Vast Solar: improving performance and reducing cost and risk using high temperature modular arrays and sodium heat transfer fluid

Craig Wood[1], Kurt Drewes[1]

[1] Vast Solar, 226-230 Liverpool Street, Darlinghurst, NSW 2010; +61 419 478 856; craig.wood@vastsolar.com

1. Abstract

Since the development in the United States of the technology that led to the Kramer Junction SEGS plants [1] and the Solar One and Two molten salt towers [2], subsequent industrial installations of concentrated solar power (CSP) have largely been limited to the technologies of parabolic troughs and central towers. Parabolic trough technology has been widely adopted due to the high reliability of the heat transfer system. Over time, central receiver technologies have been trialled to address the primary shortcoming of parabolic trough plants, being low operating temperatures, but they too suffer from limitations that have limited their deployment. Vast Solar has adopted a sodium heat transfer fluid and developed a modular solar array design to address the shortcomings of central receiver systems and achieve high temperature steam conditions whilst maintaining the reliability benefits of trough systems. This paper discusses the fundamental benefits and constraints of these technologies and how the technology developed by Vast Solar addresses these constraints to deliver superior performance, lower cost and lower risk.

2. Current State of CSP Technology

2.1 Parabolic Troughs

Parabolic troughs represent 81% of operational installed CSP capacity globally [3]. The proliferation of this technology reflects its high level of technological maturity and a high degree of bankability (a term used in project finance to describe the acceptability to investors of the technology risks). To achieve this status, parabolic troughs have demonstrated excellent reliability and economic performance that closely follows the theoretically predicted production, indicating a high level of system availability for energy production. These two factors – reliability and utilisation – are critical to the acceptance of any technology and improving them is a necessary condition to ensure further cost reduction in the industry.

The modularity of the HTF loops of parabolic trough plants is a fundamental driver of the high reliability and high availability of these plants. HTF is circulated through the field as an aggregate and the temperature control function is performed in each loop. The temperature control has historically been achieved simply by moving the parabolic trough in and out of focus. Only recently have projects been constructed with more advanced controls such as the Noor 2 project in Morocco which utilises automated control valves in the HTF loop to provide temperature control. Furthermore, the mixing of HTF from multiple individual loops mitigates potential impacts from temperature ramps caused by cloud transients. This is an extremely important design feature, especially for CSP plants built in areas where the annual DNI is limited and more frequent transients are expected.

Dynamic temperature control through transients is extremely important in CSP. Studies by SolarDynamics (and supported by NREL) have postulated that the detailed analysis of these dynamics often leads to improved performance of commercial projects. ISE [4] has promoted the development of high resolution dynamic models as a "Digital Twin" of planned plants to fully understand and analyse the effect of these transients. The modularity of parabolic trough plant architecture regulates HTF temperature through the mixing effect and this is a fundamental reason for their simpler operation, higher reliability, higher availability and increased utilisation relative to central tower plants.

However, parabolic troughs have one severe constraint that has limited the further development and cost reduction of the technology. The oil used as the HTF in parabolic troughs has limited the upper end of the process temperature to around 380°C. This has limited the efficiency of the associated Rankine power generation cycle and, more importantly, has reduced the temperature differences in the molten salt Thermal Energy Storage (TES) to around 100°C, placing significant cost pressure on the storage component of the CSP technology. Indeed, Wacker Chemie received the innovation award at SolarPACES 2017 [5] for a technology that would increase the HTF temperatures to 425°C, illustrating the importance of this factor. Similarly, there is ongoing work on the evaluation and testing of the use molten salt in line focusing systems which, if proven, would unlock higher temperature operation.

2.2 Molten Salt Central Towers

Central tower designs address this constraint by achieving much higher concentration factors (circa 800 to 1,000) compared to trough plants (circa 80). High concentration factors offer higher efficiencies at the receiver and allow for higher temperature (more efficient) steam conditions at the turbine. Two streams of development resulted: direct steam generation (i.e., Solar One, PS11, PS20 and Tonopah); then molten salt as both the HTF and TES (i.e., Solar Two, Gemasolar, Crescent Dunes, Noor III). Direct steam plants are burdened by the complexity and cost of effective thermal storage, while molten salt towers with integrated thermal storage have emerged as the leading technology representing 56% of CSP projects under development or in construction globally, a marked contrast to the central towers' 15% share of global CSP fleet today [3].

Molten salt makes an excellent TES medium, being inexpensive and having a high heat capacity. However the properties of molten salt lead to significant problems when it is used as a HTF. The salt freezes at relatively high temperatures and, to eliminate the risk of a receiver tube freeze overnight or during a long cloud transient, the receiver is drained of salt. Restarting operations each morning or after a long transient requires a complex refilling process and venting procedure. Additionally, condensation of air in receiver tubes at night time increases the risk of accelerated corrosion of the nickel alloys in the receiver.

Molten salts are known to dissociate at temperatures close to the 560°C bulk temperature (a 40°C safety margin vs. the 600°C limit) typical of central tower designs [6,7] and, as a consequence, extremely precise optics are required to attempt to eliminate the risk that film temperatures do not exceeded the limit on the receiver tube inner walls.

The high freezing temperature of solar salt and the associated risks drive the need to drain the receiver and to reduce the length of piping runs and, ultimately, the central tower layout. There is a standard central receiver design that sees two flow paths link a set of receiver panels in series. The flow in each receiver panel is determined by the flow in the whole receiver train and thus the flow per panel cannot be regulated if there is any deviation in the energy supplied to that individual panel. Furthermore, the vertical arrangement of the receiver tubes creates a stability problem on the down flow leg that necessitates high minimum flow rates [8,9]. This constraint in the regulation of HTF flow results in significant energy and temperature fluctuations emerging from the system, reducing the operating window and impacting the utilisation of central tower plants. This has led to significant underperformance in plants such as the Crescent Dunes facility (see Figure 1).

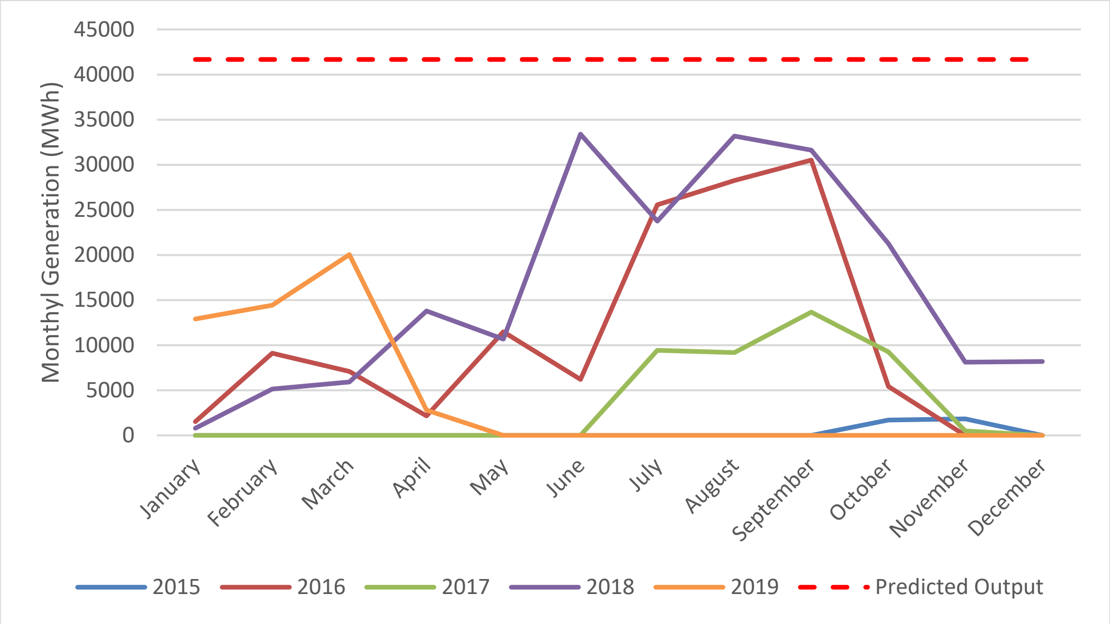

Figure 1: Crescent Dunes monthly output since commissioning [10].

The temperature ramps that are a direct result of an inability to adequately manage HTF flow have caused significant premature failure in core system components. Gemasolar and Crescent Dunes, the two facilities with a reasonable operating period and track record, have both suffered hot salt tank failures [11] and the low cycle fatigue introduced by this temperature ramping remains a significant risk and a critical issue associated with the design.

3. Technology Improvements Required to Increase Performance and Reduce Costs and Risks

The experience gained to date in the CSP industry coupled with the broad consensus on developments required to move the cost of CSP energy to a level competitive with fossil fuel generators leads to the following design requirements for any new technology solution:

3.1 Point Focusing

To achieve high temperatures and the levels of process control appropriate for such high temperatures, the use of point focusing optics becomes favourable. A point focusing strategy achieves higher concentration factors while allowing the whole receiver to be monitored. Measuring the thermal flux is a fundamental requirement for process control where transients are present, and this is problematic to achieve with line focusing systems.

3.2 Modular Array

Central tower plants with surrounding heliostat arrays have limited scalability. Increasing tower height requires the addition of mirrors further and further away from the receiver which provide diminishing returns for energy collection due to optical attenuation. Modular arrays provide the ability to scale up (or down) to suit the application, unlocking the possibility of larger turbine size and storage duration combinations than are possible with central tower designs.

The modular array design also enables localised control with smaller thermal inertia which generates faster, more precise responses than single receiver designs. Additionally, any transients that may be generated are mixed with each other and diluted by the time they reach the critical downstream components (i.e., heat exchangers).

3.3 High Operating Temperatures

A high operating temperature is critical in minimising costs, both in terms of TES energy density and the efficiency increase available at higher power cycle temperatures. In the longer term, the development of equipment using super critical CO2 as a working fluid will unleash significant cost reductions for CSP technologies capable of high temperature operation.

3.4 HTF Stability Across Operating Conditions

The HTF and TES material should be stable with a significant margin across all operating temperatures of the cycle.

3.5 Easy Operability through Process Control

The process needs to be easily to operate in order to achieve high utilisation and reliability, reduce risk by protecting assets from thermal shock and cost less to operate and maintain. Higher temperature operation makes this even more important as the materials involved are more susceptible to creep and fatigue [12, 13].

4. Vast Solar Technology

Vast Solar has developed a modular array technology utilising a point focusing system that addresses the above requirements.

Vast Solar has selected sodium as an intermediate HTF between the receiver and the molten salt TES. Sodium has been considered as a HTF by the CSP research community since its inception [14, 15] and it overcomes the constraints of the operating temperature range of both thermal oil and molten salts.

Vast Solar's modular, polar solar array provides a 17% improvement in Coefficient of Performance (a measure of the geometric efficiency of the solar array incorporating cosine, block and shading, etc.), delivering more energy per square metre of reflector than an equivalent monolithic tower CSP plant. The higher efficiency solar array provides:

- Lower capital cost
- Lower operating costs as there is less glass to clean
- Tighter packing and therefore more mutual wind shielding
- A smaller flux zone, which poses less risk to avian fauna
- Reduced glint and glare risks for aviation and neighbouring properties

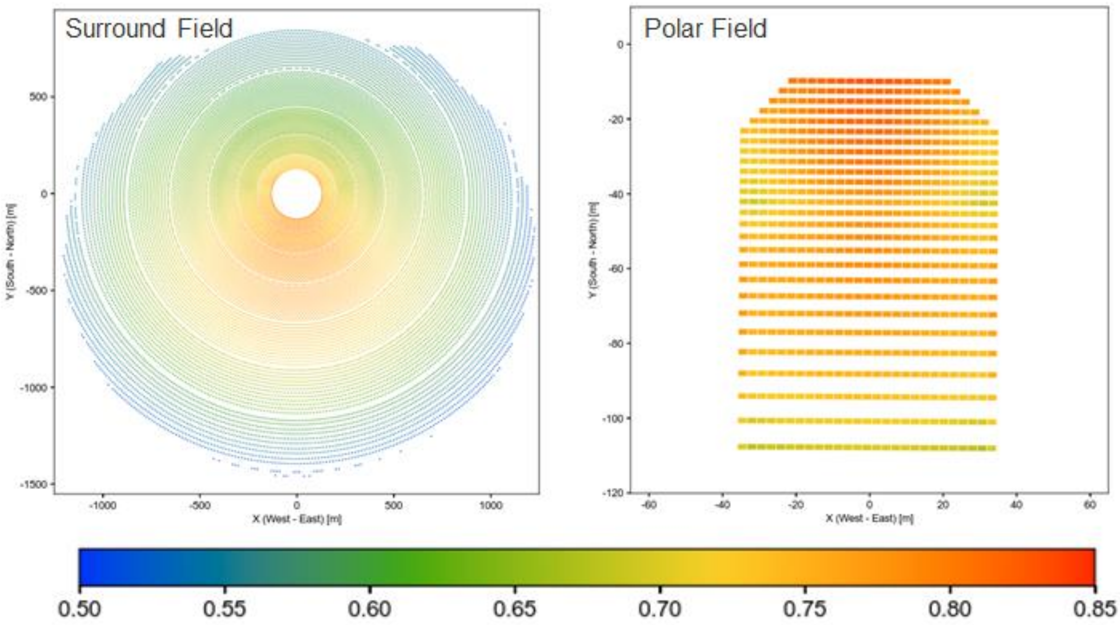

Figure 2: Comparison of Coefficient of Performance for equivalent circular (left) and Vast Solar polar (right) solar arrays (analysis carried out by schlaich bergermann partner on behalf of Vast Solar)

4.1 Pilot Plant

After initially testing its proprietary optical control system, Vast Solar built a single solar array that was tested in conjunction with a standalone sodium loop. Subsequently, Vast Solar's Pilot Plant was built to confirm the ability to safety and effectively use a liquid sodium HTF to drive full power cycle. It consists of five modular, polar solar arrays with a total of 3,500 heliostats and a nominal thermal capacity of 6MWth. Sodium is continuously circulated and not trained (in a similar fashion as the HTF circulated in a parabolic trough plant). Heliostats focus the sunlight to the top of a lattice frame tower on which a receiver is mounted.

Unlike in parabolic troughs, Vast Solar's HTF flow is actively controlled with a high degree of accuracy by optical instrumentation of each receiver to provide a direct quantitative measurement of the radiation flux. This measured flux actively controls HTF flow to provide the highest possible constant receiver outlet temperature which maximises the exergy in the system and achieves the highest possible thermodynamic efficiency.

The Pilot Plant generates superheated steam through a sodium to water heat exchanger. Due to the highly exothermic and rapid reaction in the case of a tube leak, significant care was taken in the design and robust safety systems are required. The process engineering capability relied heavily on the development of similar heat exchangers for sodium-based fast breeder nuclear reactors.

The turbine is a single stage radial overhung turbine of 1.1MW capacity and an 11kV grid connection. The thermal efficiency of the turbine is low, but as the purpose was to demonstrate the functionality of the CSP system, this was an acceptable design trade-off in the planning of the Pilot Plant.

The heat sink was provided by a MACCSol modular air-cooled condenser. The Pilot Plant is equipped with all the systems required of commercial scale power plants including:

- Grid synchronisation capability with VAR and PSS capability
- UPS and emergency diesel generator in the event of loss of grid power
- Step down and isolation transformer for the Essential Energy distribution grid for energy evacuation
- Fully automated distributed control system
- Independent SIL 3 rated standalone safety instrumentation system in case of DCS failure

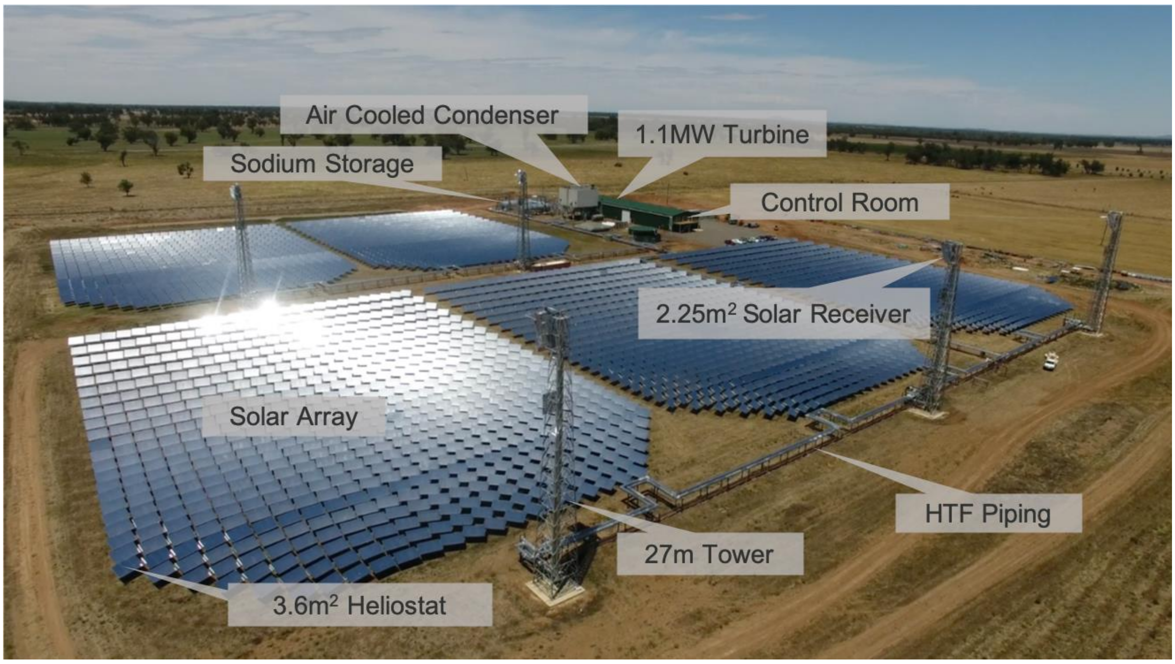

Figure 3: Aerial view of Jemalong Solar Station with key components labelled

4.2 Operational Experience

The use of sodium necessitates the implementation of sophisticated safety systems and operational procedures. Vast Solar has drawn on knowledge from the nuclear industry in relation to process design and material and equipment selection for use with sodium. Extensive operational experience at the Pilot Plant has provided Vast Solar with valuable lessons learned, in particular with respect to vessel design, pump requirements, sodium purification, sodium handling and safe management in the event of a leak.

4.3 Lower Costs in Solar Field Optics

Vast Solar's modular array allows for a 17% reduction on mirror surface area compared to a central tower design at a representative Australian site. Other studies [16] calculate differences at higher latitudes.

Additionally, to further reduce solar field costs, a new control architecture was developed. Local controllers with limited processing capabilities (hence lower cost) achieve solar tracking through polynomial approximation of sun path geometries. Although of lower precision, the loss in precision is insignificant compared to the cost reductions that are achieved through this process. Communication is done in an intrinsically safe manner through the power line cables which further reduces solar field complexity and costs.

4.4 Advanced Control System

As discussed previously, the instrumentation of the solar flux along with propriety control philosophies (currently not utilised in CSP applications) manage the flow of sodium through each solar receiver to deliver excellent dynamic response to transient events. Figure 4 shows data from operational tests whereby the plant was staged through different temperature control setpoints and despite significant solar transients the temperatures were adequately maintained. As can be seen from the graph, the system is extremely responsive to both planned (as can be seen by the orange line quickly converging with the blue line after each set point change) and unplanned changes such as transients, as can be seen by the insignificant change in outlet temperature when cloud transients reduce incident flux by 30 to 40% at 9:50am and 10:35am.

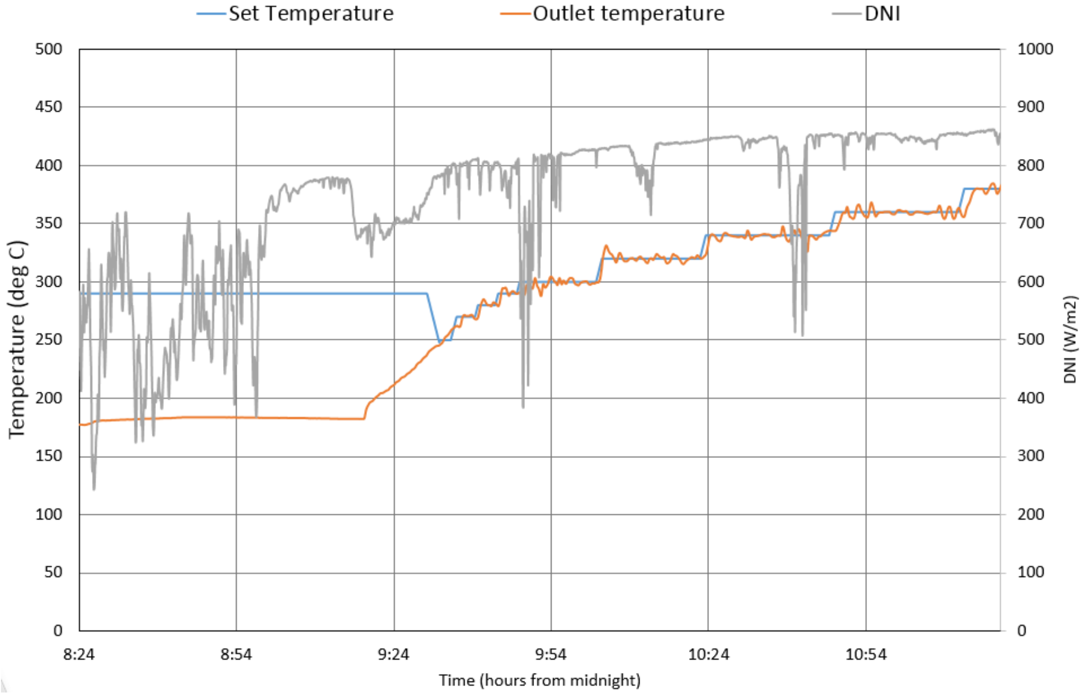

Figure 4: Time series of transient DNI and receiver outlet temperature, Jemalong Solar Station 13 May 2019

Furthermore the reduced temperature ramp rates are mixed in the network and are all but eliminated by the time they reach the power block. A simulation of this effect is represented in Figure 5.

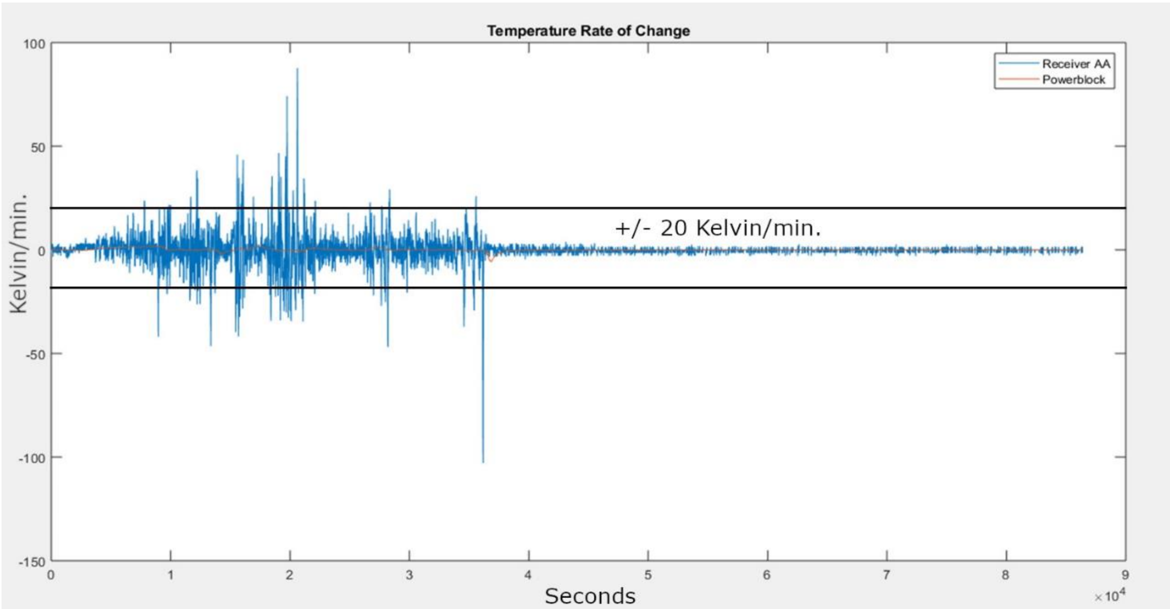

Figure 5: Impact of mixing effect on power block temperature ramps (actual receiver output data adapted and modelled for a 30 MW plant)

On close inspection, a red line can be seen in Figure 5 indicating the final ramp rate at the field HTF outlet. The flatness of this line indicates a ramp rate which is orders of magnitude lower than that specified by the heat exchanger designer (+/- 20 K/min).

5. Conclusion

The experience of designing and building a modular array CSP Pilot Plant with sodium HTF has proven the benefits of such an approach. The ability to precisely control receiver outlet temperature across the distributed network reduces the risk of thermal shock at the field outlet and increases the proportion of DNI that can be captured each year. Furthermore, modular arrays reduce the volume of reflector surface area in a plant, reducing capital and operational costs to drive down the cost of dispatchable solar power.

Vast Solar is planning the construction of its 30MW commercial demonstration project in Australia utilising modular solar arrays, a liquid sodium HTF and two-tank molten salt TES. The Pilot Plant will continue to provide further opportunities for developing improvements in the control system, developing operating and maintenance procedures around this plant design and specifically in the use of sodium as heat transfer fluid.

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