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Large scale solar process heat systems - planning, realization and system operation

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Abstract

Within the FP7-InSun project three different solar process heat systems have been installed and integrated in two different industrial processes. A 1067 m² advanced flat plate collector field and a 130 m² parabolic trough system have been installed at a ham and sausage production in Austria to preheat the feed water of a steam boiler and to prepare hot water for cleaning and drying processes. A 2640 m² Fresnel collector field installed at a brick fabrication in Italy produces steam at 180°C and 12 bars to heat air for a brick drying process. In this paper the experiences made during planning, installation, commissioning and regular system operation will be described and discussed together with measured performance data. Furthermore, system costs and cost improvements reached by optimization in the collector production and standardization of system integration devices are shown and discussed together with future application potentials on the basis of detailed simulation studies carried out during the project.

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1. Introduction

The main idea of InSun was to demonstrate the reliability and quality of large scale solar thermal systems using different types of collectors (flat plate, concentrating Fresnel, concentrating parabolic trough) for the generation of heat employed in different industrial processes at different temperature levels.
Scientific and Technology Objectives (STO) of the InSun project were:

- to demonstrate the high potential and variety of solar thermal process heat
- to increasing the reliability by automated system observation and fault detection
- to reduce cost risk factors
- to provide guidelines and easy to use design tools
- to evaluate application and market potentials for different collector technologies

Two of the InSun collector systems including flat plate collectors and concentrating parabolic through collectors are installed in Austria at the company BERGER, which is dedicated to the production of cooked ham and sausages. The third solar thermal system including concentrating Fresnel collectors is installed in Italy at the brick factory Laterizi Gambettola.

All systems have been installed, commissioned and improved. For the commissioning and automated system observation new simulation and algorithm based fault detections methods have been developed and successfully applied to the solar systems installed. During commissioning several control problems and sensor errors could be detected. For the control optimization detailed dynamic simulation tools [1], [2] have been used, e.g. for the improvement of the parameterization of PID controllers. For the parabolic trough collector system of SOLERA operating as temperature booster for the flat plate collector of SOLID at BERGER, hardware-in-the-loop test (HiL) have been used by ZAFH. In this test, the real plant with its operational boundaries is dynamically simulated on a PC simulator. The laboratory HiL simulator PC has its own hardware interfaces and exchanges signals in real time with the PLC (Programmable Logic Controller). The control algorithms can be developed, optimized and validated efficiently and without safety risks. HiL tests overcome the mostly individual and costly control calibration on site. Furthermore, the controller can be tested under critical and varying conditions without safety risk. The application of this methodology significantly reduced the commissioning time.

The monitoring data for more than two years were collected and analysed for the large collector fields of InSun. The parabolic trough collector field was finalised during the last month of the project. For this system only one month of monitoring data could be collected, which was used for the advanced model based commissioning.

The handbook for planners developed within InSun summarises the experienced gained and the lessons learned during InSun and provides useful information for planners aiming to design and install solar process heat systems. For a fast check of expected energy yields the InSun SHIP easy to use internet based design tool aims to provide first useful information for different climatic conditions and system configurations.

The InSun team participated actively in the elaboration of the integration guideline within the IEA SHC TASK 49 [3]. The contribution focused on developing a decision making tool (matrix) to identify suitable integration points for solar heat. The so-called “Suitability indicator matrix” helps planners to identify good unit operations and integration levels within an existing factory.

Industrial process heat business models have been analysed and developed within the InSun project to find ways for a fast market penetration. Activities focused on the development of one-stop-shop models, ESCo models (IEA Task 45 participation [4]), promotional activities, EU and extra EU partnership development strategies, the identification of promising target application groups, price reduction potential through process optimization and incentive schemes. Based on all findings a roadmap for a fast market deployment has been developed.

2. The InSun demonstrators

2.1. Solar systems at the cooked ham and sausage producer BERGER in Sieghartskirchen, Austria

a) Flat plate collector system

One of the demonstration plants is located in Austria providing heat for the manufacture of meat products in the factory Berger. The 2013 installed 1067m² large flat plate collector system of SOLID supplies heat to a steam boiler by heating up the make-up water up to 98°C and to the hot water system for cleaning and drying processes at 60°C. Steam is used in wet and dry meat treatment processes as well as for disinfection and defreezing. A 60 m³ large hot water storage has been integrated in the system to store the solar heat over the weekends and to account for batched processes. The system was originally planned to be installed on the roof top of the production hall. However, during planning it was realised that the construction of the roof was not strong enough to bear the collector field. Strengthening would have been too expensive. Therefore, finally a free field next to the company was used. Details of the flat plate collector system are shown in Fig. 1 and Table 1 below.

Fig. 1: Solar process heat system of SOLID installed at BERGER, Austria; (a) collector field; (b) storage installation; (d) final 60 m³ storage

Three pieces of membrane expansion vessels with 1000 l each and one 1500 l intermediate vessel keep the hot medium in the solar circuit in case of stagnation. The intermediate vessel cools down the hot medium and ensures low temperatures for the membrane vessels. 6 pieces of 1000 l membrane expansion vessels are necessary to compensate volume change in the 60m³ storage tank. The system integration in the heat supply of the production processes is shown in Fig. 3.

Table 1: Data of the flat plate collector system of SOLID

Collector type		Flat plate collector	
Manufacturer		Gluatmugl	
Product	HT 12.5 export	HT 10 export	HT 7.5 export
Unitary gross area [m^2]	12.5	10.5	7.2
Unitary aperture area [m^2]	11.5	9.6	6.6
Number of collectors	68	21	1
Optical efficiency η_o [-]		0.811	
Linear loss coefficient a_1[W/m^{2}K]		2.710	
Quadratic loss coefficient a_2 [W/m^{2}K^2]		0.010	
IAM at 50° incidence angle[-]		0.96	
Effective thermal capacity [J/m²K]		7050	
Collector slope		40°	
Total aperture area of collectors [m^2]		990.2	

Main lessons learned during planning and installation:

- Roof tops of industrial buildings are not easy to use for solar systems (static, safety, other equipment)
- Good experiences with ground screw foundation (easy, fast and cost effective)
- Space required for transportation and installation needs to be planned (handling of large storages etc.)
- Hydraulic systems in industry are mostly structures grown over decades: requires experienced personal on site

b) Parabolic trough collector system

The flat plate collector system has been extended in 2015 by a 130m² parabolic trough collector field of SOLERA which operates as temperature booster for the large flat plate collector system to increase the amount of heat transferred to the steam boiler by heating up the make-up water up to 98°C. The system consists of 36 collectors with an aperture are of 122 m² in total. Concrete foundation has been used due to higher requirement on precisions. A 20 m³ hot water storage has been installed to have a higher storage capacity during the weekends and to allow load shifting towards the afternoon. The installed system is shown in Fig. 2 and details on the collector field are given in Table 2. The system integration in the heat supply structure of the production processes is shown in Fig. 3.

Fig. 2: Parabolic trough collector system installed at BERGER, Austria; (a) parabolic trough, (b) collector field, (c) 20 m³ storage

Table 2: Data of the parabolic trough collector system of SOLERA

Collector Field Layout			NORDFELD	SÜDFELD
Layout Inputs	Number of modules per row	-	8	4
	Number of rows	-	3,0	3,0
	Collector axis orientation (from N-S)	deg	80	80
	Row spacing (center-center)	m	2,75	2,75
	End spacing for piping	m	2,25	2,25
	Distance field to plantroom	m	20	20
Layout Results	Number of SMIRRO InSun collectors	-	24	12
	Total aperture area	**m2**	**82**	**41**
	Total field length installed	m	28,5	16,5
	Total field width installed	m	11,14	11,14
	Total area needed for installation	m2	317	184

Main lessons learned during planning and installation of the parabolic trough system:

- Constant communication with suppliers is very important for a short period of planning and installation
- Setting parabolic collectors in free land areas is challenging: fix them in a specific position
- Foundation of heat storage should be perfectly plumbed, consider soil type!
- Take into account pressures and temperatures of the old and the new systems to plan a smooth integration
- Hydraulic systems have to be put in the planning at the very beginning

2.2. Fresnel collector fields of SOLTIGUA installed at Laterizi Gambettola

The second demonstration site is located in Italy at the brick producing company Laterizi Gambettola SRL. Here a large Fresnel collector system of SOLTIGUA with a total collector are of 2640 m² has been installed in 2013 to produce steam at 180°C and 12 bars to heat air for a brick drying process in a steam to air heat exchanger. The solar system has been subdivided into two fields. One field with 1072 m² is operated with thermal oil and indirect steam generation and the other field with 1608 m² is operated with direct stem generation. This allows a direct comparison of the energetic and economic performance of these two options. The installations within the InSun project were carefully planned, installed and commissioned to ensure high quality systems with high system performance and stable system operation.

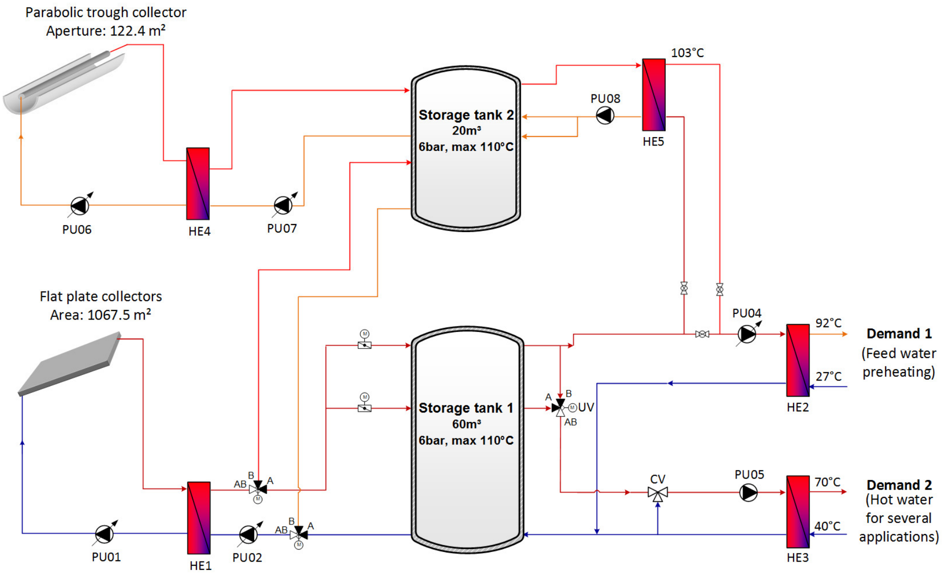

Fig. 3: System integration of the flat plate collector field of SOLID and the parabolic trough collector field of SOLERA (operated as temperature booster)

Fig. 4: Solar process heat system installed at Laterizi Gambettola SRL; (a) collector field, (b) and (c) B.O.P.'s

The production and installation of the two large collector fields was used to improve the production and the installation process which lead to significant cost reductions. Containerised solutions for the balance of plant (B.O.P.) have been developed for both systems. This helps to standardise the system installation and integration and significantly reduces the installation time and costs. Fig. 4 shows some pictures of the installed system and Fig. 5 provides some technical details. The system integration is shown in Fig. 6.

Main lessons learned during planning and installation of the parabolic trough system:

- Authorization paperwork can be very time consuming: start early!
- Involvement of key supplier (e.g. piping, civil works, balance of plant) with the main solar technology providers can save time and money
- Prefabricated container solutions for HTF (heat transfer fluid and indirect steam generation) and DSG (direct steam generation): for standardized installation
- Laboratory-like measurements are very challenging in an industrial setting. Need to use adapted validation procedures
- Pollution of mirrors: keep distance from the ground!

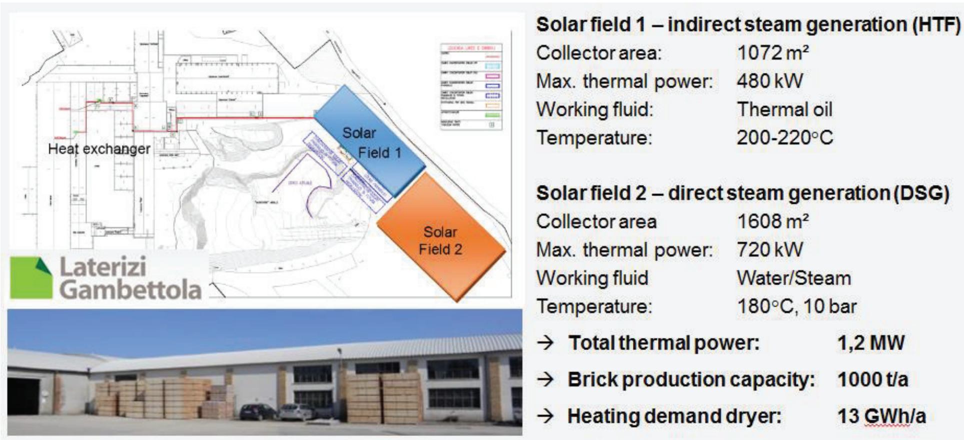

Fig. 5: Position of the two solar fields and technical data

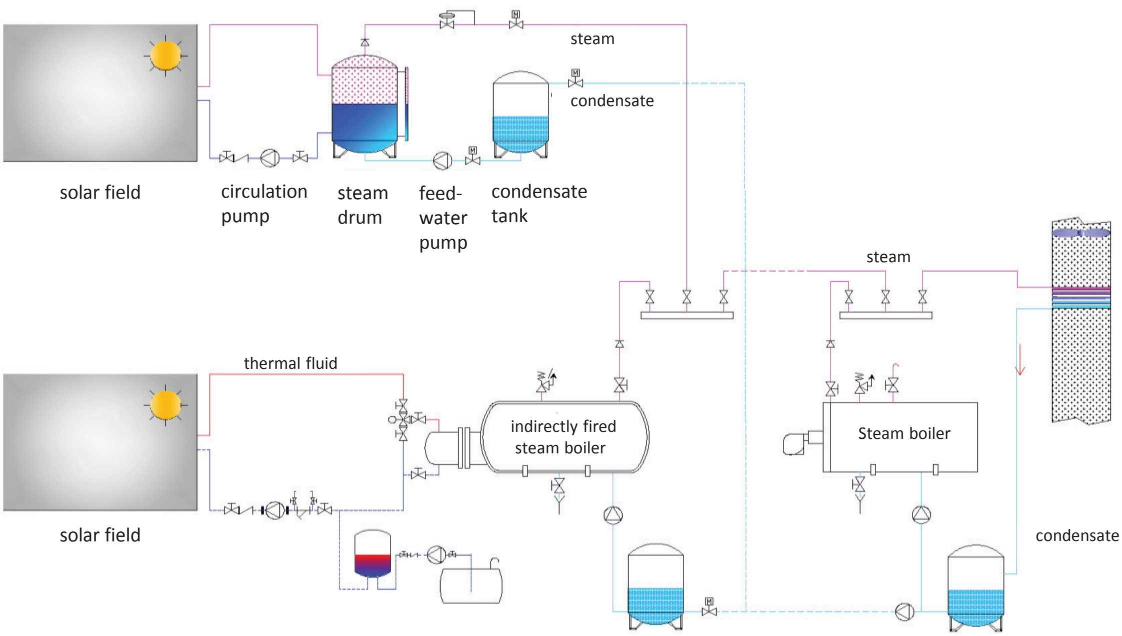

Fig. 6: Integration of the two solar fields in the brick drying process

3. Energy performance of the installed systems

3.1. Energy performance data of the flat plate collector field of SOLID at BERGER

The energy consumption at BERGER amounts annually to 10 GWh medium heavy oil (for steam generation) and 240 MWh extra light fuel oil (for hot water gerneration). Furthermore, every year 10.5 GWh of electricity are consumed. Nearly half the electricity consumption is used for cooling purposes. The compression chillers are essential for the production halls due to hygienic reasons.

The measured performance of the installed flat plate collector system is shown in the figure below on a monthly basis [5]. The graph shows the monthly amounts of specific solar irradiance (e_{rad}) on the collector plane, specific useful collector yield (e_{coll}), and specific heating energy e_{use} transferred to the production processes through the entire system, including heat exchangers and storage tank, during 2014. Around 84% of the solar gains are used for hot water preparation, while only 16 % of the solar gains are used for feed water pre-heating for the steam boiler. The figure shows that the collector utilization ratio (η_{coll}) ranges from 7% in winter to 38% in summer. The utilization ratio of the system (η_{use}) varies between 5% and 36% respectively. However, an analysis of the solar irradiance sensor, based on comparisons with a nearby weather station, showed that the measured irradiance is typically overestimated by about 20 %. While it was not possible to determine a precise correction factor to rescale all the historical data (a more detailed analysis focused on summer conditions is presented in [6]), this check suggests that the real utilization ratios are about 20 % higher than reported in the graph. The annual specific useful collector yield measured in 2014 reached 419 kWh/m²a, the specific heating energy transferred to the feed water per-heating of the steam boiler (HXf) amounts to 63.3 kWh/m²a and the specific heating energy transferred to the water heating circuit (HXh) reaches 326 kWh/m²a. The system integration losses (storage, HX and tubing) of 30 kWh/m²a, correspond to 7% of the transferred useful collector heat.

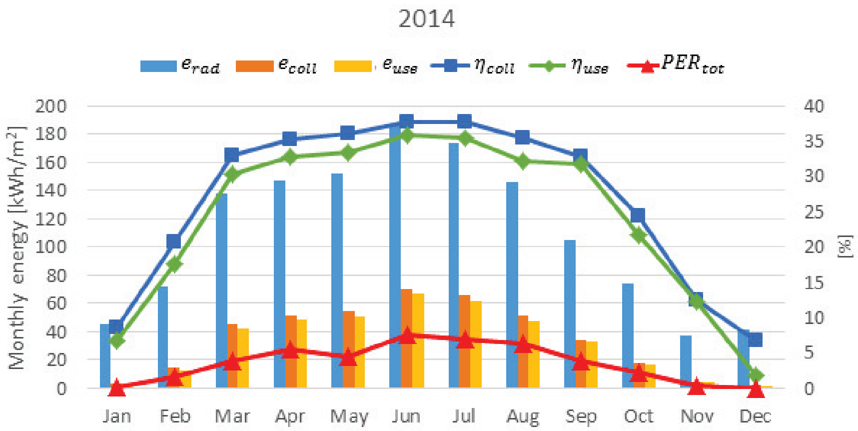

Fig. 7: Monthly performance results of 2014 for the flat plate collector system at BERGER
(η_{coll} = collector utilization ratio; η_{use} = utilization ratio of the system; e = monthly energy)

These are very good results for the installed high quality system, which has been optimized during advanced simulation based commissioning. Furthermore, different automated fault detection methods have been applied and tested on this system. The methods reach from simulation based to quite simple spectral analyses which also enable the detection of slow degradations of the performance.

3.2. Energy performance data of the small parabolic trough collector field of SOLERA at BERGER

Due to the late finalization of the installation of the small parabolic trough collector field, only some weeks of data could be collected. However, a comparison between the measured and the simulated performance showed a good agreement. Therefore, it is expected that the system reaches the simulated net annual amount of energy delivered at 110°C flow temperature and a spread of 15K, of around 31 MWh. We calculate with thermal system losses of 5% and with a plant availability of 98% of the year. Related to the collector area this corresponds to a specific value of 250kWh/m² year. A buffer- tank of 20m³ was taken into account, and two plate heat exchangers with 5K (solar) and 7K (heating) gradient. Which means a flow temperature in the makeup water circuit of 98°C can be reached. The system can deliver at a DNI of 700 W / m² a peak power of 51 kWth.

3.3. Energy performance data of the Fresnel collector field of SOLTIGUA

For the Fresnel collector fields of Soltigua with indirect (HTF) and direct (DSG) steam generation installed at Laterizi Gambettola, Italy performance data from 2014 and 2015 have been collected and analyzed in detail. It is important to note that data from 2014 have been used to optimize both the monitoring system and the management of the two solar fields. For some months of 2014, some anomalies in sensors or in operating conditions occurred. Further details on this issue are discussed in deliverable 4.7, which is provided as download on the InSun homepage (http://www.fp7-insun.eu/InSun_Main_results.html). In the graphs below only data of 2015 are shown, because they represent the normal operation of the system. During commissioning some control problems were realized leading to strong fluctuations in the steam production. These problems were analyzed in the simulation environment and then optimized. Now the two systems operate very well without these control problems.

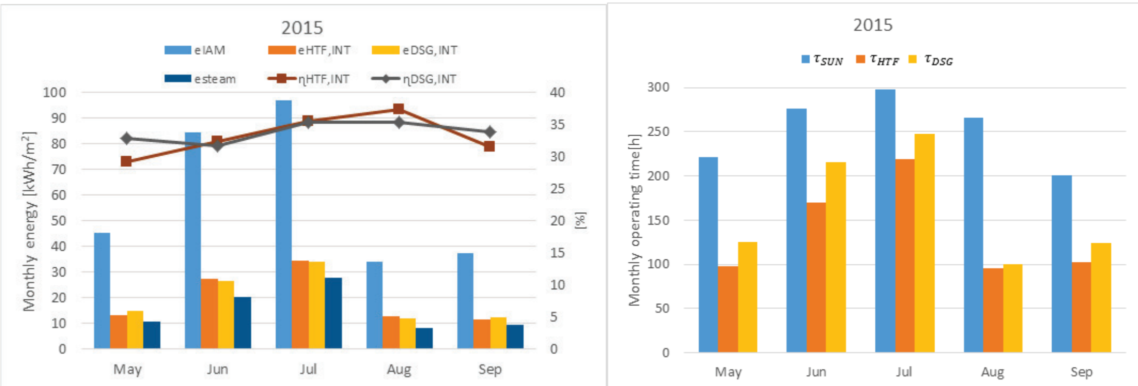

Fig. 8: left part - Specific energy outputs and related quantities by month (May-September 2015) right part - Monthly daylight hours and monthly operating times for HTF and DSG fields. ($\eta_{HTF,INT}$= HTF sub-field efficiency with respect to IAM-modified irradiation; $\eta_{DSG,INT}$= DSG sub-field efficiency with respect to IAM-modified irradiation; e = monthly energy / solar radiation; τ = monthly operation time / sunshine duration)

As visible from the two graphs there is no clear winner in the comparison between DSG and HTF field. Data from January to April 2015 are not shown, as the separated or discontinuous operation of the two fields makes them not suitable for presentation with this type of filtering. In August and September the system was not operated always continually due to holiday reasons. The collector efficiency reached is quite high and varies between 30 and 37%. This is a very good result for the given climatic conditions.

4. Economic performance of the solar systems

4.1. Comparison of system costs for Fresnel collector systems for direct and indirect steam generation

Within InSun, both indirect and direct solar steam generation have been experienced and tested in the same installation site. As shown in chapter 3.3. the analysis of the monitoring data indicates that the performance of the two systems is comparable within a +- 5% range which is in the range of the measurement accuracy. The graphs below show the trends of the main cost items (in terms of € vs. net collecting surface of the solar field) of concentrating solar power plants for the generation of direct (DSG) and indirect steam (HTF). As all other costs are the same, the specific differences result from the cost of the containerized Balance Of Plant (B.O.P.) and in the solar field piping costs. As shown in the Fig. 9, the B.O.P. for indirect steam generation (HTF) is more expensive than that of the DSG. On the other hand the costs for the collector tubing are significantly higher for DSG due to the higher pressure. If these two cost groups are added there is nearly no difference between both systems visible. Therefore, also on the system cost side no clear winner was found between HTF and DSG.

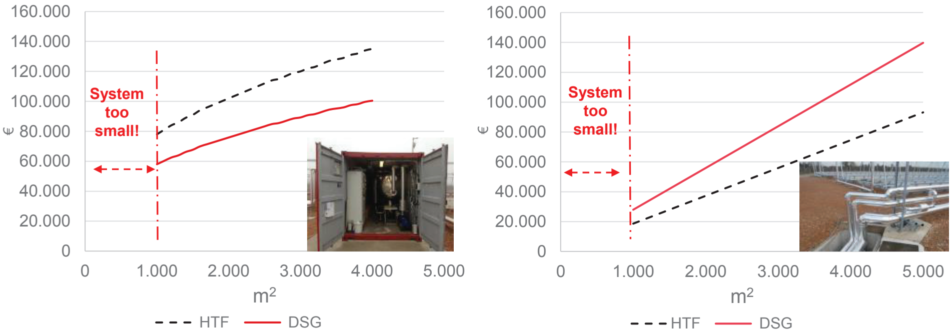

Fig. 9: Cost comparison (a) B.O.P and (b) collector tubing for indirect (HTF) and direct (DSG) steam generation

4.2. Comparison of collector system costs of different collector technologies

Based on the detailed system design, an indicative cost curve has been developed for each target group. The figure below shows three cost curves in the same chart, to carry out a comparative analysis also in terms of cost comparison – a unique opportunity to the InSun project, thanks to the fact that it makes use of three different solar technologies generating both hot water and steam. The reported data should be considered subject to a variation up to 20%. As can be seen from the figure system size is a major driver for cost reduction (combined with the fact that larger systems also deliver higher yields): large systems are the key to the successful development of solar process heat. The figure also enables us to see how the technical development started within the InSun project has enabled the Fresnel technology to reach a pricing level per m^2 similar to the one of the flat plate technology for hot water. This should not be taken as a full comparison in terms of Levelized Cost of Energy (LCOE), because—for example—the annual output of Fresnel for steam generation is less than the annual output of flat plate for hot water generation. Moreover, the 20% variation of system cost due to local conditions can impact significantly the LCOE.

4.3. Impact of available support schemes to achieve low enough payback times

A detailed cost analysis has been carried out within InSun to identify heating energy costs and payback times under consideration of national incentive schemes for solar process heat systems which are available in e.g. Germany, Italy and France. The following cases have been regarded for Fresnel collectors more in detail: Case 1 refers to the current market conditions in Sardinia, i.e. a South EU case, which is more relevant for solar concentrating collectors. Case 2A and 2B refer to the detailed study for a process steam application in South Africa in the textile sector. Table 3 shows that the introduction of incentives in Italy can reduce the nominal payback time to values comparable to the ones of high potential Extra EU countries. Without incentive schemes the payback time would be 17 years instead of 7 years. For flat plate collectors, a big influence on the net thermal energy yield by the solar thermal plant is the collector mean temperature (Row #4). The lower the average collector mean temperature, the higher the solar yield. The collector mean temperature is assumed with 60°C in each case, so that all 3 cases are comparable.

In Case 2B (Aruba) the customer only needs process heat 5 days a week, on weekends there is no heat sink available. Therefore, an additional storage tank with 60 m³ is included, to use the whole solar radiation over the whole week. The storage tank is included in the Investment costs (see row #8) with 30 EUR/m² (the rest of the cost in Palermo are similar to the ones in Graz). The Extra EU solar plant is quite large with 4000 m² instead of the other two cases with 1000 m². The bigger size leads to lower specific investment costs because of economy of scale.

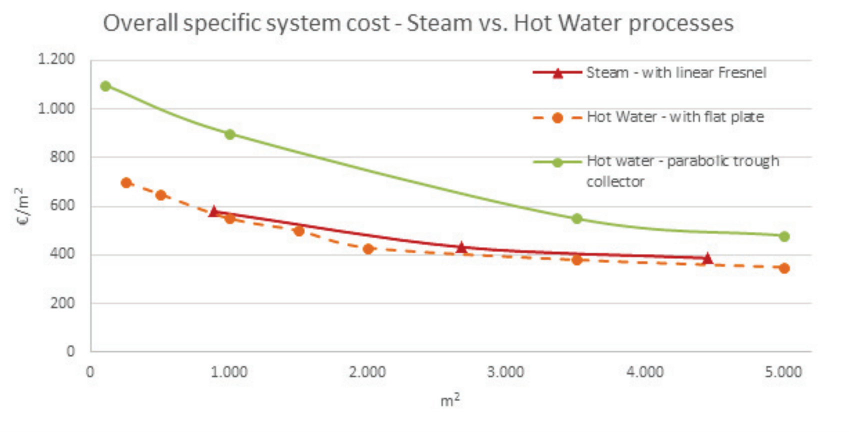

Fig. 10: Comparison of unit costs of solar steam systems with linear Fresnel collector vs. solar hot water systems with flat plate collectors and Parabolic trough collectors

All in all, also taking into account the choice to keep comparable temperature and heat value levels, Table 4 shows the importance of the following 2 parameters for the economic potential of the solar plant - size of collector field and global solar radiation. The additional costs of the storage tank also influences the payback period slightly. In Table 4 below the Austrian support scheme for flat plate collectors for the case "Central EU – Graz" has been considered, with a reduction of the investment cost of 45 % which is valid if the customer is a small or medium sized enterprise. The payback time of almost 12 years shows, that the potential in the Caribbean or in South Europe is still much higher, simply for the reason that there is much more solar radiation available. As it has been presented for the flat plate collectors, the coming table shows some examples for parabolic trough collectors in different cases in which the payback time change in relation to actual conditions for solar process hot water.

Table 3: Impact of 60% incentive scheme on South EU case vs. extra EU case

			Case 1	Case 2A	Case 2B
1	Location		South EU	Extra EU	Extra EU
2	Solar radiation available (DNI)	kWh/m2/yr	1.892	2.300	2.300
3	Gross thermal output of collectors	kWh/m2/yr	746	897	897
4	Net thermal energy yield potentially available to process	kWh/m2/yr	663	791	791
5	Days/week		6	5	7
6	Net thermal energy yield actually used by the process	kWh/m2/yr	568	565	791
7	Thermal energy value	€cent/kWh	4,5	6,9	6,9
8	Economic yield	€/m2/yr	26	39	55
10	Investment cost - total	€/m2	173	376	376
12	Payback time - total	Yr	6,8	9,6	6,9
13	Net collecting surface	m2	2.673	1.782	1.782

Table 5 represents three different case studies analysed in three different countries. Case 3 refers to a project in Central EU evaluated in Lyon (France), case 3A is an extra EU project located in Palestine and case 3B is evaluated in Murcia (Spain). The cases where analysed by SOLERA, with the oil and gas prices that the clients were paying for conventional system technologies. Compared to the other type of technologies, the situation for the parabolic trough collector is similar regarding the variability of the situations when considering different locations and projects. Every case has to be in detail studied in order to optimize the planning of the installation, so that the most of the generated energy is used and no additional costs are included due to a bad planning. Table 5 shows that the DNI is different in every location, which results in a better yield in those cases in which the DNI is higher. Payback times without incentives vary between 25 years in central EU and 9 years in EU. This highlights that concentrating collectors need locations with high DNI.

Table 4: Impact of 45% incentive scheme on Central EU case vs. extra EU case

Location		Central EU	Extra EU	South EU
		Graz	Aruba	Palermo
Global solar radiation (clear + diffuse)	kWh/m²year	1160	2171	1722
Days/week		7	5	7
Storage Tank	m³	-	60	-
Collector mean temperature	°C	60	60	60
Net thermal energy yield used by the process	kWh/m²year	485	1070	919
Thermal energy value	€cent/kWh	4.5	6.9	6.9
Economic yield	€/m²year			
Investment cost - Total	€/m²	258.5	380	470
Payback time - Total	years	11.8	5.1	7.4
Collecting surface	m²	1000	4000	1000

Table 5 Yield and payback time calculation for selected cases with concentrating collectors

Location		Case 3	Case 3A	Case 3B
		Central EU	Extra EU	South EU
Solar radiation (DNI)	kWh/m²year	1330	2255	1924
Days/week		5	5	7
Storage Tank	m³	20	20	30
Net thermal energy yield used by the process	kWh/m²year	596	838	772
Thermal energy value	€cent/kWh	3,7	5,2	8
Investment cost - Total	€/m²	550	480	550
Payback time - Total	€/m²	25	11	9
Collecting surface	m²	2700	5000	2040

Table 6 addresses the impact of available incentives on parabolic trough collectors. If the current subsidies from France are considered, with a range of between 45% and 65% of incentives in the investment cost, the payback time drops from 25 years to 14 years (45% incentives) and 9 years (65% incentives). The best result is given with the reduction of the investment cost in 65%, which is close to the subsidy given in Italy. This shows that for central EU countries the introduction of these incentives can make the payback times comparable to extra EU countries with higher solar radiation.

Table 6: Impact of 45-65% incentive scheme on Central EU case vs. extra EU case

Location		Lyon	
		45%	65%
Global solar radiation	kWh/m²year	1330	1330
Days/week		5	5
Storage Tank	m³	20	20
Net thermal energy yield used by the process	kWh/m²year	596	596
Thermal energy value	€cent/kWh	3,7	3,7
Investment cost - Total	€/m²	302,5	192,5
Payback time - Total	€/m²	14	9
Collecting surface	m²	2700	2700

5. Conclusions

The InSun project has demonstrated the reliability and quality of large scale solar thermal systems for different types of industrial process heat applications on low and medium temperature level. This has been achieved by the successful implementation of three different demonstration systems which make use of three different collector technologies.

The InSun demonstration project has provided a strong platform of facts and figures to support confidence in this technology. In particular, by the end of the project three different installations were completed and two of these three installations have been in operation for more than two years each, with performance data duly registered in monthly monitoring reports. Significant cost reduction has been achieved in the course of the project at least for concentrating solar collectors, which makes it possible to achieve the targets of the European Solar Thermal Technology Platform of about 400 € per m² collector area. It has been found that system size is a major driver for cost reduction (combined to the fact that larger systems also deliver higher yields): large systems are the key to the successful development of solar process heat.

The successful implementation within InSun has also proved that – despite of the fact that solar process heat has not reached its full industrial maturity yet - it is possible to provide one stop shop business models for this type of technology. Market deployment activities have highlighted a higher than expected difficulty in achieving early sales, also due to the strong unexpected fall of oil prices, which have reduced the convenience of the technology. More specifically, the oil price decrease of nearly 40% during the course of the project (2012 - 2015) has made it difficult to offer the expected payback time of about 10 years without any incentive within European states. To adequately support the EU target RES increase for solar thermal within the EU 27 countries adequate financial incentive schemes or regulations on the minimum amount of renewable energy fraction on the heating energy demand in the industry (similar to the renewable energy law in Germany) should be designed and implemented. Moreover, the InSun project has shown that extra EU countries have in some selected cases a higher potential for the implementation of this technology. This suggests the inclusion of adequate support mechanisms to support the implementation of EU-supplied solar process heat systems in those countries and to account them as part of EU's efforts for solar thermal targets. All technical reports of the InSun project can be downloaded from the homepage at http://www.fp7-insun.eu/InSun_Main_results.htm.

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