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Experimental performance of a parabolic trough collector system for an industrial process heat application

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ABSTRACT

Manufacturing is responsible for 60% of the fuel consumption in Cyprus and the industrial sector is the second biggest fuel consumer, mainly for steam production. Thus, the use of parabolic trough collector (PTC) systems for the production of steam or hot water can be a promising solution for the industrial sector. This study presents the first industrial PTC system in Cyprus, installed at the biggest soft drinks factory. The system consists of 288 m^2 of PTC, a steam generator and concrete thermal energy storage (CTES) in order to keep the system dispatchable. To achieve that, two operation strategies are developed which are controlled automatically by the main processor of the system. The first strategy is enabled when there is a steam demand and the second when the energy can be stored directly to the CTES. Both strategies are tested, and it is shown that under Strategy 1 the PTC system can produce 940 litters of steam per day, and under Strategy 2 it can store 107.3 kWh_{th}. In two months period tests, it is proved that it can supply the required amount of steam to the factory even when solar radiation is low, with the support from the CTES.

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1. Introduction

After the 20th century, many countries have focused on renewable sources of energy for thermal and electricity production. The general objective is to reduce the environmental impact due to the increased use of fossil fuels. The dominant renewable energy source is solar energy, and many technologies were developed to exploit this resource, such as thermal plants and photovoltaics.

Cyprus is fully dependent on imported fuels for its energy production and the section, which is responsible for 60% of the whole amount of fuel consumption, is the manufacturing. The second biggest fuel consumer in Cyprus, mainly for steam production is the industrial sector. In order to decrease the use of fossil fuels and based on the European Union (EU) regulations, the use of renewable energy systems has increased during the last years, especially the solar energy-based systems. Considering the large amount of fuel that is needed to cover the energy needs of the industrial sector and the fact that most of it is mainly used to produce steam, the parabolic trough collector (PTC) technology seems to be the best system to cover the needs of several industrial plants with higher temperature requirements than the ones that can be achieved from the widely used flat plate collectors on the island.

According to the International Energy Agency (IEA) in 2008, 30% of the global energy needs is consumed by the industrial sector [1] {Formatting Citation}. Many types of industries, such as chemical, food and beverage, fabrics, textiles and laundries, have a thermal energy demand for steam or hot water at the middle to high temperatures of about 100 °C–300 °C used for various processes.

Thus, the use of PTC systems is the most appropriate for a wide range of applications in industries and can contribute to their thermal energy production, that could have had significant economic, environmental, and social impacts. Particularly, the industry where such a system is installed, could be independent of the fluctuation of the fuel costs and this could stabilize the final product prices produced by that industry at a lower level. The energy safety that results from the lower dependence of the fuel suppliers is the most significant motivation for this kind of investment. The application of these systems, in addition to the short payback times offered for various industries, could also help to mitigate the global climate change phenomena, as less fossil fuel consumption could lead to less environmental pollution, and thus they help to achieve a healthier living environment.

Many solar thermal systems for industrial process heat (IPH) are

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reported worldwide. According to IEA [2], 120 solar thermal plants are in operation, covering an area of 125,000 m^2 (88 MW_{th}). Fig. 1 presents the current total thermal power installed per sector. Up to now, there are 61 PTC systems installed and operating worldwide for industrial process heat applications, with a total thermal power of 13.9 MW_{th}. The dominant sector in terms of the number of PTC plants is in the dairy and beverage sectors, with 18 PTC plants installed, while in terms of installed power capacity, the dominant sector is the food products with 4 MW_{th} [3]. The biggest PTC plant is under construction in a mining and quarrying factory in South Oman, which is expected to be able produce 6000 tons of steam per day [4].

Many of the PTC plants are pilot units that have been installed as part of research funding projects. Thus, there is plenty of research work done to evaluate the performance and operation of these systems. The experience earned from these plants is significant to enable the optimization of existing and new plants in order to develop systems with higher efficiency in the future.

A performance investigation of a PTC system installed in 1989 at the silk factory of Mysore is presented by Thomas [5]. The system consists of 30 collectors covering an area of 192 m^2. The plant produces steam for the processes of the factory by expanding hot pressurized water at 150 °C in a flash Steam Generator (SG) and the peak heat transfer fluid (HTF) outlet temperature is 179 °C. The HTF is water and the system performance is evaluated on a clear day of April with average daily efficiency of 33.5% (ratio of energy collected to steam produced).

Pietruschka et al. [6] presented a PTC system installed for energy production and fuel consumption reduction. It is covering an area of 2040 m^2, with thermo oil as the HTF, and a maximum HTF temperature of 200 °C. The HTF is fed to an indirect SG to produce and supply steam to the industry's steam network. The steam could also support the milk pasteurization, washing processes and washing machines, when the milk drying process is not in operation. They estimated that the CO_2 reduction per year is around 290 tons.

In Texas, Johnson & Johnson manufacturing plant, a PTC plant is installed that produces steam at 174 °C, covering an area of 1068 m^2. The HTF is pressurized water that flashes to a SG from where the steam is supplied to the industrial processes. The investigation of the system was carried out by Brink et al. [7] who presented the evaluation of the system on a clear day of September. The average daily efficiency was 30–40%, and the average hourly efficiency varies from 38 to 42% in clear days.

Moreover, NEP solar company has installed three PTC plants for IPH in different industries located in Switzerland [8]. The first is a dairy industry in Bever in which a PTC system is installed on the roof of the factory. It covers an area of 115 m^2 and produces steam at 190 °C for milk processing. A bigger plant has been installed at a cheese manufacturing industry at Saignelegier. This system has an area of 627 m^2 and produces steam at 125 °C. The system is

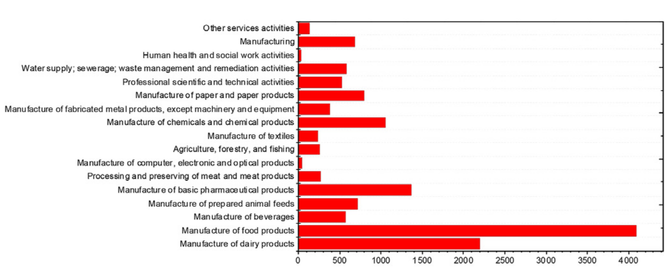


Fig. 1. Share of thermal power installed (kW). Compiled from data obtained from (Solar Thermal Plants Database | Solar Heat for Industrial Processes) [3].

combined with two oil fired boilers (of 1 MW capacity) for preheating when the solar radiation is low. The third solar plant is installed in Fribourg and covers 587 m^2. The HTF used is water heated at 165 °C for milk processing. Rittmann-Frank et al. [9] carried out a technical evaluation of these three plants. At Bever, the annual efficiency of the system was 23% in 2014 and improvement tasks have been carried out to increase the performance of the plant. At Saignelegier the highest performance in the three-year period examined (2014, 2015, 2016) was 37% (year: 2015), which corresponds to 263 MWh and met the expected production. The PTC production covers 12% of the load and has an annual CO_2 saving of 69 tons. At Fribourg the annual performance was 40% (year: 2016) which corresponds to more than 220 MWh and exceeded the design expectations.

Another PTC system installed in Egypt, covers an area of 1958.4 m^2 and produces steam at a rate of 1.3 tons/h, at 8 Bar and 175 °C. Abdel-Dayem et al. [10] evaluated the performance of the system by developing a mathematical model simulating the various processes. Based on the economic analysis (life cycle savings method) the authors concluded that the optimized area of the collector should be 538 m^2. This proposed system can cover 10% of the heat demand of the factory.

In addition, there are many studies which pay attention at the thermal energy storage (TES) system which is essential for any solar thermal system as it can collect energy and use it at a later time (3–12 h). The main scope of a TES is to cover the thermal requirements of the industry during cloudy hours or insufficient solar radiation. It can also be used in the early morning hours for preheating purposes when the sun is not shining. For the steam production to be readily available by 7 am, most of the industries start the preheating of the SG and pipelines at least 2–3 h earlier when there is little or no solar radiation. So, it is important to have a highly efficient TES that can supply heat during these hours and cover the thermal energy. A TES can also be used as a buffer to maintain a more stable system condition (temperature and pressure). It minimizes also the variabilities of the system behavior in case of significant fluctuation of solar radiation. By employing a TES in a solar system, the solar fraction is increased leading to significant advantages due to lower fuel consumption, environmental impact, and less payback time [11].

Kumaresan et al. [12] showed an experimental setup of the PTC system, including TES, pump, and a tracking unit. The TES system used consists of a vertical cylindrical storage tank (550 mm in diameter and 1100 mm in length) with a volume of 230 L. The TES is insulated with glass wool (0.15 m). The HTF used is Therminol 55, which is stored in the well-insulated tank. The authors examined the instantaneous efficiency, which varied from 50 to 62.5%, with the peak efficiency occurring at noon. As the TES is charged at 120 °C and left undistributed for 45 h, they concluded that the average heat loss per hour is 1120 kJ. The efficiency of the energy collected to the energy stored from 8 am to 2 pm varied from 41% to 60% and the maximum overall system efficiency was close to 40%.

The high thermal conductivity and specific heat, the excellent mechanical properties, the similar thermal expansion rate of cement compared with steel pipes, and the low cost of the material makes concrete TES very promising for future applications. The most severe challenge regarding TES is the high investment cost. Many researches are focused on how to achieve a better TES performance at a lower price. At Plataforma Solar de Almeria in Spain, the German Aerospace Center tested the first TES using concrete, which is a cheaper storage technology [13]. If should be noted that during heating up of concrete, residual water in the core of the concrete storage evaporates and can build up a critical vapor pressure if the permeability is too low. Therefore, the properities of the concrete are the storage capacity, thermal conductivity and sufficient permeability for the vapor (so it will not be damaged). These are demonstrated and tested in a concrete storage module which consists of 132 tubes (9 m length 18 mm diameter), concrete and pressure-resistant thermal insulation. The tests were performed for four months for a temperature range between 300 °C and 400 °C. For 6 h of charging and discharging the module estimated to have a total capacity of 25.6 kWh/m^3 [13].

Martins et al. [14] examined concrete TES for PTC systems at 393 °C with a capacity of 280 kW_{th} under real solar conditions. A comparison of its concrete mixture (Heatcrete®) with two existing concrete mixtures developed by the German Aerospace Center (DLR) and the University of Arkansas (UA), revealed that the most promising properties identified are for the Heatcrete® combination. The presence of small cracks in DLR and UA concrete at higher temperatures are due to the slight difference in thermal expansion factor between the concrete mixture and the steel pipes. After several thermal cycles of the UA concrete, the compressive strength was reduced significantly due to the local overpressure in the porous system. Thermal cycles occurring on Heatcrete® concrete show good performance regarding the degradation, change of color, and crack formation. However, there was a weight loss at the beginning of the tests because of the vapor leakages which is trapped at samples due to the thermal decomposition accompanied by the release of Carbon dioxide. This weight loss was not considered significant and the Heatcrete® behavior is stable up to 400 °C and its specific heat is high at 0.75 kWh/m^{3}K.

Several industries in different countries have realized the benefits of the PTC systems and set targets for their usage in thermal production strategies. Cyprus has a great potential to exploit solar thermal energy systems due to the abundance of sunshine available all year round. Moreover, the industrial sector is the second biggest fuel consumer with 20% share after the transportation sector which accounts for 57% of the total fuel consumption. Accordingly, it is believed that the application of this technology on the industrial thermal production processes in Cyprus will lead to the drastical reduction of the fuel imports, helping the island to achieve the 2030 EU target of reducing the fossil fuel imports by 12%. Additionally, the installation of PTC systems in the industrial sector of Cyprus could cover a significant percentage of the 32% EU target regarding the Cyprus energy consumption that must come from renewable energy sources [15].

Considering the above, this study presents novel PTC system installed at the biggest soft drinks factory in Limassol, Cyprus under the Solar ERA-NET project, named 'Evaluation of the Dispatchability of a Parabolic Trough Collector System with Concrete Storage' with acronym 'EDITOR'. The scope of this paper is to present the performance of this system and prove that it could operate in industries with steam demand in the middle to high temperature range. The innovation of this system is the TES system employed which is made from concrete and can store thermal energy up to 640 kW_{th}. Accordingly, the novelty of this work is the dispatchability of power and the utilization of concrete storage for industrial process heat applications.The response of the novel concrete thermal energy storage (CTES) system is examined with the objective to prove that the PTC system is dispatchable. The system is operating under two operation strategies based on the industry's timetable. The first strategy is set from Monday to Friday and the second one during the weekend, where the factory is closed. The operation modes of these strategies are also analysed individually for two clear days during summer, estimating the system's efficiency, power output, and steam production by the PTCs. The overall system performance is also presented for two continuous months of operation with the scope of proving that the predefined strategies can make the system dispatchable for a long period.

2. Real system demonstration

As part of the EDITOR project, a novel PTC system has been installed at KEAN soft drinks factory, located in Limassol, Cyprus [16]. A sky-view photo of the factory is shown in Fig. 2. The processes that require heat are the cleaning/disinfecting of the glass bottles and machinery parts, pasteurization and sterilization. It should be noted that the size of the solar system is a fraction of the actual heat demand required by the industry. The installed PTC system is a pilot system developed with the primary objective to prove that this technology is feasible for the Cyprus industries.

The solar system consists of 8 PTC (CF100) connected in 2 parallel rows of 4, with an aperture of 3 m and a length of 12 m. The nominal thermal power of the system is 125 kW_{th}. The CF100 PTCs used have been built by Protarget AG in cooperation with the DLR and other industrial partners [17]. These PTCs employ a highly efficient receiver tube for operation at temperatures up to 425 °C (Fig. 3a). The CTES is constructed by S.L. CADE Company in Spain [18] (Fig. 3b).

As can be seen from Fig. 4, a weather station, provided by Solar-Institute Jülich (SIJ) [16], is also installed to record on-site weather data. The data provided from the weather station were also used by the system controller to protect the collectors in case of extreme weather conditions. Furthermore, the recorded values of the available solar radiation are used for the estimation of the system efficiency.

The third part is the SG (Fig. 5a), which is constructed by Protarget to produce steam at 10 Bar_g, 188 °C. In the SG, freshwater is entering at ambient conditions from a water tank installed at the roof of the container (Fig. 5b). The SG is filling with fresh water up to a predefined level, leaving space for the steam. The HTF is circulated through the spiral pipes inside the SG, and thus transferring heat from the HTF to the freshwater and saturated steam at 188 °C is produced. The HTF employed is a new environmental-friendly silicone-based thermal oil named HELISOL®XA circulated by the variable speed pump (Fig. 5c). The HTF is a non-reactive polydimethylsiloxane, which is clear, odorless, and colorless. It has a long life, no hazard classification and is also a non-corrosive [19]. A number of control valves are also placed to control the system's operation modes and strategies (Fig. 5d).

For the evaluation of the system, various sensors were used to measure a large number of parameters such as the temperature of the HTF at the outlet of the collector and at various points throughout the system's workflow, the temperature of the CTES modules, the pressure at the SG, the pressure at the variable speed pump, the mass flow rate at the variable speed pump and from the feed water tank to the SG, the power of the PTC, CTES, SG and the pressure at the outlet of the collector. The main variable measured and analysed for the evaluation of the system is the temperature at different parts of the systems. For the temperature measurements, isolated thermocouples Type K, were used with the specifications shown in Table 1. Regarding the temperature of the CTES, 24 measurement points were set, to record the temperature of both the fluid in the storage and the concrete itself. All measurements were performed with time interval of 1 min and the data were stored at the main processor in the control unit which were accessible for analysis any time.

2.1. Operation modes and strategies

A schematic diagram of the system is shown in Fig. 6. In general, the collector consists of an absorber tube and a series parabolic mirrors. The absorber tube is coated with a selective coating of high absorptance (up to 94%) and low emittance, and it is placed in the focal line surrounded by a glass envelope. Vacuum is maintained in

Fig. 2. Sky-view showing the KEAN factory and the location of the PTC system (left) and the PTC system in a closer view (right).

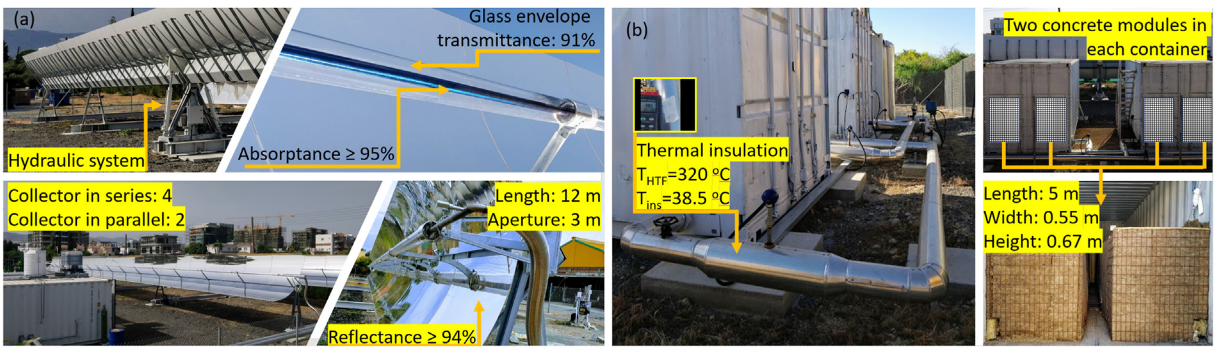


Fig. 3. (a) The solar field (SF) installed in KEAN soft and drinks industry (b) CTES system.

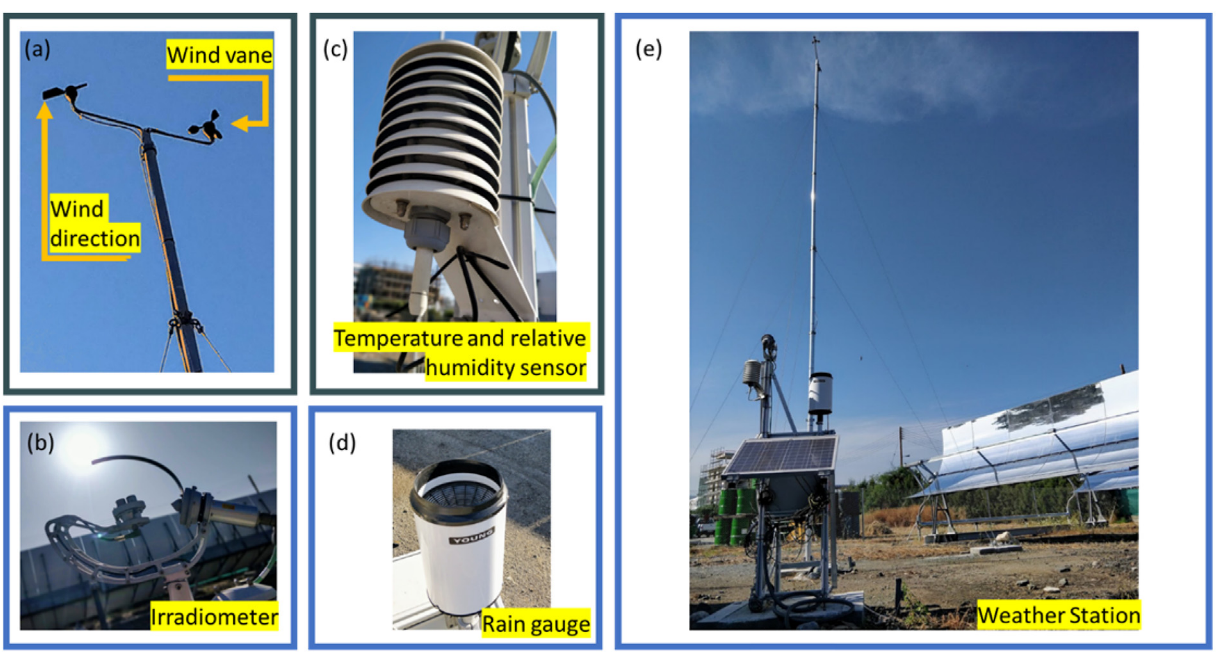


Fig. 4. (a) anemometer (b) irradiometer (c) Temperature and relative humidity sensor (d) rain gauge (e) weather station.

the space between the tube and the glass to reduce heat losses, to increase thermal efficiency, and protect the absorber coating from the ambient conditions. The PTC is installed in a north-south direction tracking the sun from east to west with two high accuracy hydraulic systems. The incident rays of the sun fall on the parabolic reflector, which has a reflectivity close to 95%, and the Direct Normal Irradiance (DNI) is concentrated on the absorber tube where the HTF is circulating. The HTF is then directed to the SG or to the CTES depending on the operation modes. As can be seen from Fig. 6, the CTES is connected in parallel and it is enabled according to the operation modes with the help of various electric valves. It should be noted that in Fig. 6, V denotes valve and T the

Fig. 5. (a) Feed water tanks (b) variable speed pump (c) control valves (d) steam generator.

Table 1
Specifications of the thermocouples.

Type	K
Range	−250 °C−1200 °C
Accuracy	±0.5 °C
Resolution	0.1 °C (1 μV)
Accuracy	−250 to 1200 °C: ±0.5%

temperature measurement point. As already mentioned, there are 24 temperature measurment points in the CTES modules, 6 in each one, as shown in Fig. 6 for module 1, only for clarity.

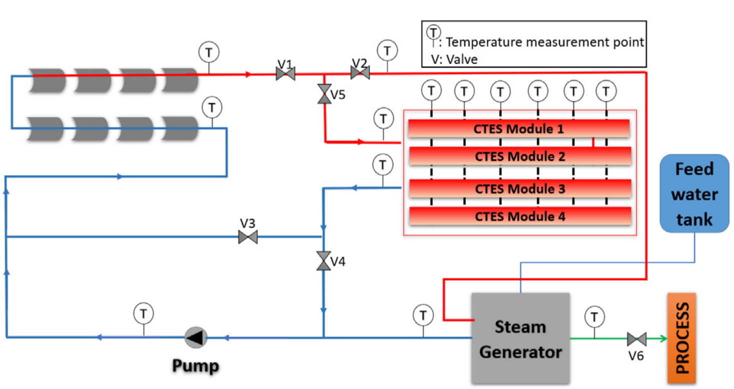
To achieve the different operation strategies, individual operation modes have been developed and optimized for the whole system. Depending on the operation mode and strategy, the corresponding valves are opened or closed. The scope of these modes and strategies is to make the system dispatchable and autonomous. The only constraint is that the system must always follow the steam demand acoording to the production shifts of the industry.

Thus, the KEAN industry operation is divided in two strategies, one from Monday to Friday with a steam demand at 188 °C and 10 Bar_g from 5 am to 3 pm and one during the weekend where there is no steam demand. Consequently, Strategies 1 and 2 have been developed to satisfy the thermal needs of the industry from Monday to Friday and to charge the CTES on Saturday and Sunday. The two operation strategies are shown in Fig. 7.

During the two strategies various modes are enabled and disabled based on the temperature of the HTF, the average temperature of the CTES, the thermal energy needs of the factory processes served and the solar radiation availability. The two strategies are as follows:

- Strategy 1 enables the following modes: TES Cold-Start Mode, TES Discharge Mode, TES Discharge and Solar Field Recirculation Mode, TES discharge and Generation Mode, Generation Mode and TES Charge Mode (blue colored process in Fig. 7).
- Strategy 2 enables the following modes: Solar Field Preheating Mode and TES Charge Mode (brown colored process in Fig. 7).

Strategy 1 is enabled at 4 am and the system is set on the ‘TES Cold-Start Mode’. During this mode, the thermal energy stored in the CTES is transferred to the SG with the circulation of the HTF



Mode	Pump	V1	V2	V3	V4	V5	V6
TES cold start	ON	C	O	O	C	R	C
TES discharge	ON	C	O	O	C	R	O
TES discharge and SF recirculation	ON	R	O	O	C	R	O
TES discharge and Generation	ON	R	O	O	C	R	O
Generation	ON	O	O	C	O	C	O
TES Charge	ON	O	C	C	O	O	C
SF preheating	ON	R	O	C	C	C	C
Plant off	OFF	O	C	C	O	C	C
% OPEN CLOSE REGULATED		O=100%		C=0%		R=10-90%	

Fig. 6. System workflow configuration and table showing the valves condition for the various modes of operation.

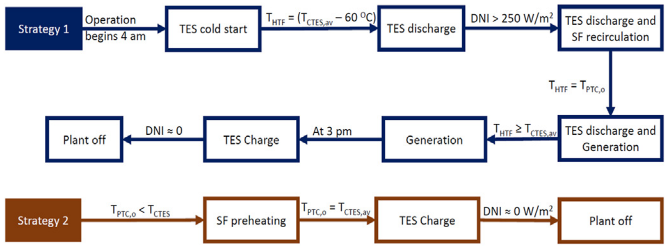


Fig. 7. System operation strategies.

between the CTES and the SG. This mode is used to increase the HTF temperature from 35 °C until it has a temperature difference of 60 °C from the CTES. To achieve this increament, without damaging the concrete structure (cracking), the process is ramped up slowly, with low mass flow rate and by controlling Valve 5 opening (valve numbers are shown in Fig. 6). At the same time, the SG pressure is also increased. As the HTF temperature raises to a difference of temperature of 60 °C from the CTES and the time is 5 am the 'TES Discharge Mode' is enabled. If by 5 am this temperature is not achieved some more time is allowed until this temperature is reached. This mode is enabled while the solar radiation is close to zero and the HTF flows from the CTES directly to the SG at 50% pump speed to provide the required power at the desired steam temperature and pressure. This mode ensures steam provision from the solar system (actually from CTES) to the industry when the solar radiaton is zero. Valves 1 and 4 remain closed during this process and Valves 2, 3 and 6 are fully opened. As the solar radiation is increasing both troughs are set on tracking mode, and the 'TES Discharge & SF Recirculation Mode' and 'TES Discharge & Generation Mode' are enabled. In the first hybrid mode the energy is transferred from the CTES to the SG for steam production and the HTF is circulated through the solar field (SF) to increase its temperature. As the HTF temperature homoginize while circulating through the system, the 'TES Discharge & Generation Mode' is enabled. To achieve this mode Valves 2, 3 and 6 open and Valve 4 closes. Additionally Valves 1 and 5 are regulating.

When the temperature of the HTF coming from the SF ($T_{PTC,o}$) is greater than the CTES average temperature ($T_{CTES,av}$) 'Generation Mode' is enabled. This is done automatically based on the HTF temperature and the pressure difference which is controlled by the valve openings. In this mode the HTF circulates through the SG and the SF, transferring the energy collected to the SG. The feed water tank supplies make-up water at ambient conditions to the SG, and steam is produced from the SG and delivered to the industrial processes. During this mode the system is operating with a HTF collector outlet temperature around 350 °C that corresponds to 125 kW_{th} of power to produce steam at 10 Bar_g (±0.2 Bar_g). This mode is enabled until 3 pm where the industry production shift ends. During 'Generation Mode' Valves 1, 2, 4 and 6 are open and Valves 3 and 5 remain closed.

After 3 pm the solar radiation is still high and the system turns automatically to the 'TES Charge Mode'. During this mode the SG is isolated and the HTF is circulating through the SF and CTES transferring the energy collected to the CTES. In charging mode Valves 2 and 3 remain closed and Valve 1, 4 and 5 remain open. Subsequently, when the solar radiation is insufficient, around 6:30 pm, the plant is set to off until the next day at 4 am, where the cycle is repeated.

On Saturday and Sunday as there is no steam demand from the industry, the system works with Strategy 2. When the solar radiation increases, both troughs are on tracking mode and the SF is preheating. When the HTF temperature gets equal to the average CTES temperature, Valve 5 opens and the 'TES Charge Mode' is enabled until the solar radiation is sufficient.

3. Results

3.1. Operation modes and strategies

On site data measurements from the system are analysed in order to evaluate the various operation modes involved in the two operation strategies. Two clear days during summer period were selected for evaluation.

Fig. 8 shows the steam pressure (Pr_{st}) in the steam line, the DNI, the temperature of the HTF at the outlet of the collector ($T_{PTC,o}$), the temperature in the HTF coming from the CTES ($T_{charging,\ discharging}$) and the average temperature of the CTES ($T_{CTES,av}$) concerning this day, for Strategy 1.

The following temperatures and times refer to the day examined but are about applicable for every day. At 4 am, the system is in the 'TES Cold-Start Mode'. As the solar radiation is zero at that time, the CTES heats the HTF slowly to 236 °C and the steam pressure raise to 5.1 Bar_g. The $T_{CTES,av}$ at that time is 279 °C in that particular day. As the HTF had a temperature difference of less than 60 °C compared to that of CTES, the system is turned to the 'TES Discharge Mode' at 5 a.m. From 5 am to 6:30 am, steam is produced solely from the CTES. The steam pressure has raised to 10 Bar_g and the HTF temperature was 242 °C by 6:30 a.m. Then as the solar radiation is increased, the HTF temperature in the SF, which is at ambient temperature, must homogenize with HTF circulating from the CTES. Both troughs are set on tracking mode and the hybrid mode 'CTES Discharge and SF Recirculation Mode' is enabled until 7:42 am, when the temperature of the HTF of the whole system is homogenized at 233 °C. Then 'TES Discharging and Generation Mode' is enabled, producing steam up to 8 a.m. At that time, the ($T_{PTC,o}$) was 259 °C and exceeded the $T_{CTES,av}$ which was 253 °C. Consequently, the system turns to the 'Generation Mode' with steam production only from the SF until 3 p.m. The ($T_{PTC,o}$) was maintained at 350 °C to satisfy the SG parameters. The 'Generation Mode' is operating in an average DNI of 783 W/m^2. Later on, at 3 pm, the 'TES Charge Mode' is initiated until sunset and the $T_{CTES,av}$ increased from 245 to 282 °C for an average DNI of 756 W/m^2. Finally, the $T_{CTES,av}$ throughout the day was 284 °C at 4 am, at 3 pm fall to 245 °C and through the charging mode which starts at 3 pm and ends at 6:30 pm it was raised again to 284 °C.

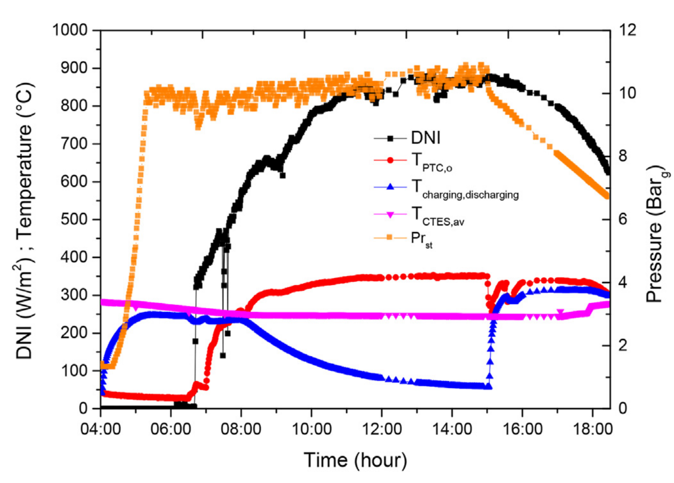


Fig. 8. Variation of the HTF temperature, DNI and steam pressure with respect to time during the operation Strategy 1.

Fig. 9 shows the power produced from the collector (P_{PTC}), the steam produced from the SG (Q_{st}), the power transfer from and to the CTES (P_{CTES}) and the ratio of the power collected from the sun to the power produced from the PTC (η_{PTC}). As can be observed, there is an uninterrupted steam supply from 5 am to 3 pm proving that the PTC system can satisfy the thermal needs of the industry according to the production shifts.

The CTES makes the system dispatchable as in the early morning hours although there is no solar radiation the system can produce steam. For that reason the P_{CTES} appears to have negative values on the graph at the early morning hours, due to the energy which is transferred from the CTES to the SG (and later to the SF) and after 3 pm has positive values due to the energy transferred from the PTC to the CTES for charging purposes. Additionally, the P_{PTC} in the early morning hours is also negative, since the energy is transferred from the CTES to the SF in order to homogenize the HTF temperature.

The P_{CTES}, P_{PTC} and the Q_{st} are calculated using the following equations:

$$P_{CTES} = \dot{m}_{HTF} \times c_{p,HTF} \times (T_{CTES,o} - T_{CTES,i}) \tag{1}$$

$$PTC_{power} = \dot{m}_{HTF} c_{p,HTF} (T_{PTC,outlet} - T_{PTC,inlet}) \tag{2}$$

$$Q_{st} = m_w \times c_{p,w} \times (T_{st,o} - T_{w,i}) \tag{3}$$

Where $\dot{m}$ is the mass flow (kg/s), c_p is the specific heat (kJ/kg·K), $T_{CTES,i}$ is the temperature of the HTF at the inlet of the CTES (°C), $T_{CTES,o}$ is the temperature of the HTF at the outlet of the CTES (°C), $T_{st,o}$ is the steam temperature at the outlet of the SG (°C) and the $T_{w,i}$ the temperature of the water entering the SG (°C).

The η_{PTC}, estimated using Eq. (4), varies from 36 to 52%. As shown in Fig. 9, the average η_{PTC} during the generation and charging mode is equal to 44%. The steam produced for the examined day is 940 L which is calculated by measuring the quantity of the make-up water. For this particular day, using Eq. (3), the Q_{st} was estimated around 601 MJ. The total energy stored (Q_{CTES}) from 3 pm to 6:30 pm was calculated using Eq. (5) and is equal to 77.5 kWh_{th}.

$$\eta_{PTC} = \frac{P_{PTC}}{DNI \times N \times L \times w} \tag{4}$$

$$Q_{CTES} = \sum \dot{m}_{HTF} \times c_{p,HTF} \times (T_{CTES,av,j+1} - T_{CTES,av,j}) \tag{5}$$

Where N is the number of collectors and L,w are the length and width of each collector respectively (m). The $T_{CTES,av,j}$ is the average temperature from the 24 thermocouples installed at various heights of CTES at any time j, and $T_{CTES,av,j+1}$ is the average temperature from the 24 thermocouples at various heights of CTES after an interval of 1-min.

Fig. 10 shows the DNI, the $T_{PTC,o}$, the *T-charging,discharging* and the $T_{CTES,av}$ concerning an operating day for Strategy 2.

As can be seen, the preheating of the HTF occurs from 10 am to 11 am with an average DNI of 755 W/m^2 and the $T_{PTC,o}$ increased from 41 °C to 296 °C. As the $T_{PTC,o}$ was equal to the $T_{CTES,av}$ (296 °C) the 'TES charge mode' is enabled until sunset. The $T_{CTES,av}$ was thus increased from 296 °C to 348 °C during this particular day which has an average DNI of 753 W/m^2.

Fig. 11 shows the P_{PTC}, the P_{CTES} and the η_{PTC}. As can be observed, at 11 am for 10 min the P_{CTES} is negative and this is happened because of the HTF which was in the pipe just outside the CTES, passing from Valve 5 to the CTES, where although there is thermal insulation, it is exposed to ambient conditions. Thus, it took 10 min to the HTF temperature to homogenize with the overall HTF temperature. The Q_{CTES} for 7 h of operation during Strategy 2 was 107.3 kWh_{th}, estimated with Eq. (5). The η_{PTC} varied from 35% to 48% (Fig. 11) and the average η_{PTC} during the day is equal to 39%.

The system is also examined for a longer period for two continuous months, from August to September. This long period data is shown in Fig. 12. As can be seen from Fig. 12, the system is operating at about 350 °C ($T_{PTC,o}$) and the $T_{CTES,av}$ is about 350 °C during the weekends and 200 °C on Fridays. As the CTES is charging after 3 pm every day, the system becomes dispatchable as it can follow the steam demand in the morning hours where there is no solar radiation. During August (Month 1) there is a gap during the production because of the summer holidays of the industry. During this period the solar system was shut down and the two troughs remained parked not able to receive any sunshine. The total of steam produced during this period was 36 tons which corresponds to 23 GJ.

An economic analysis of the system proves that the system has an economic payback time of 4 years. The cost of the steam produced with the conventional boiler is 50 EUR per ton (at fuel cost of 700 EUR per ton) compared with a cost of the PTC produced steam which is at 10 EUR per ton. Finally, considering the carbon content of the fuel to be 20 $kgCO_2$/GJ a considerable amount of greenhouse gas emissions are avoided because of the use of solar.

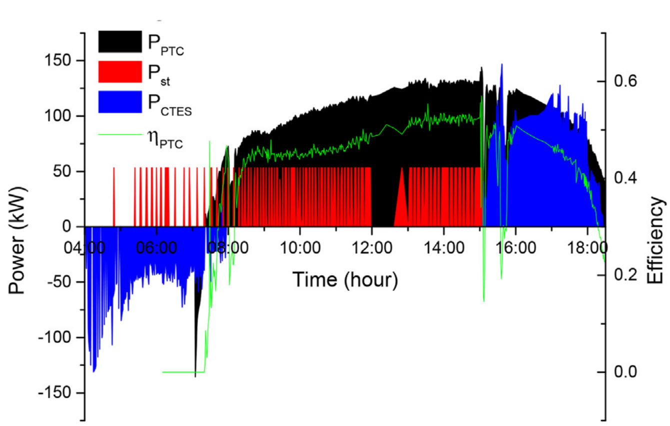


Fig. 9. Variation of the PTC, CTES, steam power and the PTC efficiency with respect to time during Strategy 1.

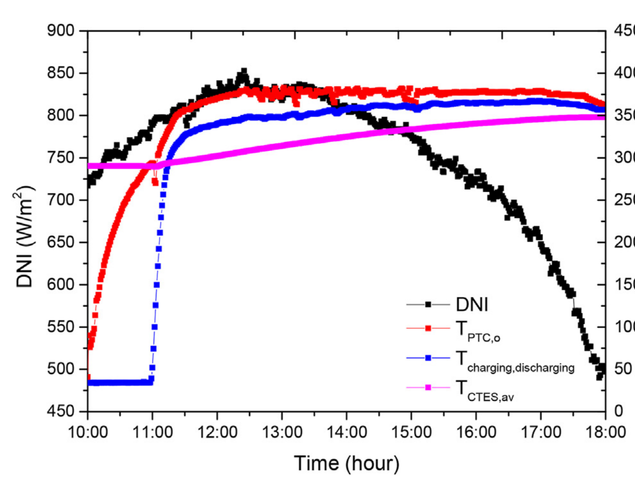


Fig. 10. Variation of the HTF temperature, DNI and steam pressure with respect to time during the operation Strategy 2.

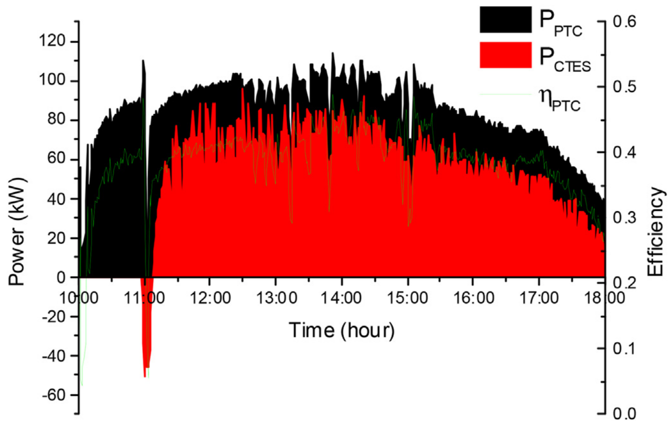


Fig. 11. Variation of the PTC, CTES power and the PTC efficiency with respect to time during Strategy 2.

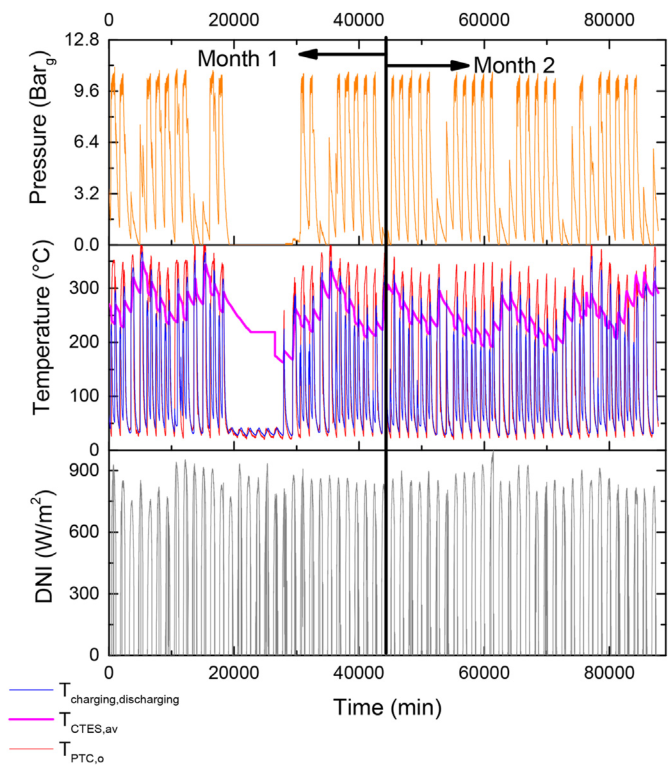


Fig. 12. Variation of the HTF temperature, DNI and steam pressure with respect to time during two continuous months of operation (August, September).

3.2. Concrete thermal energy storage

Another interesting test that is carried out during the first operating period of the system was to observe the CTES heat loss behavior when remained with no HTF distribution (i.e., without charging) for 209 h. The ambient temperature during this period of 9 days is shown in Fig. 13.

The temperature measured at the four blocks of CTES during this period of 209 h which was left uncharged is shown in Fig. 14. The measured values are shown with uncertainty boxes since temperature was being measured by numerous thermocouples as mentioned before. However, there is small uncertainty since all the values are between ±3 °C, which is proven by the fact that the uncertainty boxes are shown as a straight line. As can be seen, the CTES average temperature dropped from 268 °C to 132 °C during this period. From Fig. 15 which shows the CTES temperature drop for 9 days, it can be observed that during the 1st and 2nd day the temperature drop was around 23 °C and later it was less than 17 °C per day.

The overall heat losses (U_{loss}) for a temperature drop of 10 °C for the four CTES modules are calculated using Eq. (6) and it is shown in Fig. 16. As can be seen, the U_{loss} varies from 12 to 21 W/m^{2}K for all four CTES modules. In Figs. 14–16, the asterix denotes extreme values, the square the mean value and the uncertaintly boxes the most frequently appearing values.

$$U_{loss} = \frac{Q_{loss}}{A_{st} \times LMTD} \tag{6}$$

Where A_{st} is the surface area of the storage blocks (m^2). The energy loss (Q_{loss}) and Log Mean Temperature Difference ($LMTD$) values are estimated with Eqs. (7) and (8) respectively:

$$Q_{loss} = \frac{m_{CTES} \times Cp_{CTES} \times \left(T_{CTES,j} - T_{CTES,j+1}\right)_{st}}{t} \tag{7}$$

$$LMTD = \frac{\left(T_{CTES,j} - T_a\right) - \left(T_{CTES,j+1} - T_a\right)}{\ln\left(\frac{T_{CTES,j} - T_a}{T_{CTES,j+1} - T_a}\right)} \tag{8}$$

Where, m_{CTES} is the mass of the concrete mixture in the CTES (kg), Cp_{CTES} is the specific heat of the concrete mixture (kJ/kg K), t is the duration of the time step between the time intervals j and j+1 which corresponds to 3600 s, T_{CTES} is the temperature measured from the thermocouples in the CTES at time steps j and j+1, and T_a is the ambient temperature (°C).

Since all the above data were measured during the initial operating period of the system, the effect of the dust accumulation on the mirrors of the PTC need to be investigated. Mirror reflectivity measurements were performed using a Condor reflectometer from Abengoa Solar [20]. For each collector row, there are ten measurement points along their length where three sets of reflectivity measurements were taken (Fig. 17a). The measurement points are at the middle and at two edges of the mirrors at four different

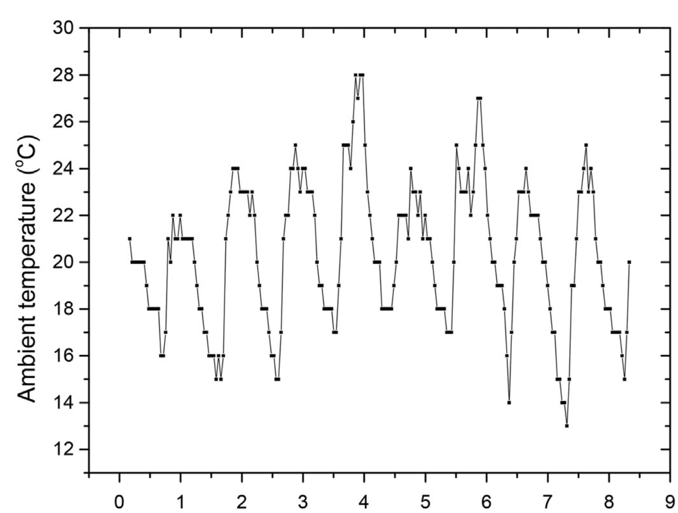


Fig. 13. The ambient temperature during the CTES loss behavior test.

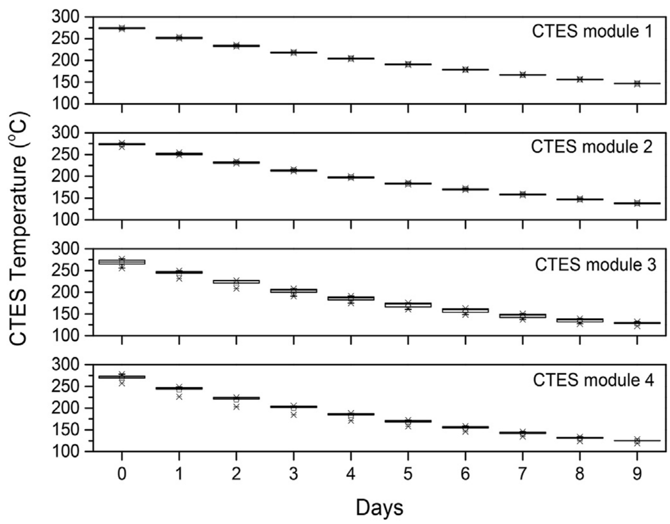


Fig. 14. CTES blocks temperature over a period of 209 h measured on site.

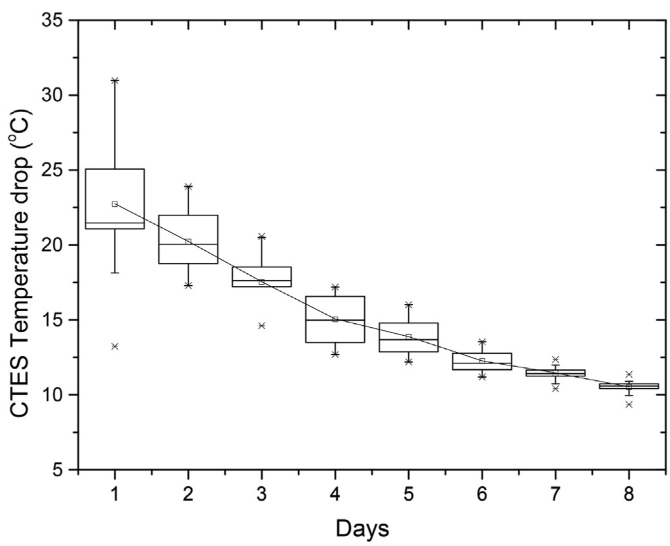


Fig. 15. CTES temperature drop for 9 days.

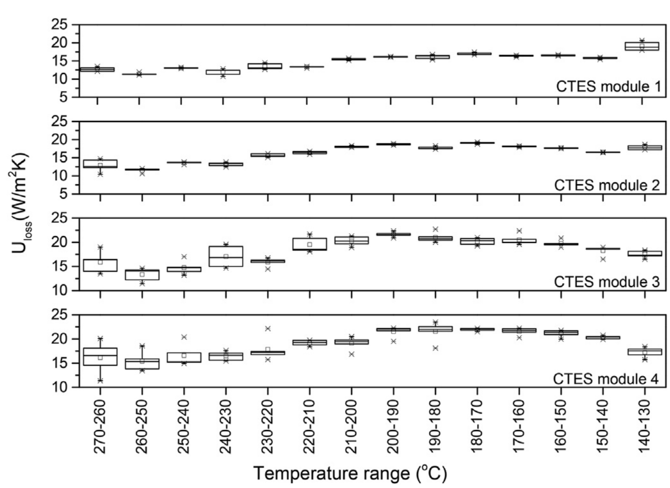


Fig. 16. Heat losses estimation for each CTES module.

locations as shown. Based on Fig. 17b, the dirt coefficient is estimated to be 0.96, i.e., a drop of 4% from the clean value, and thus it was decided to clean the mirrors once a week in order to keep reflectivity in high levels.

4. Conclusions

This study presents the data obtained from the initial operating period of the first PTC system installed in Cyprus island for IPH. The operation Strategies and Modes are explained, and real measured data were used to quantify the behavior of the system, not only in particular days but in a longer period of two continuous months of operation. Furthermore, the CTES heat loss behavior was tested as well as the dirt mirror reflectivity coefficient.

More specifically, the following conclusions can be drawn:

1. Under the Strategy 1 with average DNI of 757 W/m^2, the CTES stored 77.5 kWh_{th} in 3.5 h and the PTC system produced 940 litters of steam which is suppliled to the factory for the various industrial process which corresponds to 601 MJ of energy.
2. When system was operating under Strategy 1, from 5 am to 8 am the steam was produced from the energy stored in the CTES and from 8 am to 3 pm the steam was produced only from the PTC system.
3. In the experimental procedure where the CTES left undisturbed and uncharged for 209 h, its temperature dropped by 136 °C during this period. Although this is not a bad outcome, considering the solar radiation that prevail in Cyprus, there is no possibility for the system to be without solar radiation for such a long period but in the worst-case scenario the factory has as a back-up its conventional boilers.
4. The overall thermal losses coefficient of the CTES vary from 12 to 21 W/m^2K for a temperature drop of 10 °C.
5. The reflectivity measurements taken on a daily basis when the mirrors were left uncleaned showed that the reflectivity dropped 4% during a 5 days period and thus was concluded that they need to be cleaned once a week with water.
6. During Strategy 1 in the early morning hours when solar radiation is zero, the system is in the 'TES Cold-Start Mode' and the HTF is being heated from the CTES to 236 °C.
7. In Strategy 2, on a day with average DNI of 753 W/m^2, the CTES temperature increased from 290 °C to 348 °C, the HTF temperature homogenized in 10 min, and the total energy stored in the CTES for 7 h of operation was 107.3 kWh_{th}.
8. The instantaneous PTC efficiency varied from 35% to 48% and the average efficiency during the day is equal to 39%.
9. The CTES is charging after 3 pm every day and thus it can follow the steam demand in the morning hours where there is no solar radiation.
10. For two months of operation the total steam produced was 36 tons (23 GJ).

Concerning the results presented, it can be concluded that the system responds perfectly to the Strategies and Modes and supply the required amount of steam to the factory when is needed even at times when there is no solar radiation with the support of the energy stored in CTES, and this makes the system dispatchable. It is believed that such a system has great potential for countries with good solar resource as this is able to provide heat at the required pressure and temperature continuously.

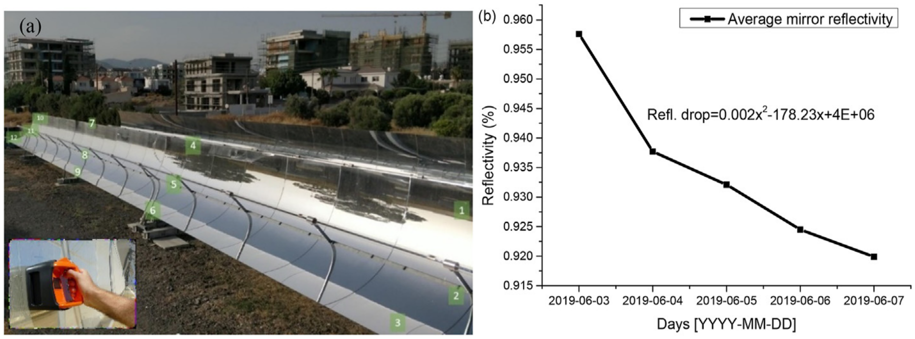


Fig. 17. (a) Reflectivity measurement points along the collector length (b) Reflectivity reduction in one typical summer week.

Credit author statement

Rafaela Agathokleous: Formal analysis, Data curation, Visualization. Panayiotis Ktistis: Investigation, Software, Validation, Writing - original draft. Soteris Kalogirou: Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

A	Area (m^2)
c_p	Specific heat capacity (kJ/kgK)
L	Length (m)
$\dot{m}$	Mass flow rate (kg/s)
m	Mass (kg)
N	Number of collectors
P	Power (J)

Abbreviations

CTES	Concrete Thermal Energy Storage
DLR	German Aerospace Center
DNI	Direct Normal Irradiance
EU	European Union
HTF	Heat Transfer fluid
IEA	International Energy Agency
IPH	Industrial Process Heat

Subscripts

av	average
i	inlet
j	Time step
th	Thermal energy

Greek symbols

α	Ambient
η	Efficiency (%)
Pr	Pressure (Bar_g)
Q	Energy (W)
T	Temperature (°C)
t	time (s)
U_{loss}	Heat loss (W/m^2K)
w	width (m)
LMTD	Log Mean Temperature Difference
PTC	Parabolic Trough Collector
SF	Solar Field
SG	Steam Generator
TES	Thermal Energy Storage
UA	University of Arkansas
o	outlet
st	steam
w	water

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