and solar fuel production.

Author's comment: I spent quite a bit of time reviewing various DOE information-sources to make sure that the molten salt pathway is indeed dead, and I concluded it was. There was much confusion caused by many old (before March 25, 2021, when this decision was made) sources still hanging around, and DOE's habit of not dating their web pages. I finally found a few sources that were dated as either 2022 or 2023, and the text below is mostly from those. The first two paragraphs below are still from reference 2.

3.2. Solar Receivers and Storage

Over the course of two and a half years, the Generation 3 Concentrating Solar Power Systems (Gen3 CSP) funding program evaluated three technology pathways as described above. The U.S. Department of Energy (DOE) announced that Sandia National Laboratories (SNL) would build a next-generation CSP plant using the solid-particle pathway.

Conventional CSP power towers have tubular receivers with a fluid, such as molten salt, flowing through the system and absorbing thermal energy. In a falling-particle receiver, sand or manufactured particles are heated directly by a beam of concentrated sunlight as they fall through open air. The SNL project team uses particles based on aluminum oxide, with a diameter of about 300 micrometers. The heated particles are then stored in an insulated bin before passing through a particle-to-working-fluid heat exchanger. The heat exchanger's working fluid will simulate a high-efficiency Brayton cycle using supercritical carbon dioxide (sCO2) with an exit temperature of 720°C. Then the cooled particles are collected and moved back to the top of the receiver via a bucket elevator...

Particles:

Candidate particles include commercial ceramic particles from Carbo Ceramic, but alternatives will also be considered to reduce costs and improve optical/thermal/ mechanical properties.[3]

CARBO Ceramics will provide new formulations for particles that have improved particle durability and maintain desired optical properties after long-term exposure to high temperatures (in-kind). KSU[4] *and Adelaide*[5] *will investigate alternative cost-effective particles that can significantly reduce costs, especially when the temperature is only ~200 °C.*

---

[3] Jeremy Sment, Sandia.gov, "Gen 3 Particle Pilot Plant (G3P3)," 2022, https://energy.sandia.gov/programs/renewable-energy/csp/current-research-projects/gen-3-particle-pilot-plant-g3p3/

[4] I'm guessing that KSU is Kennesaw State University (Georgia), as they seem to have the research facilities needed to do this work, https://engineering.kennesaw.edu/mechanical/students/thermodynamics-lab.php

[5] Probably University of Adelaide's Centre for Energy Technology, High Temperature Minerals Processing (HiTeMP) Forum, https://www.adelaide.edu.au/cet/hitemp/about-hitemp

ASTRI[6] will carry out a sensitivity study on particle source/material (natural or synthesized) and properties (different sizes and density) in relation with falling particle hydrodynamics/heat transfer and durability/degradation. KSU[4] will investigate other minerals such as red sands and olivine sands as well as other minerals found to be promising low-cost alternative to current bauxite-based products. We'll investigate the physics of dust formation and particle attrition using high-resolution imaging methods under different particle conditions. Models will be developed using first principles or empirical correlations to predict particle attrition as a function of operating conditions in the Gen 3 Particle Pilot Plant (G3P3) system.

Phases 1 and 2 Risk Reduction:

- *CARBO HSP 40/70 selected for G3P3-USA based on demonstrated solar absorptance, durability and flow-ability at high temperatures*
- *CARBO HSP 40/70 particles were exposed to 10,000 irradiance cycles reaching 1000°C per cycle which resulted in a 1% decrease in absorptivity. Particles held at a constant temperature of 800°C for 400 hours also resulted in a 1% decrease in absorptivity.*
- *Particle flow processes and alternative low-cost particles were evaluated*
- *Impact of particle properties on levelized cost of energy (LCOE) and other solar thermal applications were evaluated*

Storage Systems:

Scalable particle storage systems will be designed and engineered in Phases 1 and 2, working with industry partners. Our previous studies have investigated both steel and non-steel structures to reduce costs and risks associated with erosion and heat loss.

Phases 1 and 2 Risk Reduction:

- *Flat-bottomed G3P3 storage bins were designed to induce funnel flow, reducing wall erosion and heat loss via stagnant self-insulating particles*
- *Small-scale tests were performed to validate particle flow and heat-transfer models*
- *Pre-cast refractory liner materials were tested for erosion and thermal expansion; shotcrete application methods were investigated and tested*
- *Methods for cooling of concrete slab were investigated*
- *Tower-integrated and ground-based storage bins designs were evaluated for commercial systems with capacities from 10 – 100 MWe with consideration of heat loss (<1%) and the structural limitations of tower-integrated systems in regions with high seismicity*
- *Cost models for ground-based and tower-integrated storage were developed*

[6] Probably Australian Solar Thermal Research Institute, https://www.csiro.au/en/research/technology-space/energy/Solar-thermal/ASTRI

3.3. Heat Exchanger and Particle Lift Systems

Small-scale moving-packed-bed and fluidized-bed particle heat exchangers that can operate at >700 °C and >20 MPa have been designed and studied by the team. Larger-scale (≥ 1 MW-thermal (MWt)) systems that meet performance requirements will be evaluated to reduce cost and performance risks based on lessons learned from these previous studies. Low particle-side heat transfer, material erosion, and high-temperature creep/fatigue are risks for the high-pressure tubes or plates that will contain the working fluid flowing through the heat exchanger. Component testing and analysis will be performed to better understand and mitigate these risks. We will also design and fabricate a ≥ 1 MWt sCO_2 flow loop using lessons learned from the design of Sandia's 100 kWt sCO_2 loop to provide high-pressure sCO_2 to the heat exchanger.

Phases 1 and 2 Risk Reduction:

- *Simulations and testing of 100 kWt SuNLaMP HX and shell-and-tube KSU heat exchanger provided lessons learned and informed design of G3P3 HX*
- *Shell-and-plate G3P3 HX design with integral headers, closer plate spacing (~3 mm), and counter-flow design provided >300 – 400 W/m2-K with <2% (500 kPa) pressure drop based on modeling*
- *Subscale (20 kWt) prototype was manufactured from stainless steel with novel design features to understand manufacturing steps and verify performance*
- *Subscale prototype was tested up to 500 °C at 17 MPa, which yielded overall heat transfer coefficients of >300 W/m2-K and pressure drop <7 kPa (0.04%)*
- *Particle flow testing was performed at 650 °C with varying plate spacing (1.5-6 mm) to demonstrate reliable and uniform particle flow in narrow vertical channels at operating temperature*
- *Bonding, brazing, and chemically etching of IN740H was conducted, but bond strength has not yet met ASME code requirement. Parallel efforts provided the bond, braze, and etch development for constructing the heat exchanger from Inconel 617 (IN617) and HAYNES 230 (HR230) alloys*
- *sCO2 corrosion of 800H was larger than expected; corrosion testing is being planned for Inconel alloys 800H, 740H, 617, and/or HR230*

Particle Lift Systems:

Our team has demonstrated the use of screw-type (Olds) elevators to lift high-temperature particles for previous on-sun testing, but the lift efficiency was low (~5%) due to friction, which likely caused significant particle abrasion and attrition. We will work with industry to consider alternative designs studied by the team such as mine hoists and bucket elevators to reduce risks of particle attrition and meet the desired performance requirements.

Phases 1 and 2 Risk Reduction:

- *Bucket elevator selected for G3P3-USA due to excessive costs for small-scale skip hoist; skip hoist was designed and evaluated for 100 MWe plant*
- *Heat loss from the G3P3 bucket elevator was modeled, and insulation was designed to minimize heat losses and particle temperature drops to < 3 °C*
- *Transient heat loss and costs were evaluated for commercial-scale skip hoist*

3.4. Power Cycle

The power system uses heated supercritical carbon dioxide instead of steam to generate electricity and is based on a closed-loop Brayton cycle. The Brayton cycle is named after 19th century engineer George Brayton, who developed this method of using hot, pressurized fluid to spin a turbine, much like a jet engine.[7]

For the first time, Sandia National Laboratories researchers delivered electricity produced by this new power-generating system to the Sandia-Kirtland Air Force Base electrical grid.

Supercritical carbon dioxide (sCO2) is a non-toxic, stable material that is under so much pressure it acts like both a liquid and a gas. This carbon dioxide, which stays within the system and is not released as a greenhouse gas, can get much hotter than steam — 1,290 degrees Fahrenheit or 700 Celsius. Because so much energy is lost turning steam back into water in the Rankine cycle, at most a third of the power in the steam can be converted into electricity.

"We've been striving to get here for a number of years, and to be able to demonstrate that we can connect our system through a commercial device to the grid is the first bridge to more efficient electricity generation," said Rodney Keith, manager for the advanced concepts group working on the Brayton cycle technology. "Maybe it's just a pontoon bridge, but it's definitely a bridge. It may not sound super significant, but it was quite a path to get here. Now that we can get across the river, we can get a lot more going."

On April 12, the Sandia engineering team heated up their supercritical CO_2 system to 600 degrees Fahrenheit and provided power to the grid for almost one hour, at times producing up to 10 kilowatts. Ten kilowatts isn't much electricity, an average home uses 30 kilowatt hours per day, but it is a significant step. For years, the team would dump electricity produced by their tests into a toaster-like resistive load bank, said Darryn Fleming, the lead researcher on the project.

"We successfully started our turbine-alternator-compressor in a simple supercritical CO_2 Brayton cycle three times and had three controlled shutdowns, and we injected power into the Sandia-Kirtland grid steadily for 50 minutes," Fleming said. "The most important thing about this test is that we got Sandia to agree to take the power. It took us a long time to get the data needed to let us connect to the grid. Any person who controls an electrical grid is very cautious about what you sync to their grid, because you could disrupt the grid. You can operate these systems all day long and dump the power into load banks, but putting even a little power on the grid is an important step."

In a simple closed-loop Brayton cycle, the supercritical CO_2 is heated by a heat exchanger. Then the energy is extracted from the CO_2 in a turbine. After the CO_2 exits the turbine, it is cooled in a recuperator before entering a compressor. The compressor gets the supercritical CO_2 up to the necessary pressure before it meets up with waste heat in the recuperator and returns to the heater to continue the cycle. The recuperator improves the overall efficiency of the system…

[7] Mollie Rappe, Sandia Labs News Release, "'We've Got the Power': Sandia technology test delivers electricity to the grid," Aug 9, 2022, https://newsreleases.sandia.gov/brayton_power/

3.5. DOE Breaks Ground on G3P3

The Department of Energy (DOE) has broken ground on the Generation 3 Particle Pilot Plant (G3P3), a novel concentrating solar power (CSP) facility at Sandia National Laboratory that will use sand-like ceramic particles instead of molten salt to produce and store high-temperature energy.[8]

When completed in 2024, the "multi-megawatt" solar thermal pilot project will utilize an existing heliostat field[9] *at Sandia's National Solar Thermal Test Facility (NSTTF) in Albuquerque, New Mexico, to concentrate sunlight on a gravity-driven particle-based receiver and heat the receiver's ceramic-based particles to more than 700°C. Along with potentially enabling at least six hours of particle-based energy storage, the system will notably demonstrate heating of a working fluid—supercritical carbon dioxide (sCO_2)—to 700°C or more, using a highly efficient sCO_2 Brayton cycle to generate electricity…*

"If successful, this type of solar power plant could provide 100 MW of power continuously, around the clock, at low cost" and "showcase storage technology that could provide one gigawatt of storage for one hour at a single plant," the DOE said on Feb. 17. The pilot could also pivotally prove that a particle-based CSP plant can achieve the DOE's goal of making electricity-plus-storage from CSP at $0.05/kWh.

That would be a "game-changer," Alejandro Moreno, acting assistant secretary for the DOE's Office of Energy Efficiency and Renewable Energy (EERE), said on Friday. "This pilot facility will demonstrate how CSP systems can meet the challenges of providing long-duration energy storage while reducing costs and complexity for solar thermal technology. At the same time, it also provides a pathway to commercialization for industrial process heat," he said.

Final author's comment: Note from the above references that the U.S. and Australia seem to be taking the lead on this new energy technology. Obviously the Western U.S. and the Australian Outback have huge amounts of land with a large percentage of direct sunlight (needed for CSP). Also this could be leveraged for any manufacturing process needing high temperatures.

In the future-world where we are not allowed to burn fossil fuel, the above areas could seal the march on countries without this advantage by developing high-temperature manufacturing processes with no fuel costs nor emissions. See the series referenced in this paper's Introduction for more information.

[8] Sonal Patel, Power, "DOE Breaks Ground on Next-Generation Concentrating Solar Power Pilot," Feb 21, 2023, https://www.powermag.com/doe-breaks-ground-on-next-generation-concentrating-solar-power-pilot/

[9] A heliostat is a device that includes a mirror, usually a flat mirror, which turns so as to keep reflecting sunlight toward a predetermined target, compensating for the sun's apparent motions in the sky.