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Development of an integrated solar-fossil powered steam generation system for industrial applications

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Abstract

To this day solar technologies do not cover a significant share of the industrial steam demand, despite the fact that concentrating solar collectors are market available, are well capable of reaching the required operating temperatures, and are able to generate steam directly. In addition to the low cost of fossil fuels and emission permits, other reasons for the slow market penetration of solar thermal technologies for industrial process heat applications are the lack of awareness within industry that such technologies exist, along with the lack of standard package solutions. Currently, every solar process heat system must be custom tailored and integrated with the fossil fuel fired heat source of the system. This results in considerable costs for engineering services and approval. Therefore Viessmann, a leading provider of industrial steam boilers, and Industrial Solar, a renowned manufacturer of linear Fresnel collectors and turnkey provider of solar process heat systems, have joined forces to develop a standardized solar-fossil fuel powered steam generation system for industrial applications. The two industrial partners are being supported by the German Aerospace Center, DLR, which has more than 20 years of research experience with concentrating solar thermal technologies and direct steam generation.
Our conference paper provides insight into the current status of the project and the activities planned.
This development is funded by the Federal Environment Ministry under the project title "SolSteam" and will form the basis for the development of a commercially available product.

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1. Introduction

In its 6th Energy Research Programme, the Federal Government of Germany plans a very ambitious reduction in primary energy consumption: 60% of the country's energy consumption should be delivered in the form of renewable energy by 2050. This can only be achieved if the industrial process heat demand can be supplied partly by renewable energies. Viessmann, Industrial Solar, and DLR have joined forces to develop a solution that will enable industry to contribute its share to reach this goal by 2050.

The Viessmann Group is one of the world's leading manufacturers of heating and renewable energy systems. Viessmann employs over 9,400 employees worldwide and has an annual turnover of approximately 1.7 billion Euros. As a market leader in industrial steam boilers, and with their strong commitment to make steam generation more sustainable, Viessmann is an ideal partner for this project.

Industrial Solar (IS) was founded in 2008 in the environment of the Fraunhofer Institute for Solar Energy Systems in Freiburg. IS manufactures linear concentrating Fresnel collectors and provides turn-key installations of solar process heat systems for industrial applications. Back in 2009 they realized their first direct steam generation system and have continued to develop this technology since then.

Since the late 1970's, when the IEA Small Solar Power Plant Project laid the foundations for modern solar thermal power plant technology, DLR has contributed greatly to the technological progress in this field. Basic research in direct steam generation started in the 1990's and led to its first commercial application in solar thermal power plants in Spain and Thailand [1] as well as pilot installations of process steam in Germany and Thailand [2],[3].

1.1. Motivation

Industrial process steam as a market segment has been opened up poorly by renewable energies so far. Concentrating solar collectors can efficiently utilize solar energy at the high temperature levels required for such applications. Of great advantage with respect to investment cost and operation behavior, is the direct steam generation (DSG) inside the solar collector system. The ideal combination of a solar steam generator with a fossil fuel fired back-up ensures a safe and steady supply of steam for any production process, independent of weather conditions or daylight hours.

A main obstacle for the dissemination of solar process steam systems is the disproportionally high cost of demanding engineering services, permits for compliance with industrial regulations, and system certification, when each system is individually tailored to suit a specific industrial process. This problem is addressed by developing an integrated, modular system.

The project aims to answer the basic technical questions of combining a direct steam generating solar collector with a fossil fuel fired steam generator, thereby laying the foundation for the development of a solar-fossil fuel hybrid system. The commercial availability of such a system is the precondition for swift entry of renewable energy into the industrial process heat market. This solution combines cost-efficiency with security of steam supply.

The results of this project will lead directly to the development of a marketable system. Additionally, new insights into further optimization of the technology are expected, in addition to the identification of new scientific questions. In 2 to 4 years, simulation tools will be optimized so that manufacturers will be able to plan cost effective and accurate process heat systems with the integration of direct steam generating solar collectors.

1.2. Market potential

A great share of the energy consumption worldwide is used for production processes. In European countries, 28% of the total energy consumption is used for industrial purposes [4], while roughly 2/3 of this is used for process heat. As reported by the ecoheatcool study [5], 57% of process heat is demanded at temperatures below 400°C, which solar collectors are technically capable of providing. Figure 1 depicts the distribution in temperature ranges needed within a variety of industry sectors in Europe. Linear concentrating collectors can easily reach up to 400°C though, while non-concentrating collectors can cover the demand at low temperatures (<100 °C). Therefore, solar thermal systems can play a major role in covering the industrial process heat demand. Process steam, which is what the SolSteam project focuses on, is only used in the range between about 100°C and 250°C. The heat demand in this range is still significant with 3200 PJ per year.

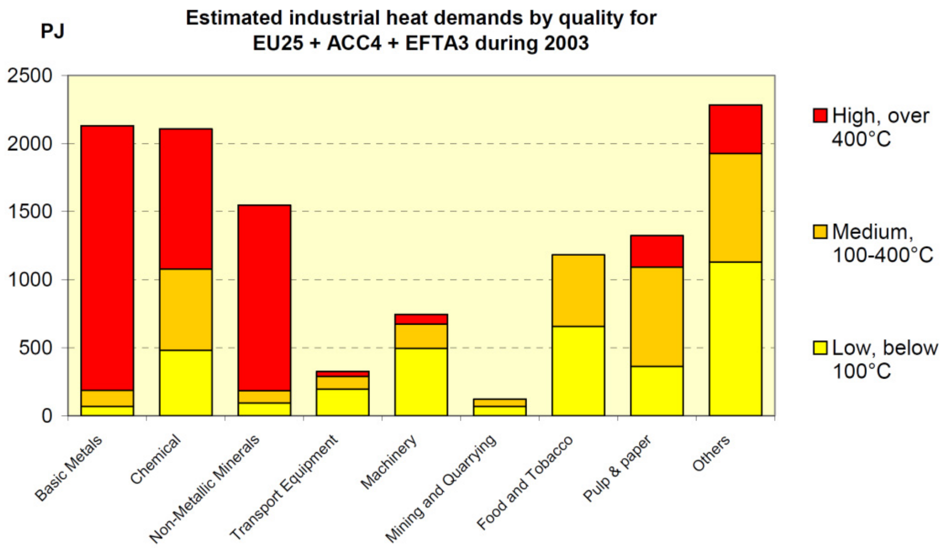

Figure 1: Industrial heat demands estimated by temperature and by manufacturing sector for 32 European countries [5]

2. The SolSteam Project

2.1. Project aims

The aim of this project is a thorough analysis of all questions that arise when a direct steam generation concentrating solar collector is combined with a fossil fuel fired high-pressure steam generator. The results of this work will form the basis for developing a standardized solar-fossil fuel driven steam generation system for industrial applications. This will result in rapid market expansion of renewable energy integration in industrial process heat systems while still ensuring the security of steam supply at the highest possible cost efficiency.

2.2. Time schedule

The project officially started in August 2013 and has a duration of about 3 and a half years, ending in 2016. After identifying market requirements a concept for the first pilot system will be developed. This pilot system will then be realized with an industrial customer in 2014. Following a monitoring period, the design of the system will be optimized and used as a basis for a standard package hybrid system.

2.3. Components

The two main components of the proposed hybrid system are a steam boiler and a linear concentrating Fresnel collector.

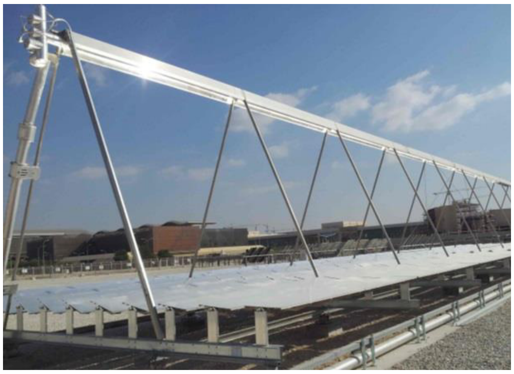
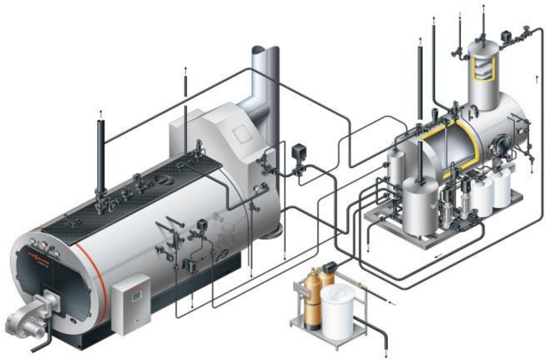

Figure 2: (a) Industrial Solar Fresnel collector; (b) Viessmann steam boiler with peripheral components.

2.3.1. Steam boiler

The horizontal return tubular boiler is one of the most commonly used steam generation boilers in the world. The heating in this type of boiler takes place inside the flame tube and flue gas pipes. Within the flame tube and the subsequent flue gas pipes, flue gases formed during combustion are led through a series of changes in direction within reversing chambers along the cylindrical axis of the outer shell.

Conventional systems for steam generation feed supply water to the boiler via thermal water treatment and a pumping station (Figure 2b). The heating and vaporization of the feed water takes place in the outer shell of the shell boiler. The approach of this research is to use a shell boiler for its traditional purpose of steam generation, in addition to replacing the steam drum of the solar collector and acting as a volume reservoir for the feed water supply to the collector. Thus, thermal water treatment for the entire system will be centralized. Operating such a hybrid system requires a complex control system.

The complex control system is a technical challenge. It must control the boiler water level with no detectable measure of the precise collector output quality. Furthermore, the boiler firing activation controls are pressure dependent. The individual operating conditions of both steam producers will play a crucial role in the proposed commercial use. The primary criteria for commercial acceptance from the consumer are fluctuations in steam demand, security and quality of steam, of course the cost relative to conventional systems.

Currently, the different operating conditions of the two systems – the boiler and the Fresnel collector – are being determined and evaluated. An initial understanding of the reactions of the two steam generators with different operating conditions is currently underway.

2.3.2. Fresnel collector

The Fresnel collector (Figure 2a) is a linear concentrating solar thermal collector for industrial process heat applications, used as a solar boiler. The collector is made up of 4.06 m long modules, defined by the length of the SCHOTT PTR70 vacuum absorber tube. Three modules are depicted in Figure 3 below. The total collector width is 7.5 m, while the aperture width – the cumulative width of the 11 primary mirror rows – is 5.5 m. The total height of the collector is around 4.5 m, depending on the type of ground and the foundations. The 11 mirror rows are tracking the sun in one axis, while the receiver, consisting of an absorber tube, secondary mirror and housing, remains fixed.

The efficiency of these collector systems depends on various factors, including geographic location, operating conditions (e.g. operating temperature and corresponding heat losses), field layout, and orientation of the collector field.

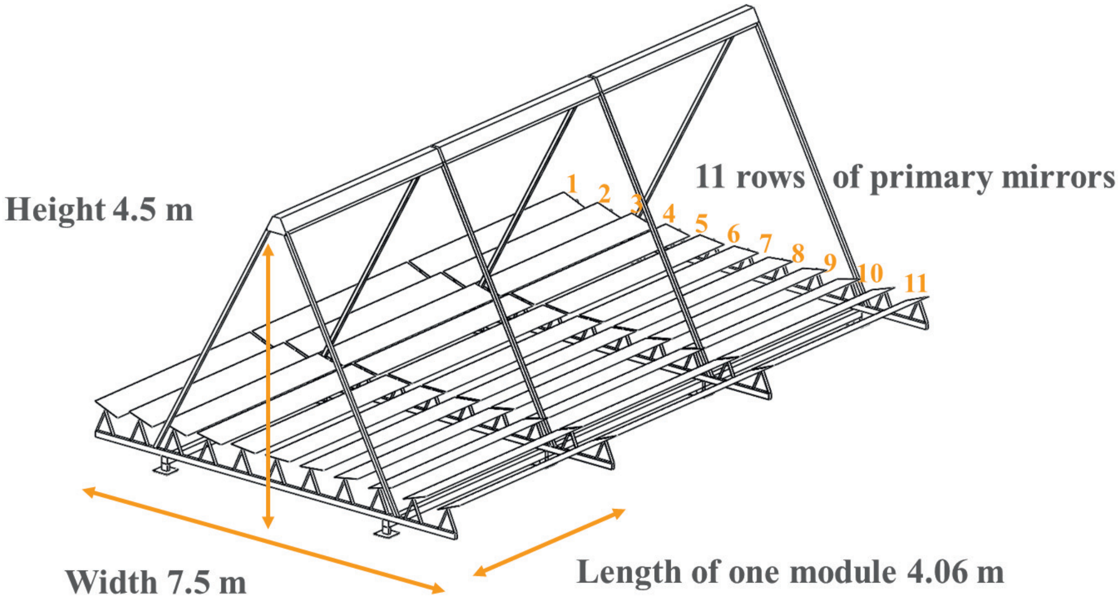

Figure 3: Three modules of the Industrial Solar Linear Fresnel Collector

The optical efficiency of the collector is dependent on the incidence angle of direct solar irradiation. By definition, η_0 is the optical efficiency at normal incidence (i.e. sun in zenith), and under ideal conditions (i.e. with 100% clean reflectors and receiver glass tube). For the collector described, it had been determined by IS via raytracing, being:

$\eta_0 = 0.635$

To calculate the efficiency for any other incidence angle, an incidence angle modifier (IAM) is defined as a correction factor to be multiplied with η_0. The transversal IAM is independent of the field design, whereas due to end losses along the fixed axis, the longitudinal IAM depends on the number of modules being combined in one string. Data on a representative IAM are shown in Figure 4.

Because of shading effects, the IAM is greater than 1.0 for some sun positions. Therefore the optical performance is not at its maximum when the sun is in zenith position. The maximum efficiency will be reached when the sun is at a transversal zenith angle of 5° and a longitudinal zenith angle of 0°.

$\eta_{max} = 0.663$ *(for sun at 5° transversal zenith angle, 0°longitudinal zenith angle)*

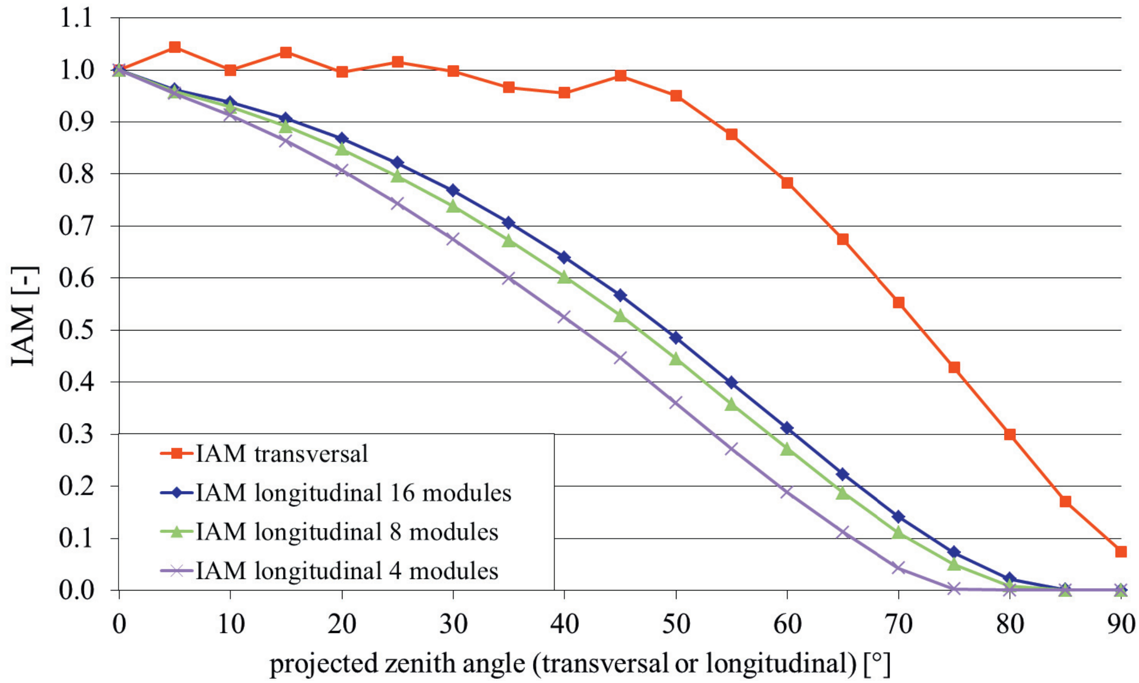

Figure 4: IAM of a string of 4/8/16 IS Fresnel collector modules (referred to DNI), as obtained from ray tracing simulations by Industrial Solar.

Due to the use of a vacuum absorber, thermal performance is almost independent of wind speed. Conductive losses as well as convective losses are very low and thermal losses are dominated by radiative losses.

The thermal losses per square meter of primary reflector can be approximated in the second order by:

$$\dot{q}_{loss} = u_0 A_{aperture} \Delta T + u_1 A_{aperture} \Delta T^2$$

with ΔT being the temperature difference between absorber and ambient conditions. According to receiver measurements reported by DLR [6] and based on the collector aperture area, the heat loss coefficients of the IS-LF11 are:

$$u_0 = 0$$

$$u1 = 0.00043\ W\,m^{-2}K^{-2}$$

2.4. Integration concepts

Many industry branches use saturated steam as a medium to transfer heat to various processes. Concentrating solar collectors can supply heat to these steam lines either indirectly or directly by the so-called Direct Steam Generation (DSG) process.

Since the DSG process has been regarded as difficult to control, installations thus far have mainly been designed as a closed circuit. This has, for example, been realized in a potato chip factory in Modesto, California, where a pressurized hot water circuit with a field of 5065 m² of Abengoa PT-1 collectors operates at a temperature of up to 250°C and pressure reaching 41 bar, heating a steam generator that produces 21 bar steam for the plant steam line [7].

To avoid investing in a steam generator and to reduce thermal capacities resulting in long start-up times, DSG processes have been developed, as demonstrated in the P3 project [3] depicted below (Figure 5). To produce saturated steam, liquid water enters the solar field, is heated up to the boiling point, and starts evaporating. To avoid overheating and mechanical stress on the absorbers the control system must ensure that a portion of liquid water remains in the flow to cool the absorbers, resulting in a water-steam mixture leaving the solar field. This design still requires a steam drum to fulfill two functions: separation of steam from liquid water and compensation of water content fluctuations in the solar field and piping. The water content changes when the solar field starts generating steam in the morning, since the steam displaces liquid water in most of the collector and in the piping between solar field and boiler.

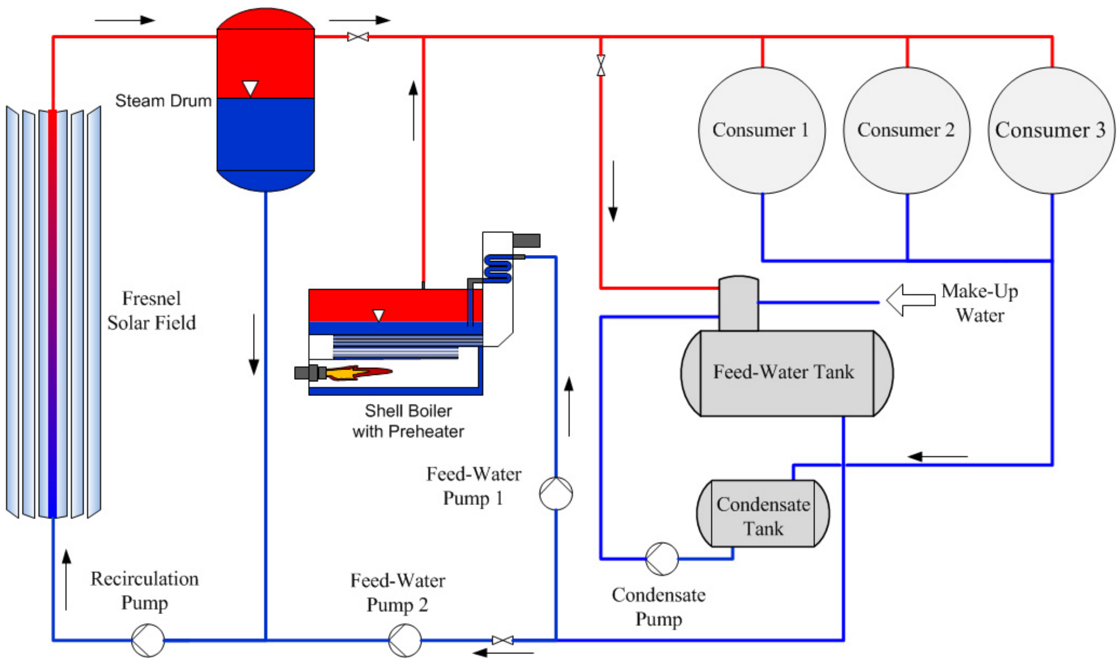

Figure 5: Proven layout for solar process heat integration in conventional steam circuit

Until now, the solar field has been regarded as a mostly independent system connected to the steam line. The SolSteam project now integrates the solar field and a fuel fired steam boiler, aiming to reduce the amount of components for the solar field integration, especially avoiding the need for a steam drum and a second feed-water pump (Figure 6). The solar field is connected to the conventional steam boiler and no longer directly to the steam piping. Water steam separation occurs inside the boiler, where also water content fluctuations in the solar field are compensated. Alternatively, a comparatively small separator may be placed before the boiler to avoid excessive turbulence inside of the boiler. This is still under consideration.

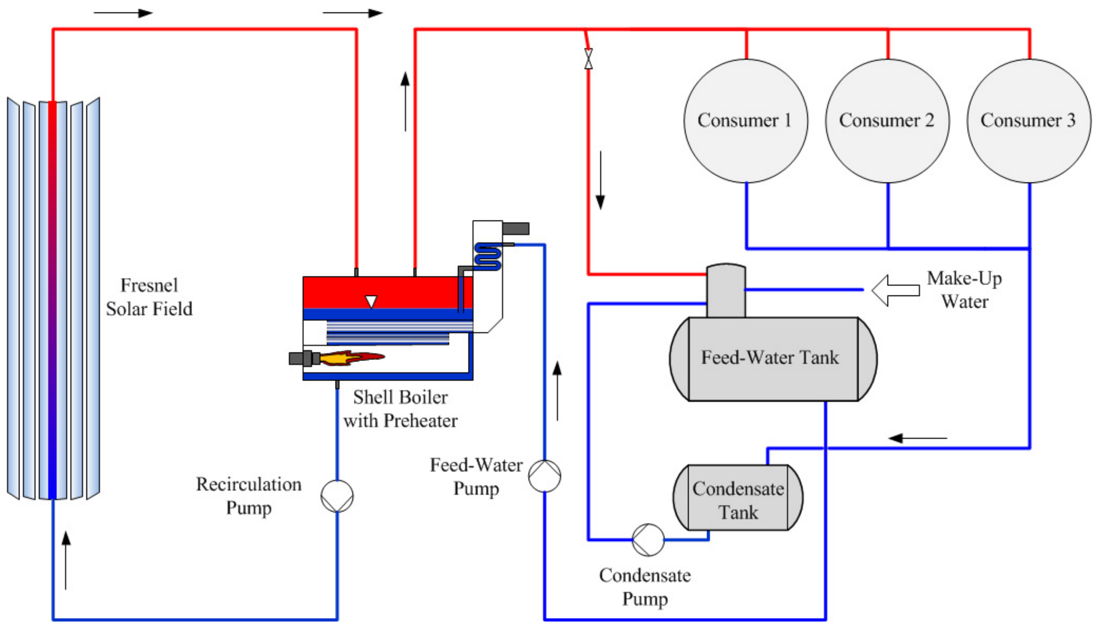

Figure 6: Design under investigation

For a solar field with a power that is small relative to the power of the steam boiler, the influence on the boiler will be small. In the best case, the fluctuations in the boiler induced by the solar field are on the same scale as consumer demand fluctuations. If larger solar shares and field sizes are considered, the current boiler design may need to be adapted for greater variations in the water level. Within SolSteam these aspects will be investigated.

2.5. Demonstration installation

Despite Germany's low levels of direct solar irradiation (used by concentrating solar collectors) in comparison to neighboring countries in the South, it would be preferable to install the demonstration system in Germany. Particularly because the close vicinity of the manufacturers is an advantage for a test facility, but also because of a subsidy program for solar process heat that supports installations with up to 50% of the investment costs. However, installation sites outside Germany are also under consideration.

2.6. Monitoring

Following commissioning of the demonstration facility, test measurements will begin. Steady-state operation and robust start-up and shut-down strategies will be tested. With load changes, the dynamic behaviour of the collector field and boiler will be examined so that operation and control strategies can be optimized. DLR will carry out an evaluation of the collector field quality.

The system behaviour under various conditions will be tested. This includes extreme temperatures, power failure, and failure of individual components, such as the tracking system or pump. Various interconnections, such as once-through in comparison with a partial recirculation will be tested.

From these tests and from the influence of the user's behaviour, optimised operation will be determined, as well as the extent of fuel savings.

3. Summary and Outlook

The cooperation of Viessmann, Industrial Solar, and DLR is developing a standardized packaged solar-fossil fuel steam generation system for industrial applications that is paving the way for a more sustainable production in sectors such as food, textile, pharmaceutical and many others. This system consists of two main components: a fresnel collector field and a shell boiler. Within the SolSteam project, integration of saturated steam supply for process heat consumers in a reliable, energy efficient and cost effective way is investigated. A variety of detailed integration options will be considered. In the second phase, a solar/fossil fuel plant will be erected, implementing the design of choice into a European plant to demonstrate the product.

Acknowledgements

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