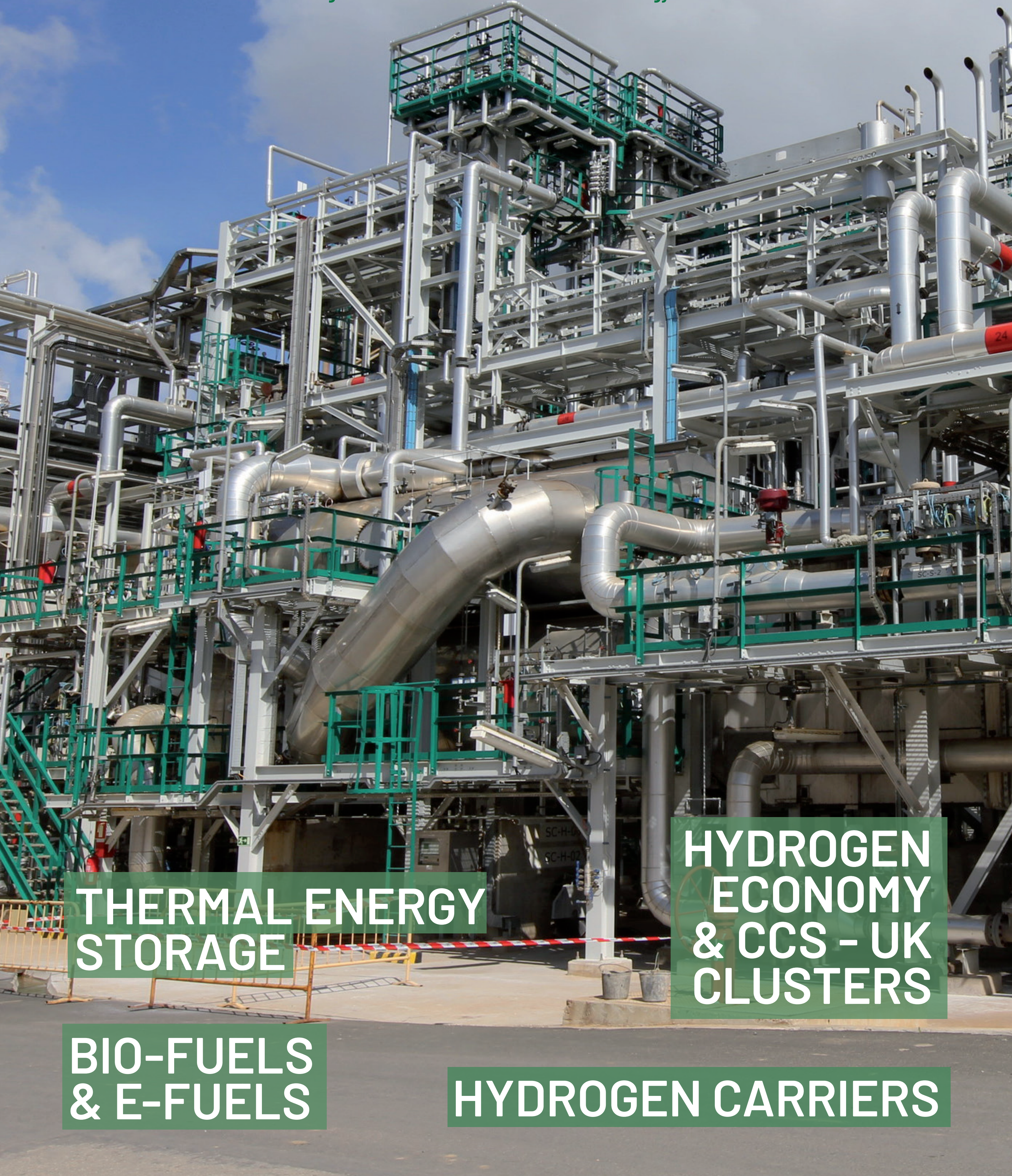
# Decarbonisation Technology

August 2022

Powering the Transition to Sustainable Fuels & Energy



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# Decarbonising through advances in heat exchange technology

## How moving bed heat exchange technology is driving innovation in thermal energy storage

Gerald Marinitsch, David Moon and Lowy Gunnewiek
**Solex Thermal Science**

Fossil fuels have been at the centre of a truly remarkable period of development and growth for the global population. In recent decades, however, the negative environmental impact and increasingly high economic cost of fossil fuel use have powered what many are dubbing the "next energy transition" – or should we say "energy evolution" – as we search for new ways to decarbonise our energy use.

Today, this drive to decarbonise our energy needs can be found everywhere – from discussions about a circular economy to the environmental, social and governance (ESG) strategies of businesses around the world.

Given the energy needs of today's highly connected and mobile world, a tremendous amount of work and money is being directed toward making decarbonised and renewable energy available to us when we need and want it.

This is leading to a pressing need for more readily available energy storage, from which a variety of different technologies are currently available or being developed, such as batteries, pumped hydro, and green hydrogen.

One of the more notable and promising developments in this arena relates to long-duration thermal energy storage (LD-TES) systems that use solid particles. This technology is garnering significant interest and investment primarily because it is targeting a need for storage systems that can provide energy for a period of 10 hours and more. To date, this has not been realised.

An example of this is taking the thermal energy that can be generated from concentrated solar power (CSP) and transferring it to solid particles so it can be stored and used later when the sun is not shining.

To enable this option for LD-TES, a new generation of moving bed heat exchangers (MBHEs) are also being developed so the thermal energy can be extracted from solid particles and subsequently converted into a useable energy form such as electricity.

In this article, we will reflect on how changing energy demands have brought us here, along with the unique challenges associated with storing and recovering thermal energy.

We will also explore recent developments in vertical tube and diffusion-bonded MBHEs that are being used – specifically, in CSP systems that incorporate LD-TES. Included will be a discussion around the background requirements for these types of systems, along with design considerations and challenges for MBHEs when being implemented.

Lastly, we will highlight several examples taken from work currently under way that will help illustrate the potential for these particle-based LD-TES systems in helping us evolve to a more decarbonised energy system.

### Changing energy demand

Prior to the Industrial Revolution, electricity played an insignificant role. Rather, chemical energy sources such as biomass or oil were common – and useful in that this energy was in a form that was 'stored' and useable whenever needed and wanted. Combustion (oxidisation reaction) of the 'fuels' typically liberated this energy for use. Concern about carbon dioxide emissions from combustion did not exist then as it does today.

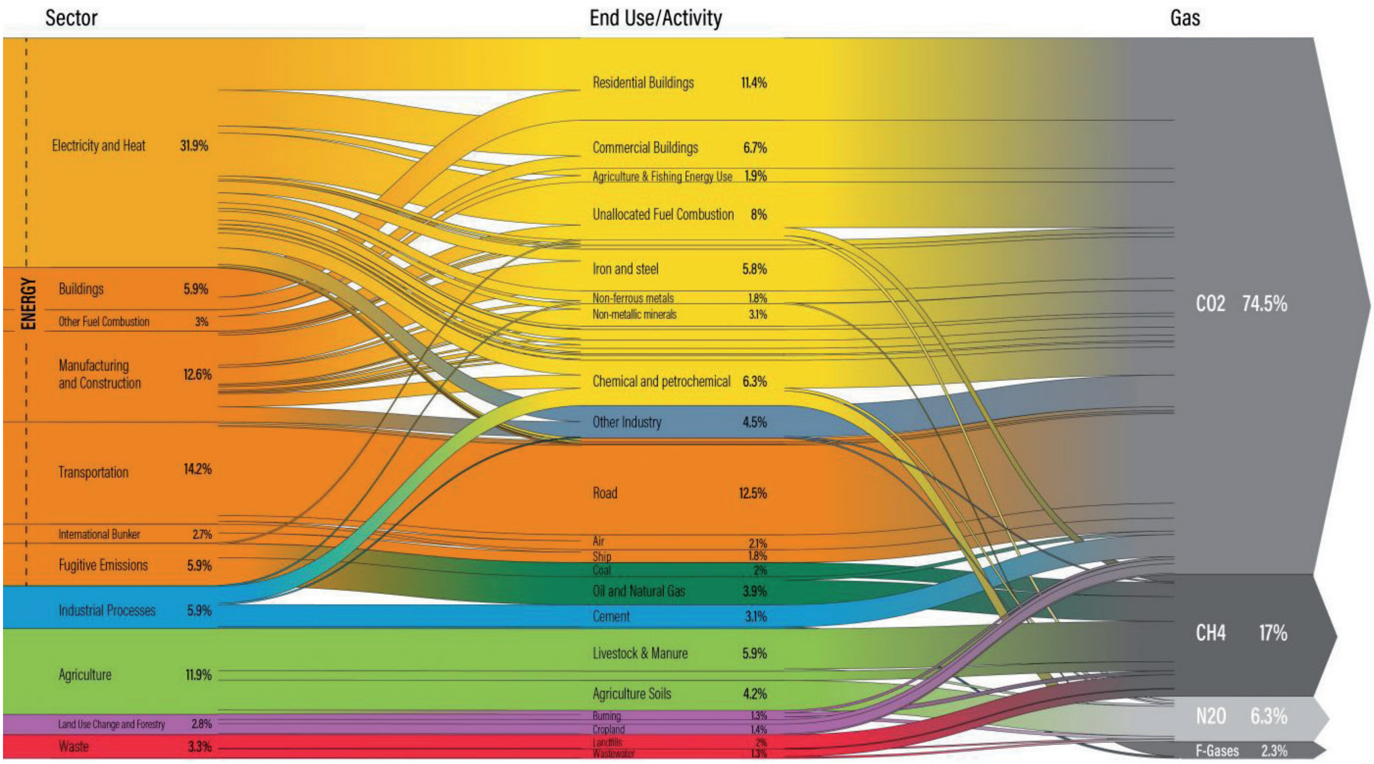


**Figure 1** An estimated 31% of greenhouse gas emissions can be traced to electricity and heat generation, according to the World Resources Institute *Credit: World Resources Institute*

Since then, we have become accustomed to using diverse types of energy in forms such as combusting fossil fuels, wind energy, and solar energy, which are generally converted to electricity for our use.

Yet, in switching from chemical to renewable energy sources such as solar, we are realising there is a shortfall in being able to provide energy whenever it is needed and wanted. To take full advantage of renewable energy as we work to displace fossil fuels in our drive to decarbonise, it is now necessary to store energy during peak production hours when it exceeds demand – which, subsequently, can be used when demand exceeds production.

With that, there are additional factors to consider. As an example, how long does the energy need to be stored? Will energy stores need to be loaded and unloaded in seconds or minutes? Or are the needs more seasonal, requiring the need to store energy for months? All this dictates storage size in closing the gap between generation and utilisation – and subsequently, the required storage technology.

That is not to mention that, with very few exceptions, stored energy will be used as thermal or electrical energy – the latter of which is also the most difficult energy form to store for long periods of time.

The most common method of storing electrical energy today is in batteries. However, batteries are limited in how much and how long they can store energy due to technical and economic limitations.

Consequently, other technologies are needed to store large amounts of energy for long durations. Such technologies are used as intermediate storage, meaning they store energy in a form that can be used to produce 'on-demand' electricity.

## Long-duration thermal energy storage

LD-TES has been identified as a critical enabler for the large-scale deployment of renewable energy – in particular, within CSP applications.

Before going any further, it is important to differentiate CSP from more commonly known photovoltaic (PV) technology. PV is the direct conversion of sunlight into electricity using the photovoltaic effect in semiconducting materials to directly generate electricity. Storing the electrical energy from PVs is economically restricted to battery technology, and current battery technology is generally limited to shortduration storage – for example, three to four hours. As such, PV technology is largely limited to supplying a base load of power while the sun is shining. In comparison, CSP can generate thermal energy by concentrating the sunlight on a collection point.

In principle, CSP can generate temperatures greater than 2,000°C. However, for practical applications, receiver temperatures operate in the range of 500°C to 1,000°C.

That thermal energy is then commonly used in a CSP plant to generate electricity via technologies such as steam turbines, Organic Rankine cycles (ORC), or supercritical carbon dioxide ($sCO_2$) cycles. In general, higher operating temperatures are desirable because the overall conversion efficiency from light to heat to electricity is higher.

While a CSP plant can easily provide on-demand base-load electricity while the sun is shining, to fully leverage the capacity of this technology, there are strong drivers to be able to store the thermal energy generated during daylight hours. The objective is to have enough thermal storage so electricity can be produced even when the sun is not shining over a period of days or longer.

Today's commercial CSP LD-TES plants commonly use molten salt to store the thermal energy collected from the sun. A key limitation of this configuration, though, is the overall conversion efficiency that can be realised due to the operating temperatures practically achieved with molten salts.

In addition, there are safety, environmental, and operating constraints with molten salt that need to be considered. This is driving the development of CSP plants that use other types of media for storing thermal energy.

Within this development arena, there is a growing preference for CSP LD-TES based on solid particles. This is primarily because solid particles can withstand temperatures greater than 1,000°C without decomposition. They are also inert, do not contain any unusual corrosion mechanism, and their erosion characteristics scale with temperature.

In addition, in the event of a system leak, particles will not cause hazards beyond the initial transient high temperatures. As a result, the systems do not require hermetic seals and are compatible with silo and storage technologies that exist already.

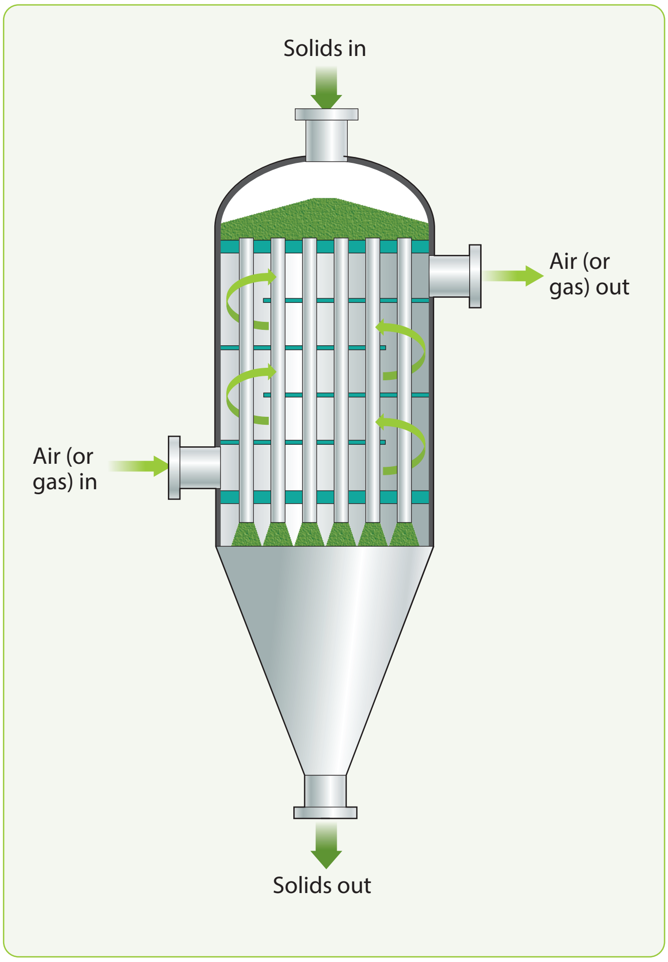


**Figure 2** If the working fluid is a gas, then a vertical tube heat exchanger is the preferred design

While the particle-handling technologies must be designed to withstand high temperatures and minimal heat losses, these are manageable engineering challenges and not fundamental challenges, at least up to around 1,000°C. And in the case of a cool-down event, particles can still flow and will not freeze, as is the case with molten salt.

These types of particle-based systems, when coupled with a CSP plant where the heliostat field heats up the particles directly as they fall into the hot storage silo, are an elegant solution for LD-TES that requires only a single MBHE to transfer the thermal energy from the hot solids to the working fluid used in the power generation block.

## MBHE design considerations

Silica sand is emerging as a preferred working media to store renewable energy for extended

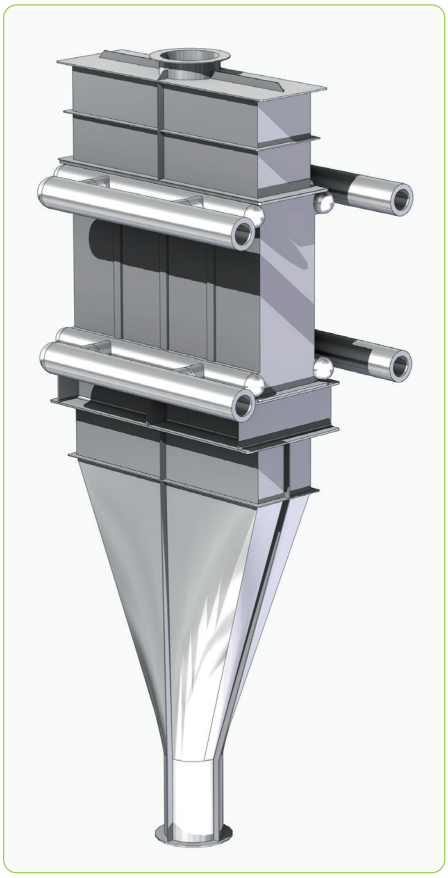

**Figure 3** Model of a diffusion-bonded heat exchanger core that is designed for a particulate material on the solid side and $CO_2$ on the fluid side

periods because it is abundant, affordable, stable, non-toxic, and can be heated up to high temperatures without degradation. In addition, the hot sand can be easily stored in silos at high temperatures.

Other materials also considered suitable for these applications include alumina, bauxite, magnetite, and engineered ceramics.

MBHEs are used to recover thermal energy from the hot sand and transfer it to the working media of the CSP power generation block – for example, $sCO_2$. These MBHEs are compact, efficient, and simple to operate as gravity is used to flow the sand through the heat exchanger. With the low velocity of the particles in these MBHEs, the natural abrasion rates on the heat exchanger surfaces are minimal, resulting in high availability and a long lifetime.

Depending on the working media, the MBHE configuration and design will vary. If the working media is a liquid, the most common option involves the use of vertically oriented pillow plates. If the working fluid is a gas – for example, air – a vertical tube heat exchanger is the preferred design (see **Figure 2**).

In situations where $sCO_2$ is the working media, a diffusion-bonded heat exchanger core is preferred because of its ability to accommodate the pressure and temperature needed for high heat exchange efficiency (see **Figure 3**).

Operating temperatures of MBHEs for CSP plants are limited by the thermal stability of the materials of construction, which today is mainly high-temperature-resistant steel such as 316 stainless steel. Nickel-based alloys can also be used, but come with increased capital cost.

To extend the operating boundaries beyond what is practical to achieve with today's technology and materials in the drive to improve the efficiency of CSP plants, MBHEs constructed from ceramic materials are also being developed.

## LD-TES in action

Canadian-headquartered Solex Thermal Science, which specialises in thermal and bulk materials engineering, is seeing increased applications of its MBHE technology within a number of CSP LD-TES project developments around the world.

Together with US-based research organisation Sandia National Laboratories and Vacuum Process Engineering (VPE) of Sacramento, Calif.,

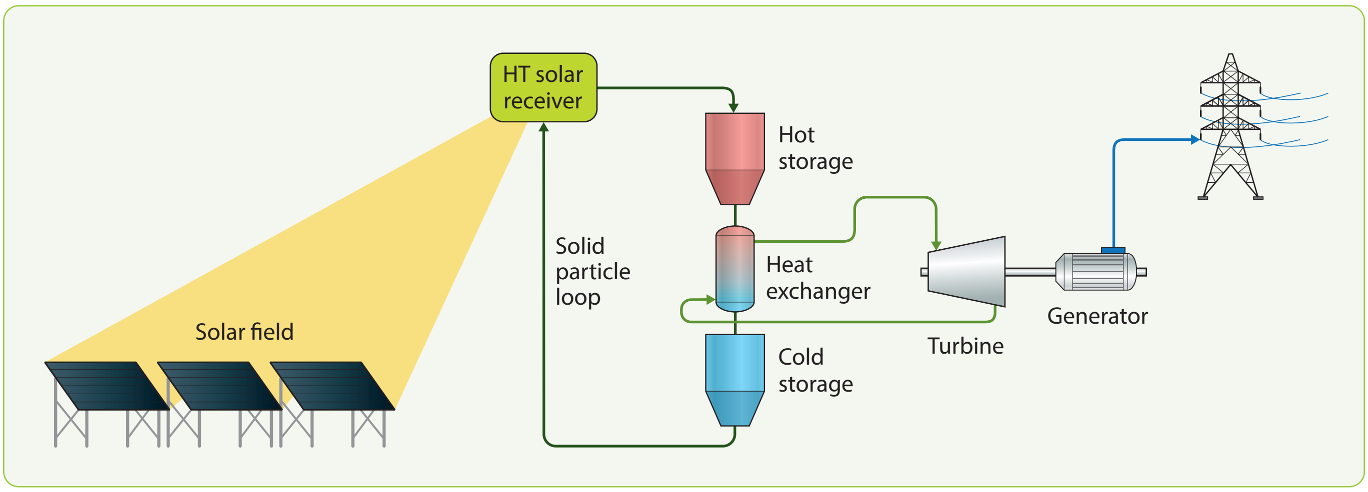


**Figure 4** Process diagram of a concentrated solar plant with solid particle energy storage

| Feature | Solid Particle Technology | Molten Nitrate Salt Technology | Molten Chloride Salt Technology | Gas Receiver Technology |
|---|---|---|---|---|
| Operating temperatures | Ambient to >1000°C | ~300-600°C | ~400-800°C | Ambient to >1000°C |
| Solar flux | No flux limitations on particles | Limited to tube-wall fluxes of 800 kW/m$^2$ | Limited to tube-wall fluxes of 800-1200 kW/m$^2$ | Limited to tube-wall fluxes of 800-1200 kW/m$^2$ or less depending on gas-side heat-transfer coefficient |
| Freezing | No freezing | Freezing below 200-300°C; requires trace heating | Freezing below 200-300°C; requires trace heating | No freezing |
| Corrosion | Inert materials, non-corrosive | Corrosive to containment materials | Extremely corrosive to containment materials in presence of air or water | Potentially corrosive depending on gas |
| Storage | Direct thermal storage | Direct thermal storage | Direct thermal storage | No direct thermal storage; requires intermediate heat exchanger |
| Ducting and containment | No hermetic seals required | Hermetic seals required | Hermetic seals required | Hermetic seals required |
| Conveyance | Particle lift (bucket elevator or skip hoist) | Long-shafted pumps | Long-shafted pumps | High-temperature blowers; lifts for particles if used as storage media |

**Table 1** Comparison of CSP technologies using different heat transfer and storage media
*Credit: Sandia National Laboratories*

Solex is collaborating on Sandia's $25 million US award to build a 1 MW demonstration plant for CSP technology. The CSP configuration utilises a heliostat field to directly heat solid particles that would then go into a hot storage silo (see **Figure 4**).

For this project, MBHE technology based on the VPE's diffusion bonded know-how and expertise is being used to transfer stored thermal energy at temperatures greater than 700°C to a $sCO_2$ power generation flow loop.

Solex is also working with Sandia to supply a 2.5 MW thermal heat exchanger using vertical tube MBHE (VT-MBHE) technology. This is part of a test programme to evaluate the performance of an upstream solar receiver. In this project, the VT-MBHE is being used in the solid media cooling loop using ambient air. This project is anticipated to be installed and commissioned in Q4 2022.

In another CSP LD-TES development, Solex and VPE are working with Heliogen Inc. on an advanced particle-to-$sCO_2$ MBHE for a 5 MWe power block. This is anticipated to be the first and largest commercially integrated recompressed Brayton cycle power block coupled with thermal storage from a CSP field.

This project includes a test loop that is being developed to evaluate and optimise the performance of the MBHE – first at the 1 MW scale prior to the implementation of the 5 MW commercial installation. Solex and VPE are providing both a diffusion bonded particle-$sCO_2$ test exchanger and a hot air-to-particle heater (to simulate a CSP field in the test loop) for the test loop.

Meanwhile, King Saud University in Saudi Arabia is pursuing CSP to generate hot compressed air that would then drive a power generation turbine. The hot air comes from thermal energy stored in sand or other particle media, with the thermal energy provided by a CSP plant.

Solex developed and built a prototype 50 kW sand-to-air heat exchanger using its VT-MBHE technology for this application. This prototype is part of the proof-of-concept work under way, including requirements to develop operational familiarity with the system.

## Final thoughts/considerations

Advances in heat transfer technology are helping to enable today's efforts to decarbonise our energy systems. This is being clearly illustrated as we harness the intermittent and variable energy provided by the sun to supply our energy needs and wants of today.

For developments that combine CSP with LD-TES based on using solids for thermal energy storage, MBHEs are instrumental in transferring energy from the solids to a working fluid used in the power generation block.

For the power generation options being incorporated in these CSP LD-TES plants, there is a need for MBHEs to accommodate the different working fluids in use, whether it be air, water, or $sCO_2$.

As such, MBHEs using vertical plates, horizontal tubes, or diffusion-bonded technology are being developed to provide elegant, effective, and efficient solutions for transferring the stored thermal energy to the working fluid – again, with the ultimate goal of generating electricity from the sun when it is not shining.

As has been illustrated through the various projects in development today and with the advancements being made in MBHE technology, we can be optimistic about the progress being made to use renewable energy as an integral part of the solution in decarbonising our energy systems.


**Gerald Marinitsch**
gerald.marinitsch@solexthermal.com

**David Moon**
david.moon@solexenergy.ca

**Lowy Gunnewiek**
lowy.gunnewiek@solexthermal.com