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STATIONARY BOOSTER REFLECTORS FOR SOLAR THERMAL PROCESS HEAT GENERATION

Stefan Hess
Solar Thermal Energy Research Group
Stellenbosch University,
Private Bag X1, Matieland 7602, South Africa
E-mail: stefanhess@sun.ac.za

ABSTRACT

The performance of a flat-plate collector with glass-foil double cover (LBM 4 GF) is compared to that of the same collector with a one-sided external CPC booster reflector (RefleC-collector) for process heat generation up to 150 °C.

Efficiency curve measurements of both collector variants are reported. Reference is made to simulation results of the annual energy gain of both variants in Würzburg, Germany and Seville, Spain, at inlet temperatures of 40 °C and 120 °C. In these simulations, a novel collector simulation model accounting for the anisotropy of diffuse irradiance was used. Compared to state-of-the-art simulations the new model calculates significantly higher additional gains of the reflectors.

Both collector types were installed at a pilot plant in a Laundry in Marburg, Germany. Monitoring results of one reference year for the overall system performance as well as for the additional gains by the booster reflectors are given. It is shown that the stationary booster reflectors highly increase the efficient operation temperature range and also the annual energy gain of the double covered flat-plates.

Finally, a simplified economic assessment is carried out. Based on the additional gains by the boosters, the marginal costs for an investment into booster reflectors are assessed. It is estimated that the costs of installed RefleC boosters should be below ca. 30 EUR/m² in Würzburg and 55 EUR/m² in Seville for the technology to enter the solar process heat market.

NOMENCLATURE

Latin

A_{ap}	m²	Aperture area
c_1	$W/(m^2K)$	Heat loss coefficient of the first order
c_2	$W/(m^2K^2)$	Heat loss coefficient of the second order
c_{eff}	$J/(m^2K)$	Effective heat capacity of the collector
f_a	1/a	Annuity factor
f_d	-	Fraction of diffuse irradiance
G_t	W/m^2	Global irradiance (tilted plane)
G_{bt}	W/m^2	Beam irradiance (tilted plane)
G_{st}	W/m^2	Diffuse sky irradiance (tilted plane)
G_{rt}	W/m^2	Diffuse ground irradiance (tilted plane)
K_b	–	IAM for beam irradiance G_{bt}
K_{inv}	EUR/m²	Investment costs
K_m	EUR/(m²a)	Maintenance costs
K_{op}	EUR/kWh	Operational costs
K_r	–	IAM for diffuse irradiance from the ground G_{rt}
K_s	–	IAM for diffuse irradiance from the sky G_{st}
K_{sol}	EUR/kWh	Solar heat generation costs
p	–	Capital interest rate
$\dot{q}_{use}$	W/m^2	Thermal collector output (dynamic, with capacity)
Q_{sol}	kWh/(m²a)	Annual solar gains
t	s	Time
T	a	Technical service life of booster reflectors
T_a	K	Ambient temperature
T_f	K	Mean collector (field) fluid temperature
T_{in}	°C	Inlet temperature
T_{out}	°C	Outlet temperature

Greek

β	rad	Collector tilt or slope from horizontal
η_0	–	Conversion factor
θ_t	°	Transversal incidence angle

Abbreviations

CPC	Compound Parabolic Concentrator
Eq.	Equation
IAM	Incidence Angle Modifier
MTTS	Medium Temperature collector Test Stand

INTRODUCTION

Concentrators for solar thermal collectors can in general be divided into focusing and non-focusing types. Focusing ones, as Fresnel- or parabolic trough reflectors, have to track the sun. They can only use beam irradiance, but very high concentration ratios are possible, so that also very high outlet temperatures can be realized. Non-focusing concentrators have low concentration ratios and thus lower outlet temperatures than focusing ones. Their advantages are that they can convert both beam and diffuse irradiance into useful heat and that they are effective without tracking the sun.

The use of fixed external so called booster reflectors for stationary collector arrays has been investigated since the 1950s, when Tabor projected the incidence angle of beam irradiance into a vertical north-south plane and determined the necessary acceptance angles of stationary concentrators [1].

Perers and Karlsson presented a simplified model to calculate the additional energy gain of flat-plate collectors equipped with flat or Compound Parabolic Concentrator (CPC) booster reflectors [2]. Perers optimized different booster geometries for a flat-plate. In his study, the maximum additional yield per ground area was achieved by flat boosters; the maximum yield per receiver flat-plate area by a CPC [3].

Hess and Hanby presented a booster reflector consisting of three flat segments approximating a one-sided CPC reflector (cp. Figure 1). For central Germany, this so called RefleC-collector has a concentration ratio 1.26, an acceptance half-angle of 35° and an optimal slope of $\beta = 55°$ [4].

Figure 1: Low-concentrating, stationary RefleC-collector at the laundry Laguna in Marburg, Germany. The positive transversal incidence angle component θ_t onto the aperture is indicated [4].

The use of beam and diffuse irradiance by stationary collectors sloped at a tilt angle β is symbolized in Figure 2. Beam irradiance G_{bt} originates directly from the sun, ground reflected irradiance G_{rt} is assumed to be isotropic and sky diffuse irradiance G_{st} can either be treated isotropic (yellow) or as in reality anisotropic (blue).

The specific useful power output $\dot{q}_{use}$ of a solar thermal collector is expressed by eq. 1.

$$\dot{q}_{use} = \eta_0 \cdot [K_b \cdot G_{bt} + K_s \cdot G_{st} + K_r \cdot G_{rt})] - c_1 \cdot (T_f - T_a) - c_2 \cdot (T_f - T_a)^2 - c_{eff} \cdot \frac{dT_f}{dt} \quad (1)$$

Herein, η_0 is the conversion factor, i.e. the fraction of perpendicular irradiance converted into useful heat when the mean fluid temperature of the collector $T_f = (T_{in} + T_{out})/2$ is identical with the ambient temperature T_a. The different irradiance components G_{bt}, G_{st} and G_{rt} are weighted with individual Incidence Angle Modifiers (IAM) K_b, K_s and K_r, to account for changes in the conversion factor due to non-perpendicular irradiance of these radiation components. The factors c_1 and c_2 are the collector's heat loss coefficients; c_{eff} is the effective thermal capacity of collector mass and fluid and ensures realistic thermal behavior at varying conditions.

The three IAMs of the irradiance components introduced above account for all optical, geometrical and thermal effects occurring when incidence of an irradiance component is not perpendicular to the aperture. The IAM leads to a reduction or increase of η_0, resulting in a parallel translation of the collector efficiency curve.

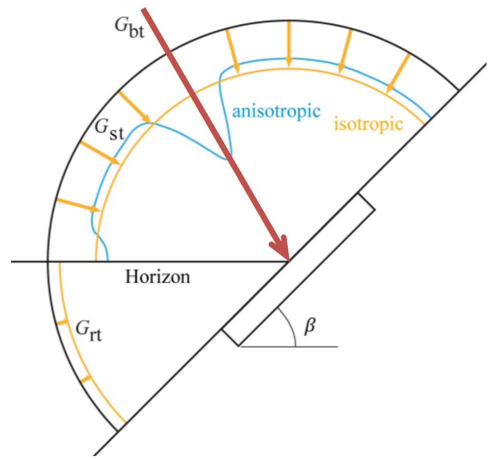

Figure 2: Solar irradiance components onto a sloped aperture plane [4].

EFFICIENCY CURVE MEASUREMENT

To simulate the annual energy gain of a collector, its efficiency curve and IAM-values must be determined. Following the international collector testing standard ISO 9806:2013 [5], conversion factor η_0 as well as the thermal losses of a collector can be determined from measurements under perpendicular irradiance onto the aperture. The stationary collector efficiency curve is approximated by a polynomial fit of second order. In Europe, the common expression for collector efficiency at stationary conditions is given in eq. 2:

$$\eta_\perp = \eta_0 - c_1 \cdot \frac{T_f - T_a}{G_t} - c_2 \cdot G_t \cdot \left(\frac{T_f - T_a}{G_t}\right)^2 \quad (2)$$

It is important to note that c_1 and c_2 are not physical parameters and that the efficiency curve is only valid within the measured temperature range.

Figure 3 shows the setup for measuring the efficiency curve parameters and K_b-values of the RefleC-collector and its receiver flat-plate collector LBM 4 GF. The efficiency curves of both collectors and partially also their IAM values were determined as close as possible to the steady-state method described in [5]. The outdoor laboratory used meets the accuracy requirements of this standard. The efficiency curve values are related to the aperture area, which is the projected area parallel to the absorber, through which radiation can reach the absorber. For the flat-plate this is basically the collector glazing, for RefleC also the projected area of the reflector adds to the aperture [4, p. 90].

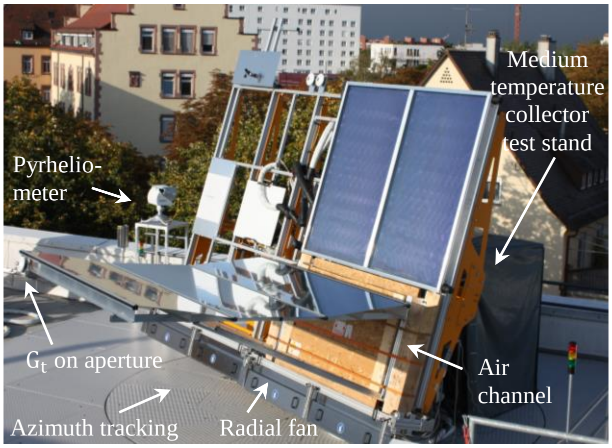

Figure 3: Setup for efficiency curve and IAM determination at the Test Lab Solar Thermal Systems of Fraunhofer ISE, Germany

For the efficiency curve tests the collectors were tracked to maintain perpendicular irradiance. Beam irradiance G_{bt} was measured by a pyrheliometer. When the measured value is subtracted from the global irradiance G_t measured at the collector aperture, the diffuse irradiance onto the aperture G_{dt} can be determined very accurately. Defined forced convection over the glass pane as required by [5] was ensured by a radial fan and an air cannel. This way the reflector was tested in a configuration similar to its real mounting and the ground and sky reflected diffuse irradiance reaching the absorber should be similar to that at the pilot plant.

The test was performed using the Medium Temperature collector Test Stand (MTTS) of Fraunhofer ISE. This test stand can measure collectors with pure water as heat carrier fluid up to temperatures of 200 °C and pressure of 20 bar. This way, the whole efficiency range of a process heat collector was tested. For the stationary tests, T_{in} was kept constant by heating/cooling the collector fluid by a thermostat. Inlet- and outlet-temperatures as well as mass-flow were measured, so that the actual collector power could be calculated. In comparison with G_t the collector efficiency for the actual mean fluid temperature T_f was determined.

The resulting efficiency curve parameters are given in Table 1. Minimal and maximal stationary fluid temperatures T_f as well as the maximal fraction of diffuse irradiance f_d are indicated as well.

Table 1: Efficiency curve test results and conditions

Collector	η_0	c_1	c_2	$T_{f,min}$	$T_{f,max}$	$f_{d,max}$
Flat-plate	0,794	1,870	0,0165	32.1	138.0	0.19
RefleC	0.741	1.761	0.0106	17.6	162.6	0.22

In Figure 4 both efficiency curves are compared at one exemplary irradiance and ambient temperature. At these conditions and based on unit aperture area, the efficiency of RefleC exceeds that of the flat-plate without reflectors at temperatures above 100 °C.

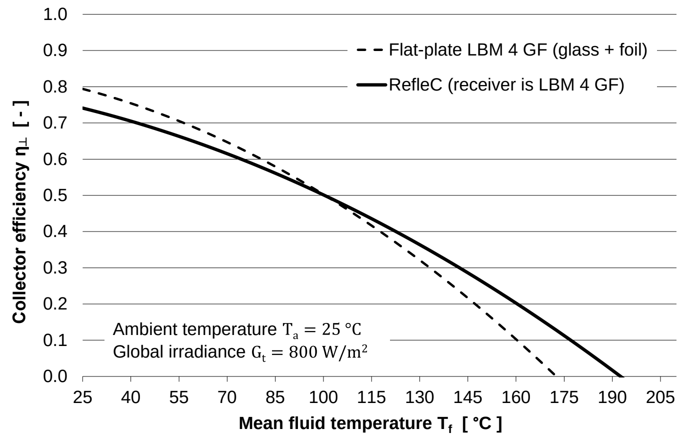

Figure 4: Efficiency curve test results for LBM 4 GF without reflectors and with reflectors.

SIMULATION

To assess the additional annual energy gain by the booster reflector, simulations with only the double covered flat-plate LBM 4 GF and with the identical flat-plate collector with reflector (RefleC) were performed for the locations Würzburg, Germany and Seville, Spain by Hess and Hanby [4].

To be able to calculate the useful energy gain according to eq. 1 by dynamic simulations, its efficiency curve, thermal capacity, and incidence angle modifiers must be known. The efficiency curve values of the double covered flat-plate with and without the booster reflectors are given in Table 1. The effective thermal capacity of the flat-plate is $c_{eff,fp} = 4.696\ \mathrm{kJ/(m^2K)}$. The factor c_{eff} is related to the aperture, but at RefleC and the reflectors are not thermally connected to their receiver flat-plates. Thus, the value $c_{eff,R} = c_{eff,fp}/1.25 = 3.757$ was used for RefleC. The IAM-curves for beam irradiance K_b of both collectors were determined by raytracing [4, p. 91] and validated punctually at the test lab (cp. above) by comparing measured conversion efficiencies for certain incidence angles of beam irradiance to the conversion factor η_0.

Hess and Hanby used a new collector simulation model, which considers the varying anisotropy of diffuse sky radiance and distinguishes between sky and ground reflected diffuse irradiance to calculate K_s and K_r from the input IAM-curves K_b for beam irradiance. To create realistic distributions of sky radiance based on clearness index and fraction of diffuse irradiance only, the approach of Brunger and Hooper [6] is used in the model. The sum of diffuse sky radiance from the weather data file is then distributed over the sky and each sky pattern is weighted with it's K_b to get a realistic IAM for anisotropic sky diffuse irradiance K_s. Diffuse irradiance from the ground is considered to be isotropic for calculation of K_r.

Hess and Hanby conclude that the state-of-the-art isotropic determination of a collector's diffuse-IAM based on raytraced or measured beam-IAM values significantly undervalues the annual output of all non-focusing solar thermal collectors. Highest relevance for application of the new model is found for high collector slopes, collectors with very angle-distinctive radiation acceptance and for low-efficiency operation as in process heat applications. The model is found very helpful whenever the dynamic collector gain has to be calculated realistically. It is also shown, that the additional gain from booster reflectors increases significally when diffuse is being simulated for anisotropic diffuse irradiance [4]. The results by Hess and Hanby reveal that the benefit of booster reflectors is higher than assumed by previous works. Table 2 summarises the results of the annual simulations.

Table 2: Annual collector gain of only the flat-plat and of the flat-plate with booster reflector (RefleC). Simulation results of [4, p. 95].

Collector type and T_{in}	**Würzburg** (RefleC: $\beta = 55°$; flat-plate: $\beta = 37.5°$)	**Seville** (RefleC: $\beta = 45°$; flat-plate: $\beta = 37.5°$)
RefleC		
40 °C	771	1397
120 °C	271	638
Flat-plate		
40 °C	645	1195
120 °C	145	415
Increase		
40 °C	126 (19.6 %)	202 (17.0 %)
120 °C	126 (87.0 %)	223 (53.7 %)

The simulations were performed for constant inlet temperatures with every positive temperature lift counted and with anisotropic diffuse irradiance. RefleC gains are related to 1 m^2 flat-plate aperture to illustrate the additional gain by the reflectors. Further simulation parameters were a constant mass flow of $25\,\mathrm{l/m^2_{Ap}}$, ground albedo 0.2, and time step = 15 min. Würzburg has moderate irradiance and a high diffuse fraction, while Seville has high irradiance and a small fraction of diffuse. For the results in Table 2, the irradiance on the tilted plane G_t was calculated by Type 109 from a TMY-2 Meteonorm file with the model of Perez et al. [7]. In Würzburg (49.48° N) at $\beta = 55°$ it is 1213 kWh/(m^2 a) with diffuse fraction $f_d = 50\ \%$ (sky: 46 %, ground 4 %), in Seville (37.25 N) at $\beta = 45°$ it is 1955 kWh/(m^2 a) with $f_d = 36$ % (sky: 33 %, ground 3 %).

Comparing both investigated locations shows a high difference in the additional energy gain by the reflectors. The increase in percentage of flat-plate gain is much higher in Würzburg than in Seville. But comparing the absolute gains leads to two important conclusions:

- The additional gain by the reflector is largely independent of the collector working temperature.
- The cost/performance ratio is better in regions with high irradiance.

MONITORING

The laundry Laguna in Marburg, Germany, was equipped with a collector field consisting of one row of RefleC-collectors and an equally sloped reference field of LBM 4 GF flat-plate collectors without reflectors in front of it (cp. Figure 5).

Figure 5: Collector field of the pilot plant at laundry Laguna viewed from east.

The collector field has an overall aperture area $A_{ap} = 56.6\ \mathrm{m^2}$ and is sloped at $\beta = 55°$ for maximal annual energy gain. The only difference between the pilot plant collectors and the test samples shown in Figure 3 is that the large-area-collectors of the pilot plant have twice the width of the test sample, i.e. the receiver flat-plates have four glass panes instead of two. The field consists of six such LBM 8 glass-foil collectors with $A_{ap} = 8.08\ \mathrm{m^2}$ each. Four of these collectors build the RefleC-trough; two of them build the reference flat-plate row in front of RefleC.

The solar loop is filled with water-glycol mixture. It has a maximum operation temperature of 130 °C and a maximum pressure of 6 bar. A charging heat exchanger transfers the heat to either the primary storage (1 m³, max. 120 °C, 3 bar) or the two secondary storages (2 x 1 m², max. 110 °C, 3 bar). The system supplies three processes of the laundry. Either boiler feed water (90 °C to 110 °C), boiler makeup water (20 °C to 90 °C) or water for the washing machines (20 °C – 60 °C) is heated. Depending on time of day and year as well as supplied processes, the mean collector temperatures T_f vary.

When the system was constructed, a monitoring system was installed in parallel. This system started operation on 2nd June 2010 and measured the system performance without interruption until it was dismantled on 27th October 2011. During this monitoring phase, at 479 days 47 sensors were logged with a measurement interval of 30 seconds. To get annual performance figures, a reference year from 01.10.2010 to 30.09.2011 is defined. For this time frame, gap-free monitoring data are available and the system control was usually close to standard-operation. Among the 365 days of the reference year, there was heat demand on 256 working days.

In the reference year, the system covered 23.2 % of the heat demand of the three processes supplied. If only the two low-temperature-processes are considered, 31.4 % of their demand was provided by the sun. The solar loop utilization ratio (i.e. the overall annual conversion efficiency of solar irradiation onto the aperture into heat charged to the storages) was 40.9 %. The system utilization ratio (i.e. the overall annual conversion efficiency of solar irradiation into heat supplied to the processes) was 35.0 %. Figure 6 shows the gain of the right RefleC subfield with reflectors (two LBM 8 glass-foil collectors with reflectors) in comparison to the flat-plate subfield (two LBM 8 glass-foil collectors without reflectors).

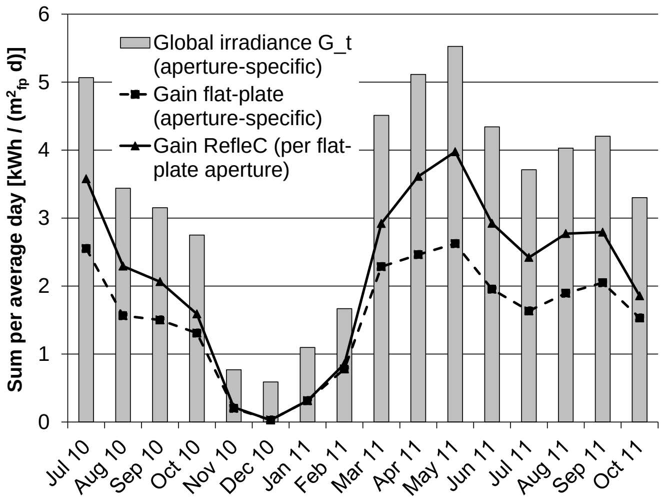

Figure 6: Mean monthly irradiance with gains of double-covered flat-plate LBM 4 GFR in comparison with the gains of RefleC with reflectors (all per m² flat-plate).

The additional gain by the reflectors highly depends on the transversal incidence angle (cp. θ_t in Figure 1). From November to February, i.e. during winter with very low solar heights, the reflector is not effective. But during the months with high solar irradiance and gains, the reflector causes a significant increase in collected energy.

In the reference year, at field inlet temperatures $T_{in} > 80$ °C the measured cumulated additional gross energy gains of the eastern RefleC subfield were 78 % higher than the gains of the flat plate subfield. When all inlet temperatures are considered, RefleC was still 39 % better. Aperture-specific, these cumulated additional gains were 42 % at $T_{in} > 80$ °C and 11 % over the whole year.

A comparison of these measured gains to the annual simulation results given above is not admissible for several reasons. The simulations are valid for a typical meteorological year in Würzburg with a collector field orientated south; the monitored field is located in Marburg with collector azimuth $\gamma = -21°$ and exposed to current weather and irradiance. The monitored flat-plate sub-field is not tilted for maximal energy gain (cp. $\beta = 55°$ at the pilot plant vs. optimized $\beta = 32.5°$ in the simulations. In the simulations, the field was operated at constant mass flow and inlet temperatures over the whole year and all positive gains were counted. At the pilot plant, the inlet temperatures were highly variable and mass flow through the field was only activated when a sufficient temperature lift was reached.

ECONOMIC ASSESSMENT

The simulations results given in [4] and discussed above show that the additional gain caused by the boosters is undervalued by isotropic, state of the art modeling. This can be of high practical relevance for the solar thermal industry, because the cost/performance ratio of boosters is actually better than previously assumed.

Taking the anisotropically calculated booster gains into account, this section aims to estimate up to which investment costs per unit reflector area boosters may be economically attractive for applications similar to the RefleC pilot plant. This estimation starts from the expression of solar heat generation costs K_{sol} [8, p. 66]:

$$K_{sol} = \frac{K_{inv} \cdot f_a + K_{main}}{Q_{sol}} + K_{op} \quad (3)$$

Therein, K_{inv} is the overall investment costs, f_a is the annuity factor accounting for the annual capital costs, K_{main} and K_{op} are the annual maintenance and operational costs, and Q_{sol} is the annual solar gains. The annuity factor f_a is calculated from the capital interest rate p and the service life T of the boosters [8, p. 66]:

$$f_a = \frac{(1+p)^T \cdot p}{(1+p)^T - 1} \quad (4)$$

At the RefleC pilot plant, the reflectors are not cleaned and therefore do not cause additional operational or maintenance costs compared to a system of flat plate collectors without reflectors. Thus, because only costs and gains related to the reflector shall be analyzed, K_{op} and K_{main} do not have to be considered and eq. 3 can be written as:

$$K_{inv} = \frac{K_{sol} \cdot Q_{sol}}{f_a} \quad (5)$$

First, the additional annual gains by the booster reflectors Q_{sol} have to be quantified. This must be the difference between an optimized system with double-covered flat-plates and a system with RefleC collectors. It was discussed at the end of the last section that the additional gains measured at the pilot plant do not represent this difference. But because the monitored system worked as theoretically expected, the simulation results for RefleC and LBM 4 GF can be used. These simulations revealed that the absolute additional collector gain caused by the boosters depends on the location, but is similar for both simulated inlet temperatures of 40 °C and 120 °C (cp. Table 2). For the following assessment, it is assumed that these temperatures mark the expected working temperature range of stationary collectors with boosters. It is further assumed that the additional gains by the boosters are temperature-independent, so that a mean value of the simulated additional gain can be used. This is in Würzburg 126.0 kWh m_{fp}^{-2} a^{-1} and in Seville 223 kWh m_{fp}^{-2} a^{-1} (cp. Table 2).

These values do not yet represent the useable heat Q_{sol}, because the simulation results give only the collector gain and do not consider losses within a solar process heat system. At the RefleC pilot plant, 70.4 % of the heat produced by the collector field was transferred to the processes. This measured system efficiency accounts for the whole spectrum of operation temperatures (30 °C up to 130 °C), for the losses caused by an active stagnation cooler, and for non-optimized system control during the first months. Although the system efficiency might be higher for larger SPH systems with boosters, the value of the RefleC pilot plant is used here. Based on this conservative system efficiency and the simulation results, the calculated additional energy supply to the processes caused by the reflectors is in Würzburg $Q_{sol} = 88.7\,\text{kWh}\,m_{fp}^{-2}\,a^{-1}$ and in Seville $Q_{sol} = 157.0\,\text{kWh}\,m_{fp}^{-2}\,a^{-1}$.

To calculate a minimal selling price for the reflectors by eq. 5, acceptable solar heat generation costs K_{sol} for the useful energy from the reflectors have to be estimated. Because the RefleC pilot plant is a laundry, conventional heating costs from the laundry sector are used as a basis for comparison. Beeh and Hess collected data of 20 laundries, most of them located in Germany and having a gas-fired steam network [9]. When losses of 20 % for heat generation and distribution are taken into account, the typical conventional heating costs at these laundries are about 0.06 EUR/kWh [9, p. 13]. As an example, the following assessment assumes that the application of booster reflectors might be attractive if they generate useful solar heat at two thirds of this price, i.e. $K_{sol} = 0.04\,\text{EUR/kWh}$. To estimate the capital costs, an interest rate $p = 4\,\%$ and a lifetime of the system of $T = 20$ years are assumed. With eq. 4 this results in an annuity factor of $f_a = 0.0736$.

From the estimations and framework conditions discussed above, the resulting investment costs K_{inv}, i.e. the minimal selling price of the reflector for one m^2 of flat-plate receiver aperture can be calculated by eq. 5. If the same framework conditions are assumed for both locations, the result is for Würzburg $K_{inv} = 48\,\text{EUR}/m_{fp}^2$ and for Seville $K_{inv} = 85\,\text{EUR}/m_{fp}^2$. The RefleC collector as applied at the pilot plant uses the flat-plate collector LBM 8 of Wagner & Co. Solartechnik with four glass panes as receiver. This flat-plate has an overall aperture area $A_{ap} = 8{,}15\,m^2$ and is equipped with an overall reflector area of $12{,}57\,m^2$ [10].

The exemplary calculation above gives a minimal reflector price for Würzburg of $K_{inv} = 31\,\text{EUR}/m^2$ (or 393 EUR per LBM 8 equipped) and for Seville of $K_{inv} = 55\,\text{EUR}/m^2$ (or 696 EUR per LBM 8). For the customer this would mean a static payback period of approx. nine years (calculated from dividing the investment for the boosters by the annually saved gas costs). It has to be stressed that other framework conditions can result in highly different values. Especially the interest rate has a very high impact on reflector price and amortization period.

CONCLUSIONS AND OUTLOOK

The investigations above have shown that external booster reflectors increase the efficiency of stationary collectors at higher working temperatures. They also highly increase the annual gains. The additional gains by the booster were found to be largely independent of the collector working temperature, which predestines the technology for process heat generation at higher temperatures.

It has also been shown that the cost/performance ratio increases with higher overall irradiation. An application of this technology in South Africa seems therefore of particular interest, since the country benefits from very high solar irradiance all over the year. Future work has to determine the possible reflector costs in regions with high irradiance and compare the RefleC-technology to focussing collectors in order to determine the economic operation temperature range of this technology.

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REFERENCES 0.5

[1] Tabor, H. (1958). Stationary mirror systems for solar collectors. Solar Energy 2(3–4): 27-33.

[2] Perers, B. and Karlsson, B. (1993). External reflectors for large solar collector arrays, simulation model and experimental results. Solar Energy 51(5): 327-337.

[3] Perers, B. (1995). Optical Modeling of Solar Collectors and Booster Reflectors under Non Stationary Conditions. Dissertation. Uppsala University.

[4] Hess, S. and Hanby, V. I. (2014). Collector Simulation Model with Dynamic Incidence Angle Modifier for Anisotropic Diffuse Irradiance. Energy Procedia 48(0): 87-96.

[5] ISO 9806:2013 Solar energy - solar thermal collectors - test methods, edition 2013-11.

[6] Brunger, A. P. and Hooper, F. C. (1993). Anisotropic sky radiance model based on narrow field of view measurements of shortwave radiance. Solar Energy 51(1): 53-64.

[7] Perez, R., Stewart, R., et al. (1988). The Development and Verification of the Perez Diffuse Radiation Model.

[8] VDI (2004). VDI 6002 Part 1: Solar heating for domestic water: General principles, system technology and use in residential building. Berlin, Beuth Verlag.

[9] Beeh, M. and Hess, S. (2014). Bericht zu Screenings und Fallstudien in SoProW. Bönnigheim.

[10] Kramp, G. (2010). Technical drawing of final RefleC collector as used for the pilot plant. STEP construction data of Wagner & Co. Solartechnik GmbH, received per email on 19.02.2010.