Techno-economic analysis for a standalone HVR membrane distillation water purification system using concentrated photovoltaic thermal (CPVT) technology

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Two billion people across the world do not have access to safely managed water resources. Specifically in the Indian state of Odisha, drinking water sources are contaminated with fluoride, which can cause health issues such as dental and skeletal fluorosis. To address this issue, HVR Water Purification AB company outfitted a primary school in Odisha with a Membrane Distillation (MD) system powered by evacuated tube collectors and PV panels. This design, however, fails to provide the required energy input to meet a demand of at least 1000 L/day of distillate. This thesis demonstrates an improvement in the system by implementing Concentrated Photovoltaic Thermal (CPVT) panels for the energy input. Three different CPVT technologies from three prominent solar companies: Naked Energy, Sun Oyster, and SunBase, were modeled using Polysun. The different CPVT technologies each have a unique optimal use-case. A design that optimizes for the Life Cycle Cost (LCC) of water should use a Sun Oyster or SunBase CPVT because their systems have the lowest LCCs (14.76 and 16.11 $\$/\mathrm{m}^3$*, respectively). A design that optimizes for efficient land use should use Naked Energy's modular system, which has the greatest yield-to-area of 43.46* $\mathrm{L/day/m}^2$*. For any system, a greater overall yield and lower LCC are obtained in systems which use 15 MD modules with per-module flow rates of 1500 L/h. Overall, the inclusion of CPVT systems in the Odisha case would be beneficial for substantially increasing the daily yield to the goal of 1000 liters per day.*

1 Introduction

1.1 Motivation

Water is fundamental to human life and therefore, this precious resource should be managed with great care, however, much of the world's population suffers from water scarcity, contaminated drinking water sources, or both (Carlos Pavon, 2019). Melting tropical glaciers, desertification, and droughts are expected to increase in severity and frequency over the next decade. The pressure that human activity places on natural fresh water resources is called water stress and it is a key indication of the sustainability of the use of water resources. Globally on average, 10% of the population lives in an area with high or critical water scarcity (UNESCO, 2021).

For the people collecting water from natural sources, one of the main contaminants present is fluoride. Fluoride contamination is mainly the result of volcanic activity in the area, punctuated by fluoride seeping into the groundwater. At low levels (<1 mg/L) fluoride in drinking water is a benefit to human health, promoting strong teeth and bones. However, at levels above the World Health Organization guideline of a maximum of 1.5 mg/L, it is detrimental to people's health (International Programme on Chemical Safety, 2002). For levels of fluoride between 1.5 and 3 mg/L, there is an elevated risk of dental fluorosis. This takes the form of browning and mottling of teeth. For high levels of fluoride contamination, ranging from 4 to 8 mg/L, skeletal problems are present such as skeletal fluorosis. And at extremely high, levels greater than 10 mg/L of contamination, crippling skeletal fluorosis can occur, in which bones begin to grow into one another, permanently impairing the movement of the individual (International Programme on Chemical Safety, 2002, Thole, 2013).

A promising technology to defluoridate drinking water is called Membrane Distillation (MD). A thermal source and a set of hydrophobic membranes are used to extract pure water and concentrate the contaminates of fluoridated drinking water. Many places which do not have access to modern water resources are also lacking modern energy access (Carlos Pavon, 2019). MD water purification can benefit these communities because it can be powered by completely off-grid energy sources.

The UN Sustainable Development Goal number 6 is to "Ensure availability and sustainable management of water and sanitation for all" (United Nations, 2015). For the scope of this thesis report, Target 6.1: "By 2030, achieve universal and equitable access to safe and affordable drinking water for all" and Target 6.4: "By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity" are the most relevant. The work of this thesis will contribute to the body of knowledge which aims at improving drinking water access, especially in rural communities suffering from fluoride-contaminated groundwater sources.

1.2 Outline of Problem

Odisha is an eastern state of India in which fluoride contamination is a major problem. Odisha is home to volcanic activity manifesting as hot springs. A sample performed showed that 39% of tested sites had levels of fluoride contamination of greater than 1 mg/L (Maitra et al., 2021). The Shakuntala hospital in Odisha noticed that the school children were exhibiting signs of fluorosis, and therefore, the leaders of the hospital approached HVR Water Purification AB to design a membrane distillation system which could defluoridate the groundwater for the nearby school.

HVR Water Purification AB ("HVR") is the sponsor of this thesis and has a long history in the field of membrane distillation. They are headquartered in Stockholm, Sweden and have ties to many research organizations such as KTH Royal Institute of Technology, the Fraunhofer Institute, and the Research Institutes of Sweden (RISE). HVR was started as a drinking water research branch of its parent company, Scarab Development AB. Other branches of Scarab Development AB include companies which focus on membrane distillation for industrial and laboratory applications (HVR Water Purification, 2022).

MD requires a thermal power source for the bulk of its water distillation process. The contaminated feed water is heated to a temperature of 50-100°C and passed through a series of selective, hydrophobic membranes. A cold feed at temperatures of 25-35°C is also passed on the opposite side of the membrane. The temperature difference between the hot and cold sides induces a vapor pressure difference in the feeds, resulting in vapor transport across the membrane, which distills as pure drinking water.

HVR's pilot project at the Baharda school had the goal of producing 1000 liters per day (L/day) of drinking water. However, current estimates put the yield at around 100 L/day. Reasons for the low yield from the current MD system at the school include limited thermal power input from a lack of collector area, sub-optimal membrane configuration due to cost restraints, and operational problems such as a damaged solar collector. In an effort to improve the current system by analyzing different thermal sources, HVR has tasked this author to determine the applicability of using Concentrated Photovoltaic Thermal (CPVT) technology for their off-grid MD systems.

1.3 Thesis Structure

This thesis is structured as follows. In Section 2, the methodology of this thesis is outlined. This section will show the approach to modelling and optimizing the systems for different technologies and use-cases. It will also show the post processing calculations and how the analysis was conducted. Sections 3 and 4 show the results and analysis from the modelling and economic study for Phase One and Phase Two, respectively. An analysis about how these results contribute to the larger goal of clean water access is also included in this section. Section 5 is a discussion about the results and their meaning is presented. Also in this section is a discussion about improving and expanding on this thesis with future work.

2 Methodology

There are many parameters which affect the yield of a CPVT + MD system, and in an effort to objectively rank different system configurations and different CPVT technologies, the modelling for this thesis was performed in two phases. In *Phase One*, a standard system design is tested through three unique cases. The three cases are named School, Community, and Goal, which will be described in more detail further in this section. The standard system design has four key configuration parameters which were allowed to vary. The four key parameters are the type of CPVT technology, the number of MD modules, the per-module feed flow rate, and the inclusion of an auxiliary immersion heater. These parameters can be seen below in Table 1. During *Phase One*, a few other system parameters were kept constant throughout each case. This was done so that the results of *Phase One* will compare CPVT technologies more objectively. These constant parameters can be seen in Table 2. *Phase Two* takes the best performing system configurations from *Phase One* and optimizes the system by varying the previously constant parameters. The purpose of *Phase Two* is to optimize each CPVT technology to determine which has the most potential if a new system was designed with that specific technology.

Table 1: Variable System Parameters

Parameter	Values
No. of Modules	5, 10, 15
Feed Flow Rates (L/h)	900, 1200, 1500
Type of CPVT Technology	Naked Energy, Sun Oyster, SunPower
Inclusion of Batteries and Auxiliary Heater	Yes, No

Table 2: Assumed Constant Parameters

Parameter	Value	Unit
T_{cold}	25	C
Q_{sp}	800	kWh/m^3
Max Solar Flow Rate	80	$l/h/m^2$

2.1 Key Performance Indicators

To determine the best system for each of the phases, a set of Key Performance Indicators (KPIs) were created which were used to objectively rank each system design against one another. The first KPI is the Life Cycle Cost (LCC) of Water, with units of $\$/m^3$. This KPI represents how much each cubic meter of water costs given the entire lifetime of the system. The second KPI is called the Goal Percentage and it is a ratio between the average daily yield of the system and the required yield rate of 1000 L/day. This demonstrates how close each system is to the target yield rate. The last KPI is the Specific Yield with units of $L/day/m^2$. This KPI demonstrates how efficiently each system uses its available collector area to yield pure water.

These KPIs are shown below in Table 3.

Table 3: Key Performance Indicators

KPI	Unit	Calculation
(1) Life Cycle Cost of Water	$\$/m^3$	Life Cycle Cost/ Lifetime Water Production
(2) Goal Percentage	%	Average Daily Yield/ 1000
(3) Specific Gross Area	$L/day/m^2$	Average Daily Yield/ Total Collector Area

2.2 Phase One: CPVT Comparison

In *Phase One*, three cases were created for the purpose of testing different system types in a variety of scenarios. The purpose behind analyzing each case will be presented in this subsection. A summary table of the which KPIs relate to which Case can be seen below in Table 4.

Table 4: Cases

Case	Key Information	KPIs
School	Collector area 55 m^2	1, 2
Community	Collector area 500 m^2	1, 2
Goal	Minimum Average Daily Yield 1000 L/day	1, 3

2.2.1 Case 1: School

The case called "School" represents what would happen if the Baharda nodal Upper Primary school was retrofitted with new energy supplies in the form of CPVT technology. The School case limits the total gross collector area to 55 m^2, representing the approximate available area of the school's roof.

2.2.2 Case 2: Community

The second case that was studied is called "Community". In this case, the total gross collector area is expanded to 500 m^2. For larger systems, the available area allows for larger thermal power generation. Therefore, an interesting use-case for CPVT technology is for a larger, community-scale system. If space was no longer a limiting factor, it would be interesting to find out how CPVT + MD would perform. Questions regarding scale, life cycle cost, and complexity will be answered in the Community case.

2.2.3 Case 3: Goal

The third case studied is called "Goal" because it is a quasi-optimization exercise in finding the best system given a goal of how much water should be produced. HVR would like to deliver 1000 L/day of purified water. This will be the benchmark for the different systems to reach. For this case, as with School and Community, the standard system will still be used and the configuration options will remain the same. However, instead of limiting the maximum area allowed, the driver will now be a minimum of 1000 liters of pure water distilled per day on average over a year. This case answers the question of, for each CPVT technology, how much area is needed if the system creates at least 1000 L/day of pure water.

2.3 Phase Two: System Optimization

Phase Two is a study based on optimizing each CPVT technology system to find the best parameters. For each system, a minimum yield of 1000 L/day on average is required. The key driver for this optimization is to minimize the Life Cycle Cost and to maximize the Specific Yield. The collector area, solar flow rates, battery capacity, heater power, and tilt angles were all adjusted to determine the best system in these respects. In this phase, the CPVT technologies are also compared against a similarly optimized system based on the technology currently being used in Odisha as a benchmark.

2.4 Polysun Model

The modelling software used in this thesis is Polysun (Velasolaris, 2022). The control strategy of the system has two main parts, the solar loop and the feed loop.

For the solar loop, the CPVT can be thought of as a thermal battery in which the sun charges the collector until it reaches the upper temperature set point. It is then allowed to discharge until the lower temperature set point. For the simulations in Phase One, the upper set point was set to 80 °C and the lower set point was set to 60 °C.

The feed flow loop control depends on if the system has a battery and heater or not. For the system without batteries, the feed flow pumps run continuously if there is enough electric energy generated by the CPVT or the PV panels. This type of control was chosen as a means to reduce the number of on/off times for the feed flow pumps. If the system has a battery and heater, the pumps run if there is enough available electric energy that is currently being generated or if the state of charge is high enough in the batteries. For these systems, the minimum state of charge of the batteries was set to 30%. The system is also controlled so that if the temperature of the feed is not hot enough to generate distillate, battery charging is prioritized over running the pumps. For either type of system (battery and heater or without) the pumps are running if there is energy available.

The storage tank on the feed loop is included as a representation of the ground water well near the school. The cooling loop is run based on this storage tank. Water temperature of approximately 30 °C is taken from the bottom port of the storage tank and put through a heat sink which acts as a chiller, dropping the temperature of the feed water to 25 °C. In the same loop, the cold feed water loop is put through a heat source which represents the cold side of the MD modules. In this step, the feed water is heated by a constant power. Based on data provided by HVR Water Purification AB, the cold-side water temperature rise is about 13 °C. This value is held constant throughout the modelling for simplicity. The feed water returns to the storage tank at a temperature of 38 °C.

The two main system designs are with and without an auxiliary heater. The system that includes battery energy storage and an auxiliary heater can be seen in Figure 1. The system without a battery and auxiliary heater looks the same, except without the battery element and heated storage tank. With these two systems, parameters were adjusted according to the cases and optimization goals previously described.

2.5 MD Model

Because Polysun was designed for residential energy system modelling, it does not support a membrane distillation specific component. Rather, a heat sink and heat source component is used as an approximation of the MD module. For the heat sink in Polysun, a specified constant power and volumetric flow rate can be used to remove energy from the system. The heat source is similar, except that it adds energy to the system.

The heat sink represents the hot side of an MD module while the heat source represents the cold side of an MD module. Thermodynamically, this is an accurate representation of the MD module because the specific energy needed to distill

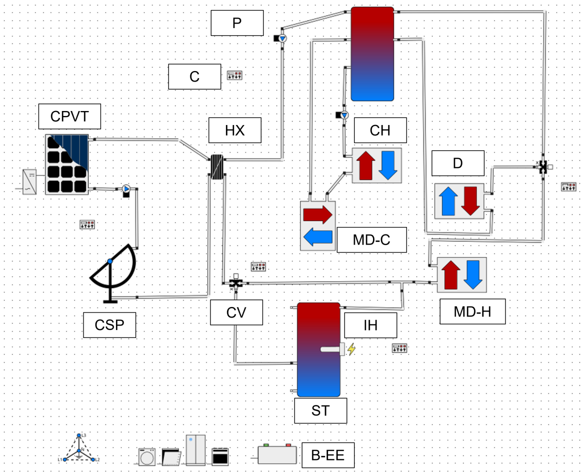


Figure 1: Polysun CPVT + MD system with a battery and heating element. Legend: CPVT - Concentrated Photovoltaic Thermal Collector, CSP - Concentrated Solar Power Collector, P - Pump, C - Controller, HX - Heat Exchanger, CV - Control Valve, ST - Storage Tank, B-EE - Battery and Electrical Elements, CH - Chiller, MD-C - Membrane Distillation Module Cold Side, IH - Immersion Heater, D - Distillate Module, MD-H - Membrane Distillation Module Hot Side

water is a known quantity from Woldemariam, 2017.

For the heat sinks and sources in Polysun, the main input parameter needed to represent the hot or cold side of the MD modules is the power removed or added. To calculate the power requirements, Equation 1 is used. The temperature difference ($T_i - T_o$) is an approximation based on data from HVR's experimental results, previously shown in Figure 2.

$$\dot{Q_{MD}} = \dot{V}_{dist}\rho_w c_p (T_i - T_o) \qquad (1)$$

In Equation 1, $\dot{Q_{MD}}$ is the power requirement of the MD module in units of Watts. æ_w is the density of water in units of kg/m^3 and c_p is the specific heat capacity of water in units of $J/(kgK)$. The term $\dot{V}_{dist}$ is the distillate volumetric flow rate in units of m^3/s. This value is a known quantity derived from the experimental data provided by HVR Water Purification AB. As can be seen in Figure 2, the distillate yield follows a polynomial relation with the hot side inlet temperature. This relation, when programmed into the Polysun control valve, determines how much pure water distillate is generated based on the hot-side inlet temperature of the MD module.

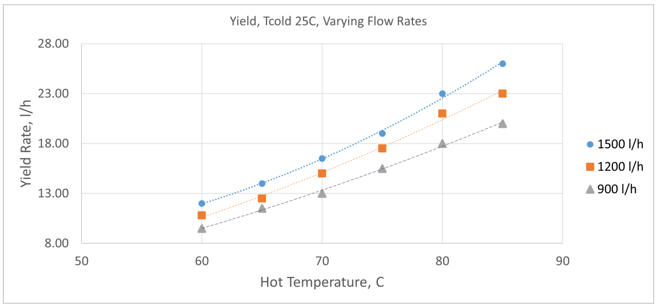


Figure 2: Distillate Yield vs. Hot Feed Inlet Temperature for a range of flow rates, Courtesy of Scarab Development AB

2.6 Current Odisha System Comparison

The current system in Odisha uses an array of Evacuated Tube Collectors (ETCs) and a separate array of PV panels. The ETCs used have a collector area of 15.8 m^2. The exact ETCs used in the Odisha system are not part of the Polysun catalog, so a standard vacuum tube collector is used to match collector area and thermal capacity. The PV panels are the Waaree Energies WSM-330 monocrystalline panels. There are 20 PV models with a total area of 38.8 m^2 and a total nominal DC capacity of 6.6 kW.

The model for the current Odisha system is optimized in a similar manner to that of the other CPVT systems in Phase Two, however, the collector area is kept constant. The system is optimized based on LCC of Water and Specific Yield. The parameters which are varied to produce the optimized system are the maximum specific flow rate, the collector tilt angle, the battery capacity, and the heater power.

2.7 Post Process Calculations

2.7.1 Distillate Calculations

The main parameters exported from the Polysun simulation include the flow rate of distillate ($\dot{V}_{dist}$), the inlet temperature to the MD modules (T_i), the outlet temperature from the MD modules (T_o), and the flow rate in the MD modules ($\dot{V}_{MD}$). The post processing calculations needed for the analysis involved finding the amount of distillate yield produced and the specific energy required by the MD module. For the yield, Equations 2, 3, and 4 are used.

$$Yield_{day} = \sum_{t=1}^{n_{ts}} Yield_t * \Delta t_{ts} \qquad (2)$$

$$Yield_{avg,daily} = \frac{\sum_{d=1}^{365} Yield_{day}}{365} \qquad (3)$$

$$yield_{sp,avg,daily} = \frac{Yield_{avg,daily}}{A_{total,gross}} \qquad (4)$$

Here, in Equation 2 n_{ts} is the number of time steps in a day. For the majority of calculations, the time step is 15 minutes. Therefore, for a day, there are 96 time steps per day. In Equation 4 the term, $A_{total,gross}$ is the total gross area of the collectors plus any separate PV modules that may be included. This calculation was done to determine how well each system used the available area.

2.7.2 Economic Calculations

The economic calculations for the model revolve around KPI 1 - the life cycle cost of water. To calculate this metric, many factors are used which will be detailed below. The constants used during the economic modelling are shown in Table 5. These constants are based on the work of Banat and Jwaied, 2008 and from the information provided by HVR Water Purification AB.

Additionally, some assumptions were used to make the calculations more uniform. The installation cost is assumed to be

Table 5: Economic Constants

Parameter	Value	Source
Interest Rate	5%	Banat and Jwaied, 2008
System Lifetime	20	HVR Water Purification AB
Amortization Factor	0.08	Calculated, Equation 8
Plant Availability	90%	Banat and Jwaied, 2008
Membrane Replacement	20%	HVR Water Purification AB
Battery Replacement	25%	HVR Water Purification AB

25% of the total equipment cost, the instrumentation and control cost is assumed to be 25% of the total equipment cost, and the operation and maintenance cost is assumed to be 20% of the annual cost. These assumptions were described in the economic method from Banat and Jwaied, 2008.

The calculation steps for the Life Cycle Cost (LCC) of the different systems can be seen below in the following equations.

$$\text{Capital Costs} = (\sum \text{Equipment Cost}) + \text{Installation Cost} + \text{Instrument and Control Cost} \quad (5)$$

$$\text{Annual Costs} = \text{Loan Repayment} + \text{O\&M} + \text{Membrane Replacement} + \text{Battery Replacement} \quad (6)$$

$$\text{Loan Repayment} = (\sum \text{Capital Costs})a \quad (7)$$

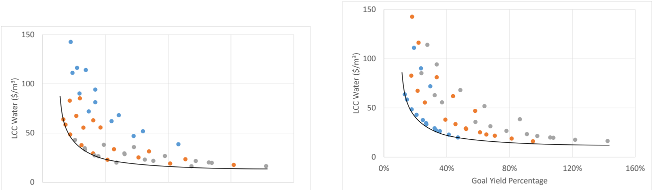
$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (8)$$

$$\text{Unit Production Cost} = \frac{\sum(\text{Annual Costs})}{(\text{Plant Availability})(\text{Capacity})365} \quad (9)$$

$$NPC = \sum_{t=0}^{n} \frac{CF_t}{(1+i)^t} \quad (10)$$

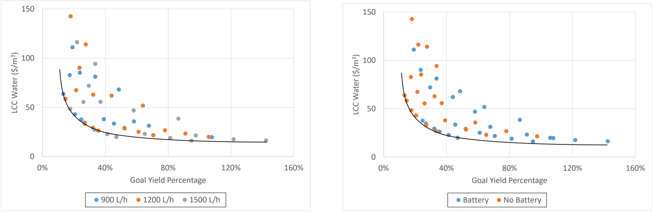
$$\text{Life Cycle Cost} = \frac{\text{NPC}}{(\text{Annual Yield})(\text{Lifetime})} \quad (11)$$

In these equations, a is the amortization factor which is used to bring the value of costs to the present time. Next, i is the interest rate. The term, n, is the lifetime of the system in years. The term, CF_t, is the Cash Flow at a specific year indexed by the term, t. And lastly, the term NPC is the Net Present Cost of the system. This term takes into account all the expenditures over the lifetime of the system.



(a) School Pareto Frontier, comparing CPVT technologies

(b) School Pareto Frontier, comparing the number of MD modules used



(c) School Pareto Frontier, comparing MD module feed flow

(d) School Pareto Frontier, comparing use of batteries

Figure 3: Pareto Frontiers for the School Case. Each point in the graph represents a unique system simulated in Polysun for a year. The nondominated results, representing the Pareto Frontier line, is shown as the black line. Each graph shows the same output, but with four different variables highlighted. Graph (a) shows a variation in the type of CPVT technology used. Graph (b) shows the difference in the number of MD modules in the system. Graph (c) shows the difference in the per-MD module feed flow rate. Graph (d) shows the difference in a system which uses batteries versus those without batteries.

3 Phase 1 Results: Standardized System Comparisons

3.1 Case 1: School

The first case to be studied is the School scenario in which the total gross collector area is limited to 55 m^2 to simulate the rooftop area of the primary school in Odisha, India. The KPIs used to quantify the performance of each system configuration are KPI 1: Life Cycle Cost (LCC) of Water and KPI 2: Goal Yield Percentage. An annual simulation for each system configuration was performed in Polysun and the results of which are shown below in the School Case Pareto Frontier, Figure 3.

The Pareto Frontier for the school case has been adapted to show the difference between systems which have 5, 10, and 15 modules. This can be seen in Sub Figure 3b. At lower production rates, five MD modules are the more cost effective option. However, as the production of the system increases, it is more effective to have 15 MD modules. Overall, it is better to have a greater number of modules because as the production rate increases, the LCC decreases as well.

The per-module feed flow rate also has an impact on the performance of the systems. The top performing system uses a higher feed flow rate of 1500 L/h. However, per-module feed flow rate is not a definitive determinant of performance, as there are 900 and 1200 L/h systems which have good results at higher production rates. This is even more evident at lower production rates, in which there is no distinguishing trend between flow rates. These results can be seen in Sub Figure 3c.

The difference between systems which have a battery and auxiliary heater and those who do not is significant. The battery systems generally have a higher production rate and have a lower cost. There are some outlying non-battery systems which outperform others, however, there is a clear distinction in performance when analyzing systems with or without batteries as seen in Sub Figure 3d.

The best systems have a low Life Cycle Cost (LCC) and a high Goal Yield Percentage. For the School Case, the SunBase and Sun Oyster systems have a lower LCC than the Naked Energy systems. The best performing systems overall for the School case can be seen in more detail in Figure 4. The best system in the School case resulted in a configuration using Sun Oyster modules, 15 MD modules, a feed flow rate of 1500 L/h, and includes an auxiliary heater. For this system, the Life Cycle Cost of water came to 15.00 $\$/m^3$ and a goal production rate percentage of 142%, which is a 1420 L/day average.

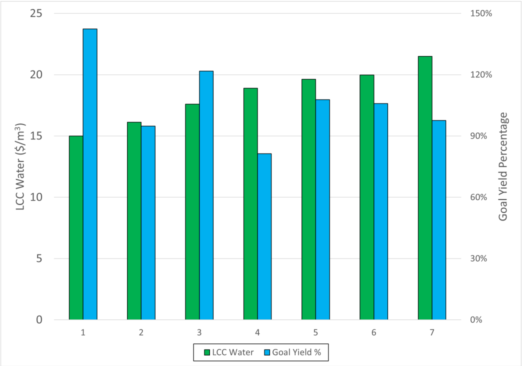


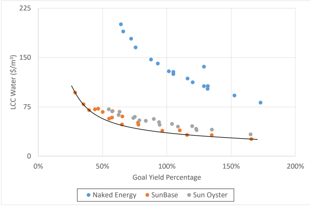
Figure 4: Top Performing Systems for the School Case. These systems demonstrated the combined best results for both KPI 1 and KPI 2. The top systems, from left to right, are as follows. (1) Sun Oyster, 15 MD modules, 1500 L/h, Battery. (2) Sun Oyster, 10 MD modules, 1500 L/h, Battery. (3) Sunbase, 15 MD modules, 1500 L/h, Battery. (4) Sunbase, 10 MD modules, 1500 L/h, Battery. (5) Sun Oyster, 15 MD modules, 900 L/h, Battery. (6) Sun Oyster, 15 MD modules, 1200 L/h, Battery. (7) Sun Oyster 15 MD modules, 1500 L/h, No Battery.

3.2 Case 2: Community

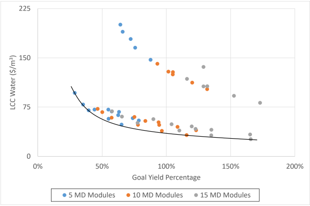
The second case that was analyzed was for a Community sized system of 500 m^2. This system represents a feasible community-sized system near the primary school in Odisha, India. The Pareto Frontiers for the community case can be seen in Figure 5, where each point represents a different system configuration. As compared to the School case, there are much more systems which reach the 1000 L/day goal, as seen by the number of points beyond the 100% line.

There is a clear distinction between costs for the Naked Energy modules and the others. The Naked Energy modules have a specific cost of 575.02 $\$/m^2$ and 506.38 $\$/m^2$ for their virtuPVT and virtuHOT modules, respectively. The Sun Oyster has a specific cost of 337.55 $\$/m^2$ and the Sunbase system has a specific cost of 85.47 $\$/m^2$. This difference in cost is a what makes the Naked Energy configurations much more expensive than the others.

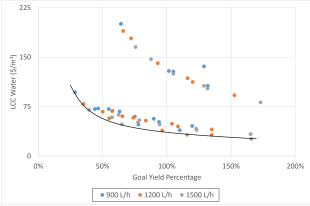
There is a pronounced difference between performance when looking at the number of MD modules for the Community case. The greater the number of MD modules, the greater the performance for nearly all cases. There are some configurations in which a 10 MD module system out-performs a 15 MD module system, but there is no case in which a 5 MD module system out-performs a 15 MD module system. A modified Pareto frontier showing the performance between systems with different number of MD modules can be seen in Sub Figure 5b.



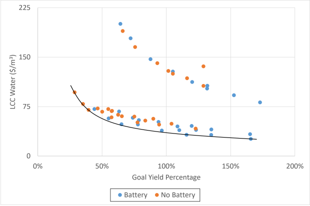
(a) Community Pareto Frontier, comparing CPVT technologies



(b) Community Pareto Frontier, comparing the number of MD modules used



(c) Community Pareto Frontier, comparing MD module feed flow



(d) Community Pareto Frontier, comparing use of batteries

Figure 5: Pareto Frontiers for the Community Case. Each point in the figure represents a unique system simulated in Polysun for a year. The nondominated results, representing the Pareto Frontier line, is shown as the black line. Each figure shows the same output, but with four different variables highlighted. Figure (a) shows a variation in the type of CPVT technology used. Figure (b) shows the difference in the number of MD modules in the system. Figure (c) shows the difference in the per-MD module feed flow rate. Figure (d) shows the difference in a system which uses batteries versus those without batteries.

When the collector area is increased, the absolute solar flow rate is also increased because the specific solar flow rate is held constant at 80 $L/h/m^2$. This allows for a high transfer of thermal energy to the MD modules. And as each MD module has a limit to how much distillate it can produce, at low MD module numbers, this limit is quickly reached and the yearly performance does not increase. With a low number of MD modules coupled with a high collector area, the system is over designed and not able to properly perform.

The per-module feed flow rate did not result in a definitive driver of performance for systems overall. The feed flow rate does, however, prove to be a more localized driver of performance when looking at similar systems with similar parameters. In these cases, a higher per-module feed flow rate has a higher performance than lower per-module feed flow rates in every circumstance. This can be seen in Sub Figure 5c.

All the extremely high performing systems use a battery and an auxiliary heater, as can be seen in Sub Figure 5d. The inclusion of the battery extends the MD module on-time, which allows for a greater amount of time that the MD modules can produce distillate. As described earlier, the MD modules only generate distillate when the inlet temperature is greater than 50 °C. Using a battery and auxiliary heater allows for operating times even when the radiation is not enough to maintain a 50 °C inlet temperature for the MD module. This is a significant improvement in MD module on time. For example, the top performing system is the Sunbase, 15 MD module, 1500 L/h, and battery system. For this configuration, the overall percentage of time that the MD module was producing distillate for a year is 45.83%. For its sister-configuration which does not use a battery and heater, the MD on time was 14.21%. This difference speaks to the fact that for a better performing system, it is wise to extend the amount of time that the MD module is producing distillate by using an auxiliary heater.

The top performing system for the Community case is the Sunbase configuration using 15 MD modules, 1500 L/h feed rate, and includes a battery and heater, as previously mentioned. For this system the LCC of Water resulted in 26.12 $\$/m^3$ and a Goal Yield Percentage of 166%, equating to 1660 L/day average yield. The other top performing systems used the large CPVT technologies (Sun Oyster or Sunbase), had high flow rates (1500 or 1200 L/h), and all included batteries and heaters. These results can be seen in Figure 6.

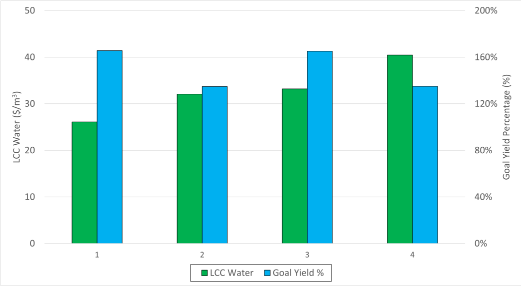


Figure 6: Top Performing Systems for the Community Case. These systems demonstrated the combined best results for both KPI 1 and KPI 2. The top systems, from left to right, are as follows. (1) Sunbase, 15 MD modules, 1500 L/h, Battery. (2) Sunbase, 15 MD modules, 1200 L/h, Battery. (3) Sun Oyster, 15 MD modules, 1500 L/h, Battery. (4) Sun Oyster, 15 MD modules, 1200 L/h, Battery.

3.3 Case 3: Goal

In the Goal case, six system configurations where simulated for a year. These six systems all contained 15 MD modules and used a per-module feed flow of 1500 L/h. For these systems, an iterative simulation process was used to ensure a minimum daily yield of 1000 L/day. The the total collector area was decreased until the yield was as close to 1000 L/day as possible. The purpose of this test is to determine what size system is needed if the ultimate goal of the CPVT + MD system is to generate at least 1000 L/day of pure water. The KPIs which are used to rank the systems are KPI 1: Life Cycle Cost of Water and KPI 3: Specific Yield. These are used to determine which is the most cost-efficient and area-efficient systems. The results of the Goal case can be seen in Figure 7.

The top performing system for the Goal case is Sun Oyster configuration using 15 MD modules, 1500 L/h feed flow, and includes an auxiliary heater and battery. This system has a Life Cycle Cost of water of 18.95 $\$/m^3$ and a Specific Yield of 20.26 $L/day/m^2$.

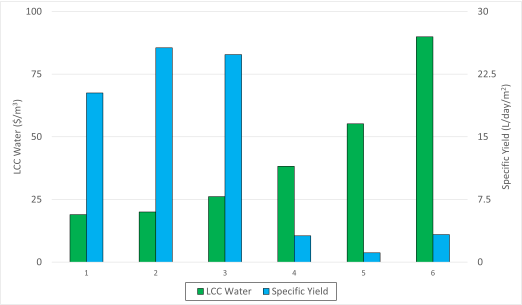


Figure 7: Simulation Results for the Goal Case. The systems, from left to right in order of increasing LCC are as follows. (1) Sun Oyster, 15 MD modules, 1500 L/h, Battery. (2) Sunbase, 15 MD modules, 1500 L/h, Battery. (3) Naked Energy, 15 MD modules, 1500 L/h, Battery. (4) Sun Oyster, 15 MD modules, 1500 L/h, No Battery. (5) Sunbase, 15 MD modules, 1500 L/h, No Battery. (6) Naked Energy, 15 MD modules, 1500 L/h, No Battery.

The inclusion of an auxiliary heater and battery is a clear differentiator between the systems simulated. The average LCC of battery systems for the Goal Case is 21.70 $\$/m^3$, whereas the average LCC of non-battery system is 61.12 $\$/m^3$ - a nearly three times more expensive LCC. An even more distinct difference is in the Specific Yield differences. For battery systems, the average Specific Yield is 23.59 $L/day/m^2$ and for non-battery systems, the average Specific Yield is 2.52 $L/day/m^2$. This is a ten-times improvement in land use efficiency if a system includes a battery. This is expected because a high thermal power capacity is needed to constantly keep the inlet water temperature at a minimum of 50 °C.

4 Phase 2 Results: System Optimization

The second phase of the modelling procedure is an optimization based on the conclusions derived from Phase One. From the first phase, it was determined that the best performing systems for all three KPIs, used 15 MD modules, 1500 L/h feed flow rate, and an auxiliary heater and battery. Then, for Phase Two, these parameters will be held constant while an iterative optimization is performed to determine which other parameters improve the performance of the system. These parameters included maximum specific flow rate in liters per hour per collector aperture area ($L/h/m^2$), tilt angle (for the applicable collectors without tracking), total battery capacity (kWh), and immersion heater power (W).

For this phase, having a minimum yield of 1000 L/day is the key index, while a secondary index is the LCC of water. Lastly, the configurations will be judged on their specific area use. The results for each of the three CPVT technologies can be seen in Figure 8 and Table 6.

For all three systems, the thermal energy produced over the year is about three to five times as much as the electric energy used by the electric heater. The annual thermal energy production is highest for the Naked Energy modules because they have been optimized to be more inclined towards thermal production than electricity production due to their modular nature. The Sunbase has the second greatest thermal energy production, and last is the Sun Oyster system. The Naked Energy system uses the least electric energy. Next in terms

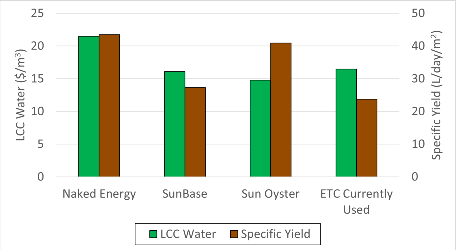


Figure 8: Results based on KPI 1: LCC of Water ($\$/\mathrm{m}^3$) and KPI 3: Specific Yield ($\mathrm{L/day/m}^2$). Results compare the three different CPVT technologies simulated. Also included is the result from running the Polysun system using the current energy technology in Odisha - Evacuated Tube Collectors (ETCs) and PV.

Table 6: Tabulated Optimization Results

	Naked Energy	**Sunbase**	**Sun Oyster**
Collector Area (m2)	29.25	49.14	36.65
Yearly Yield (L)	464,022	489,546	547,478
Daily Average Yield (L/day)	1271.29	1341.22	1499.94
NPV ($)	(199,263)	(157,709)	(161,661)
LCC ($ /m3)	(21.47)	(16.11)	(14.76)
Specific Yield (L/day/m2	43.46	27.29	40.93

of electric energy use is the Sunbase system. And lastly, with the most electric energy use is the Sun Oyster system.

The reverse order is the ranking for the amount of electric energy used for the immersion heater. These results can be seen in Figure 9.

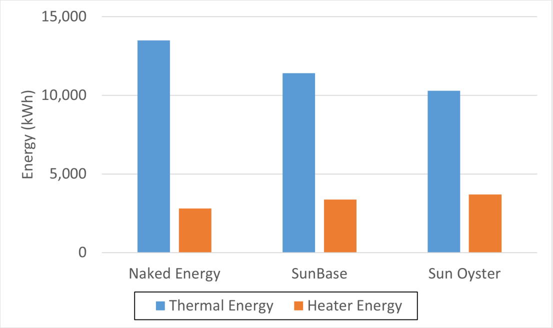


Figure 9: Results of the total annual energy used for heating the feed water input for the MD modules in kWh. The Naked Energy CPVT system uses 13,500 kWh of thermal energy and 2,800 kWh of electric energy. The Sunbase system uses 11,400 kWh of thermal energy and 3,400 kWh of electric energy. The Sun Oyster system uses 10,300 kWh of thermal energy and 3,700 kWh of electric energy.

4.0.1 Naked Energy Optimized System

The Naked Energy modules demonstrated a large potential for optimizing for a 1000 L/day system because of their modularity and customization based on thermal and electrical power requirements. This allowed for a much better load matching than the Sun Oyster or Sunbase systems. This is how the Naked Energy has the greatest land-use efficiency. The parameters for the Naked Energy system which proved to be the most optimal for a 1000 L/day system can be seen below in Table 7.

Table 7: Naked Energy Optimized Parameters

Parameter	**Value**
Number of MD Modules	15
Feed Flow Rate [L/h]	1500
Max Specific Flow Rate [L/h/m2]	80
Tilt Angle [°]	21
Battery Capacity [kWh]	3.2
Heater Power [W]	1000

The average MD module inlet temperature for the optimized Naked Energy system was 50.02 °C and the maximum inlet temperature was 55.3 °C. The MD module On-Percentage was 38.66 %. This shows that the Naked Energy system optimization proved to be load-oriented. The system which produced the most yield was the system who could have the most amount of time at the minimum required inlet temperature of 50 °C. For the Naked Energy system, it was unnecessary to have a larger collector area than 29.25 m^2 because it was more area- and cost-efficient to have minimum required power to keep the inlet temperature of the MD module at 50 °C.

For the optimized Naked Energy system, the equipment cost's largest shares belong to the MD modules and the CPVT modules with 52% and 36% shares, respectively. The CPVT modules for the Naked Energy system are the most expensive out of the three CPVT technologies modelled. Therefore, for the Naked Energy system, it was important to balance the total collector area with the power requirements due to the large cost. This is also another factor as to why the system optimized to have an average MD inlet temperature as low as possible. For the annual cost breakdown, the largest portions are the loan amortization repayment and the yearly membrane replacement with 49% and 40% shares, respectively.

4.0.2 Sunbase Optimized System

The optimized Sunbase system was the second best system in terms of LCC of water and the worst system in terms of land-use efficiency when compared with the other CPVT technologies. The LCC of water for the Sunbase system was a competitive 16.11 $\$/\mathrm{m}^3$. The specific area was 27.29 $\mathrm{L/day/m}^2$. Because the Sunbase system has a large fixed area for one collector of 16.38 m^2, it was harder to load-match like that of the Naked Energy system. The Sunbase system required a large area because it was limited by its low electricity production. Having the battery and heater proved to be a necessary upgrade to keep production high, but by doing so, the Sunbase system required three modules to keep up with the electricity demand. This put the Sunbase module at a disadvantage in specific yield. The optimized system parameters for the Sunbase system can be seen in Table 8.

The optimized Sunbase system had excellent yield performance with a daily average yield of 1341 L/day. This is due to the MD on-time percentage of 40.79%. The large collector area allows for such a consistent temperature going into the

Table 8: Sunbase Optimized Parameters

Parameter	Value
Number of MD Modules	15
Feed Flow Rate [L/h]	1500
Max Specific Flow Rate [L/h/m2]	81.4
Tilt Angle [°]	Single Axis Tracking
Battery Capacity [kWh]	3.2
Heater Power [W]	1000

MD module. The limitation for the Sunbase module was the balance between heater power and available electric energy. A heater power of 1000 W proved to be the most optimal, but this required a three Sunbase modules to meet the electric energy requirements.

For the Sunbase system, the MD modules represents the largest share of the equipment cost, at 71% of the total. The Sunbase modules have the lowest cost compared to the other CPVT technologies, and therefore the main cost driver for the Sunbase systems is the MD module cost. The largest shares for the annual cost are the membrane replacements and the load amortization repayment at 49% and 42%, respectively.

4.0.3 Sun Oyster Optimized System

The Sun Oyster optimized system had the lowest LCC of water for any system simulated, at 14.76 $\$/m^3$. The Sun Oyster system only required one of its CPVT modules to meet the 1000 L/day goal. In fact, with only one Sun Oyster module, the system was able to reach a yield of 1500 L/day, the most of any of the optimized systems. The Sun Oyster modules have a high concentration factor and a large PV capacity which lend well to a consistent thermal input to the MD modules. Because of this, the specific yield is also very high for the Sun Oyster module, at 40.93 $L/day/m^2$ of gross collector area. The optimized parameters for the Sun Oyster module can be seen in Table 9.

Table 9: Sun Oyster Optimized Parameters

Parameter	Value
Number of MD Modules	15
Feed Flow Rate [L/h]	1500
Max Specific Flow Rate [L/h/m2]	77.9
Tilt Angle [°]	Dual Axis Tracking
Battery Capacity [kWh]	3.2
Heater Power [W]	1000

The Sun Oyster's thermal power capacity allowed for an MD on-time percentage of 45.62%, the highest of the three systems tested. This system was also optimized to meet the 50°C requirement for the MD yield. The average inlet temperature to the MD modules was 50.13°C.

The Sun Oyster system has a moderate cost for their collectors, at 337.55 $\$/m^2$. However, the MD modules still present the largest share of equipment cost, at 68%, while the CPVT modules have a share of 16%. The annual cost breakdown is similar to the other optimized systems in which the membrane replacement and the loan amortization repayment represent the two largest annual cost shares, of 48% and 42%, respectively.

4.0.4 Current Technology in Odisha

The system used to test the current technology in Odisha performed well in cost, but poorly in specific yield. The LCC for this system is 16.45 $\$/m^3$ while the specific yield is 23.73 $L/day/m^2$. This result is not surprising because of the low cost for the evacuated tube collectors (ETCs) and PV panels. The cost for the ETCs 101.27 $\$/m^2$ of collector area which totals to \$1,600 for the ETCs. The PV panels are also inexpensive, with a unit cost of 89 \$/panel. With 20 panels, this total cost comes to \$1,780. The specific yield for this system is quite low, due to the low amount of yield produced for the large total collector area (ETC+PV).

The daily average yield for this system has been simulated to be 1,295 L/day, which is a big improvement from the results currently being seen. This is because the modelled system includes 15 MD modules and an immersion heater - as opposed to the currently used 5 MD modules and only thermal input from the collectors. The system also uses a larger flow rate for the modules of 1500 L/h which generates a greater amount of distillate.

5 Discussion and Conclusion

From the analysis of both Phases, many key take-aways became present. A CPVT + MD system can be customized and optimized many different ways depending on what are the design constraints and what are the goals of the developers. If these two underlying facts are known, then there are ways to develop a competitive water purification system in an off-grid CPVT + MD configuration.

If the Life Cycle Cost of water is the greatest driver and the developer wants to develop the most cost-competitive CPVT + MD system, then a system which uses larger concentration CPVT modules would be the best. It is also worth MD companies to focus on reducing the cost of MD Modules and to improve their lifetime. A leading capital cost driver is the MD module cost and a leading operational cost driver is the membrane replacement. If these factors can be improved, then the CPVT + MD system would be even more cost-competitive.

If a development company wants to produce a system with a large yield, such as for a community, a hospital, or a school, then it is recommended to use a system with a large number of MD modules and a large per-module feed flow rate. Both of these parameters increase the yield of the CPVT + MD system, however, more MD modules and a larger flow rate add costs to the system.

If the available collector area is the main constraint, such as for a rooftop, then a modular CPVT technology would be the best choice. For this system, a large yield can still be obtained, albeit with a larger cost.

The technology currently being used in Odisha is by no means obsolete, but it comes with a few drawbacks. If area is a concern, such as in the school in Odisha which can only offer its rooftop for area, then the ETC + MD system is hindered by ETCs low thermal capacity. ETCs are, however, much cheaper than the CPVT technologies being studied. ETCs also have a more stable supply chain and industry expertise because it is a mature thermal technology. The upgraded systems which use CPVT all perform better than the current Odisha technology in KPI 3, Specific Yield, because the CPVT technologies have a greater thermal power output than ETCs, as expected.

Compared to other Solar + MD systems from literature, the results of the CPVT + MD systems presented competitive costs. For example, researchers showed that for Scarab MD modules, the Life Cycle Cost of coupling MD with FPC, CPC, and ETC are 55.68, 56.60, and 49.40 $\$/m^3$, respectively. These costs have been much improved by coupling MD with CPVT, with the best performing Sun Oyster system having an LCC of 14.76 $\$/m^3$ (Guillén-Burrieza et al., 2015).

Although the costs and yield present promising results, there still needs to be improvement in the CPVT market for these systems to be feasible. At the moment, Naked Energy is the only market ready technology provider. Sun Oyster is close, but more projects are needed from them and a manufacturing site is needed to produce many more modules. The Sunbase system is also promising based on the simulation results, however, they would need to make a return to the market with their advanced PV technology if they want to be considered in the solar-thermal market. Solarus is promising a new CPVT supplier who would be a direct competitor with Naked Energy because they would serve a similar niche of modular CPVT technologies. However, it is uncertain how far the development is for the new Solarus CPVT design.

With these results, it can be determined that introducing CPVT for the Odisha system would be feasible if the developers are willing to pay a slightly higher price for the production of water. For the Odisha case, only the Naked Energy modules would make sense for a direct replacement. However, if a new pilot project is being considered, it is recommended to allow for a larger collector area and the possibility of mounting the collectors on the ground where larger CPVT modules can be placed.

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