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SolSteam - Innovative integration concepts for solar-fossil hybrid process steam generation

H. Schenk[a], S. Dieckmann[b], M. Berger[c], C. Zahler[d], O. Stoppok[e], D. Schulz[f], D. Krüger[g]

[a]M. Sc., Researcher, German Aerospace Center (DLR), Institute of Solar Research, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, Phone +49 711 6862 740, e-mail: Heiko.Schenk@dlr.de

[b]Dipl.-Ing. Dipl.-Wirt.Ing., Researcher, German Aerospace Center (DLR), Institute of Solar Research, Linder Höhe, 51147 Köln, Phone +49 2203 601 4068

[c]Dipl.-Phys., Engineering, Industrial Solar GmbH, Emmy-Noether-Str. 2, 79110 Freiburg, Phone +49 761 767111 44 44

[d]Dipl.-Phys., Managing Director, Industrial Solar GmbH, Emmy-Noether-Str. 2, 79110 Freiburg, Phone +49 761 767111 47

[e]Dipl. Ing., Team Leader, Viessmann Berlin GmbH, Kanalstraße 13, 12357 Berlin, Phone +49 30 6602 457

[f]Dipl. Ing., Viessmann Berlin GmbH, Kanalstraße 13, 12357 Berlin, Phone +49 30 6602 757

[g]Dipl.-Ing., Researcher, German Aerospace Center (DLR), Institute of Solar Research

Abstract

Within the 6th Energy Research Program, the German Government aims at a significant reduction of the primary energy consumption and 60% of the country's energy shall be provided by renewable energy sources by 2050, see [1]. The process heat sector represents a considerable part of the total energy consumption. Heat within the temperature range between 100 °C and 400 °C was identified as the target market for concentrated solar applications. The Solsteam project aims at the development of a solar-hybrid steam generating system for industrial process heat, see [1]. In cooperation with the DLR (German Aerospace Center) that has a long-time experience in concentrated solar power, the system shall be developed that consists of a gas-fired steam boiler of the German Company Viessmann GmbH and a Fresnel Collector of the company Industrial Solar, Freiburg, Germany, both specialists in their field. In the present paper various possible integration solutions are discussed. Three concepts have been identified as promising and are therefore described in detail. The preliminary assumptions for input parameters do not allow a final decision for one of the three concepts. However, a techno-economic evaluation of one exemplary system has been carried out for three typical sites in Europe: Freiburg, Rome, and Antalya. The size of the solar field has been optimized individually taking into account common profitability criteria for projects. As expected, the optimum of the solar field size depends on boundary conditions, such as irradiation and subsidies on the investment.

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Keywords: Solar-hybrid steam generation system, Linear Fresnel Collector, techno-economic optimization

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1. Introduction

In 2012 the total primary energy consumption of the European Union summed up to 1104 Mtoe (10^6 equivalent tons of oil) or 46.242 EJ (Exajoule), [2]. According to [3] 28 % of this amount of energy is consumed for industrial applications. 34 % of the energy is used for electricity and 66 % for process heat. 27 % of the heat demand requires temperatures between 100 and 400 °C, which corresponds to 2.3 EJ. These 2.3 EJ have been identified as the potential market for concentrated solar process heat applications, see [4]. Within the 6th Energy Research Program, the German Government aims at a reduction of the primary energy consumption and 60% of the country's energy shall be provided by renewable energy sources by 2050, see [1]. In industrial applications, such as for example heating, distilling, disinfecting, cooking, drying, steam is used as heat transfer medium. The SolSteam project aims on the development of a market-ready solar-hybrid process heat system for the medium temperature range, as already published in [1]. In this system a gas-fired steam boiler shall produce steam in parallel with a Fresnel solar field, leading to a significant reduction of the fossil energy consumption. For these means the DLR (German Aerospace Center), the Viessmann GmbH, and Industrial Solar are closely working together.
In a first step a variety of different solar-hybrid integration concepts were defined and evaluated. Subsequently promising concepts were chosen and compared in a techno-economic analysis. The next step in the project will be the development and installation of a demonstrator system.

2. Description of systems

2.1. Conventional steam boiler

Viessmann produces steam generators for industrial heat applications, as for example the Vitomax M73A series. These boilers are designed as three-pass furnace boilers and are available with different capacities and different working pressures. With the integrated economizer ECO 200 an allover efficiency of 95.1 % can be reached (depending on to pressure level). Figure 1 shows the boiler model which is considered in the SolSteam project with all relevant data in Table 1. The boiler produces 2 t/h of dry steam at nominal operating conditions, 10 bar, and 184 °C, at a nominal thermal efficiency of 94.6 %.

Combustion takes place in the furnace tube. The resulting flue gas is fed through two reversal chambers into smoke tubes which act as second and third pass. Back rear plate as well as burner inlet are water-cooled which reduces emissions and increases efficiency. Water is heated inside the boiler and partially evaporated by the flue gas created from combustion of natural gas. Before being released the flue gas is cooled down to 130 °C in the integrated economizer. In that manner the feed-water is heated from 102 °C to 140 °C, increasing the boiler's efficiency. The thermal power is adapted to the steam demand by maintaining constant pressure inside the boiler. The water liquid level of the boiler is controlled with the feed-water pump.

Fig 1: Viessman Vitomax M73A steam generator

Table 1: Relevant parameters for the steam generator

Parameter	Unit	Value
Working Pressure	[bar]	11
Steam Mass Flow	[t/h]	2
Total Fluid Volume	[m³]	4,57
Nominal Thermal Power	[kW]	1380
Nominal Thermal Efficiency	[%]	94,6
Max. residual oxygen content in flue gas	[%]	3
Nominal feed-water temperature	[°C]	102
Nominal saturation pressure; temperature	[bar; °C]	11; 184,2
Enthalpy of saturated liquid; gas	[kJ/kg]	782; 2781

2.2. Fresnel collector

2.2.1. Collector description

The Fresnel collector is a linear concentrating solar thermal collector for industrial process heat applications, see Fig 2. The collector is made up of modules, which are connected by welding the absorber pipes together to form collector strings. 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 operation temperature as well as the maximum pressure of the collector is determined by the absorber tube (see Table 2).

The thermal efficiency of the collector is variable, mainly due to the sun position, so that the resulting yearly average efficiency depends on various factors, including geographic location, weather, operating conditions (e.g. operating temperature and corresponding heat losses), field layout, and orientation of the collector field. The Industrial Solar LF11 makes use of the Schott PTR 70 vacuum receiver. Data for heat losses of the receiver can be found in [5]. Conductive losses as well as convective losses are very low and thermal losses are dominated by radiative losses.

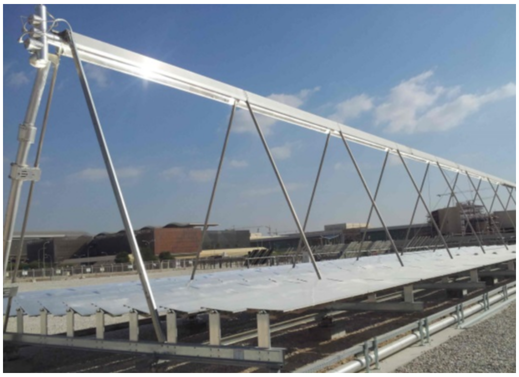

Fig 2: Picture of a linear Fresnel collector.

Table 2: Relevant parameters of the linear Fresnel collector.

Parameter	Unit	Value
Width	[m]	7.5
Parallel mirror rows	[-]	11
Aperture width	[m]	5.5
Height	[m]	~ 4.5
Aperture area per module	[m^2]	22
Total fluid volume per module	[l]	13.9
Peak power under rated conditions	[kW$_{th}$]	12.3
Maximum operation temperature	[°C]	400
Maximum operation pressure	[bar]	40 / 120
Optical efficiency for zenith position of the sun η_0	[-]	0.635
Heat loss correlation	$\dot{q}_{\text{loss}} = u_0 \cdot \Delta T + u_3 \cdot (\Delta T)^4$ $u_0 = 3.291 \cdot 10^{-2}$ W/m²K $u_3 = 1.484 \cdot 10^{-9}$ W/m²K^4 ΔT: Difference between average absorber temperature and ambient	
Thermal efficiency*	$\eta_{\text{th}} = \eta_0 \cdot IAM - \frac{\dot{q}_{\text{loss}}}{DNI}$	

2.2.2. Applications and heat transfer fluid

Due to its low heat losses and its exclusive use of direct solar irradiation, the collector is primarily designed for applications at high operation temperatures (>100 °C), like for industrial process heat applications, and for regions with high annual direct irradiation. It is designed smaller and lighter than typical power plant solar collectors, so that it can be easily erected on flat rooftops of manufacturing sites. As heat transfer fluid, pressurized water, thermal oil or steam can be used. Typically, industrial processes use pressurized water or steam for temperatures below 200 °C, whereas for temperatures above 250 °C thermal oil is more common.

* IAM is the incidence angle modifier, DNI the direct horizontal irradiance

3. Integration concepts

In the SolSteam project only solar-hybrid systems are considered in which the steam boiler always covers the heat demand when the solar field is not in operation. Various integration approaches were evaluated. These can be subdivided in the following categories:

- **Direct steam generation**: Steam is produced directly in the collectors and in parallel to the conventional steam boiler
- **Single-Phase Fluid (indirect).** A single-phase fluid is heated in the collector circuit and transfers heat via a heat exchanger to the conventional steam boiler. In the case of process heat, depending on operating temperatures, usually pressurized water or synthetic oil is used.
- **Pre-heating:** The solar field works in pressurized water mode, as well. The thermal energy from the solar field is either transferred to the feed-water upstream of the steam generator or between the pre-heater and the boiler vessel.
- **Flash:** Similar to flash cycles in geothermal power plants water under pressure is circulated and heated up in the solar field. Steam is produced by flash evaporation due to a pressure reduction in a valve.

After a selection process the first two categories were judged as promising and were pursued in the SolSteam project. In fact, the other approaches were considered as disadvantageous for various reasons. The application of synthetic oil was considered as unnecessary in the given operating temperature range. The pre-heating concepts were dismissed due to the very limited solar shares that can be realized. Flash cycles are applied for high-temperature geothermal heat sources where hot water above 200 °C is available. However, the application of a flash cycle in a solar field would not offer any advantage compared to a direct steam generation mode but would entail a higher operating pressure and temperature and exergy losses. Two concepts (A and B) from category 1 and one concept from category 2 (C) were chosen for a qualitative and techno-economic evaluation in the present paper. These concepts are described in the following:

Concept A: Hybrid steam generation in a single Circuit, section 3.1
Concept B: Hybrid Steam generation in two separate circuits with a steam drum, section 3.2
Concept C: Single-Phase solar field with heat exchanger inside the boiler, section 3.3

3.1. Concept A: Hybrid steam generation in a single circuit

In Concept A, steam is generated in parallel in the solar field and steam generator, see Fig. 3. Coming from the water treatment, the Feed-water is pre-heated in the economizer before entering the steam boiler, and is then evaporated on the surface of the tube bundles inside the vessel.

During regular solar field operation a mixture of liquid water from the steam boiler and feed-water is pumped into the solar field, where wet steam is produced. In order to avoid super-heating or sub-cooling, usually a maximum steam quality around 0.5 is chosen. For stable steam boiler operation the surface of the saturated water inside the boiler must be kept calm. For these means, the liquid and gaseous phase of the wet steam from the solar field are pre-separated before entering the boiler, so that the condensate will enter the boiler below the water surface, while the steam will enter from the top.

Figure 3 also shows a typical open industrial steam system. The condensate is pumped into the feed-water tank, where it is thermally de-aerated and make-up water is admixed. The feed-water is pumped into the steam generator and solar field by separate pumps. The water streams are split with the same ratio as the current ratio of thermal power supply of steam boiler and solar field. In that manner, the temperature down-stream of the economizer can be kept constant. Furthermore, the admixture of cold feed-water (about 100 °C) upstream of the recirculation pump reduces the risk of cavitation, since the temperature is below saturation temperature.

Due to transient irradiation conditions, evaporation can be unsteady in the solar field, causing water surges which entail increases of the liquid level in the boiler. Additionally, during start-up of the solar field water surges can emerge, once the solar field reaches saturation temperature and solar steam generation begins. Vice versa, when solar steam generation stops in the evening or during cloudy periods, the collector fills up with liquid, thereby reducing the condensate level in the boiler vessel. In order to cope with these changes in fill-level, the volume of the boiler vessel must be increased causing supplementary costs. Alternatively, depending on the level of supplementary costs, an optional start-up vessel can be used, indicated in Fig. 3 in grey color. This start-up vessel would be almost filled up with condensate during regular solar steam generation, while the fill level would drop significantly during evening or due to clouds. The rest of the start-up vessel volume would be filled with steam.

During the night and before start-up the solar field is filled with sub-cooled water. The above-mentioned start-up vessel would also enable to start-up the solar field separately during boiler operation. With the start-up vessel water from the solar field can be recirculated until the required steam parameters are attained. In that manner it is avoided that cold fluid from the collector enters the steam boiler, causing cavitation.

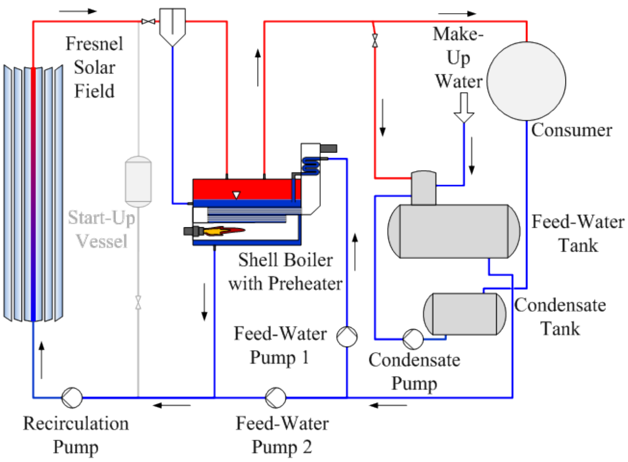

Fig 3: Scheme of Concept A.

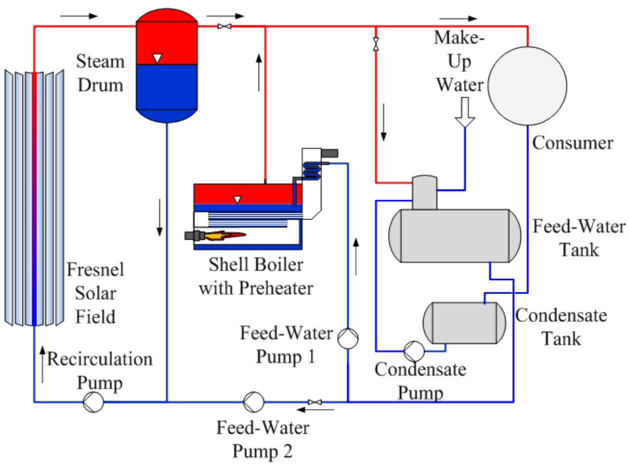

Fig 4: Scheme of Concept B.

3.2. Concept B: Hybrid steam generation in two separate circuits

In Concept B wet steam is also produced directly in the solar field, but in a separate circuit with a steam drum, see Fig. 4. This classic direct steam generation concept already has been applied and tested in other prototype installations, e. g. see [6], In contrast to Concept C steam is separated in the steam drum, which acts as a buffer storage at the same time. The liquid phase is circulated back to the solar field whereas the gaseous phase is fed directly into the steam line in parallel to the steam produced by the boiler. As in Concept A, two separate feed-water pumps for each system and a separate solar field recirculation pump are necessary. Since fill level fluctuations in the steam drum are not problematic, the function of the optional start-up vessel from Concept A would also be accomplished by the steam drum.

In contrast to Concept A it is not necessary to adopt the design of the steam boiler for the solar application or to add a start-up vessel. However, additional investment costs for the steam drum must be taken into account.

3.3. Concept C: Single-phase solar field with heat exchanger inside the boiler

Figure 5 shows Concept C where the solar field is operated in pressurized water mode in a separate circuit. Thermal power from the solar field is transferred to the steam circuit via an additional heat exchanger tube bundle inside the boiler vessel. In order to deal with the changing density the water in the circuit of the solar field must be equipped with an expansion vessel, and a stratified pressure vessel upstream to the expansion vessel to protect the diaphragm. Furthermore there is a by-pass around the additional heat exchanger tube bundle in the boiler that is used while the solar field shall be started up without cooling the boiler.

Due to the temperature difference in the heat exchanger, the operating temperature in the solar field must be higher than the one of the saturated water inside the steam boiler. Compared to the other two concepts this causes additional heat losses.

While there is no need for a steam drum additional investment costs for the adaption of the steam boiler as well as for the expansion vessel must be allowed. However, in order to keep pressure variation in the solar system small, the expansion vessel would likely become quite large. For large collector fields, the costs for such a diaphragm expansion vessel together with the upstream pressure vessel are getting high compared to a pumping station, which could be connected to the feed-water tank and which can be used instead for pressure maintenance.

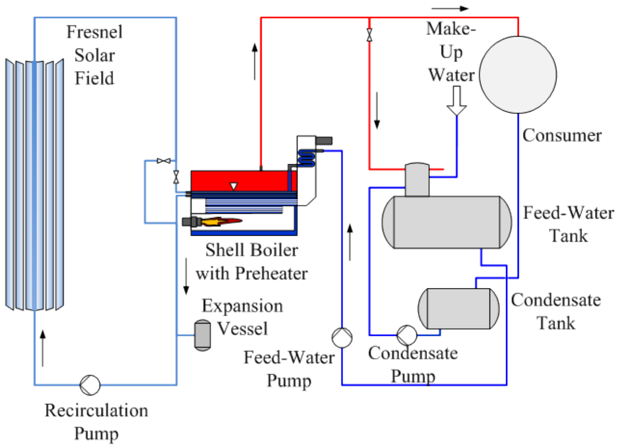

Fig 5: Scheme of Concept C.

4. Energetic and economic comparison of concepts

4.1. Thermodynamic and economic modelling with Greenius

The Greenius simulation environment allows fast performance analyses of renewable energy projects. It is developed by DLR and can be downloaded and used free of charge since December 2013, see [8]. While the main focus of Greenius lies on concentrated solarthermal heat and electricity production it also includes photovoltaics, wind power, non-concentrating solar process heat and solar cooling. For all technologies Greenius provides a detailed economic analysis for the whole life time of the plant including financing, construction, cash flow, payback period and net present value. An overview of the possibilities of Greenius is presented in [7] and [8].

Greenius solves a steady-state model for each hour of the year. However, start-up processes are taken in to account. For direct steam generation, a representative loop is divided into subsections in order to determine the correct temperature profile throughout the loop. When using a heat transfer fluid without phase change (e.g. thermal oil) during operation the mean collector temperature is sufficient for the estimation of heat losses.

4.2. Site specification

Three different sites have been chosen for the SolSteam preliminary design phase in order to forecast the solar field output and thus the cost-effectiveness of the hybrid steam generation. Freiburg represents a low irradiation site while Rome and Antalya both offer higher DNI and an attractive economic environment (regarding investment incentives). Table 3 shows an overview of the site data. The meteorological data is taken from Meteonorm version 7.0. The price of the fossil heat generation (66 €/MWh_{th}) is calculated on the basis of the given annual mean boiler efficiency of 91 % and the fossil fuel prize is assumed to be 60 €/MWh with a yearly increase of 7%. This is roughly the rate observed during the last two decades not only in Germany (about 8%, [9]) but all over Europe [10]. The subsidies for the investment are assumed 50 % in Germany and 60% in Italy, based on [11]. However, there are no subsidies in Turkey.

Table 3: Meteorological data and financial boundary conditions of Antalya, Rome and Freiburg.

Parameter	Unit	Antalya, Turkey	Rome, Italy	Freiburg, Germany
Latitude / Longitude	[°]	36.87°N, 30.73°E	41.88°N, 12.50°E	48.00°N, 7.85°E
Annual DNI Sum	[kWh/m²]	1893	1705	946
Temperature (Mean / Min / Max)	[°C]	19.1 / 1.0 / 41.7	16.6 / -4.0 / 37.3	10.7 / -10.4 / 33.9
Subsidies relative to investment costs	[%]	-	60	50
Price of fossil heat generation (annual increase)	[€/MWh_{th}]		66 (7%), for all concepts	

4.3. Thermodynamic and economic input parameters

The design point for all three concepts is defined at an ambient temperature of 25 °C and a DNI of 850 W/m² at perpendicular irradiance. The total aperture area of the solar field is 1760 m² for all concepts while the design load is 2 t/h. Table 4 gives an overview of the technical and economic input parameters.

In concepts A and B steam is generated directly in the solar collector. The pressure of the saturated steam at the outlet is set to 10 bar which corresponds to a temperature of 180 °C. The inlet temperature is assumed to be 120°C for concept A, where the collector is fed with a mixture of feed water and saturated water from the fossil steam generator, respectively 103°C for concept B where the collector is supplied solely with feed water.

Table 4: Technical and financial parameters of the systems.

Parameter	Unit	Concept A	Concept B	Concept C
Feed water temperature	[°C]		103, for all concepts	
Total aperture area of SF	[m²]		1760, for all concepts	
Pressure / temperature at SF inlet	[bar; °C]	11; 120	11; 103	31; 180
Pressure / temperature at SF outlet	[bar; °C]	10; 180	10; 180	30; 220
Nominal steam quality at SF outlet	[-]	0.2	0.2	-
Thermal power of SF at design point	[kW]	903	903	898
Nominal thermal power of steam generator at design point	[kW]		1380, for all concepts	
Peak thermal load demand	[kW]	1,303	1,303	1,303
mass flow at DP	[kg/s]	0.397	0.384	4.88
Total costs of investment	[k€]	1,473	1,476	1,422
Project life-time	[a]		20, for all concepts	
O&M costs relative to total invest	[€/(m²·a)]		4, for all concepts	
Discount rate	[%]		4, for all concepts †	

The outlet temperature of 220°C in concept C requires a pressure of about 40 bar. The mass flow is more than 10 times higher due to the smaller specific enthalpy difference between inlet and outlet. The cost estimations of the three concepts are preliminary and are assumed to change during the next phases. Based on the current estimation, the difference in capital investment of the systems is only 3 %.

4.4. Load demand and operating strategy

The cost-effectiveness of the hybridization of the steam supply depends highly on the demand profile of the coupled process since the storage capacity is usually only dimensioned for short term. For this reason a load profile was defined, see Fig. 6. It is based on the monthly average load and the measured load on one certain day for a

† At perpendicular irradiance optical angle-losses are zero. 850 W/m² is a standard value in the financial studies in the SolSteam project.

process in the clothing industry. The measured data is scaled to a maximum load of 2 t/h (corresponding to 1303 kW thermal power) respecting the monthly variation of the demand. The average demand from June to December is significantly higher than in the first five months of the year (0.65 t/h vs. 1.07 t/h).

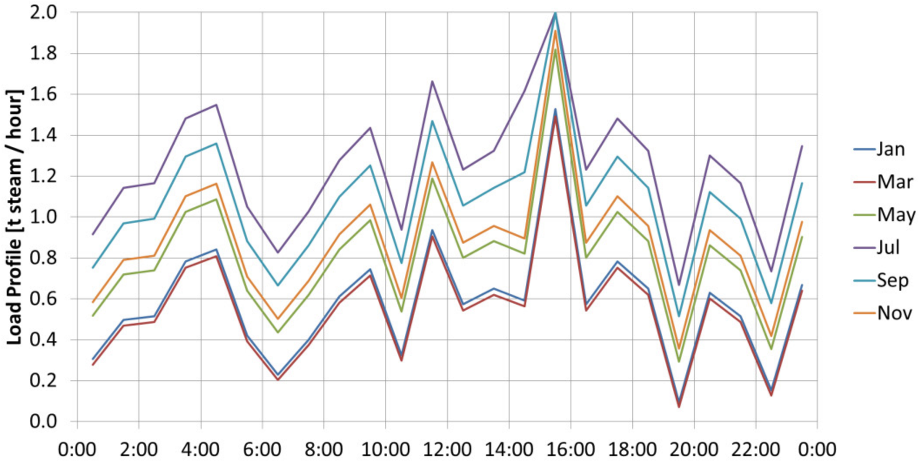

Fig. 6: Daily load profiles for different months.

4.5. Thermodynamic comparison of the three concepts based on a typical operation year

The software Greenius is used for a first evaluation of the solar field for the three presented concepts. The simulations are performed for a site in Antalya with an assumed average mirror cleanliness of 97 %. The mirror cleanliness is a very important factor for the output of a solar field. However it depends highly on the exact site, meteorological conditions and washing intervals which themselves depend on the economic boundary conditions. The results for a typical operation year are shown in Table 5, Fig. 7a and 7b.

Table 5: Net heat output and heat losses of the three concepts for Antalya.

Quantity	Unit	Concept A	Concept B	Concept C
Net Heat Output	[MWh]	1,236	1,202	1,224
Absorbed Solar Energy	[MWh]	1,365	1,365	1,365
Heat Losses Receiver	[MWh]	73	72	86
Heat Losses Piping	[MWh]	49	48	56
Heat Losses Steam Drum	[MWh]	0	10.0	0
Potential Losses	[MWh]	7	34	0

Concept A yields a net output of 1,236 MWh for a typical operation year which corresponds to an overall efficiency of 37.1 % (solar irradiation on net aperture area to net heat output). The net output of concept B is 2.8% below the output of concept A although the mean temperature in the solar field and thus the heat losses are slightly lower. The lower performance is due to the introduction of the steam drum into the system which entails additional heat losses and a higher fluid volume that must be heated up during start-up phase. The simulation model currently used in Greenius assumes that the system operates at a constant pressure profile and is completely filled with water before start-up. The thermal expansion during start-up causes water to leave simulation boundaries at a higher temperature than feed water. The enthalpy difference is accounted as start-up loss, but can be reduced in reality using an optimized operating strategy. In Fig. 5a and b, the start-up losses are therefore mentioned as 'Potential Loss System'. Concept C does not reach the output of concept A due to higher heat losses caused by the increased mean collector temperature.

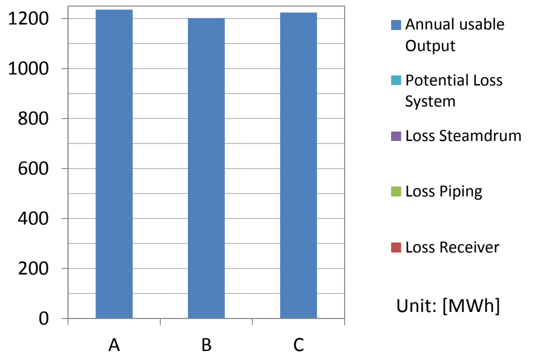

Fig. 7a: Absorbed energy, losses, and usable output for typical operation year in Antalya.

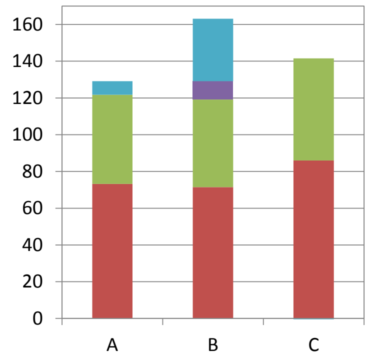

Fig. 7b: Magnification of Fig 5a focusing on different loss types.

4.6. Site comparison: Technical results

The difference of the thermal output of the three concepts is very small. However, concept A yields the best thermal performance while concept C has the lowest investment costs. Technical and costs assumptions are of rather preliminary nature a final decision for one of the concepts cannot be made at this stage of the project. As an example concept A is chosen in order to perform a general economic evaluation of the three sites described above.

Table 6: Thermodynamic results for Concept A

Quantity	**Unit**	**Antalya**	**Rome**	**Freiburg**
Heat demand	[MWh]	5018, for all sites		
DNI on aperture area	[MWh]	3332	3001	1665
Total thermal output solar field	[MWh]	1236	1058	523
Efficiency solar field	[%]	37.1	35.3	31.4
Dump rate	[%]	6.1	6.5	5.1
Solar share	[%]	23.1	19.7	9.9

Table 6 gives a comparison of the insolation conditions and thermodynamic performance of the solar field. Antalya offers the best insolation of the three sites and reaches a thermal solar field output of 1236 MWh at a solar field efficiency of 37.1 %. Rome is on a comparable level while Freiburg does not exceed 523 MWh solar output.

The demand profile is essential for a solar process heat system because the storage capacity for steam is usually small. Consequently, high correlation of insolation and demand are favorable for the solar share of the system. The used load profile offers quite attractive characteristics with diurnal peak load in the afternoon and a seasonal peak in the summer. Figure 8 shows a monthly breakdown of the solar and fossil steam production for all three sites. The highest solar share is realized in June and July while significant dumping occurs from March to May because the demand is still low compared to the good insolation. Overall the dump rate is about 6%, the solar share reaches 23.1 % for Antalya.

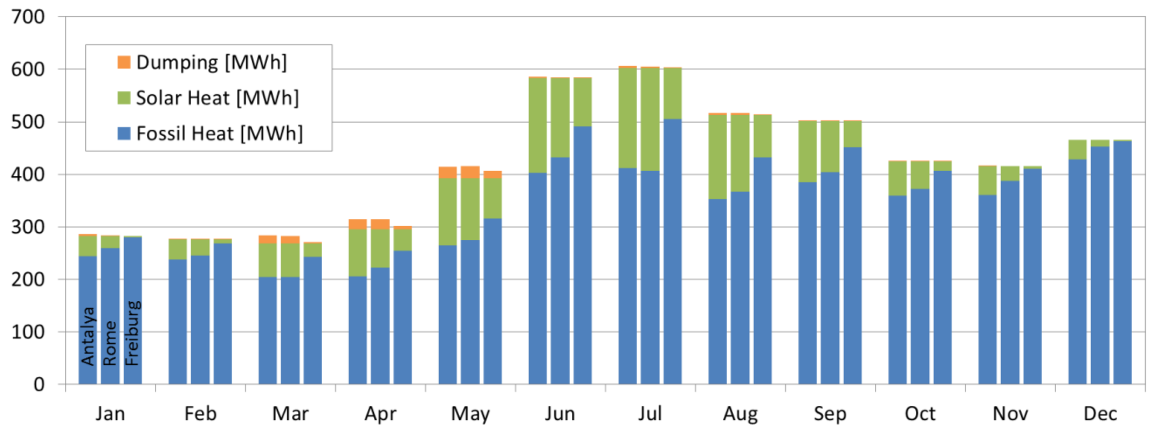

Fig 8: Monthly energy production of Concept A for Antalya, Rome, and Freiburg.

4.7. Site comparison: Economic results

In this section the economic results for the three sites (Antalya, Rome, and Freiburg) are discussed. This economic evaluation only considers the additional investment for the hybridization of the fossil steam generator which is compared with the fuel savings provided by the solar collector (66 €/MWh for the first operation year). The cost-effectiveness of the fossil steam generator itself is not investigated. A description of the used economic terms may be found in [12]. Generally, if a project is to be profitable, the internal rate for return (IRR) must be above the overall discount rate of the project and the net present value (NPV) must be greater 0.

The economic results are shown in Table 7. The high investment costs compared to fossil-based systems are disadvantageous for cost-effectiveness of solar technologies. Nevertheless, the addition of a solar field to a fossil steam generator is financially attractive even without subsidies for the two sites in Antalya and Rome. The (IRR) can reach values above 10 %. Including subsidies into the calculation also Freiburg becomes profitable and Antalya and Rome yield IRR values above 20 %.

Table 7: Cost-effectiveness of the solar hybridization of a fossil steam generator for Concept A.

Quantity	**Unit**	**Without subsidies**			**With subsidies**		
		Antalya	**Rome**	**Freiburg**	**Antalya (50% sub)**	**Rome (60% sub)**	**Freiburg (50% sub)**
Net Present Value NPV	[k€]	1008	701	-179	1483	1272	296
Payback Period	[a]	9.4	10.6	17.23	5.5	5.3	11.3
Payback Period Discounted	[a]	11.3	13.0	n/a	6.2	5.9	13.9
Internal Rate of Return IRR	[%]	11.5	9.5	2.2	21.6	22.6	8.7

4.8. Site-specific economic optimization of solar field size

The previous calculations are based on an aperture area of 1760 m² corresponding to a nominal thermal power of 903 kW which is below the minimal load demand. The investment cost of the solar field is assumed to be composed of 15 % fixed costs while the rest is proportional to the field size. Therefore, increasing the solar field size leads to lower area-specific investment costs, on the one hand, and on the other hand to more dumping, see Fig. 9. The economic optimum of the solar field size is reached when the degree of dumping over-compensates the decreasing specific solar field costs. In order to find this optimum for the 3 sites (as listed in Table 3), Greenius has been used. As seen in the economic evaluation in the previous section the return on investment of the given project mainly depends on the irradiation conditions and the investment subsidies (compare Table 7). For the calculations described in this section, subsidy ratios of existing programs in Italy (60%) and Germany (50%) are assumed while the site in Antalya does not benefit from investment incentives. As a consequence, an investment in Antalya is less attractive than in Rome even though the irradiation is better.

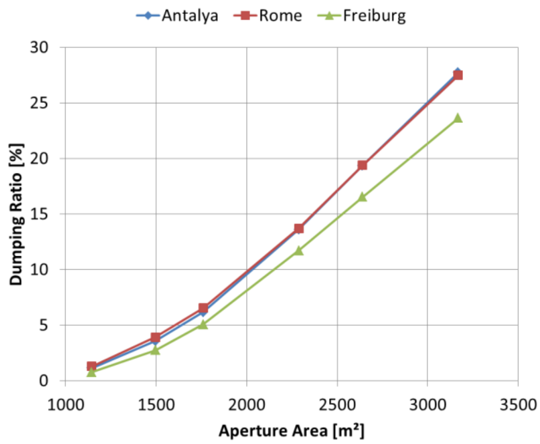

Fig. 9: Dumping ratio of Concept A as a function of the aperture area for Antalya, Rome and Freiburg.

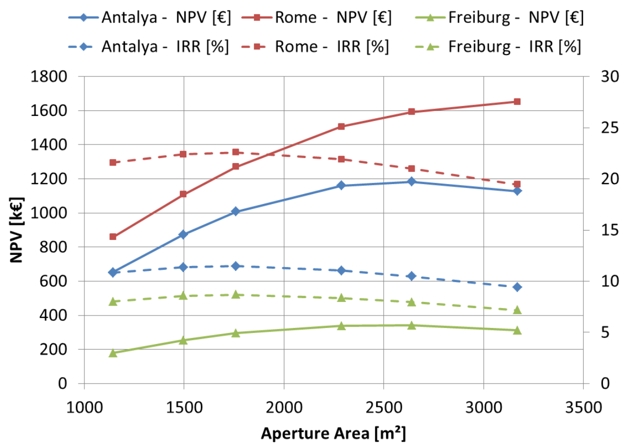

Fig. 10: NPV and IRR of Concept A over aperture area for Antalya (0% subsidy), Rome (60%) and Freiburg (50%).

Figure 10 shows the two main parameters for the economic evaluation of the project, net present Value (NPV) and internal rate of return (IRR) as a function of the aperture area for all three sites. The result of the optimization of the field size depends on the used criterion. While the IRR peaks at 1760 m² for all three sites the NPV implies not only in general bigger field sizes than the IRR criterion, but especially for sites with good irradiance and low investment costs. For Antalya, the NPV peaks at about 2600 m², for Rome above 3200 m².

The difference between the two optimization criteria can be explained by interpreting the IRR as an interest rate on the investment. The overall interest rate of the investment increases with the solar field size as long as the positive effect of decreasing specific investment costs is not yet completely compensated by the increase of the dumping ratio. Due to the similar development of the dumping ratio against the solar field size as shown in Fig. 7 the IRR peak coincides for all three considered sites. When the solar field size is increased beyond the IRR optimum the NPV increases as long as the interest rate of the added field size is still above the discount rate. The choice of the optimization criterion depends on the financial intention of the project. Decision makers without many alternative investment options and a budget that exceeds significantly the project investment will rather head for the NPV optimum. In contrast, a limited budget suggests an orientation at the IRR maximum in order to maximize the return on investment. Additionally, the amortization period is an important factor for many decision makers. Note that the minimum of the amortization period coincides with the maximum of the IRR.

Finally, it must be noted that the calculations are based on preliminary cost assumptions. The real shape of the shown NPV and IRR curves is expected to be less continuous due to technical restrictions in the dimensioning of e.g. pumps and valves.

5. Conclusion

Three solar-hybrid integration concepts have been compared qualitatively in a first step, and in a second step in a techno-economic analysis. The results show, the concept A is the preferable solution in terms thermodynamic performance, while concept C has the lowest investment costs. Since the parameters are preliminary, in this phase of project, a decision for one system cannot be taken. Instead, as an example, a techno-economic analysis has been carried out for with concept A, for the sites, Freiburg, Rome and Antalya. Furthermore, the size of the solar field has been economically optimized.

Results show, that one of the presented solar hybrid systems would not be profitable in Freiburg without subsidies. However, with a subsidy of 50 % on the capital investment, a project with acceptable economic parameters, an NPV of 296 k€ and an IRR of 8.7 % could be achieved. The same installation in Rome or in Antalya would already be profitable without subsidies. With subsidies, e. g. in Antalya an NPV of 1483 k€ and an IRR of 22 % can be achieved.

A subsequent site-specific optimization of the solar field size showed, that the size of 1760 m² of the standard configuration already yields the lowest value for the IRR. If the project is to be optimized in terms of NPV, a solar field size of 2600 m² in Antalya and 3200 m² in Rome shall be chosen.

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