COST REDUCTION BY COMBINING SOLAR THERMAL TECHNOLOGIES FOR A DISPATCHABLE STEAM GENERATION

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Abstract

Compound Parabolic Concentrator's (CPC) are usually not associated with the production of steam, as with the required high operating temperature to produce steam the thermal losses of the CPC are predominant. In this paper a system is presented to include a CPC solar field into the solar thermal generation of steam for a process heat consumer. The presented system includes a Parabolic Trough Collector (PTC) field to generate steam at 188°C/11barg. The CPC system is used to pre-heat the feed water to 95°C. This combined solar system is built by the protarget AG in Cyprus, Limassol at the premises of KEAN soft drinks Ltd. to provide heat for the orange juice production. In this paper it is shown how both technologies, the CPC system with 225m² collector gross area and the PTC system with 283m² collector gross area, are integrated in the same industrial process. The consumption of process heat at this specific application starts early in the morning with no sunshine available. Therefore, an arrangement including a Thermal Energy Storage (TES) for each of the technologies is found. The operating behaviour of both technologies contributing to the same energy consumer is presented. The innovation of combining these two technologies promises a cost reduction; therefore, a detailed economic analysis is shown and the cost reduction potential is explained. The economic calculation is indicating an advantage of the combined system instead of a solely PTC system. The PTC only system generated the steam at ca. +2.5% of the cost compared to a combined system considering a 1.25MW nominal thermal power application built in Limassol, Cyprus. This paper validates the benchmark calculation and how a variation of the installed system size will impact the cost reduction.

Keywords: Parabolic Trough Collector, PTC, Compound Parabolic Concentrator, CPC, Thermal Energy Storage, TES, process heat, cost reduction

1. Introduction

As part of the European "Green Deal", the European Commission proposed on the 4th of March 2020 the first European Climate Law to formulate the 2050 climate-neutrality target – to realize this mark an economy with net-zero greenhouse gas emissions is required. A net-zero emission is defining that all man-made greenhouse gas emissions must be absorbed from the atmosphere via natural and artificial sinks. The Climate Law underlines the EU's commitment to the global climate action under the Paris agreement. The objective of the Paris agreement is to keep the global temperature increase to below 2°C and pursue efforts to keep it to 1.5°C.

To realize these temperature targets the introduction and establishment of renewable energies in all energy consuming sectors from the power sector to industry, mobility, buildings and agriculture is required. To facilitate and accelerate the elemental shift to a clean energy economy several measures have to be taken. These measures are made of political stimulations on different levels (policies, subsidies, legislation, etc.) as well as intensified technical research and development to reduce the costs of renewable energy systems itself. The Members of the European Union agreed in July 2020 on contributing to the goals of the European Green Deal and that 30% of the overall 1.8 trillion € budget will be assigned to climate related investments.

In 2017, the transport sector accounted for 28% of total final energy consumption in Europe. This sector is followed by the residential sector with (24 %), the industrial sector with 24% and others like commercial and public services with equally 24%. The industrial sector itself consumes ca. 66% of its energy in the form of heat. Of this heat consumption only a fraction off ca. 0.1% is supplied by solar thermal systems. The highest fraction of the heat consumption is covered by burning natural gas, followed by coal and oil products (International Energy Agency, 2017).

The market of solar thermal energy in the industry is still untapped, indicating the great and wide potential of possible applications. Solar thermal solutions may be a key factor realizing the European "Green Deal".

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The distribution of the Global Horizontal Irradiance (GHI) within Europe indicates that especially for countries in the south of Europe solar thermal technologies are showing a potentially high energy yield. In addition to the solar resource, solar thermal energy is of special interest to the industry, if prices for fossil fuels are high (as it is the case for instance in Cyprus). The dependence on the import of petroleum products can be observed in the majority of European countries. A typical imported fuel used by the industry is Light Fuel Oil (LFO). This is also the fuel used by KEAN to fire the conventional steam boiler.

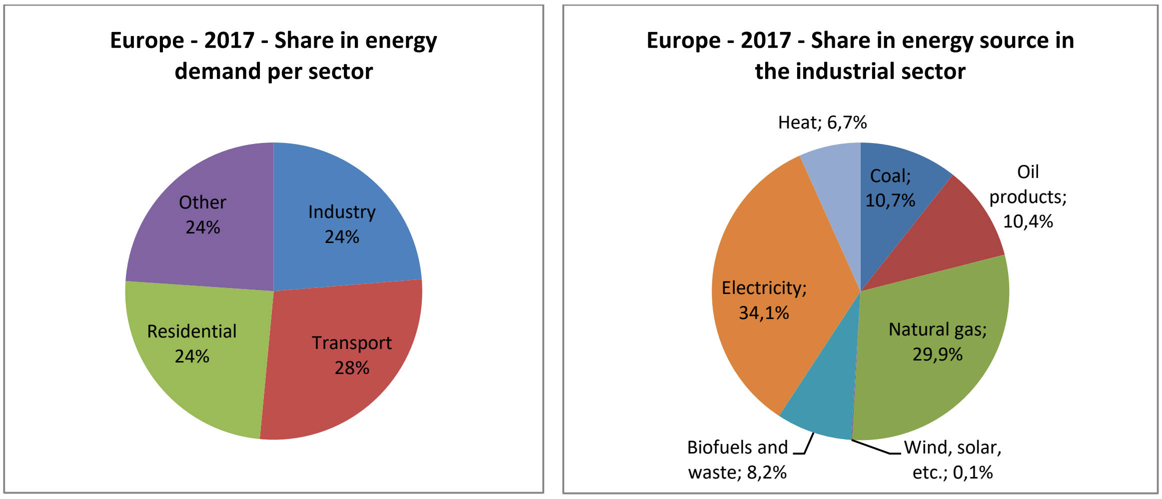

Fig. 1: Share in Europe's total energy demand in 2017 indicating the energy sources of the industrial sector (IEA, 2017)

Research and development on solar thermal systems is carried out for many years. Allot of studies and projects are aiming to reduce the levelized cost of heat, for instance of the steam generated for an industrial consumer. The result of lower steam cost of a solar thermal system is resulting in a reduced Return on Invest (RoI). The development presented in this paper is an integral solar thermal system consisting of a combination of two solar technologies. The aim of this concept is to apply both systems at the optimal operation point and therefore reduce the total investment cost by maintaining at the same time the energy yield compared to a single system. In order to make solar thermal technologies more attractive to the industry, Thermal Energy Storage solutions are further developed as well. The application of a TES may have an additional positive impact on the RoI as dumping of solar thermal energy can be reduced and energy can be made available when it is required by the consumer, thus decoupled from the availability of sunshine.

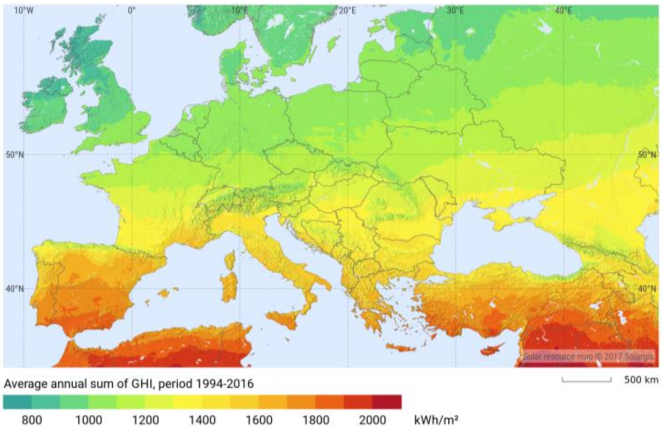

Fig. 2: Global Horizontal Irradiation in Europe (Average of 1994-2016) (Solar resource map © 2019 Solargis, 2020)

The characteristics of the two combined solar technologies are explained in this paper. The efficiency under different operation temperatures is shown for both technologies. The TES chosen in each of the systems is described and the key parameters are given. In order to combine the two technologies and make use of their optimum operational range, the consumer side has to be considered to adapt the technologies to the requirements of the present process. To understand the heat supplying process of the application certain measurements are executed to identify the consumption and operation pattern. In addition, the optimal integration point of the consumer has to be identified. This pre-design procedure and its results are described in this paper.

The realized system and the parameters are given in this paper. It is shown how a CPC feed water heating system is sized. A layout of the entire system displaying the conventional and the solar thermal energy sources is given.

The reduction of the cost of generated steam by means of solar thermal power is the content of the presented work. Therefore, an economic analysis is calculating the benefit of combining the two solar thermal technologies. The investment cost for the low temperature (CPC) and the high temperature (PTC) solar thermal systems are included, as well as the maintenance and operational costs. The specific costs of the different TES are built-in the economic model as well.

Fig. 3: A picture showing both technologies at KEAN (CPC foreground and PTC in the background) ©protarget AG

2. Methodology to integrate the technologies

The purpose of the solar thermal systems is to generate process heat and save conventional energy resources (in this case Light Fuel Oil consumed by a conventional steam boiler). After examination of the conventional steam generation system of the industrial consumer the most suitable integration point has been identified.

2.1 Measurement campaign

During the pre-design study an ultrasonic water flow meter has been installed to exactly determine the amount and time of the feed water is supplied into the conventional steam boiler. By the results of the measurement and the identification of the operation pattern throughout the day, it was found that the low temperature collectors can be used to heat up the feed water of the conventional steam generator. Nevertheless, the operation pattern showed that a TES is required based on the amount of water required during times with no sunshine available (basically early in the morning during the beginning of the production).

One pattern of the feed water supply the measurements underlined is that in the beginning of the production at 4:00AM local time a high amount of feed water is pumped into the steam boiler. After examining the level gauge of the steam boiler, it was found that during the night the water in the boiler cools down to an extent resulting in a substantially reduced volume of the water in the steam boiler. The feed water pump of the steam boiler is triggered by the water level switch of the steam boiler and as the steam boiler is switched on in the morning a high amount of water at low temperatures (ambient temperatures) is pumped into the boiler till the set water level is reached. This effect causes the steam boiler to heat up very slowly in the morning as a huge amount of cold water is within the steam boiler. The measurement values shown in Figure 4 are reflecting an average day in September. Especially in the time of the juice extraction between February and April the amount of required feed water i.e. steam is much higher.

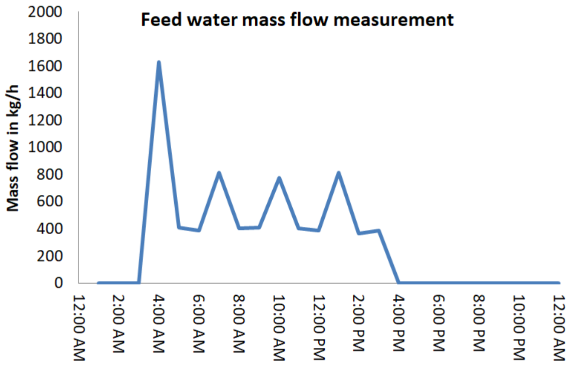

Fig. 4: Graph indicating the mass flow of the feed water into the existing steam boiler

2.2 Energy integration

Under energy integration it is understood how a CPC solar field could contribute to the steam generation of an industrial process heat consumer. Considering the Enthalpy-Temperature (h-T) correlation of water at the process pressure of 10barg the steam generating process can be explained. The enthalpy of the feed water at KEAN is in average about 25°C (depending on the amount of condensate return it can go up to ca. 40°C). Condensate return can be taken into account when the system is already in operation, but is not being observed during start-up or after cooldown phases. The enthalpy of water at 25°C is 104.8kJ/kg and it is 398.0kJ/kg at 95°C. The resulting difference when heating water from 25°C to 95°C is 293.2kJ/kg. Converting water from 25°C directly into steam at 10barg (184°C) takes 2675.8kJ/kg. The share of heating the water to 95°C is about 11% of the total energy required for this process. This energy can be delivered by the CPC system and the share is independent on the amount of power actually required. This calculation with the exemplary process parameters for the KEAN factory shows that the CPC system can be seized individually from a PTC field.

2.3 Technical integration

As described under the Deliverable B2: Integration Guideline from the IEA SHC Task 49 (Muster, 2015) the integration of solar thermal energy can be divided between the integration on supply level and the integration on process level. The CPC system is applied on the supply level by heating the feed water. The PTC system integration point is for the KEAN case on the process level. The PTC system has been built close to the tetra pack line of the KEAN factory and the load profile of the tetra pack line is assuring a very complete usage of the PTC generated steam. In the schematic layout in Fig. 5 the integration of both systems at KEAN can be seen. The higher the rated power of the PTC plant in comparison to the total amount of required power of the plant the more advantageous it is to integrate on the supply level to allow for more flexibility. Feed water is heated only for the conventional steam boiler in the KEAN.

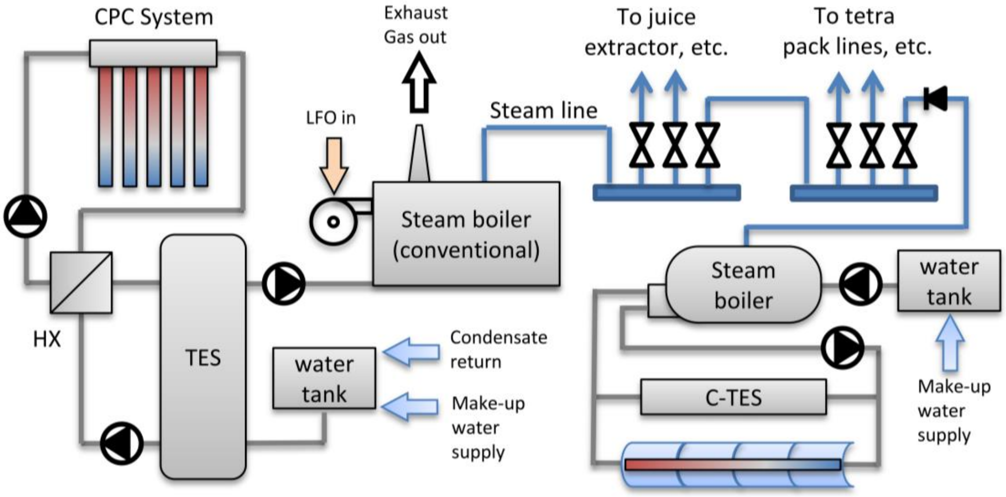

Fig. 5: Schematic layout of the combined solar system and conventional boiler

3. System description

The company protarget AG has developed and installed a system of a combination of a PTC and a CPC solar field to lower the overall cost. It is suitable for any industrial steam consumer, but in this case providing solar thermal generated steam for an orange juice factory. Therefore, the application can be categorized into the following industry sector definitions C10.3 - Processing and preserving of fruit and vegetables or alternatively C11 – Manufacture of beverages. Worldwide only 39 solar systems can be counted falling into these two sectors (SHIP, 2020). By means of this number it can be seen that the introduction of solar thermal energies into this industry sector has just begun and further effort is required to provide this huge sector with the existing solutions. The individual solar thermal systems are described in this section giving the key parameters.

Fig. 6: Aerial view of the CPC and PTC combined system, ©protarget AG

3.1 PTC system

The Parabolic Trough Collector system at KEAN involves a two-row parabolic trough collector loop. The aperture of the collector is of about 3 metres and the row length is of ca. 48m. The gross area of the PTC is in total about 283m². A two-module Concrete Thermal Energy Storage (C-TES) and a fairly standard kettle-type steam boiler for steam generation are the other main components of the system. The parts are shown and denominated in Fig. 5. The two-module C-TES and the steam boiler including the oil handling unit like pumps and expansion vessels are placed within shipping containers (as it may be seen in the aerial view in Fig. 6). The so-called control container including the steam boiler and the system technology has been fully manufactured in the workshop of the protarget AG in Cologne and is designed for a simple connection without mayor interventions on site. Considering Fig. 6 the size and localization of the parabolic trough collector system at the KEAN factory can be estimated as well. The Heat Transfer Fluid for this system is of HELISOL® XA silicone oil from WACKER Chemie AG. This fluid can be heated up to 425°C and is fairly new on the market. At the KEAN factory, steam is required early in the morning when the production starts, in this case the CTES is discharged and the stored energy is used to produce steam. The C-TES is partly charged in the afternoons and fully charged on weekends when the factory is closed. This operation mode allows the PTC system to produce steam at about 11barg/188°C (slightly above the 10barg of the conventional steam boiler) early in the morning when no sunshine is available. The rated capacity of the C-TES is about 640kWh. Further information about the PTC plant can be found in various publications (Sattler, 2018/2019).

3.2 CPC system

The CPC system is installed on a roof with east-west orientation and an elevation of about 17.2°. The solar field is therefore split into two independent operating circuits with separate pumps. The indirect heated thermocline storage of a capacity of about 400kWh is providing energy in the early morning at the start of the production and at times with bad weather conditions. The employed CPC collector consists of 18 vacuum tubes with a highly selective absorber layer and is of a gross area of 3.41m². 66 Collectors have been installed forming a solar field gross area of 225m². As a working fluid demineralized water is used without additives like glycol.

The split in an east and west oriented solar field as shown in Fig. 6 provides an even solar thermal energy distribution throughout the day. The CPC system is operated at a temperature at the exit of the solar field of about 100°C. This provides that the TES is charged with water up to 95°C. In this order, the at atmospheric pressure operated TES stores the energy at the maximum possible temperature avoiding the generation of steam within the storage itself.

3.3 Operation characteristics

In the following section the operating behaviour of both technologies contributing to the same energy consumer are shown and explained. In Fig. 7 the feed water heating of the CPC System is shown and at the same time the steam generation from the PTC system. This figure is given to demonstrate the feasibility of the concept of having two solar technologies within the same process heat network, where "SF" stands for solar field.

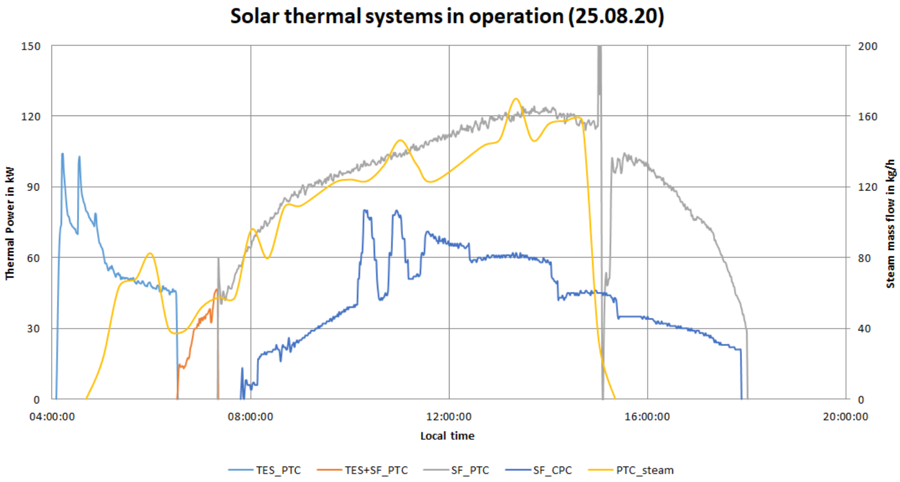

Fig. 7: Operational curves for PTC and CPC

It has been observed during operation that the conventional steam boiler is quickly (about 1.5 hours sooner than without a CPC pre heater) heated up and at the desired temperature, thus ready to produce steam. This effect is explained by the introduction of the hot water from the feed water thermocline TES in the morning into the steam boiler instead of cold water. Considering the water volume required in the boiler in the morning this makes a significant difference of the temperature of the water in the steam boiler at the beginning of the start-up procedure. The plant still begins the start-up phase at 4am, but the production of the beverages can be ramped up earlier as steam is available earlier. This results in theory in a higher production volume per day and therefore is a benefit in terms of efficiency of the production process of the beverages itself.

3.4 Efficiency comparison

The thermal efficiency curves of the two applied technologies are shown in Fig. 8. The thermal efficiency decreases with an increasing mean temperature in the collector. The given Curves are based on a Direct Normal Irradiance (DNI) of 850W/m² and a Diffuse Horizontal Irradiance (DHI) of 150W/m². The efficiency decrease of the PTC at higher temperatures is smaller than the pronounced efficiency drop of the CPC.

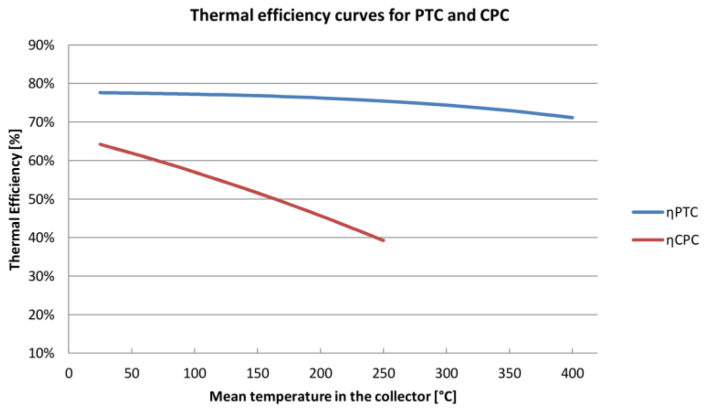

Fig. 8: Thermal efficiency curves for PTC and CPC

4. Economic analysis and cost reduction potential

To expose the cost reduction potential of applying both presented technologies in one system a holistic approach is chosen. This means, besides the specific investment cost of both of the technologies the specific investment of the Thermal Energy Storage and the specific maintenance and operation costs have to be considered. A CPC System can be mounted on a roof as executed at the presented system; therefore, land cost can be saved and the system can be installed very close to the conventional steam boiler to minimize piping losses (and cost). Nevertheless, land costs are not considered in this study as the variance on possible sites is too high to pic a representative value. A CPC solar field may also be installed on the ground under certain conditions and therefore also create land cost as a PTC system. In order to combine both technologies, the adequate solar field size has to be found for both. The approach followed in this paper is based on the calculations shown in Chapter 2 “Methodology to integrate the technologies” under Subchapter 2.2 “Energy integration”. The concept basically applies that the feed water heating demand of up to 95°C is about 11% of the total energy demand to produce steam to the required parameters. Therefore, a simple, but yet meaningful economic analysis is to compare a solar field with 10 Solar Collector Assemblies (SCA) of a PTC with a solar field of 9 SCA of a PTC and a CPC solar field with 120 collectors. This system design is set for the benchmark calculation to demonstrate the cost reduction potential. In the graph shown in Fig. 9 the system design philosophy is visualized. In can be seen that both system arrangements are resulting in a similar amount of energy generated, namely 3144 MWh/a for the PTC system only and 3200 MWh/a for the combined system. The question answered in this paper is which arrangement generates energy to better overall costs.

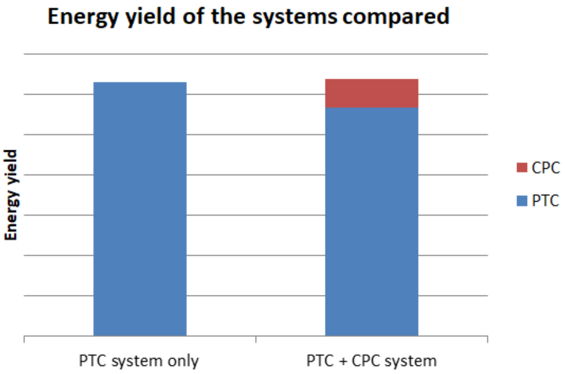

Fig. 9: Energy yield of the systems compared

The specific investment cost of a low temperature thermocline storage is calculated with 10,000€/MWh capacity. In comparison, the specific cost of storing energy at temperature levels up to 425°C in a C-TES are located at 50,000€/MWh capacity for the defined storage size. The sizing of the two TES is done similarly then the sizing of the solar field design philosophy resulting in a C-TES capacity of 4.3MWh and a 0.55MWh capacity for the feed water thermocline TES. Accordingly, the storage capacity for the PTC only system is 4.85MWh (C-TES). The total investment cost of both systems is very similar, namely 1.455.740€ for the purely PTC system and 1.464.216€ for the combined system. The specific operation and maintenance cost (€/kWh per annum) of a CPC system are at 0.001€/kWh$_{th}$ and therefore around a third of the specific cost of a PTC system with 0.0035€/kWh$_{th}$.

The economic analysis is based on an interest rate of 5% and a lifetime of both technologies of 25years. As a reference site to determine the solar resource and environmental conditions, the location of the present combined system at Limassol, Cyprus is defined.

4.1 Results

The cost for the thermal energy generated by the combined system of the CPC and PTC is about 0.0242€/kWh$_{th}$. For the PTC only system the cost of the generated thermal energy is 0.0248€/kWh$_{th}$. Considering the given steam parameter at the defined application the cost of steam is 18.00€/ton of steam (CPC and PTC) and 18.44€/ton of steam (PTC only). This analysis shows that the energy cost of a PTC system only for the specified benchmark is about 2.5% higher than a combined system of CPC and PTC.

4.2 Discussion

A CPC system includes lower specific cost for the collector, the TES and the maintenance and operation. Nevertheless, a CPC collector is less efficient in terms of optical and thermal efficiency and harvests less energy throughout the day as it is a non-tracking collector. On the other side a CPC collector is able to make use of DHI and converts it into thermal energy. With the economic calculation it was found that considering the current status with the given efficiencies, costs and properties of both technologies a combination is sensible and demonstrates a cost reduction. The system arrangements both result in very similar investment cost with 0.5% more investment cost for the combined system. The combined system produces about 1.7% more energy and shows a noticeable reduction in overall maintenance costs of 7.1%.

The presented analysis is limited by the weather conditions on the specific site. For other sites with different values for the DNI, DHI and ambient temperature, the cost difference of the systems may shape different. Especially a higher share in DHI of the GHI as found in India for instance may be even more advantageous for the combined system. For countries with lower ambient temperature throughout the year the thermal yield of the CPC would be reduced and impacting the cost reduction potential. For the applied system size the specific investment cost for a CPC are already settled down to a degree where the reduction from the economy of scale is minor. On the other hand, the difference of 9 or 10 SCA of a PTC in terms of the specific investment is considerable. For a system with increased capacity for instance with 36 SCA of PTC + 480 CPC and 40 SCA of PTC the cost reduction becomes less due to the noticeable drop of the specific investment cost of the PTC.

5. Conclusion

Under the specified conditions the combination of the CPC and PTC technology results in a reduced cost of the generated thermal energy. With the operational combined system at the KEAN juice factory the feasibility of integrating both technologies into one industrial heat consumer is demonstrated and verified. Both technologies are operating with a Thermal Energy Storage to supply the energy when requested by the consumer. The presented development makes a solar process heat system economically more attractive and may contribute to cover a higher share of the industrial heat demand by solar thermal power than currently observed.

6. Acknowledgments

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