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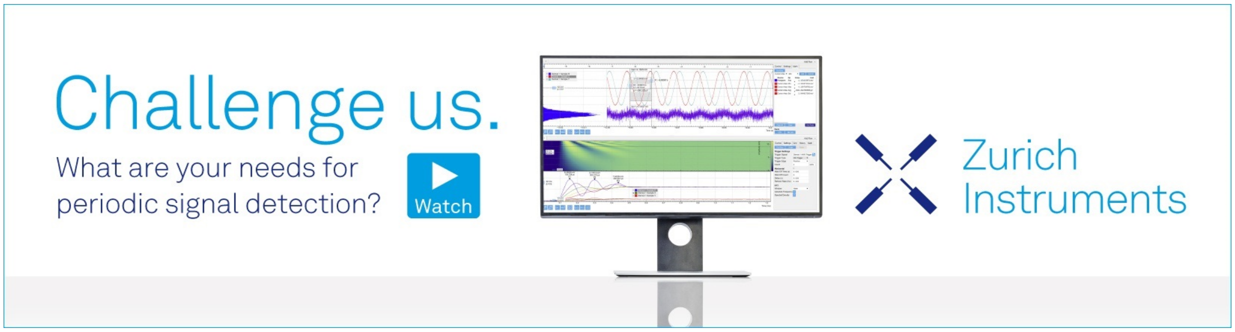

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Operational Experience and Behaviour of a Parabolic Trough Collector System with Concrete Thermal Energy Storage for Process Steam Generation in Cyprus

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Abstract. As part of the transnational research project EDITOR, a parabolic trough collector system (PTC) with concrete thermal energy storage (C-TES) was installed and commissioned in Limassol, Cyprus. The system is located on the premises of the beverage manufacturer KEAN Soft Drinks Ltd. and its function is to supply process steam for the factory's pasteurisation process [1]. Depending on the factory's seasonally varying capacity for beverage production, the solar system delivers between 5 and 25 % of the total steam demand. In combination with the C-TES, the solar plant can supply process steam on demand before sunrise or after sunset. Furthermore, the C-TES compensates the PTC during the day in fluctuating weather conditions. The parabolic trough collector as well as the control and oil handling unit is designed and manufactured by Protarget AG, Germany. The C-TES is designed and produced by CADE Soluciones de Ingeniería, S.L., Spain. In the focus of this paper is the description of the operational experience with the PTC, C-TES and boiler during the commissioning and operation phase. Additionally, innovative optimisation measures are presented.

INTRODUCTION

Solar power plants for supplying thermal power to industrial consumers are becoming increasingly important. Worldwide, dozens of such plants – predominantly parabolic trough systems – are already installed [2]. A very important requirement with respect to the operation of solar thermal plants is the ability to supply thermal power on demand at any time of the day. A fully dispatchable system not only increases the consumers' confidence into solar technology, it also proves that solar thermal systems can be flexible due to the ability to operate during the night or at temporary cloud passages during the day. Especially for industry that operates fossil-fired steam generation systems, it is not unusual that work shifts start and end in the night or even require 24/7 attendance. This paper presents operational experience as well as data of a parabolic trough system with implemented concrete thermal energy storage at the location Limassol in Cyprus. The concentrating solar system supplies dispatchable thermal power and therefore meets the industrial needs for stable thermal power supply. Solar supply of energy is especially of interest to the industry if prices for fossil fuel are high, as is the case for Cyprus. Cyprus has a high dependence on fossil-fuel imports, importing more than 80 % in petroleum products [3]. A typical imported fuel used by the industry is light fuel oil

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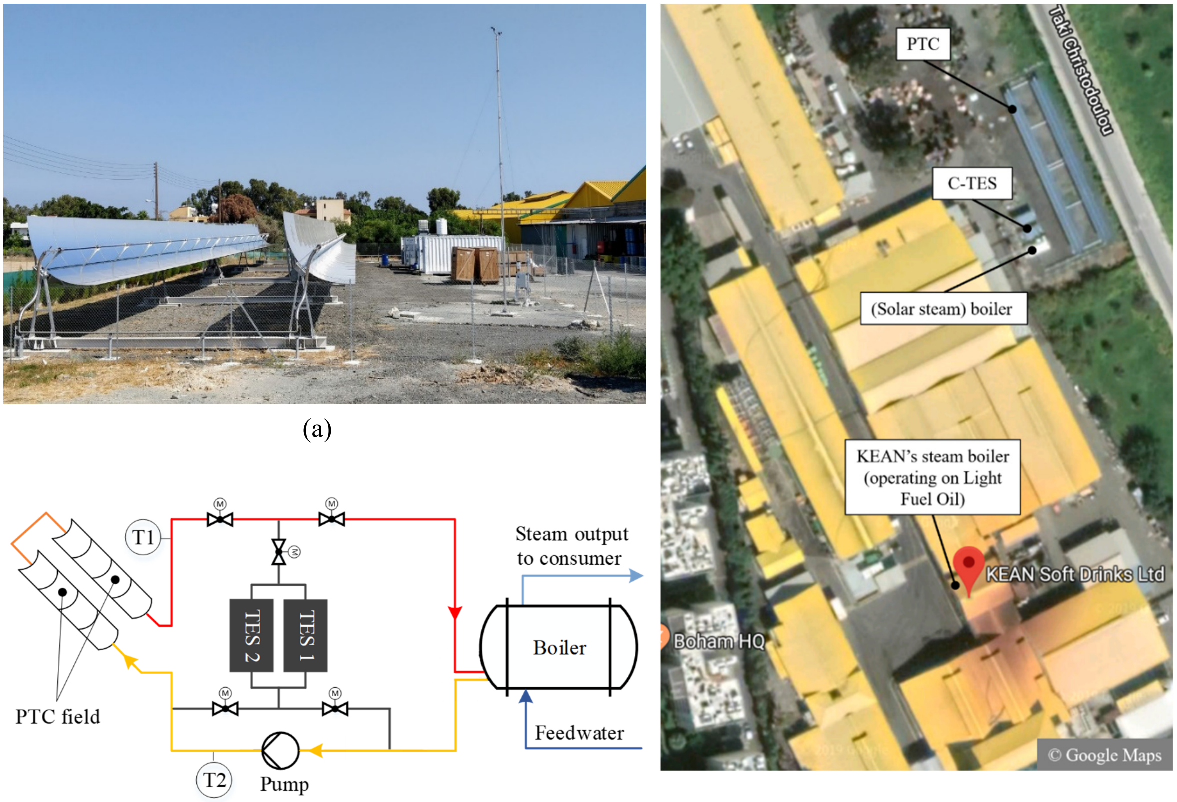
(LFO). This is also the fuel used by KEAN to fire their steam boiler. The prices have varied greatly over the years. In the year 2017, the price for LFO in Cyprus was 564.56 € per tonne, compared to, for example, 745.52 € per tonne in 2013, 424.89 € per tonne in 2009 and just 189.09 € per tonne in 2003. Between 1991 and 2002 the price for LFO was constant at merely 128.81 € per tonne. The given prices are yearly average retail market prices based on a sample of filling stations that include excise taxes but exclude VAT [4]. Due to the soaring and strongly fluctuating prices, solar energy may become a very cost-efficient energy source for the Cypriot industrial sector.

TECHNICAL DETAILS OF THE SOLAR THERMAL PLANT

The solar thermal plant at KEAN consists of a two-row parabolic trough collector loop with an aperture of about 3 metres and a total length of 96 m, an implemented two-module C-TES and a kettle-type boiler for steam generation. The components are shown in Fig. 1(a) whereby the two-module C-TES and boiler are placed within shipping containers. The schematic of the installed plant is presented in Fig. 1(b). An impression of the size of the parabolic trough collector system at the KEAN factory is given from the satellite image in Fig. 1(c). The plant deploys the HELISOL® XA silicone oil from WACKER Chemie AG, which can be heated up to 425 °C and is fairly new on the market. At the KEAN factory, steam is required either for 8 or 16 hours depending on the workload. The C-TES is fully charged on weekends when the factory is closed and partly charged as often as possible during the weekdays.



(a)

(b)

(c)

FIGURE 1. (a) Photo of the two-row PTC system, weather station as well as three shipping containers accommodating the C-TES and boiler (Photo provided by and © Protarget). (b) Schematic representation of the PTC system with C-TES (modules installed in parallel). (c) Aerial view of the KEAN factory including the installed solar system © Google Maps.

OPERATIONAL EXPERIENCE AND BEHAVIOUR OF THE CONCENTRATING SOLAR SYSTEM

The dispatchable and fully automatic operation of the solar plant at the KEAN factory was achieved by developing various modes of operation and control strategies. The modes had to comply with temperature and pressure limits, transient effects while switching between modes, variance in the solar irradiance as well as demand schedules from the consumer side. All modes function in a synchronised manner in order to control and handle the collected solar energy. Operation modes such as energy generation, storage charge or discharge, solar field preheating as well as hybrid modes have been developed and tested in the commissioning phase. During the testing phase the dispatchability was successfully proven, demonstrating that steam production in the early morning hours before sunrise is possible by means of discharging the C-TES. With the C-TES, and in accordance to the production schedule of KEAN, steam is produced by 5:30 am.

The operational behavior of the steam boiler has been investigated too. The heat-up time has been tested with different water levels and the advantages and disadvantages of an increased/decreased water volume have been investigated. In addition, the efficiency of the boiler has been determined to verify and approve the yield calculations executed for this and other plants. To verify thermal loss calculations of the system, extensive tests have been run to determine the thermal losses in the solar field including receiver tubes, flex hoses and the field piping. The plant is now fully commissioned and is in uninterrupted operation since March 2019. Steam has been produced for about 1000 hours. The maximum thermal oil temperature that the plant was operated at was 415 °C. However, for the specific requirements of the KEAN factory, a nominal operating temperature of 350 °C was chosen.

Commissioning Phase

The commissioning phase started in 2018 and ended in February 2019. During the commissioning phase, the shift from steam production to storage charging mode was identified as the biggest control challenge especially due to the high thermal oil temperatures and because the C-TES must be protected from thermal shocks. A fully automated control system with different modes of operation was developed to maintain a stable oil temperature and to minimise solar dumping. The fully automatic operation of the plant has been successfully demonstrated and is fully implemented in the process control system. With the developed control modes working in automated operation, the consumer's needs for steam can be individually met and adapted. The storage allows the production of steam according to the demand, which includes times when the sun is not available (e.g. before sunrise or after sunset) and seasonal variations in the production schedule or work shifts. These modes as well as a PTC tracking method developed by Protarget AG are described in this section.

From the control system's various modes of operation, only the most important ones are outlined below. The control system, in general, can deal with any type of weather and uses in-house developed algorithms for a smooth operation. The modes of operation automatically switch amongst each other based on the pre-determined steam requirements of the consumer and weather conditions. As for the case of the KEAN factory, the demand for steam depends on the weekday as well as the workload. The factory is operational Mondays to Fridays, but not on weekends. Depending on the work load the factory shift is 8 or 16 hours long. During the week the steam boiler requires startup early enough before the actual juice production starts. The weekday's strategy is shown in Table 1 below.

TABLE 1. Weekday schedule

Time	4 am – 6 am	6 am – 8 am		8 am – 3 pm	3 pm – 7 pm	7 pm – 4 am
Mode	C-TES discharge	C-TES discharge + Solar field preheating	C-TES discharge + Solar steam generation	Solar steam generation	C-TES charge	Plant off

The individual modes are described below but may be combined with other modes as per Table 1.

C-TES discharge:

In this mode, the heat transfer fluid (HTF) flows from the C-TES directly to the boiler in order to produce steam before sunrise. The energy stored in the C-TES is, at first, transferred to the water in the boiler at a low mass flow due to ramp limits that are active to protect the concrete from thermal shocks. Once the C-TES discharge parameters are met, the discharge mode will increase the oil mass flow through the storage to provide the required thermal power to the boiler for constant steam production at the desired parameters.

Solar field preheating:

This mode sets both solar field's parabolic trough collector rows to sun tracking such that the HTF is heated to the desired temperature value for constant steam generation.

Solar steam generation:

During sunny conditions during the day, the HTF is heated in the solar field and transfers the thermal energy to the water in the boiler. The boiler produces saturated steam and feeds it into the steam piping system from the KEAN factory. The steam parameters are controlled by the main system by means of controlling the amount of energy passing through the boiler. The control works with a PID controller that adjusts the HTF pump's mass flow based on the amount of direct normal irradiance (DNI), HTF temperatures (inlet and outlet of the field) and collector tracking of the system.

C-TES charge:

In this mode, the HTF flows from the solar field to the TES, transferring the collected energy to the concrete storage. The charging takes place either at a reduced mass flow or at maximum mass flow. The C-TES has thermal constraints that must be abided by such that, for example, a thermal shock to the steel pipes and concrete is avoided. Therefore, for a minimum of 10 minutes after initiating the charging mode, the initial temperature difference between the HTF entering the storage blocks and the average temperature of the blocks should not exceed 50 °C. After the heat-up phase, the C-TES can be charged at full thermal power delivered by the solar field. The temperature difference limit is increased to 100 °C.

Example of modes in operation:

Figure 2 shows measurement data for 30 July 2019 in which the behaviour of the defined operation modes can be observed. The graph shows the steam pressure, the HTF temperature at the solar field outlet (Temperature SF), the HTF temperature at the exit of the C-TES from discharging (Temperature TES) as well as the DNI. An uninterrupted steam supply from 5 am to 3 pm, as required by the consumer, can be observed. At approximately 4 am, steam production from C-TES discharge is initiated. At about 5.30 am steam was fed into the KEAN steam piping system. Until about 6 am, steam is produced solely from C-TES discharge. From approximately 6 am to 7 am, a hybrid mode is initiated with C-TES discharge and solar field preheating occurring at the same time. Then, from about 7 am to 8 am, steam is produced via combining the C-TES discharge and steam generation modes whereby both operate in part load. At about 8 am, the C-TES discharge is discontinued and steam is solely produced by the solar field. At 3 pm, the C-TES charging mode is initiated until sunset. It should be noted that the abrupt DNI drop is due to shadow on the weather station's sensors while the solar field is still receiving sun light.

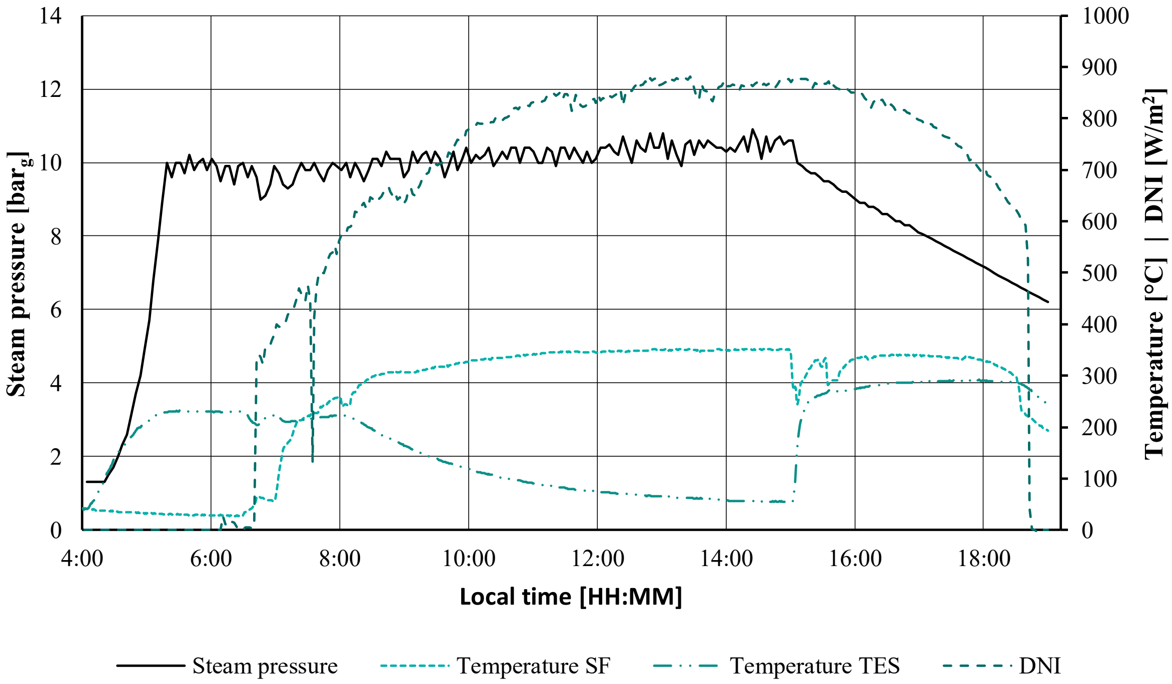


FIGURE 2. Various operation modes run in a single day on 30 July 2019

Solar tracking system

The solar tracking system of the parabolic trough collectors is based on an algorithm that determines the sun's position and accordingly operates the hydraulic actuators for tracking and focusing the sun light. The tracking angle is influenced by the orientation of the axes of the parabolic trough rows which is usually given in relation to the true north. In the case of the plant in Limassol, the offset to the true north is, by design, −23.7°. A field analysis was carried out to understand the effects that the adjusted tracking algorithms has on the tracking accuracy, especially in different seasons. The field analysis proofed the tracking to be accurate within its design specification. To increase tracking accuracy, parabolic trough collectors normally also deploy a tracking method based on two PV cells placed underneath the absorber tube. If accurately aligned with the sun position, the PV cells will produce the same electrical power as both cells are equally shaded from the absorber tube. Protarget AG successfully developed a self-optimising tracking method that does not require the use of PV cells. The concept is based on slightly changing the tracking angle of a collector row at selected times during the day at stable DNI conditions, upon which a change in thermal oil temperature is detected shortly afterwards. By varying the tracking angle such that it is slightly ahead as well as lagging behind the original actuator's alignment, then the optimum tracking angle that leads to the highest thermal oil temperature can be identified. This calibration procedure is repeated throughout the year to adapt to seasonally dependent errors. This sequence is promising an increase in performance of the PTC system and will be further refined in the future.

Performance in Normal Operation Phase

In order to determine the thermal losses of the solar field, a special test campaign was carried out over the course of several nights. In this test the C-TES is charged during the day to a pre-specified temperature level such that it can be discharged overnight after sunset. By passing the hot thermal oil through the collectors in the night, it is possible to determine the temperatures at various points in the solar field without the influence of solar irradiance, thus giving the true temperature loss. During the test in the night, the parabolic trough collectors where positioned into stow position. The wind conditions on the site were suitable (<3m/s) for analysing the thermal losses. Initial results show that the heat loss at the receiver tube joints is more significant than expected (40-50 W/m in operation). Also the heat loss of the solar field piping is higher than calculated. It should be noted that the specific heat loss reduces for larger solar fields. However, research and development work with the aim of finding solutions that further reduce the thermal losses in the solar field is still required. The reduction of thermal losses through the metal support stands and connections that hold the field piping are a priority. This is followed by the need of minimising the losses through receiver tube joints.

Significant improvements to the control system were made. A software based PID controller was developed that ensures a nearly constant steam pressure in the kettle-type boiler even under fluctuating direct normal irradiance (DNI). The PID control functions by controlling the pump speed, thereby controlling the mass flow of the HTF trough the solar field and/or by controlling the energy collected by the PTC system by means of changing the tracking angles (changing offsets). The results of using this controller are shown in Fig. 3 below. The target steam pressure was set to 10.5 bar_g with a permissible deviation of about ±0.2 bar. During the plant start-up the pressure ramp smoothly approaches the target pressure without overshooting it. It can also be observed that during afternoon when the DNI is decreasing the steam pressure remains relatively constant.

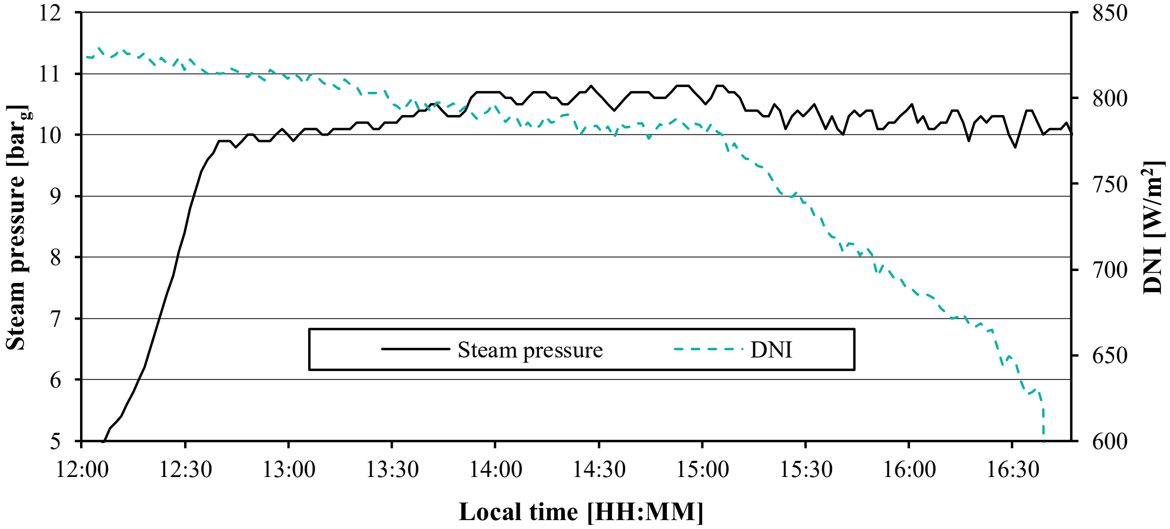


FIGURE 3. Measurements of steam pressure and DNI on 8 April 2019

With respect to the steam boiler's thermal losses during operation, measurements and calculations are indicating that the thermal losses are in the expected range. The results reveal a constant thermal loss of 2.8 kW in operation. This loss is about 2 % of the nominal rated thermal power of the steam boiler. To test the behaviour of the boiler in operation, the boiler's water level was varied for selected time periods. The tests showed that setting high water levels in the boiler has an advantage during temporary and sudden cloud passages. The advantage is that steam can be produced even in the absence of solar irradiance by means of reducing the boiler pressure temporarily. By reducing the pressure, the evaporation temperature is reduced too and thus a portion of the water will evaporate. This procedure can be carried out for a limited period time and must be stopped at a safe minimum water level. In the meantime, storage discharge can compensate until the solar field is in operation again. In contrast, operating the boiler at a low water level has the advantage that the plant can start-up quicker as a smaller volume of water must be heated to the boiling point. An analysis of the performance of both boiler level control modes has shown that a low water level serves sufficiently well as a steam buffer. Thus this configuration has been implemented permanently. For future projects, these and other findings are important with respect to optimising the steam boiler design, to reduce costs and to predict the thermal yield more precisely and reliable.

The C-TES at the KEAN factory has a capacity of 600 kWh allowing on-demand and continuous supply of steam. For small C-TES systems like the presented one, it is possible to ship these in containers as shown in Fig. 4. It should be noted that the concrete blocks including insulation only take up around 1/3 of the container volume. For large C-TES systems, it is foreseen that the concrete modules will be casted on-site.

FIGURE 4. C-TES modules in containers at the KEAN factory in Limassol, Cyprus

The C-TES is fully implemented in the plants automated control system. Among the C-TES data that was evaluated by CADE are the starting-up as well as the continuous operation procedures. Figure 5 shows the storage charging, stand-still and discharge over the period of one week in July 2019. The charging rate is about 15 Kelvin/hour. During the weekdays from 22 to 26 July the storage was partly charged during the day and discharged in the early morning as per described operation modes. On the weekend the KEAN factory is closed. The weekend is therefore used to charge the storage as much as possible (depending on the solar conditions) such that the stored energy can be used during the weekdays. During stand-still times over night, a temperature loss of about 20 K is observed. Due to the relatively small volume of the concrete blocks compared to the high surface area, a larger thermal loss into the environment was expected and is not seen as an issue. The reason is that for larger systems the specific thermal loss will decrease as the ratio of volume to surface area increases. As for the demonstration storage at KEAN, it could also be fitted with a thicker insulation layer. The conductivity of the storage is as expected and shows no abnormality.

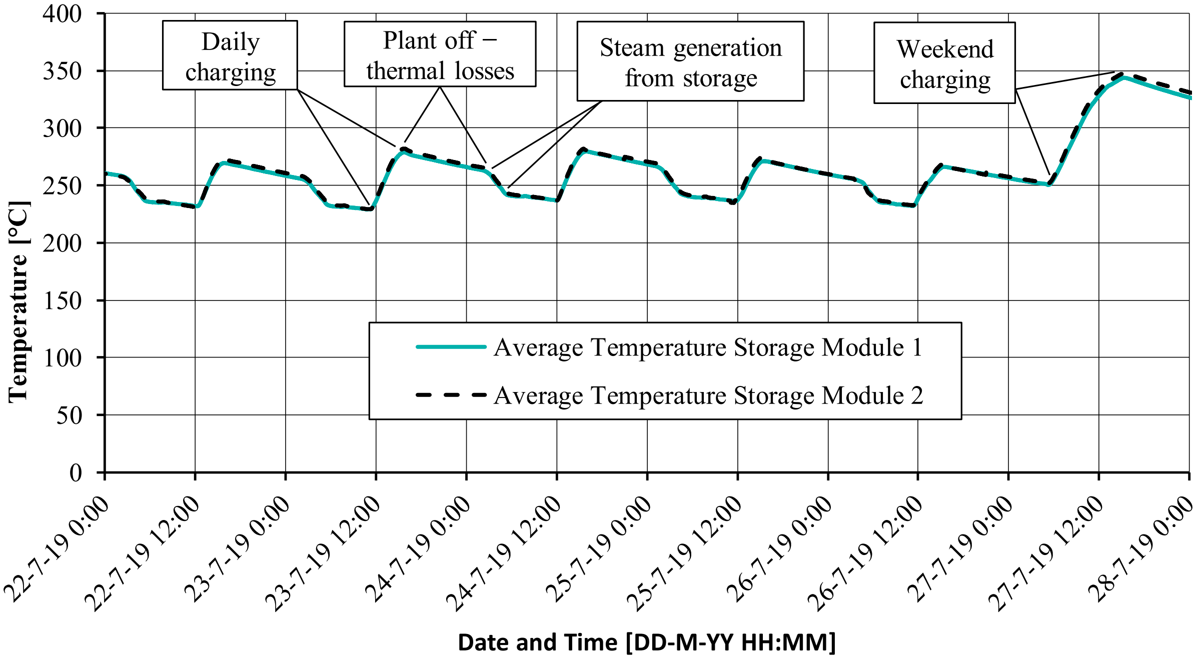


FIGURE 5. Storage charging, stand-still and discharge over the period of 1 week

The concrete's specific heat capacity was measured after several months of continuous operation. Figure 6 shows the measured specific heat capacity for various temperatures. From simulation results it could be validated that the specific heat capacity values appear to be accurate.

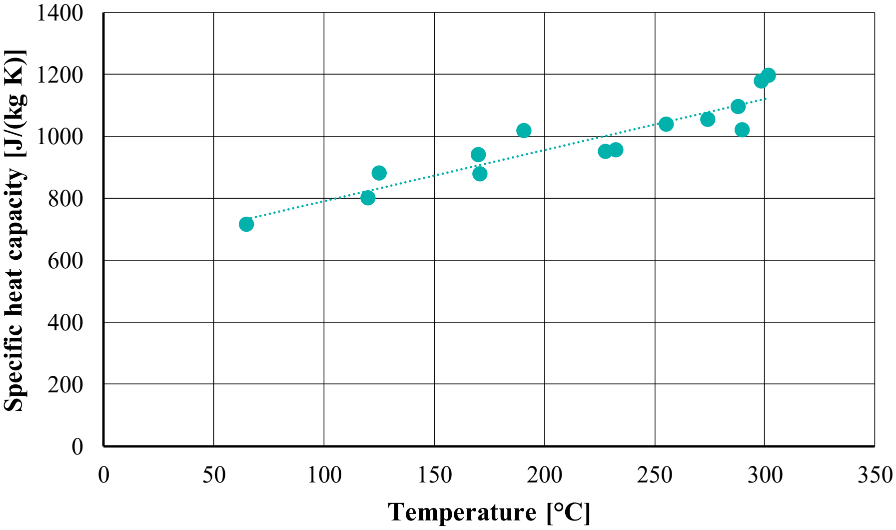


FIGURE 6. Measured specific heat capacity of the concrete for a range of temperatures

Generally, the fast response time of the C-TES enables a constant steam supply to the consumer KEAN. Regarding operational restrictions during operation, the permissible temperature difference between the thermal oil and the concrete temperature must not be exceeded. Other than that, the storage has a very robust design and is easy to handle.

Maintenance Strategy and Thermal Oil Performance Tests

The Cyprus University of Technology (CUT) is responsible for the maintenance of the weather station, mirror reflectivity measurement and evaluation as well as data monitoring. CUT determined cost-effective, time-dependent washing intervals at the site by means of (i) evaluating the mirror reflectivity in different weather conditions, and (ii) developing a coefficient of soiling by comparing the actual value with the clean mirror state. The reflectivity measurements are carried out with a Condor® reflectometer from Abengoa Solar. For each collector row there are ten measurement points along the length (two points every 12 m) for which reflectometer measurements are taken. The measurement points are at the centre and towards one of the edges of the mirrors.

Figure 7 shows the reduction of mirror reflectivity over the course of 1 week between 3 June to 7 June 2019. All the mirrors were thoroughly cleaned on Monday 3 of June 2019 and had a reflectivity of about 95.8 % at the start of the measurement campaign. From Monday to Friday reflectivity measurements were taken every 24 hours. After one day, the reflectivity had reduced by about 2 % and over the course of the following days until 7 June the reflectivity dropped another 2 %. The coefficient of soiling is about 1 % per day. Measurements of the mirror reflectivity have been conducted extensively over the months of the operation of the parabolic trough collector.

Figure 8 shows the monthly mean values of reflectivity between July 2018 and July 2019. In that time period the mirror cleaning interval was once per week. The aim for the cleanliness was to maintain the reflectivity above 91 % at any time. As dust concentrations in the atmosphere vary strongly and therefore have a time-varying soiling effect on the mirrors, it is important to check the mirrors' reflectivity at least once a week in order to decide whether mirror washing is necessary. It should be noted that in February and May 2019 the mirrors were washed fewer times than normal.

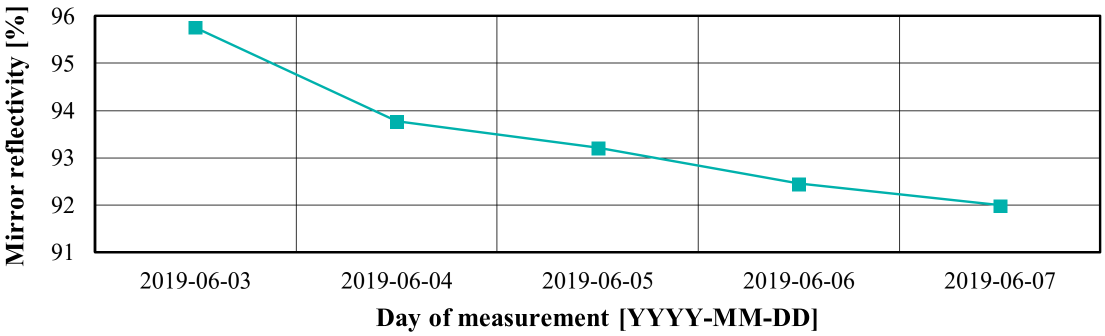


FIGURE 7. Change of mirror reflectivity over the course of 1 week

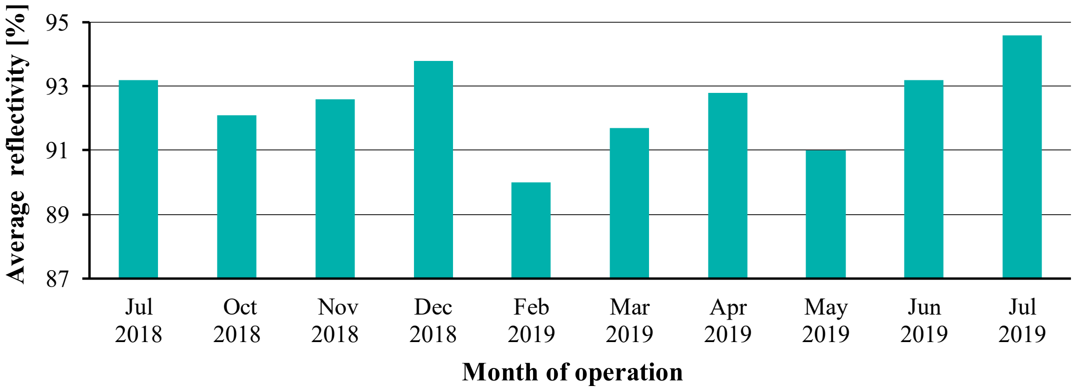


FIGURE 8. Monthly average mirror reflectivity for about 1 year

A weather station on the site continuously records data which includes the DNI, wind direction, wind speed and ambient temperature. The weather station generally requires little attendance. The pyranometers of the rotating shadowband irradiometer are cleaned only about once a week.

The German Aerospace Center (DLR) examined the thermal stability of the new HELISOL® XA at 430 °C via ageing tests according to DIN 51528 and analysis of gaseous and low boiling degradation products based on micro gas chromatography. The test series comprises the fluid alone and when it is in contact to relevant materials of construction such as carbon and stainless steels. Steel samples in mint and in pre-oxidized condition were used. The study confirms that the hydrogen formation of HELISOL® XA is comparably low, similar to HELISOL® 5A [5]. Stainless steel reveals no significant effect on the ageing characteristics of the silicone oil. The contact to carbon steel has also no impact on the formation of hydrogen. All steel qualities reveal no evidence of corrosion after 1000 hours exposure to the silicone fluid at 430 °C.

CONCLUSION

Within project EDITOR it was possible to fully automate the solar thermal plant and to prove dispatchability with the implemented C-TES system. Several tests were conducted in order to obtain the relevant characteristics of the involved systems and to verify their specification parameters. The knowledge that was gained during the commissioning phase, normal operation and tests will be very valuable for the planning of future PTC plants with C-TES. Moreover, component parts such as metal support stands and connections were identified that should be further developed in order to decrease thermal losses and thus increase the efficiency of the system. Furthermore, it can be concluded that the specific thermal losses of a PTC and C-TES system reduce for larger systems. Regarding the mirror reflectivity, it is important to determine suitable mirror cleaning intervals with seasonal and possibly annual adjustments due to the nature of strongly fluctuating dust movement in the atmosphere.

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REFERENCES

1. J. C. Sattler et al., “Dynamic Simulation Model of a Parabolic Trough Collector System with Concrete Thermal Energy Storage for Process Steam Generation”, AIP Conference Proceedings 2126, 150007 (2019).
2. Solar Thermal Plants Database, http://ship-plants.info/solar-thermal-plants-map (Last accessed on 28 August 2019).
3. Cyprus energy imports, https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2c.html (Last accessed on 29 August 2019).
4. ENERGY STATISTICS, 2017 https://www.mof.gov.cy/mof/cystat/statistics.nsf/energy_environment_81main_en/energy_environment_81main_en?OpenForm&sub=1&sel=4 (Last accessed on 28 August 2019).
5. C. Jung, J. Dersch, A. Nietsch and M. Senholdt, Energy Procedia 69, 663 – 671 (2015).
6. SOLAR-ERA.NET network, http://www.solar-era.net/ (Last accessed on 28 August 2019).