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Industrial steam supplied by a hybrid solar thermal-photovoltaic system

Summary

Solar technologies are expected to have a key role in the decarbonization of industrial heat. Hybrid systems exploit the synergy between photovoltaics and concentrating solar thermal, while leveraging the advantages of each solar technology. This study presents a hybrid solar thermal-photovoltaic system that supplies heat to dairy thermal processes, in the form of saturated steam at 175 °C. A field of parabolic trough collectors is connected sequentially with a PV-fed electric heater. The dairy industry currently satisfies its thermal load with a fossil fuel (light fuel oil) and a sustainable fuel (in-house generated biogas). The incorporation of the solar hybrid system decreases the consumption of both fuels, although - aligned with the decarbonization scope - the reduction is higher for the fossil fuel. The solar contribution is based on 81.6% solar thermal and 18.4% photovoltaic. A scalability study investigates the effect of the solar field size on the reduction of each fuel and the curtailed heat. The study employs a transient simulation model, developed using the Modelica language.

Keywords: heat decarbonization, industrial heat, hybrid solar, concentrating solar
Field of application for the findings: Industrial heat, Concentrating Solar Heat
Addressed audience: researchers, engineers, industrial stakeholders

1. Introduction

Industrial heat represents approximately 25% of the global energy consumption. However, it remains heavily dependent on fossil fuel combustion, resulting in the associated greenhouse gas emissions. This environmental impact is also reflected in the gradual implementation of carbon taxes, an additional economic burden on the inherent volatility of fossil fuels cost. Beyond financial and environmental motives, industrial heat decarbonization can provide wider macroscopic benefits such as energy security and fuel import reduction.

The two solar technologies – solar thermal and photovoltaic – can contribute to the industrial heat decarbonization. Concentrating Solar Thermal (CST) can produce heat in temperature levels that are sufficient for a wide spectrum of industrial applications. Photovoltaics (PV) can also provide heat through an electric heater (e-heater). Both technologies have distinct advantages. CST has higher efficiency with respect to the incident solar radiation, and it can exhibit higher stability through the incorporation of thermal storage. PV has simpler operation and can be mounted on lighter roof structures that abound in industrial contexts, as well as, the electric heater can be utilized for beneficial interaction with the electrical grid. The ProjectName* proposes a hybrid system that allows to benefit from the synergy and the individual characteristics of both solar technologies. This work focuses on one integration concept of this hybridization in a dairy industry that consumes heat in the form of saturated steam at 175 °C. Based on annual transient simulations, the study quantifies the monthly and annual contribution of the CST and PV, the reduction in fuels consumption and the effect of system scalability.

2. Case study and integration concept

The study focuses on IndustryName* dairy industry located in IndustryLocation*, which utilizes saturated steam at 175 °C to satisfy the thermal needs of its dairy processes. The thermal load is satisfied by two boilers; Wanson boiler consumes exclusively Light Fuel Oil (LFO), while Bosch boiler switches between LFO and the in-house biogas, which is generated on-site by valorizing a byproduct of cheese production. Figures 1 and 2 show a schematic diagram and a typical daily thermal profile of the load.

Figure 3 illustrates the integration concept under consideration. The CST field and the PV-fed e-heater are positioned sequentially. The latter is connected to the PV field and the grid. The solar loop is coupled to the

*Information omitted for the blind review

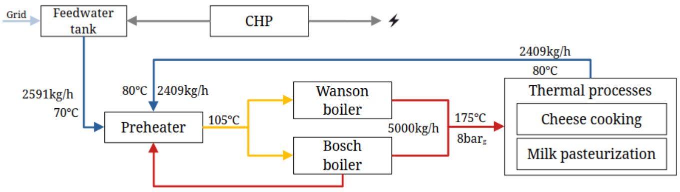

Fig. 1: Schematic diagram

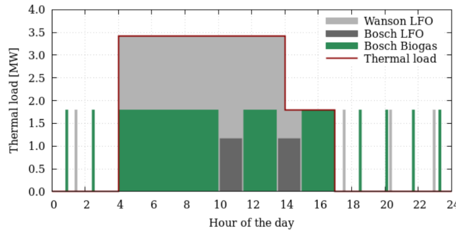

Fig. 2: Typical daily thermal profile and fuel breakdown

load loop through two heat exchangers, a preheater and a steam generator. The produced heat is converted to steam that is delivered to the dairy thermal processes, operating in parallel to the existing boiler block. The three-way valve and the by-pass are included for the preheating mode and the regulation of $T_{\text{cst,in}}$. The mass flow rate is imposed – within the minimum and maximum constraints – in order to achieve the designated outlet temperature from CST field, $T_{\text{cst,out}} = 205\,°\text{C}$. The e-heater maintains $T_{\text{EH,out}}$ at 210 °C between 07:00 and 17:00. Heat storage is not considered, since (i) 97% of the solar production is within operating hours and 1-hour shift would resolve this temporal mismatch, (ii) the start-up heat consumption is not considerable since the boilers are kept overnight at stand-by (4 bar$_g$) to avoid condensation, and (iii) the thermal load is high enough to absorb all solar contribution (elaborated in the scalability study). Although without storage, certain thermal inertia is exhibited by the thermal mass of the e-heater.

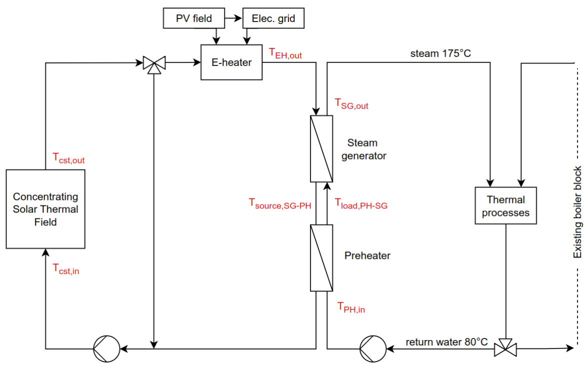

Fig. 3: Integration concept of the hybrid system

3. Computational model

The computational model is developed in-house, using the Modelica language within the OpenModelica environment. The model is transient and it is used for annual simulations. The CST field is modeled based on the ISO 9806 certificate of the parabolic solar trough collectors of SolarCompanyName*. The PV field is modelled based on a commercial monocrystalline module with temperature-dependent efficiency. The e-heater is modeled as a fully mixed cylindrical tank, equipped with an electric heater and considering heat losses. The biogas storage level is also modeled dynamically, in order to detect when it is full (newly generated biogas is rejected) or empty (dual-fuel boiler switches from biogas to LFO, and the inverse once the level recovers). The model takes into account generation and consumption rates, the latter being affected by the solar contribution.

4. Results discussion

The total annual consumption of the current configuration is 12.4 GWh$_{\text{thermal}}$ that are covered 54.7% by LFO and 45.3% by the in-house biogas. The base scenario involves the incorporation of a relatively small CST field, comprised by 3 subfields with 24 parabolic trough collectors each, with total collector surface area of 435 m^2. The annual required electricity of the hybrid system is provided by a PV field of 199 m^2. The hybrid system supplies 3.3% of the load, while in this case the LFO and the biogas provide 51.9% and 44.8% respectively. Interestingly, the reduction is not uniform between the two fuels, being 5.1% for the LFO and 1.1% for the

*Information omitted for the blind review biogas. This is a desirable effect both from economic and environmental perspectives. The solar contribution decreases the biogas consumption and delays its storage depletion, resulting in less intervals of switching to LFO. It should be noted that the CST field supplies 333.1 MWh to the load, while 7.3 MWh are produced outside the operating hours (after 17:00 in working days) and 60.2 MWh on Sundays when no operation takes place. The PV-fed e-heater supplies 75.3 MWh to the thermal load, while its total electricity consumption is 77.9 MWh, as a result of the heater's efficiency and thermal losses.

As shown in Figure 4, the share of CST and PV-fed e-heater are 81.6% and 18.4%, respectively. A steady-state calculation would yield higher CST share, however, when the solar radiation is not sufficient to achieve the target outlet temperature even with the lowest acceptable flow rate, the electric consumption is higher. This is reflected also in the monthly share of CST shown in Figure 5, which varies between 69.3% in December to 84% in June. Figure 5 also reveals the considerable non-uniformity of the solar contribution throughout the year, ranging from 7 MWh in December to 84 MWh in June.

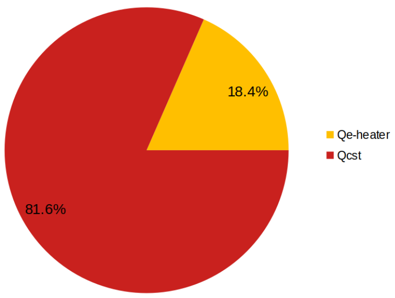

Fig. 4: Annual share of each technology

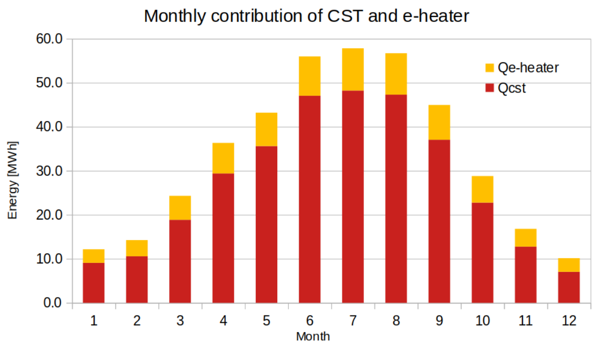

Fig. 5: Monthly energy provided and share of each technology

In the results presented above, the CST field pertains to 3 subfields comprised by 24 parabolic trough collectors. Simulations of multiples of this CST field were performed, between 3 and 30 subfields. Figure 6 illustrates the contribution of the hybrid system, the biogas and the LFO. Moreover, it presents the curtailed heat produced by the CST field during operating hours (additionally to heat curtailed outside operating hours and on Sundays), expressed as a percentage of the useful CST heat production. Up to 18 subfields (6x of the base case of 3 subfields), the system contribution is directly proportional to the multiple of the field, since the entire solar generation is always lower than the load and no excess solar heat is rejected. As illustrated in the graph, curtailed CST heat appears at 1.2% for 21 subfields and increases up to 7.4% for 30 subfields. Indicatively, at 3 subfields the solar share is 3.3%, at 18 subfields it is 19.8%, whereas at 30 subfields it is 30.9%. Moreover, the prioritization of biogas consumption results in a higher decrease in the LFO consumption and lower decrease in biogas. This effect is desirable, since LFO is a fossil fuel which is purchased, whereas the biogas is a sustainable fuel, produced on-site valorizing a byproduct of cheese production.

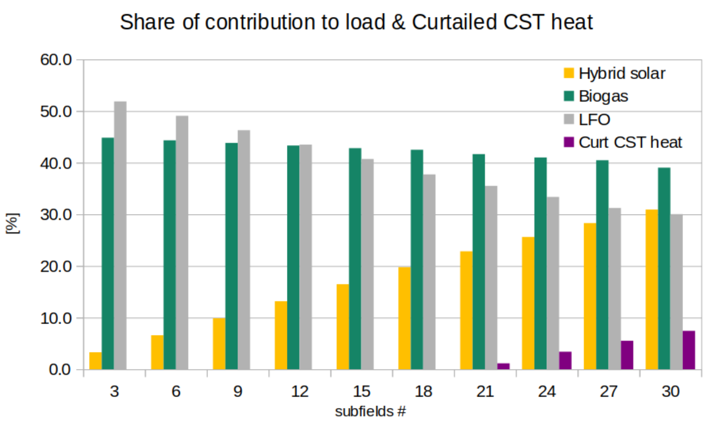

Fig. 6: Share of contribution to load and curtailed CST heat for different scales of the CST solar field