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CST Process Heat Solution for India's Top Cancer Hospital With ANU's Big Dish

Study of Solar Thermal Powered Tri-Generation System

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Abstract. India has an abundance of solar radiation, making Concentrated Solar Thermal Technologies an economical option to complement, if not replace, fossil fuels for various Industrial Applications. Some of the most viable applications are space and water heating/cooling, process heat, water desalination and effluent treatment. When hybridised with biofuels these thermal energy solutions can deliver 24 x 365 renewable energy.

India has great potential for solar industrial process heating and cooling. Recent studies have shown an addressable market potential of 6.5 GW-thermal for CST technologies out of a total of 13 GW thermal technical potential for industrial applications requiring heat of temperature up to 300°C[1]. Higher temperature applications in industry sectors such as cement, steel and chemical production add further to this potential.

Sunrise CSP's Big Dish solar concentrator, developed in collaboration with the Australian National University, is a modular 400kWthermal CST platform capable of delivering the steam requirements for the industry at temperatures currently ranging from 150°C to 600°C and pressures up to 160 bar, with new heat transfer fluids lifting temperatures to 800°C planned. The Big Dish is specifically designed for local manufacture and its modularity supports staged and scalable solar field deployment that enables socio-economically appropriate solutions spanning factory-scale to national utility-scale with a Levelized Cost of Steam (LCoS) 14% - 25% lower than fossil fuel alternatives in India.

Keywords: CST, Big Dish, Space Cooling

1. Technical Overview

1.1 The Solar Concentrator – Big Dish

Big Dish is a 500 m^2 solar parabolic concentrator designed by the Sunrise CSP Australia Team members in collaboration with the Australian National University. Big Dish has an accurate dual-axis tracking, that focuses the sun to achieve an average concentration of approximately 2200 suns. At the focal point of the parabolic dish structure is a High-Efficiency Solar Boiler (Receiver) with high solar-to-heat efficiency measured up to 97.1% by the ANU [2], which is a world record on its own.

Big Dish drew upon 30 years of research in solar thermal concentrating technologies at the ANU. It is the third-generation solar concentrator after a 20 m^2 and 400 m^2 dish, developed by the ANU, being a major improvement over both. Every component of the concentrator, from Mirrors to the Receiver, Tracking Control System to the Manufacturing Technique has been refined and improved over the years, with a continuous cost reduction and capability enhancement programme underway. Table 1 lists down key design specifications of the Big Dish Solar Concentrator.

Table 1. *Big Dish key specifications*

Particular	Value
Reflector Shape / Tracking	Paraboloidal Dish/Dual Axis
Construction Type	Patented Steel Space Frame with Patented Structural Mirror Panels
Reflector Diameter / Focal Length	25 m / 13.4 m
Mirror / Aperture Area	520 m^2 / 485 m^2
Thermal Power	413 kW_{th} @ 900 W/m^2 DNI
Concentration Ratio	2,240 suns for 95% capture
Mirror Reflectivity / Slope Error	>94% / <1.5 mrad
Receiver / Overall Thermal Efficiency	>94.9% / >80%

The prototype of the Big Dish was installed at ANU Campus, while the first commercial project was commissioned at Muni Seva Ashram, in the state of Gujarat, India.

Figure 1. *Big Dish commissioned at Muni Seva Ashram Campus, in standing position (left) and sleeping position (right).*

1.2 Steam Demand at Muni Seva Ashram

Muni Seva Ashram (MSA) is an NGO near Goraj village in Gujarat, Vadodara which is a mother organisation to many social activities. The Ashram houses Kailash Cancer Hospital & Research Center (KCHRC), known for its subsidised cancer treatments for patients who cannot afford them. The Ashram has been validated as an organisation from the CAF International [3].

MSA has two 200 TR and a single 400 TR Vapour Compression Refrigeration System that caters for the space cooling requirements of KCHRC. MSA also has an industrial Biomass

Briquette Boiler of 1 TPH that supplies steam to KCHRC for cooking in their canteen, cleaning clothes in their laundry, and sterilising surgical equipment.

MSA is renowned for its strong commitment to sustainability and renewable energy. The organisation has intensively invested in Organic Farming and Animal Husbandry. The organisation has also invested in Renewable Energy Projects of Biogas and Solar. In 2009, MSA commissioned the world's first Solar Powered Space Cooling System that comprised 100 Scheffler Dishes and a 100 TR Vapour Absorption Machine (VAM). After 6 years, the Indian Boiler Regulations (IBR), the government body that validates and approves Steam Boilers in India, made changes to their regulation. Upgrading to this new code was economically unviable and hence the VAM was decommissioned. The system was replaced by Vapour Compressor Machines, but the solar field continued to supply steam which was diverted to the other applications of steam in the Ashram.

2. Big Dish Projects for KCHRC

Sunrise CSP Australia established a subsidiary, Sunrise CSP India Pvt Ltd in 2018 to bring cost-competitive thermal energy solutions to the Indian sub-continent. The current core business focus is to deliver process heating and cooling, co- and tri-generation solutions, delivered either on an EPC basis where the customer will finance and own the plant, or an Energy Services basis where the customer enters into a Steam / Heat / Power Purchase Agreement, as applicable and Sunrise CSP finances and owns the plant. Grid-scale dispatchable electricity generation will be a future growth stage expected to commence within 3 years.

MSA desired to reduce their dependence on biomass briquettes for their existing steam demand and to thereby lower their cost of steam used for both process heating and space cooling applications, described below. Sunrise CSP proposed an energy services-based solution to MSA and entered into a Steam Purchase Agreement (Phase 1), which is to be extended into a Chilled Water Purchase Agreement (Phase 2) and a Power Purchase Agreement (Phase 3).

2.1 Phase 1 – Replacing the 100 Scheffler Dishes with Single Big Dish

The Solar Field of 100 Scheffler Dishes was decommissioned in 2019 and Big Dish was installed in the same field. The area occupied by the Big Dish was 1/3rd of that of the Scheffler Solar Field but had the same thermal output. Table 2 provides a brief comparison of the two technologies. The mirror facility to produce the 380 Solar Mirror Panels was also set up in the MSA campus.

2.1.1 Phase 1 Project Overview

Table 2. *Comparison of Solar Field of 100 Scheffler Dishes and Big Dish*

Particulars	Scheffler Dishes Solar Field	Big Dish
Number of Dishes	100 Scheffler Dishes	1 Big Dish
Total Mirror Area	1,250 m^2	520 m^2
Output	400 kg/hr steam @ 10 bar, 180°C	400 kg/hr steam @ 40 bar, 450°C
Footprint Area	2,000 m^2	625 m^2

Even though the Big Dish was already constructed once before on the ANU campus, re-constructing it in India was a challenge due to different regulations, different availability of steel grades and different local manufacturing practices. Modifications to the Big Dish Receiver and steam piping were made as per IBR and availability of materials.

Before the installation of the Big Dish in India, IBR had not permitted the use of moving Boilers and Flexible Joints. This presented a significant challenge for the Big Dish Project in India, as the design involves a boiler (Receiver) that moves throughout the day while the dish tracks the sun. In addition to the mobile boiler, the pipes that carry water and steam needed to be flexible to accommodate the sun-tracking functionality of the dish. The requirement for dual-axis tracking necessitated flexibility at two points in the piping.

Recognizing the innovation and potential of the Big Dish, IBR expressed interest in supporting the Project's progress while upholding safety regulations. Both concerns were thoroughly deliberated with IBR, leading to the introduction of new regulations following extensive engineering discussions. Notably, the Receiver of the Big Dish has achieved the distinction of being India's inaugural IBR Certified Solar Boiler and India's first Certified moving boiler. To address the issue of flexibility in the pipelines, Rotary Joints that were originally used on ANU's previous SG3 400 m^2 Solar Concentrator were adapted, produced, and subjected to testing, all under the approval of IBR – once again India's first – IBR Certified Rotary Joints. The novelty of the system with respect to India's IBR meant that from the early designing stage to the final commissioning stage, the IBR was involved at every step. The result being that every system component and the end-to-end solution are IBR compliant – a first in the CST industry in India.

The feedwater for the Big Dish is also required to comply with the IBR Norms, hence a De-Mineralised Water (DM) Plant of 10 kl/day capacity was installed. This facility operates in batch mode to treat water from the adjacent Dev River and store enough water for the Big Dish to run for one day.

The Big Dish delivers steam to a pressurised hot water system, where feed water of ambient temperature from the DM Plant is mixed with the Dish steam at 250 °C, which results in the accumulation of steam in the upper vessel and water in the bottom. The water from the bottom (250°C) is flashed into another vessel at the time when steam is required by MSA. The steam is provided to the application via a header shared by the MSA existing boiler, while the hot water condensate is stored in a third vessel that is used for bathing the next day.

The pressurised hot water system works in two modes of operation:

- *Storage Mode*: The storage tank is filled with steam from the dish and then emptied by supplying steam and hot water to the ashram on demand.
- *Continuous Mode*: The storage tank is set at a constant level during dish operations (i.e., charging and discharging at the same time). This is used when the storage tank is full and there is a demand for heat during dish operating hours.

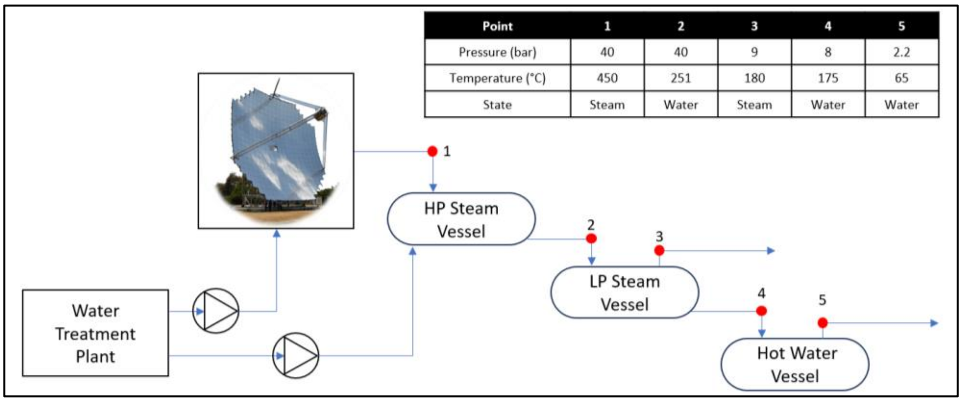

***Figure 2**. Big Dish Schematic for MSA Phase 1 Project*

2.1.2 Phase 1 Big Dish Performance

The following Figure 3. shows the estimated performance of the Big Dish.

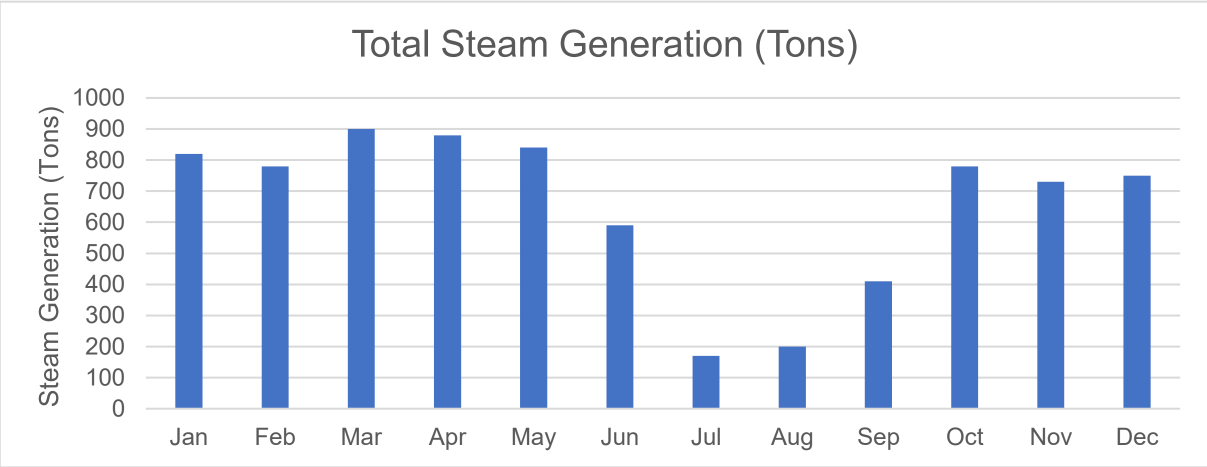

Figure 3. *Thermal performance of the Big Dish installed for MSA Phase 1 Project*

2.2 Phase 2 – 1000 TR Vapour Absorption Refrigeration System

The next phase of the project is to implement a 1000 TR Vapour Absorption Refrigeration System using 8 Big Dishes.

2.2.1 Phase 2 Project Overview

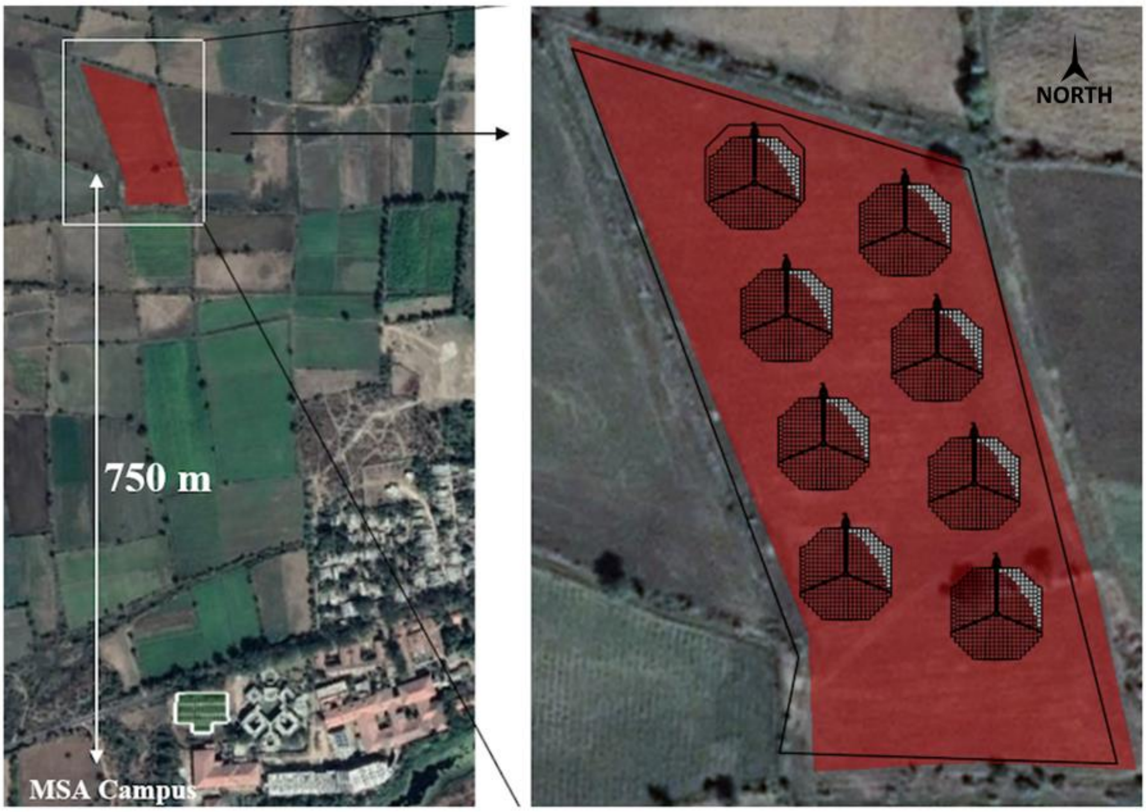

Figure 4. *Schematic for MSA Phase 2 Project*

The area selected for the project is 800 meters away from the point of application in MSA. It is decided to install the Vapour Absorption Machine (VAM) near the solar field and pump the cold water to the MSA, as it will be more energy efficient than transporting steam.

A Double-effect VAM capable of delivering 1000 TR cooling requires 3.6 TPH of saturated steam at 8 bar(g) pressure. As the Big Dish is designed for pressure and temperature well above the requirement, a Pressure-reducing and Desuperheating System (PRDS) will be used. The PRDS will inject low-temperature water into the steam flow to reduce its temperature to 180°C and a Pressure Reducing Valve (PRV), an internal component of PRDS, reduces the pressure to 8 bar(g). A steam accumulator is also installed after PRDS to stabilize the flow inlet to the VAM.

2.2.2 Phase 2 Solar VARS Performance Estimation

The location decided for installation is not a perfect rectangle and hence the dishes cannot be laid out in a rectangular manner. Figure 4 shows the layout of the solar field.

The performance of the solar field and VARS system is estimated by taking the NREL TMY data for the location. As per the TMY, the location gets 1800 kWh of Direct Normal Irradiance (DNI) per m^2 in a year with the highest DNI of 846 W/m^2. The low DNI days are in July and August due to monsoon, but apart from that, the land enjoys decent DNI in 10 months.

Other key factors assumed in the estimation are

- The location falls in the upper tropical zone, very much near the Tropic of Cancer. For some 60 days in the year, the sun goes beyond the 90° limit of the dish. For this, the dish needs to spin backwards in the azimuth direction almost instantly, but cannot do so because of motor restrictions. The control system of the dish carefully predicts this and starts the azimuth movement well before the sun is going to move to the southern hemisphere. This means the Dish loses focus over the dish for a few minutes when the DNI is very high. This minor loss is considered in the final estimations.
- The Dishes in the field will cast shadows of themselves onto the adjacent dish. Shadows appear solely during low DNI periods (mornings and evenings), resulting in a relatively minor impact on total production. This minor loss is also considered in the final estimations. Figure 5 shows how the shadow effect diminishes in the afternoon (high DNI duration) for this specific solar field.

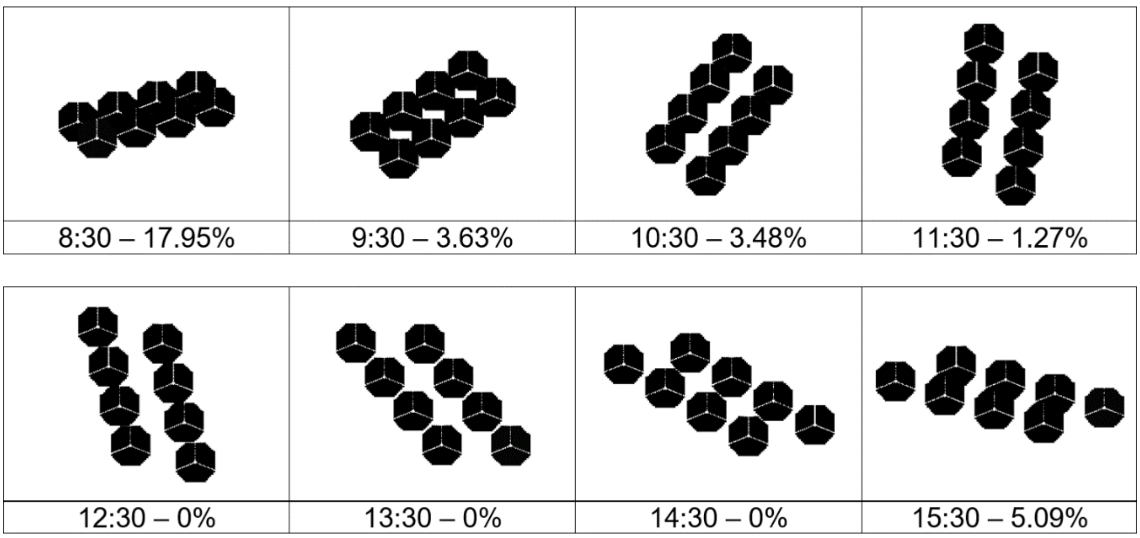

***Figure 5**. Simulated view of the 8 Dish Solar Field as seen from the direction of Sun & Overlap percentage at various times of the 1 Jan 2023.*

The methods and calculations used for the estimations the Steam and net cooling are described below:

- Solar Field Steam Flow Rate ($\dot{m}_s$) from the Dish:

$$\dot{m}_s = \frac{\eta_o I A_{ap}}{h_{out} - h_{in}} \tag{1}$$

Calculations were performed on an hourly basis, and the DNI (I) was taken for each hour from the NREL TMY Data. Overall efficiency (η_o) takes in all the efficiencies such as optical, thermal and piping efficiencies. Theoretical values of these efficiencies and the Aperture Area (A_{ap}) were taken for calculations based on the earlier research done at ANU. Enthalpy of the steam at the outlet (h_{out}) and water at inlet (h_{in}) were calculated based on the pressure and temperature conditions of steam and water. The dish would keep the temperature and pressure constant at the outlet and control the flow to compensate for the varying DNI.

- The steam properties for the VARS and its flow are defined by the vendor of the Vapour Absorption Machine (VAM). Hence the steam flow rate going into the VAM $(\dot{m}_f)$ has a maximum value (3.6 tph in this case). The dish is operated based on this limit $(\dot{m}_{s,l})$ and if it is crossed, the dish is de-focused and steam generation is halted. Feedwater Flow Rate $(\dot{m}_f)$ was calculated on simple conservation of mass and energy equations.

$$\dot{m}_{VAM} = \dot{m}_{s,l} + \dot{m}_f \tag{2}$$

$$h_{VAM}\dot{m}_{VAM} = h_{out}\dot{m}_{s,l} + h_{feed}\dot{m}_f \tag{3}$$

In the above equations, (h_{feed}) is the enthalpy of feedwater and (h_{VAM}) is the enthalpy of steam required at VAM inlet.

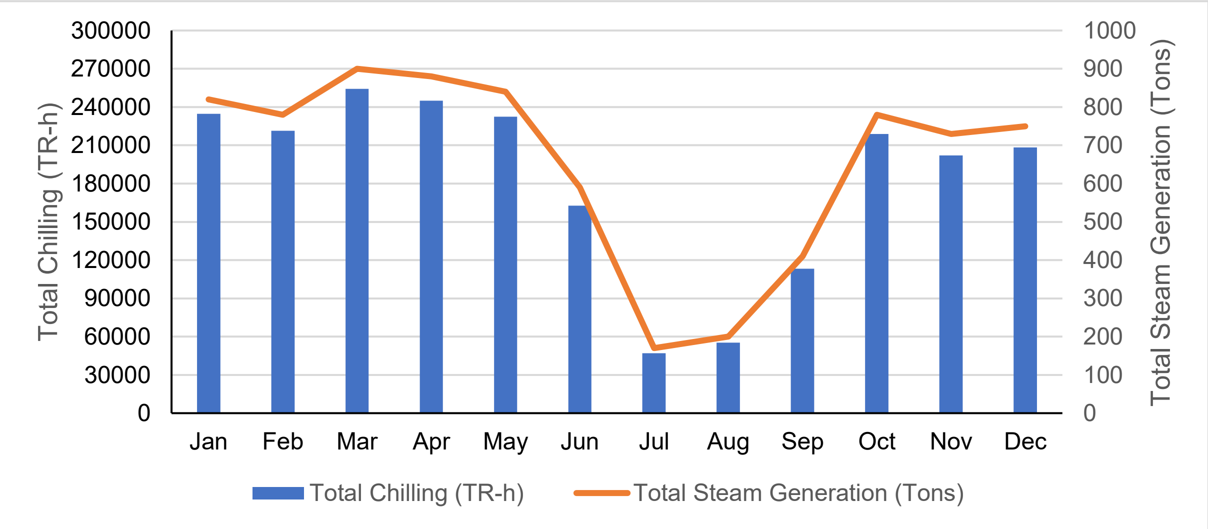

***Figure 6**. Estimated Performance of MSA Phase 2 Project*

2.2.3 Levelized Cost of Refrigeration

Levelized Cost of Refrigeration (LCoR), was calculated to be ₹6.76/TR for 25 Years of operation. 0.5% degradation in the Steam Production was assumed for each year. The cost of 1 TRh with Solar Big Dish was compared with the fossil fuel scenario, assuming a 1% escalation in fuel costs. The comparison is shown in Figure 7. The cost of fossil fuels considered is for the Muni Seva Ashram.

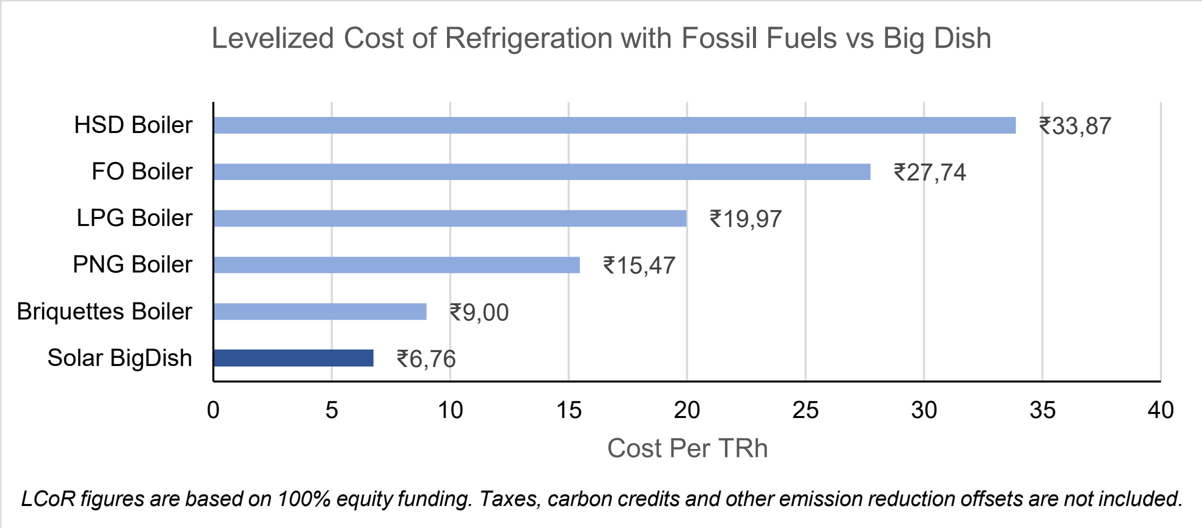

Figure 7. *Comparison of LCoR with Big Dish powered VAM with Fossil Fuel Power VAM.*

2.3 Phase 3 – 1 MW$_e$ Trigeneration Power Plant

The last phase of the project is to implement a 1 MW$_e$ Trigeneration Power by adding 12 more dishes to the Phase 2 Big Dish Solar Field. These 20 dishes will run a condensing turbine, and a bleed from this will be used for VARS and other applications at MSA.

The Trigeneration System aims to utilize the maximum amount of energy from solar steam while fulfilling multiple applications of an organisation or an industry.

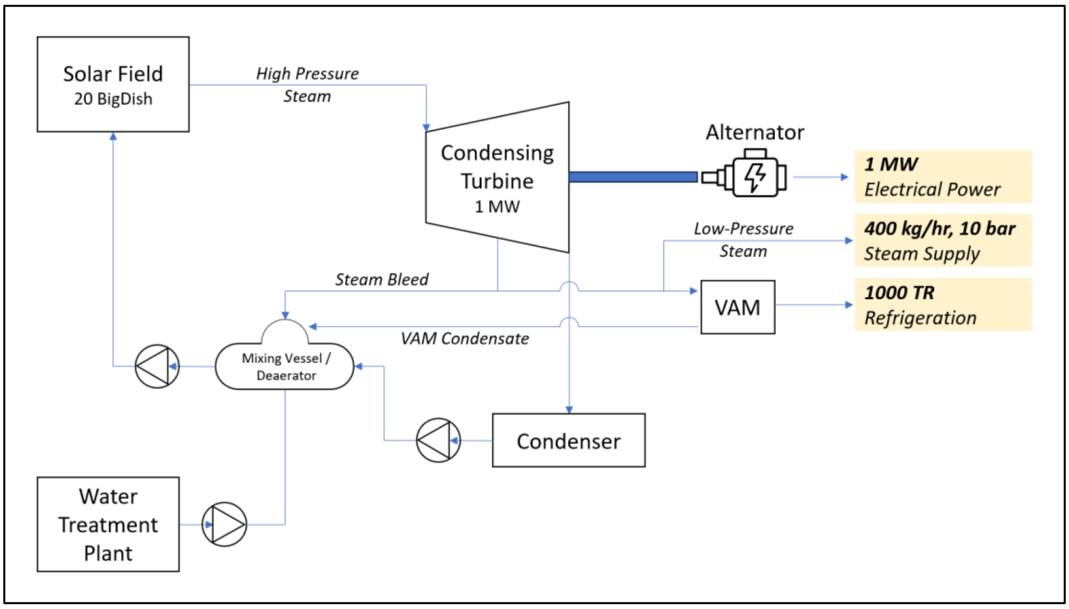

Figure 8. *Conceptual Layout of Trigeneration System for MSA Phase 3 Project*

2.3.1 Phase 3 Project Overview

The concept of the Trigeneration Project is at the design stage. The project aims to demonstrate how solar Electricity, Space Cooling and Steam for Process heating can be provided with the same solar field. Figure 8. shows 400kg/hr of low-pressure steam which is sufficient for various applications like Cooking for almost 2500 people per day, laundry, Sterilization, 20000 ltr hot water, etc.

3. Conclusion

The project to replace 100 Scheffler Dishes with a single Big Dish at Muni Seva Ashram has successfully concluded, overcoming various technical and commercial challenges. Over the next few months, the Big Dish will undergo several tests while meeting the thermal demands of the KCHRC. The experience gained during the manufacturing of the Big Dish has highlighted opportunities for enhancing both the manufacturing process and the design to optimize the cost and performance of the solar concentrator. Additionally, insights into the dish's performance will be obtained from operational tests.

The Sunrise CSP team plans to refine the design based on their manufacturing experience and operational data. These enhancements will be implemented into the Space Cooling (Phase 2) and Trigeneration (Phase 3) projects at MSA.

Author contributions

Artur Zawadski: Supervision, Writing – review & editing.

Pranav Gadhia: Conceptualization, Project administration, Writing – review & editing.

Aditya Soni: Investigation, Data curation, Formal analysis, Writing – original draft.

Competing interests

This paper provides an overview of a commercial project undertaken by Sunrise CSP. The authors are all employees of Sunrise CSP companies based in Australia, Cyprus, and India.

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The project described in this paper is a commercial project developed under an Energy Services Company (ESCO) model that has been entirely funded by Sunrise CSP who own the infrastructure and will deliver steam (Stage 1), chilled water (Stage 2) and electricity (Stage 3) to the Kailash Cancer Hospital under a Steam/Chilled Water/Power Purchase Agreement.

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