



# Solar Thermal-Based Desalination Using Non-Imaging Evacuated Tube Collectors with Compound Parabolic Concentrator

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**Abstract.** Water scarcity is a major issue in coastal areas which is addressed by converting sea water to potable water through reverse osmosis known as Seawater reverse-osmosis (SWRO). This process requires heat which is often achieved through electrical energy. In the first-of-its-kind facility in India, a 120 tons per day solar thermal based sea water desalination was developed, and deployed at NTECL Vallur, which utilizes Non-Imaging Evacuated Tube Collectors (ETCs) integrated with Compound Parabolic Concentrators (CPCs) enclosed in toughened glass covers to harness Global Horizontal Irradiance (GHI). This system eliminates the need for solar tracking. The system produces hot water at an average temperature of 68°C, with an 11°C temperature differential across the solar field under an average GHI of 557 W/m<sup>2</sup>. The heated water is supplied to a six-effect Multiple Effect Distillation (MED) unit for desalination. Over a six-hour operating window, the plant achieved a distillate production rate of 5.5 tons per hour, with a product water conductivity of approximately 4.3 µS/cm, TDS of 40 mg/L, and pH of 7.2.

**Keywords:** Solar Thermal, Evacuated Tube Collectors, Compound Parabolic Concentrator

## Abbreviations:

|       |                                                   |
|-------|---------------------------------------------------|
| TPD   | Tons per day                                      |
| NETRA | NTPC Energy Technology Research Alliance          |
| NTECL | NTPC Tamil Nadu Energy Company Limited            |
| GHI   | Global Horizontal Irradiance                      |
| DNI   | Direct Normal Irradiation                         |
| NIC   | Non-imaging Concentrator                          |
| EPC   | Evacuated Tube Collectors with Compound Parabolic |
| CPC   | Concentrator                                      |
| MED   | Multi-Effect Distillation                         |
| MSF   | Multi-Stage Flash Evaporation                     |
| SWRO  | Seawater reverse-osmosis                          |

## 1 Introduction

The global scarcity of drinking water is intensifying rapidly, driven by population growth, industrialization, and climate variability. The widening gap between water demand and available freshwater resources presents a critical challenge, particularly in coastal and arid regions. Conventionally, freshwater is sourced from lakes, rivers, and reservoirs, followed by treatment to meet potable water standards. However, with growing stress on these conventional sources, saline water—particularly seawater—has emerged as a viable alternative for freshwater generation through desalination technologies [1].

Among desalination methods, seawater reverse osmosis (SWRO) has been widely adopted in countries with access to coastal waters due to its lower specific energy consumption and cost for large-scale plants [2]. Nonetheless, SWRO systems require a stable power supply and skilled operation, which limits their deployment in remote or underdeveloped areas. In such regions, where water demand is typically modest, the use of small-scale thermal desalination systems becomes attractive due to their operational simplicity and reduced reliance on high-pressure components [3].

Thermal desalination technologies, such as Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED), rely heavily on heat energy, which constitutes a significant portion of their operating costs [4]. However, when these systems are integrated with waste heat from power plants or renewable sources like solar thermal energy, the overall cost of water production can be substantially reduced, improving economic viability [5]. Loewy et al. [6] recommended hybrid desalination systems combining power and desalination in the Gaza Strip to enhance resource efficiency and energy recovery.

In this context, solar thermal-based desalination offers a promising, environment-friendly solution. Particularly in coastal regions, where seawater is abundant and solar insolation is high, solar-assisted thermal desalination can provide a decentralized, off-grid method for freshwater generation. Recent developments in compound parabolic concentrators (CPCs) and non-imaging evacuated tube collectors (ETCs) have enabled efficient harvesting of Global Horizontal Irradiance (GHI) without the need for mechanical solar tracking, thus improving system reliability and reducing operational complexity [7].

The present work describes the design, development, and performance evaluation of a 120 TPD solar thermal desalination pilot plant, installed by NTPC Energy Technology Research Alliance (NETRA) at the NTECL Vallur site in Chennai. The system utilizes CPC-integrated non-imaging ETCs to supply hot water to a six-effect MED unit. This study demonstrates a sustainable and modular desalination solution tailored for remote and resource-constrained coastal environments.

## **2 Selection of Technology**

### **2.1 Thermal Desalination Technology Methods:**

There are mainly two types of distillation systems used in thermal desalination: multi-stage flash evaporation (MSF) and multi-effect distillation (MED) units [8]. Among these, MED systems are generally more energy-efficient, as they reuse the latent heat of vapor from one effect to drive evaporation in the next, thereby increasing freshwater yield per unit of thermal input [9]. In cases where severe scaling issues are encountered, multi-effect flash evaporation is preferred due to its better handling of high-salinity and scaling-prone feedwater [10]. To further enhance efficiency, mechanical vapor compression (MVC) can be employed, wherein vapor from the last stage of the MED unit is compressed and reused in the first stage, significantly improving the gain output ratio (GOR).

In support of such design approaches, Viswanathan et al. [11] shared key insights from the RAMDAS project on solar desalination, which highlighted the importance of deploying low-maintenance, robust systems tailored for rural and remote settings where skilled technical manpower is limited. The study underscored the effectiveness of integrating solar thermal energy sources with simple MED configurations and emphasized the need for modular, user-friendly designs that can operate reliably in decentralized infrastructure without heavy operational oversight.

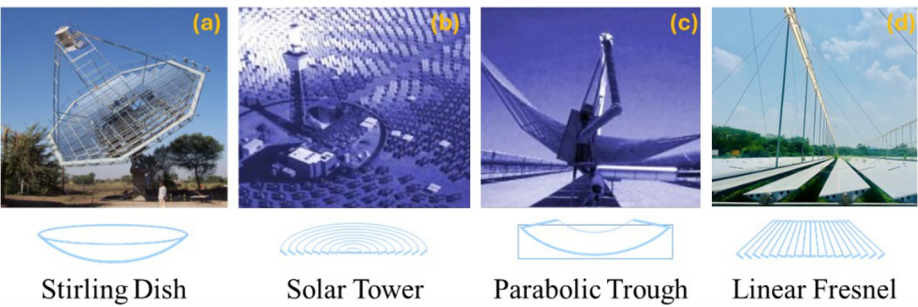
### **2.2 Solar Thermal Collectors:**

Solar radiation reaching the Earth's surface can be categorized into two main components, and solar thermal collectors are typically designed to operate based on either of these [12]. Direct Normal Irradiation (DNI) refers to solar radiation that arrives in a straight line from the sun, with minimal scattering or absorption, and is measured on a surface oriented perpendicular to the sun's rays. GHI represents the total solar energy received on a horizontal surface, including both direct and diffuse components.

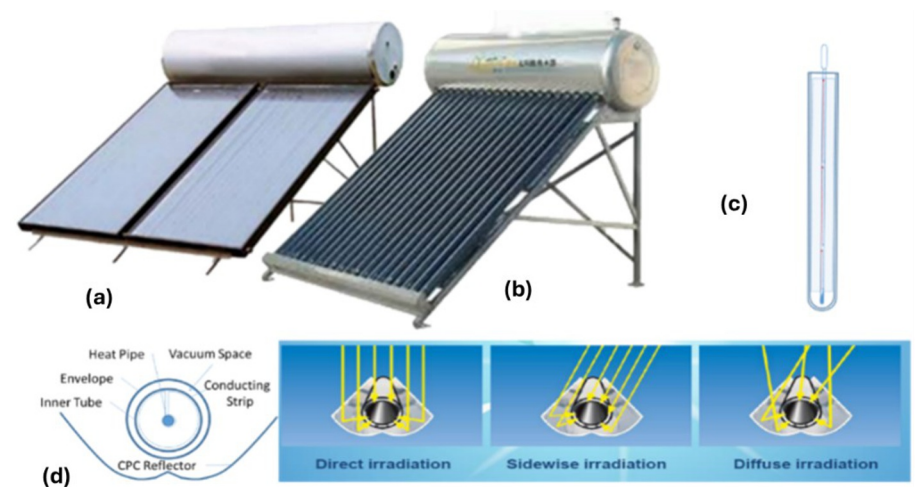
While photovoltaic (PV) systems primarily operate within the visible portion of the electromagnetic spectrum and rely on GHI, solar thermal collectors - especially those used in concentrating systems, are typically designed to harness DNI. These collectors absorb a broader range of the solar spectrum, including infrared radiation, and generally require sun-tracking mechanisms to maintain optimal alignment with the sun throughout the day [13].

#### **2.2.1 DNI Type Solar Collectors:**

Solar Thermal collectors operating on DNI are Parabolic Trough, Linear Fresnel, Dish, and Tower Dish, Tower, Parabolic Trough, and Linear Fresnel. The collectors are shown in the Fig. 1. However, for efficient operation of these systems, the efficiency of the solar tracker must be considered as the heat energy generated from these solar thermal technologies utilizes DNI component of the solar radiation.



**Fig. 1.** Different types of solar thermal collectors based on Direct Normal Irradiation (DNI) (a) Stirling Dish (b) Solar Tower (c) Parabolic Trough (d) Linear Fresnel.



**Fig. 2.** Collectors for Global Horizontal Irradiation (GHI) (a) Flat Plate Collector (b) Evacuated Tube Collector (c) Heat Pipe (d) CPC reflector

The solar tracker requires control system, rotating parts and electricity for motors which in turn increase capital cost and operating cost.

### 2.2.2 GHI Type Solar Collectors:

As shown in the Fig. 2, flat plate collectors and evacuated tube collectors are GHI-type collectors. In GHI type of collectors, evacuated tube collectors are the most efficient type of hot water solar collectors. These collectors have evacuated glass, allowing them to operate well in colder climates. Inside this evacuated type of collector, there can be either a U-tube or a heat pipe for circulating the process fluid that absorbs heat within the evacuated tube. In the heat pipe configuration, the tube is partially filled with a working fluid under evacuated conditions. When exposed to solar radiation, the fluid evaporates and rises, transferring heat to the process liquid through a condenser interface. Upon condensation, the liquid returns to the bottom of the pipe via gravity, enabling a passive, continuous heat transfer cycle [13]. The performance, durability, and quality of these collectors were validated according to the EN 12975 standard, which specifies the general requirements and testing methods for solar thermal collectors, including evacuated tube systems [14]. The arrangement of the heat-pipe in the evacuated tube is shown in Fig 3 (c).

Souliotis et al. [15] demonstrated that the integration of CPCs with evacuated tube collectors significantly enhances solar collection efficiency. CPCs operate on GHI and do not require sun-tracking systems, making them especially effective for passive, low-maintenance designs. These reflectors have been shown to improve thermal performance by increasing water temperature and enhancing heat retention, as illustrated in Fig. 3 (d). Solar thermal desalination systems, particularly those based on MED, can operate efficiently at moderate temperatures below 100 °C [16], making them compatible with CPC-based solar collectors. Mortazavi et al. [17] further confirmed the cost-effectiveness, thermal efficiency, and suitability of CPCs for low-temperature applications in solar desalination, especially in off-grid or semi-urban environments.



**Fig. 3.** Single collector ETC-CPC, with Toughened Glass Cover and Multi Effect Distillation over the structure.

Transmittance is an important property, especially in applications like solar panels, optical devices, and displays, as it affects the amount of light or radiation that can be transmitted through the material. To facilitate easy cleaning, the ETC-CPC collector was designed and developed within a housing box equipped with toughened cover glass, which has a transmittance  $\geq 91\%$  and CPC having reflectivity  $\geq 86\%$ . The quality of the toughened cover glass was validated in accordance with ISO 9001 standards. The setup is shown in Fig. 3. General standards and considerations for cover glass are:

### 1. Material Composition

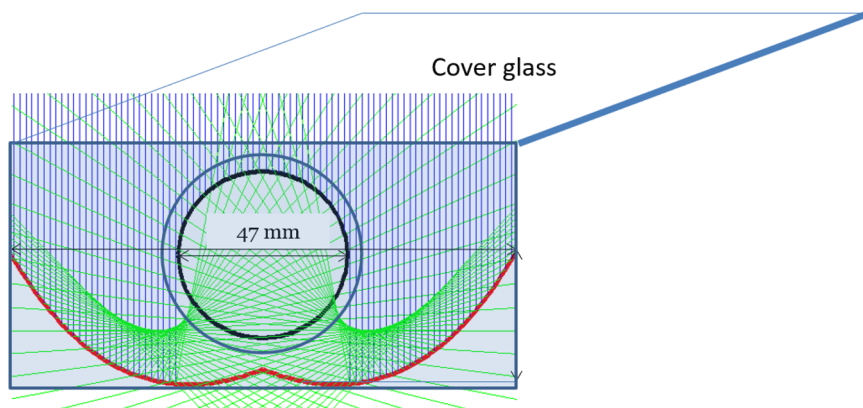
- **Glass Type:** Typically, soda-lime or low-iron glass is used in solar applications to achieve high solar transmittance due to its lower iron content and higher clarity [18].
- **Coatings:** Anti-reflective (AR) coatings are commonly applied to reduce reflection losses and further enhance light transmission through the glass [19].

### 2. Thickness of the Glass

The thickness of the glass significantly influences its transmittance. Thinner glass typically permits more light to pass through, though optical performance is also affected by coating type and base material selection [20].

### 3. Surface Quality

High-quality cover glass should have a smooth, clear surface with minimal imperfections. Scratches, dust, or any contaminants can reduce effective transmittance.



**Fig. 4.** Raytracing on a Single Evacuated Tube with CPC and Glass Cover.

- **Optical Clarity:** The glass should be free from defects, such as bubbles or inclusions, that could scatter or absorb light.

The evaluation of optical performance of ETC-CPC with cover glass was carried out using the Ray-tracing Method in MATLAB as shown in Fig. 4. Ray-tracing techniques are appropriate for evaluating line-axis systems. Considering all the above merits / demerits, a best combination of non-imaging type CPC along with multi-effect distillation was configured for an efficient desalination system near coastal regions.

### 3 Results and Discussion

#### 3.1 Process Description

The present solar thermal desalination system was installed at NTECL Vallur. The desalination plant is divided into two parts. First is the LP steam Generator Block and the other is the Desalination block. In the present set up the solar thermal collector working on GHI were deployed. Instead of a U-tube, a heat pipe which is dry plug system was used inside the evacuated tube to carry thermal energy in this project. Based on our experience, in heat-pipe not only there is any requirement to isolate the damaged evacuated tube, but the replacement of the evacuated tube is also easy. To minimize both capital and operating cost, GHI type collectors were used. A block diagram of the system is shown in Fig. 5.

#### 3.2 LP steam Generation Block

This block is mainly designed to produce hot water via solar thermal technology only. This technology consists of a CPC for generating of hot water. The generated hot water is flashed in a flash chamber which is maintained under partial vacuum to generate low pressure steam. This steam is then utilized as a motive steam in next block.

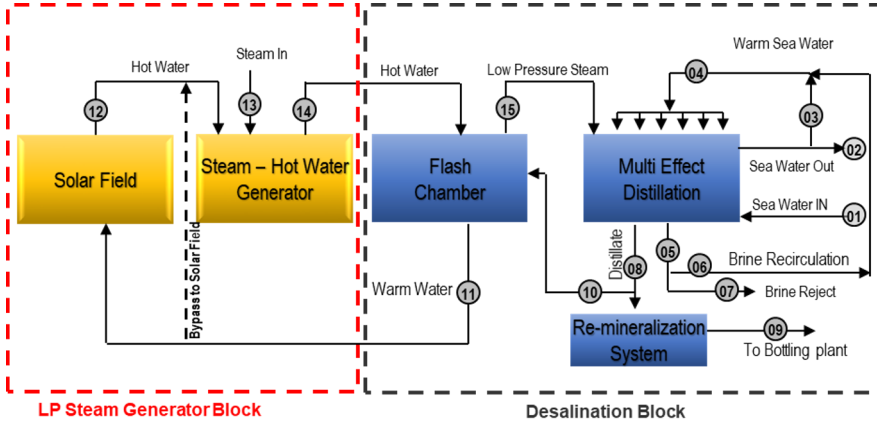


Fig. 5. Block diagram of solar thermal desalination system

### 3.3 Desalination Block

The MED is operated under partial vacuum. The hot water coming from the solar block is sprayed in flash chamber. In the flash chamber, which is maintained under vacuum, the hot water is flashed to produce low-pressure (LP) steam. The reduced pressure in the chamber lowers the boiling point of water, causing a portion of it to evaporate using the sensible heat of the water. The remaining warm water in the flash chamber is then returned to the solar field to generate additional hot water during the daytime. The produced flash steam serves as motive steam for the first effect of the MED system, also maintained under vacuum. In this chamber, seawater is sprayed over the LP steam piping. The combination of the high skin temperature of the piping and the vacuum environment causes part of the sprayed seawater to evaporate. This vapor is then directed to the subsequent distillation chamber, where it acts as working steam, repeating this process through eight effects with a gain output ratio (GOR) of approximately six (6). To maximize thermal energy efficiency within a desalination system, effects are used. The desalinated vapours produced in last effect is condensed in a condenser, and the resulting distilled water in each effect and condenser is sent to a remineralization system to ensure high-quality potable drinking water. The design details are given in Table 1 and the installed plant is shown in Fig. 6. Liu et al., [21] developed mathematical and economic models for thermal and economic performance on solar desalination system with evacuated tube collectors and low-temperature multi-effect distillation. They analyzed two independent parameters heating steam temperature of the first effect and number of effects. With the increasing number of effects, the freshwater cost decreases gradually.

Thermal inertia refers to the ability of a system to resist changes in temperature, meaning it can absorb or release heat with minimal immediate fluctuation in its thermal state [22]. In distillation and other thermally-driven processes, maintaining adequate thermal inertia is critical to ensure temperature stability, which helps prevent performance drops, product quality degradation, and equipment stress due to abrupt thermal shifts. The process requires a stable, consistent heat source to maintain steady distillation operations. Sudden variations in temperature can lead to inefficiency, lower product quality, or even equipment stress. To achieve consistent distillate production of 120 TPD (tons per day) and maintain thermal inertia, an alternate source of heat, such as low-pressure steam, can be supplied from a power plant. Low-pressure steam is an efficient and cost-effective heat source in many industrial processes, particularly in systems that require consistent, moderate heating over extended periods. Power plants often have excess steam that can be used for processes like distillation. Supplying low-pressure steam from a power plant helps in ensuring that the required thermal energy for distillation is available continuously without interruptions.

The differential average temperature maintained between the output and input of the solar field was 11°C. The solar field generated hot water at an average temperature of 68°C, with an average GHI of 557 W/m<sup>2</sup>. The performance of the Solar Thermal Desalination Plant is plotted in Graph 1. Over a six-hour period, the average distillate water production rate was 5.5 tons per hour, with an average conductivity of approximately 4.3 µS/cm. The reliance on sophisticated mechanical rotating components like solar trackers has been significantly reduced by using NIC in solar thermal desalination, leading to increased system reliability and decreased electricity consumption. Various solar thermal and desalination technologies were examined to identify the most economical option suitable for installation and operation in remote coastal areas, requiring minimal electricity and manpower. Nevertheless, the author is of the view that due to rising costs of energy, desalination costs may not decrease in the future despite technological advancement in existing technology, raw materials and future operating costs.

**Table 1.** Design details of Solar thermal seawater desalination pilot plant.

| Multi Effect Distillation (MED)                                                                                                                                                                                                                                   | Solar Field                                                                                                                                                                                                                                                            |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• Integrated Design with Flash Chamber &amp; MED</li> <li>• Number of Effects in MED: 8 Nos</li> <li>• Gain Output Ratio: 6</li> <li>• Capacity= 120 TPD</li> <li>• Output distilled water quality: TDS ≤ 5 ppm</li> </ul> | <ul style="list-style-type: none"> <li>• Number of Bay: 5 Nos</li> <li>• Modules in each Bay: 110 Nos (22x 5)</li> <li>• Collectors in each Module: 24 Nos</li> <li>• Total number of Modules: 550 Nos</li> <li>• Total Collector Area: 2,420 m<sup>2</sup></li> </ul> |



**Fig. 6.** Site photograph of the Solar Thermal (ETC-CPC) field of 2,420 m<sup>2</sup>

#### **4 Benefits of the present system**

- a) **Sustainable and Environment-Friendly Green Energy:** Utilizes renewable solar energy, significantly reducing dependence on fossil fuels and lowering greenhouse gas emissions.
- b) **Minimal Chemical Consumption:** The Multi-Effect Distillation (MED) process operates at a design temperature of 65°C, which is below the solubility limits of scaling compounds such as: Carbonates (70°C), Sulfates (67°C). This minimizes scaling and reduces the need for antiscalant chemicals.
- c) **Continuous Operation:** Unlike intermittent systems, solar thermal desalination can support continuous operation when coupled with thermal energy storage. This ensures: (1) High water yield, (2) Increased plant availability and reliability.
- d) **Modular and Scalable Design:** The system architecture allows for: (1) Easy expansion based on water demand, (2) Flexible integration with existing infrastructure.

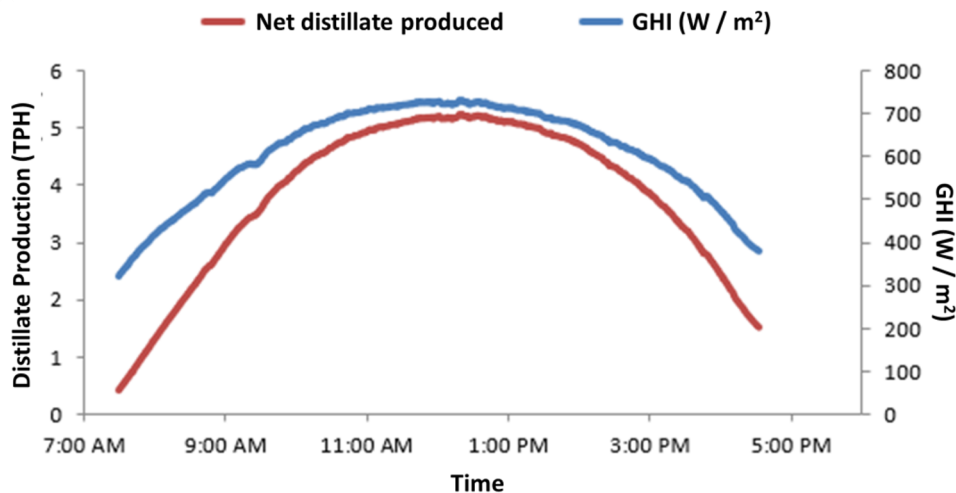


Fig 7. Plot showing the production of Distillate and time of the day along with corresponding

## 5 Applications of ETC-CPC

In addition to Cost-effective seawater desalination, these collectors are used for pre-heating fluids in various applications, including solar thermal cooking, milk pasteurization, and solar thermal air conditioning. The distilled water produced through solar thermal desalination can also be utilized in electrolyzers for hydrogen generation. This approach can help reduce the reliance on freshwater for hydrogen production, particularly in coastal regions.

## 6 Conclusions

- i. The present project has deployed Solar Thermal based Desalination using Non-Imaging Evacuated Tube Collectors with Compound Parabolic Concentrator at NTECL Vallur and is successfully running. Though covered glass is used, it does not have considerable effect on the production of hot water in the system.
- ii. The plant is producing 120 TPD of drinking water conforming to IS 10500 standards. The water achieved the TDS of 40 mg/l and pH 7.2, which makes it slightly alkaline. Potassium carbonate and Magnesium chloride levels were 20 ppm each.
- iii. The levelized cost of water production comes around INR 0.31 per litre, assuming the plant life of 25 years.
- iv. The mean emissions calculated for solar thermal-based desalination are 3.88 kg CO<sub>2</sub> eq./m<sup>3</sup>. When comparing this to Reverse Osmosis (RO) systems, using solar thermal desalination to produce 5,833 m<sup>3</sup> of distilled water annually results in a total reduction of 18,206 kg of CO<sub>2</sub> emissions per year.

- v. Among the cost constitution of ETC solar desalination system, the proportion of the cost of evacuated tube collector is the largest (31%), then the cost of civil installation and auxiliary equipment and the cost of manpower is second (15%).

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