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Technical assessment of a concentrating solar thermal system for industrial process steam

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Abstract

The aim of this study is to present a techno-economic assessment of a concentrating solar thermal system for steam production for a food industry located in Kalamata, Greece. The solar system mainly consists of the parabolic trough collectors, the steam generator and the thermal oil storage.

Initially, the potential hydraulic configurations of the system were demonstrated and evaluated. Following a thorough evaluation of a series of parameters, the most appropriate one was selected for analytical energy simulation. Energy simulation was performed with the Greenius software; the outcome of the simulations leads to measurable indicators of the overall system performance. The energy results of the selected system were presented in details followed by a parametric analysis modifying important system variables. The last section of this study provides technical conclusions accompanied with recent economic figures.

Present study aims to further assist the penetration of such systems to a market which is still under development in Greece.

Keywords: Concentrating solar thermal system, parabolic trough collectors, industrial process heat, solar steam

1. Introduction

Worldwide, 66% of heat is generated by fossil fuels and 45% of that is used in industry as process heat (European Union, 2013). At European level, 27% of total energy concerns heat consumed by industries. 30% regards temperatures below 100 ^{o}C, 27% temperatures in the range of 100 - 400 ^{o}C and the remaining 43% at higher temperatures (European Commission, 2009).

The efficacy of solar thermal systems in applications other than hot water production i.e. process heat and solar cooling has already been presented in former studies (Tsekouras et al., 2014; Tsoutsos et al., 2009; Drosou et al., 2009). However solar heat for industrial processes still presents a quite modest share of about 88 MWth installed capacity (0.3% of total installed solar thermal capacity, at European level) (Ecoheatcool, 2006). Solar thermal systems are considered to be cost effective mainly in low temperature applications. Moreover, at a European level there is intense research activity to broaden the applications of solar thermal systems beyond their established domains and to foster their participation in the energy maps of the EU-Member States.

The Concentrating Solar Thermal (CST) systems are expected to play a key role in this effort, especially for medium temperatures needed for industrial applications. The CST systems use a combination of mirrors or lenses to concentrate the direct irradiation radiation to produce heat. The most mature CST technologies are the parabolic trough collectors, the central receivers and the linear Fresnel collectors.

Greece is identified as one of the world-leading countries in the use of solar systems for hot water production presenting one of the highest ratios in the installed solar thermal collector area per capita. The main solar thermal product was, and still is, the thermosiphon water heater, comprising of flat plate collectors and

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storage tank. From the early 1990s to the present, several successful solar thermal systems for industrial process heating applications have been in operation in Greek industries; however, they are limited to flat plate solar systems, mainly due to the low level temperatures for hot water production. Among the industrial applications in Greece food industry, textiles, chemical industry and beverage industry are identified as presenting significant amounts of heat needs at a medium temperature level. As the industrial heat in Greece is produced by costly and polluting use of fuels (heavy oil, natural gas, fuel oil) this sector is ideal for solar thermal systems in terms of technical, environmental and economic feasibility. Apart from that, the climate change and the rising trend in energy costs require sustainable solutions that may use the domestic high solar potential.

2. Description of industrial user

For the purpose of the study, an existing industry was chosen, whereas the CST system will support the production steam needs. The industry is a food process industry situated in Kalamata, Greece. The production schedule requires energy throughout the year, seven days per week from 07:00 to 18:00, as depicted in Fig 1.

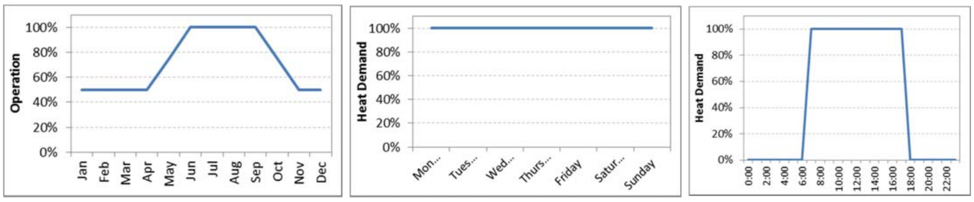

Fig 1: Time profile for year, week and day operation

Currently, the thermal energy requirements are covered by a conventional steam oil boiler with the technical characteristics summarised in Table 1.

Table 1 : Technical characteristics of the existent energy system

Description	Value
Steam temperature	170 ^{o}C
Steam pressure	7 bar
Steam supply	700 kg/hr
Annual energy consumption	1.554 MWh p.a.
Oil boiler efficiency	75 %
Annual oil consumption	207 tn p.a.

The meteorological data for the Kalamata site is extracted from the Meteonorm software, having a reference period from 1986 to 2005. The concenetrating solar collectors use only the Direct Normal Irradiation (DNI) which accounts for the specific site to 1,923 kWh/m^2 per year.

The DNI monthly distribution shows high mean daily values of approximately 8.7 kWh/m^2 during the summer period and low values of 3.1kWh/m^2. Fig 2 shows the distribution of DNI during a summer day.

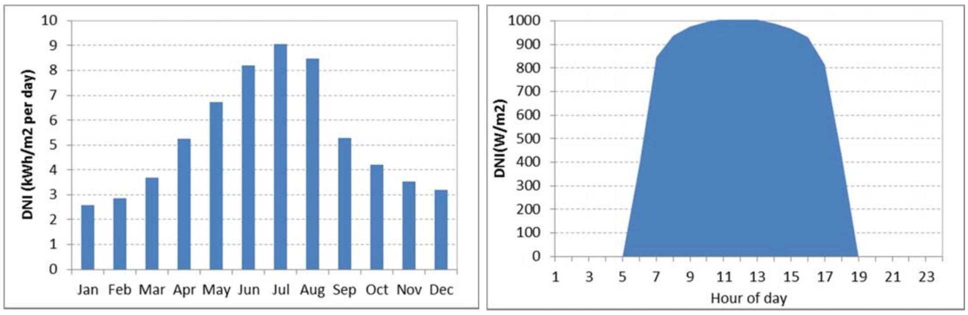

Fig 2: DNI distribution per month (left) and per hour of a summer day (right)

Fig 3 shows the number of hours during a calendar year when the irradiation exceeds a specific level. As such it can be noticed that, out of the annual 8760 hours the 1957 hours have DNI level higher than 500 W/m^2. This duration is a quite important factor for the annual system performance of a concentrating solar system considering that high radiation levels are provided during a significant part of the year. DNI of 500W/m^2 can be deemed as general threshold for CST plants operation. In this sense the optimum regions for CST plants are those with high levels of DNI occurred in long time in daily and yearly basis.

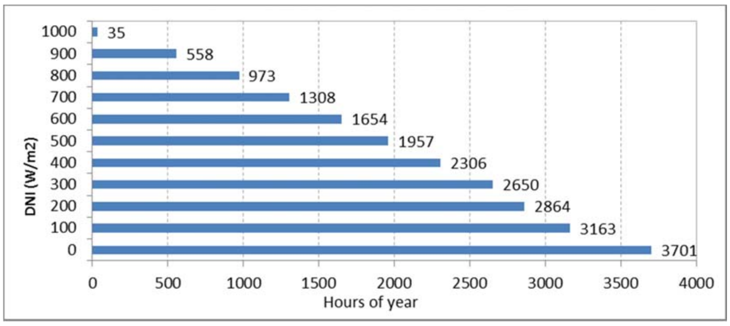

Fig 3: Annual distribution of hours for specific DNI irradiation levels.

3. Solar system configurations for industrial applications

In the following section, three suitable solar configurations for steam production using the solar system in parallel with the conventional one are examined. The parabolic trough collectors can operate either with thermal fluid (indirect steam production) or with two phase water (direct steam production).

3.1 Configuration C1: Indirect steam production via parabolic trough collectors with liquid thermal fluid and no storage

Starting from the concentrating solar collectors, the parabolic mirrors track the sun in one axis in order to concentrate the solar irradiation into the linear receiver located at the focal line. The receiver converts the concentrated irradiation to useful heat raising the temperature of the liquid thermal fluid which is circulated inside the receiver pipe. The thermal fluid, in higher temperature now, transfers its solar heat to the water in the steam boiler. When the produced steam reaches the required conditions, the steam is supplied to the thermal processes. If the solar system supplies less steam than the required amount, the conventional steam boiler covers the remaining requirements.

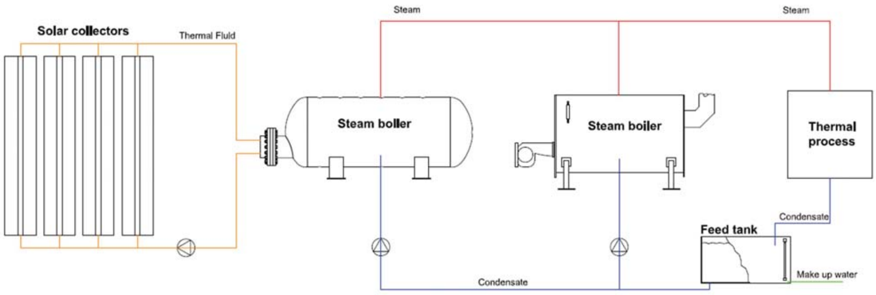

Fig 4: Configuration C1 -Indirect steam production via parabolic trough collectors with liquid thermal fluid and no storage

3.2 Configuration C2: Indirect steam production via parabolic trough collectors with liquid thermal fluid and thermal storage

This configuration is similar to C1, with only difference the integration of a thermal energy storage to the system which aims to exploit better the solar heat especially in cases when the solar heat flows are higher than the required. In this way, when appropriate sun conditions exist the thermal fluid is circulated at the parabolic trough collectors absorbing heat. Then the heated up thermal oil is stored at the thermal energy storage. In case of steam demand, the thermal fluid from the storage drives the steam boiler. In this way the energy supply and demand are decoupled to some extent.

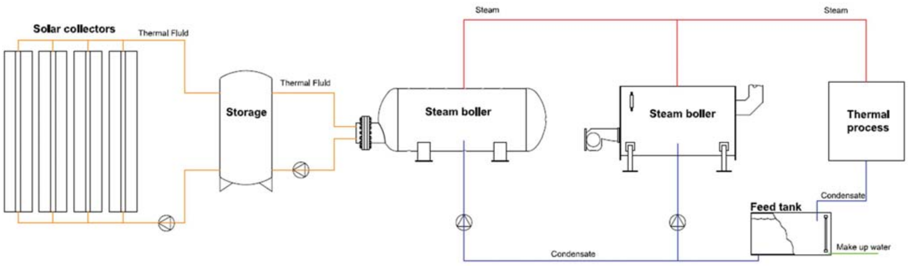

Fig 5: Configuration C2 - Indirect steam production via parabolic trough collectors with liquid thermal fluid with storage

3.3 Configuration C3: Direct steam production via parabolic trough collectors

This is the simplest configuration since it does not have additional steam boiler and storage system. Instead of a liquid thermal fluid, the two phase water is circulated inside the receiver pipes. In brief, the water passes through the first part of the solar collectors and it is heated up to the saturated liquid point. When it passes through the second part, the heated up liquid water starts boiling and being converted to steam and then to superheated steam. The produced steam enters directly the steam network and heads to the consumption.

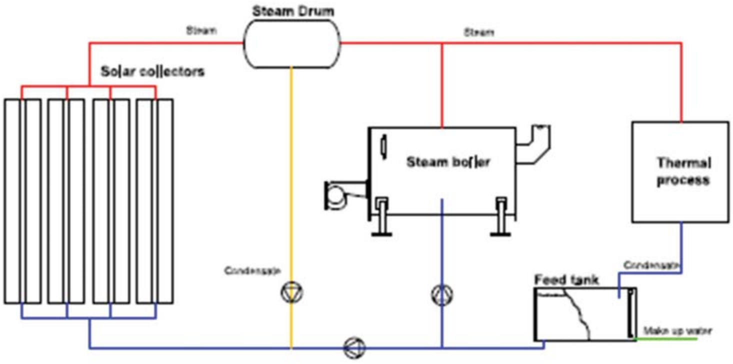

Fig 6: Configuration C3 - Direct steam production via parabolic trough collectors

4. Methodology

The initial scope of this study is present a proposal for implementation of a CST system in the industrial sector. Specifically, an integrated CST using parabolic trough solar collectors is discussed, used to support the steam production for a food industry located in Kalamata, Greece.

The Configuration C2 was selected for the purpose of this study as it combines the following advantages: good heat transfer characteristics, modest cost of heat transfer medium, lower operational pressure of solar system and commercial maturity. This section presents the technical characteristics of the major system components. In the present study, the below system case is used as the base scenario for the parametric analysis.

The technical characteristics and efficiency curves of the parabolic trough collector are summarized in Table 2 and Fig 7. The solar field consists of 80 solar collectors with reflective area of 1,056 m^2. The solar collectors are aligned in 8 parallel series with North – South orientation and 10 collectors in series. The optical losses due to dust in the mirrors are assumed to be 3% all year long, taking into consideration a regular cleaning and maintenance schedule.

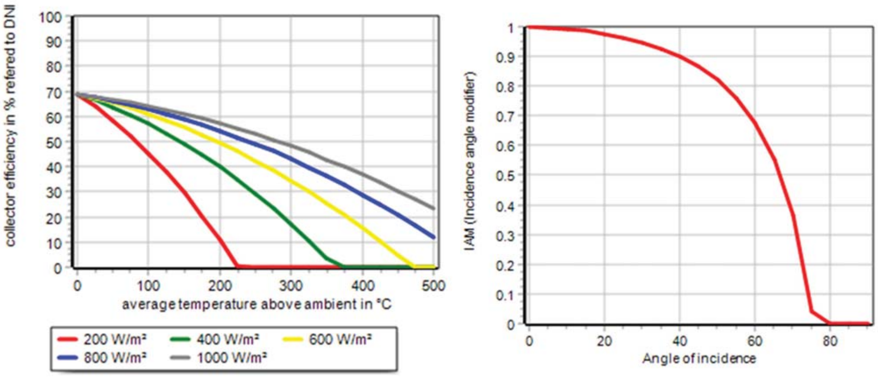

Fig 7: Efficiency curves of the parabolic trough collectors

Table 2 : Technical characteristics of the parabolic trough collector

Description	Value
Aperture width	2.3 m
Collector length	5.75 m
Effective mirror area	13.2 m^2
Receiver diameter	0.0508 m
n_o	0.689
a_1	0.36 $W/(m^2K)$
a_2	0.0011 $W/(m^2K^2)$
Number of collectors / rows / collectors per row	80 / 8 / 10
Orientation	North - South
Total effective mirror area	1056 m^2
Total absorber length	460 m

For the selected configuration, a specific type of thermal oil has been selected for the solar field that meets the following prerequisites: liquid state in the operational temperature range, low freezing point, good heat transfer, thermal stability, non-corrosive, low initial cost. As the parametric analysis included operation of the solar field in temperature up to 350°C the selected thermal oil has the following characteristics. In the base scenario the thermal oil supply temperature from the solar collectors is 250°C with returning temperature of 200°C.

Table 3 : Properties of the thermal oil

Temperature (oC)	Density (kg/m^3)	Heat capacity (Wh/kg.K)
65 / 255 / 355	1023.7 / 854 / 734	0.4725 / 0.6197 / 0.712

The thermal storage is a single tank with volume of 10 m^3 corresponding to thermal storage capacity of 250kWh in the range of 200-250°C.

Table 4 : Technical characteristics of the thermal storage

Description	Value
Thermal energy capacity	250 kWh
Operational temperature range	200 - 250 °C
Storage volume	10 m^3

Tank material	Stainless steel
Insulation material	Mineral wool 100kg/m^3
Insulation thickness	50 cm

5. Results and Discussion

5.1 Methodology

The energy study is conducted with the software Greenius (Greenius, 2016), considering the simulation algorithm as shown in Fig 8. . In brief, the simulation starts by reading the climate data (i.e. DNI, ambient air temperature, sun position) of the specific location. The climate data along with the characteristics of the parabolic trough collectors (i.e. solar module characteristics, efficiency coefficients, incidence angle modifier), the solar field (i.e. number of modules, orientation, series distance, operating temperature, piping characteristics) and the thermal storage result in the potential solar heat gains from the solar collectors. This heat is divided in the heat losses and the useful solar field heat. The later can be exploited by the end user (useful solar heat) in order to cover the energy requirements. Still, there is a small portion of the solar field heat that owing to time and load restrictions cannot be utilized (dump solar heat). The heat load is calculated based on the energy profile of the end user. When the solar system cannot meet the full energy demand, the auxiliary boiler is activated supplying the extra heat required.

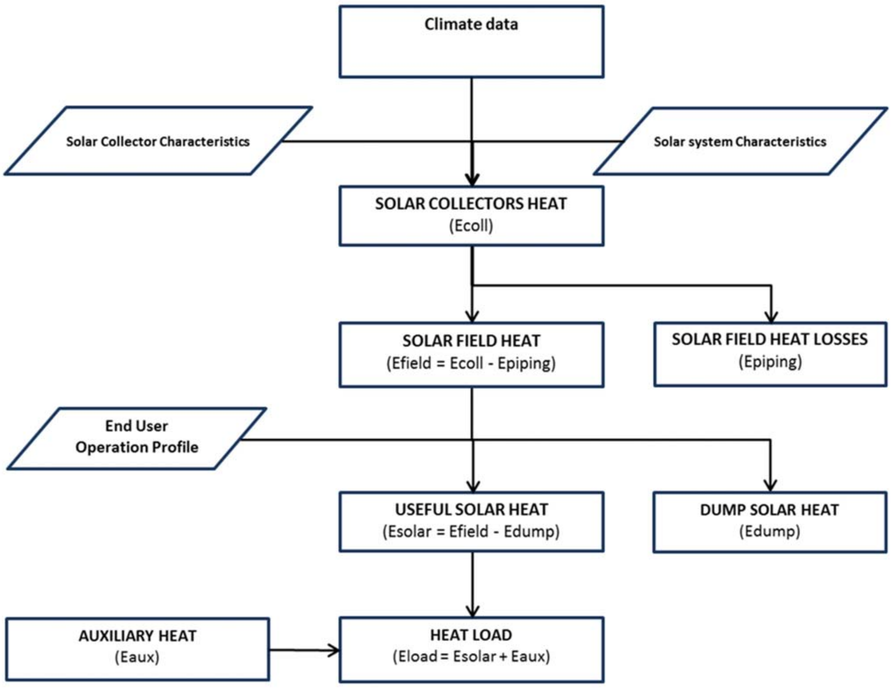

Fig 8: Algorithm for energy simulation of the system

5.2 Energy results

For the specific dimensioning and configuration that analyzed in the previous sections, the simulation energy results are presented below. The graphical representation of the direct normal irradiation (DNI) annual variation, the heat produced by the solar collectors (Ecoll), the solar collectors efficiency ($\eta_{\_coll}$), the solar heat produced by the solar field (Efield), the dump energy (Edump), the useful solar heat of the solar plant (Esolar = Efield – Edump), the solar field efficiency (η_field), the overall solar fraction (RF) and the heat load (Eload) variation are shown in Table 5, 6, 7 and Figure 9 & 10.

Table 5: Summary of energy simulation results

Parameter	**Value**
Direct Normal Irradiation (DNI)	2 031 MWh
Solar collector heat (Ecoll)	739 MWh
Solar collectors efficiency (n_coll)	36 %
Useful solar heat (Esolar)	655 MWh
Solar Fraction (SF)	42 %
Oil saving	87 333 lt
Reduction of CO_2 emmissions	213 960 kg

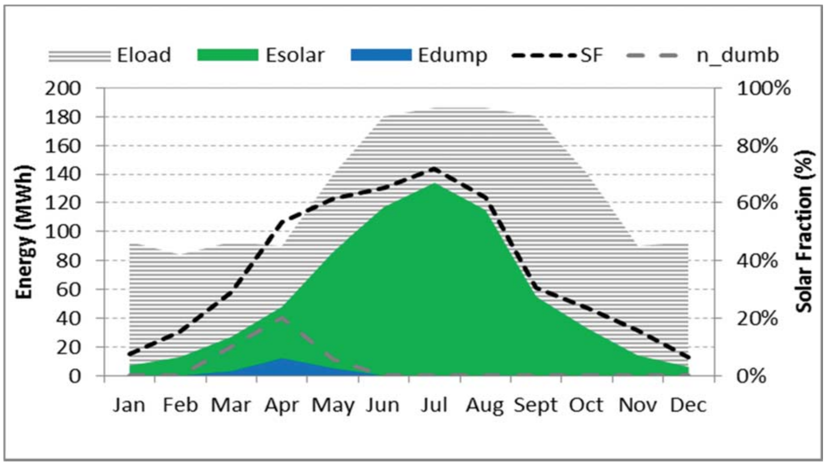

Fig 9: Overall system energy performance

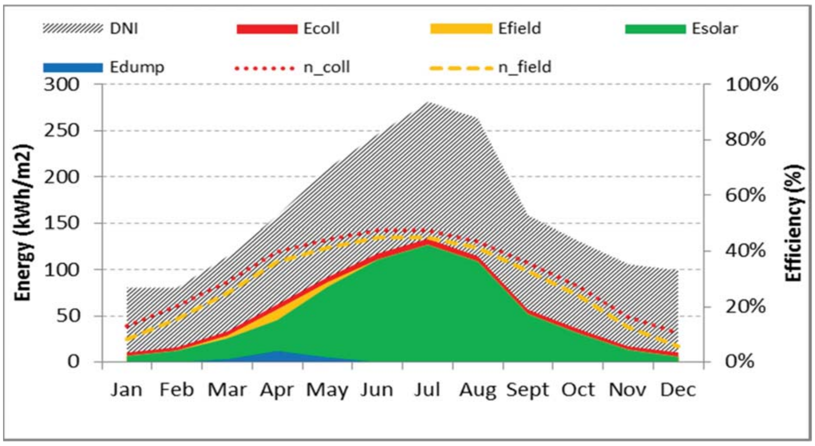

Fig 10: Solar field energy performance

The annual solar irradiation is 2,031 MWh (or 1,923 kWh/m^2), with the solar collectors being able to produce at maximum 739 MWh (700 kWh/m^2) of heat operating with an annual efficiency of 36%. Given the heat losses and the thermal inertia of the solar system, the available solar field heat (Efield) is at maximum 675 MWh (639 kWh/m^2). Moreover, owing to the mismatching of the supply and demand, a small portion of the solar heat cannot be exploited (Edump) and therefore the final heat supplied to the end user (Esolar) equals to 655 (620 kWh/m^2). The solar system achieves solar fraction (SF) of 42%, with the energy savings corresponding to oil savings of 87 tn per year and CO_2 emissions of 213tn.

Table 6 summarizes the energy results in monthly base.

Table 6: Energy simulation results in monthly basis (part I)

	Direct Normal Irradiation	**Solar collector heat**	**Solar field heat**	**Dump solar heat**	**Useful solar heat**	**Auxiliary heat**	**Heat load**	**Solar fraction**
	DNI	Ecoll	Efield	Edump	Esolar	Eaux	Eload	SF
	MWh	MWh	MWh	MWh	MWh	MWh	MWh	-
Jan	85	11	7	0	7	86	93	8%
Feb	84	17	13	0	13	71	84	15%
Mar	121	35	30	3	27	66	93	29%
Apr	166	66	60	12	48	42	90	53%
May	220	97	91	5	86	54	140	61%
Jun	260	124	117	0	117	63	180	65%
Jul	297	141	134	0	134	52	186	72%
Aug	278	121	115	0	115	71	186	62%
Sep	167	60	55	0	55	125	180	31%
Oct	138	38	33	0	33	106	140	24%
Nov	111	18	14	0	14	76	90	16%
Dec	104	11	6	0	6	87	93	6%
Year	2031	739	675	20	655	899	1555	42%

Table 7: Energy simulation results in monthly basis (part II)

	Direct Normal Irradiation	**Solar collector heat**	**Solar field heat**	**Dump solar heat**	**Useful solar heat**	**Solar Collectors efficiency**	**Solar Field efficiency**	**Solar System efficiency**	**Percentage of dump solar heat**
	DNI	Ecoll	Efield	Edump	Esolar	n_coll	n_field	n_solar	n_dump
	kWh/m^2	kWh/m^2	kWh/m^2	kWh/m^2	kWh/m^2	-	-	-	-
Jan	80	10	7	0	7	13%	8%	8%	0%
Feb	80	16	12	0	12	20%	15%	15%	0%
Mar	115	33	28	3	26	29%	25%	22%	10%
Apr	157	63	57	11	45	40%	36%	29%	20%
May	208	92	86	5	81	44%	41%	39%	5%
Jun	246	117	111	0	111	48%	45%	45%	0%
Jul	281	134	127	0	127	47%	45%	45%	0%
Aug	263	115	109	0	109	44%	41%	41%	0%
Sep	158	57	52	0	52	36%	33%	33%	0%
Oct	131	36	31	0	31	28%	24%	24%	0%
Nov	105	17	13	0	13	16%	13%	13%	0%
Dec	98	10	6	0	6	11%	6%	6%	0%
Year	1923	700	639	19	620	36%	33%	32%	3%

5.3 Parametric analysis

The solar system of the previous paragraphs has been used as the base scenario for each parametric analysis as a result of the 35 cases that were examined and analyzed in

Table 8.

Table 8: Variables of parametric simulations

Variable	Minimum	Maximum	Step	Number of simulations	Value of base scenario
Orientation of the parabolic trough collectors	0°	90°	10°	10	0°
Outlet temperature from the solar collectors with constant DT =50K	225 °C	350 °C	25°C	6	250°C
Outlet temperature from the solar collectors with constant inlet temperature of 200°C	225 °C	350°C	25 °C	6	250°C
Solar aperture area	500	2,000	250	7	1056 m^2
Series distance expressed in multiples of the collector aperture width	1	4	0,5/1	6	2.5

5.3.1 Variable 1 - Orientation of the parabolic trough collectors

In this parametric set, the effect of the orientation of the parabolic trough collectors at the system energy performance was investigated. In total 10 cases were simulated from the North-South orientation to the East - West with a step of 10° field rotation.

The optimum orientation is the North – South with annual solar field heat accounts for 639 kWh/m^2 and solar system efficiency of 33%. Deviations up to 20° in the orientation result in small reduction in the system efficiency up to 3%. The reduction is evident in cases with deviation from 30° up to 90° (East-West) in which there is 27% less heat production.

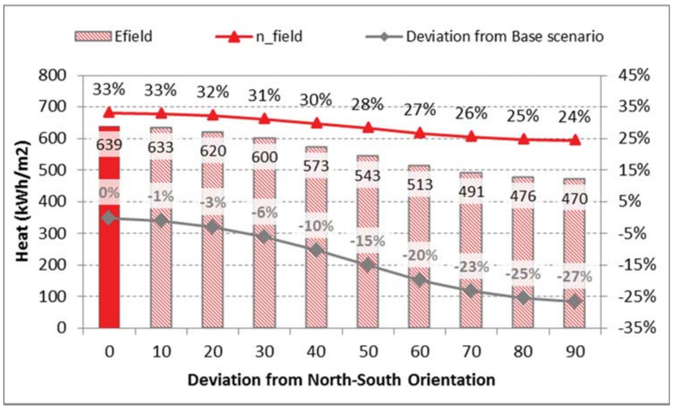

Fig 10: Effect of the orientation at the system energy solar field heat (Efield) production and the solar field efficiency (n_field)

5.3.2 Variable 2 - Outlet temperature from the solar collectors with constant temperature difference

In this parametric set, the effect of the outlet temperature from the solar collectors at the system energy performance was investigated, keeping constant the temperature difference (outlet and inlet in the solar field) DT =50K. In total 6 cases were simulated from outlet temperature of 225 to 350°C with a step of 25°C.

The outlet temperature of 225°C results in 8% increase in the energy production compared to the base scenario, whereas the outlet temperature of 275, 300 and 350°C results in less energy production by 8, 16 and 31% respectively. The significant decrease in the efficiency was expected as the specific parabolic trough model is optimized for operation at around 250°C and in higher operational temperature presents significant reduction in the solar heat production. In system level, the increase of the operational temperature leads to use of hydraulic equipment, pumps and thermal oil of higher temperature and this leads to increased system cost. On the other hand, the increase of the operational temperature reduces the heat exchanger of the steam boiler and therefore its initial cost. Balancing the above reasons the outlet temperature of 250°C was selected as base scenario.

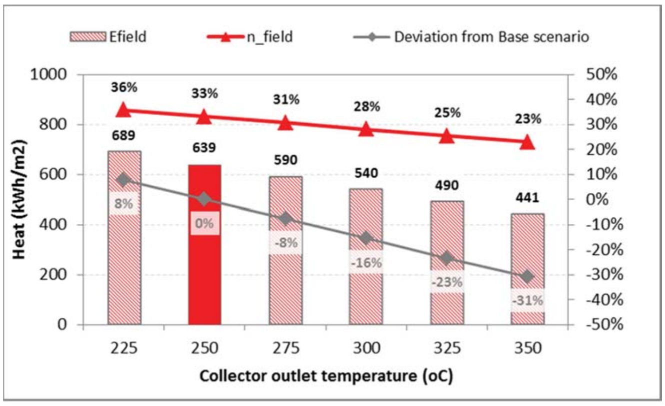

Fig 11: Effect of the Outlet temperature from the solar collectors with constant DT =50K at the system energy solar field heat (Efield) production and the solar field efficiency (n_field)

5.3.3 Variable 3 - Outlet temperature from the solar collectors with constant inlet temperature

In this parametric set, the effect of the outlet temperature from the solar collectors with constant inlet temperature of 200°C at the system energy performance was investigated. In total 6 cases were simulated from outlet temperature of 225 to 350°C with a step of 25°C.

On the contrary to the previous parametric set, the increase in the outlet temperature has limited effect on the system energy performance up to 5%. This is explained by the fact that the mean temperature is kept in lower levels owing to the constant inlet temperature.

Even though, there is limited effect in the energy yield, this case may have crucial effect on the systems economics especially in cases where high thermal storage volume is required in order to smooth high difference between supply and demand. The higher thermal oil operation temperature reduces the storage volume and consequently the system cost. Though, special care is required in the dimensioning of the solar field as the minimum required flow rate should be ensured. On the other hand, the gain from the thermal storage cost should counterbalance the extra cost of the more expensive equipment in the solar field including the thermal oil owing to the higher operation temperature.

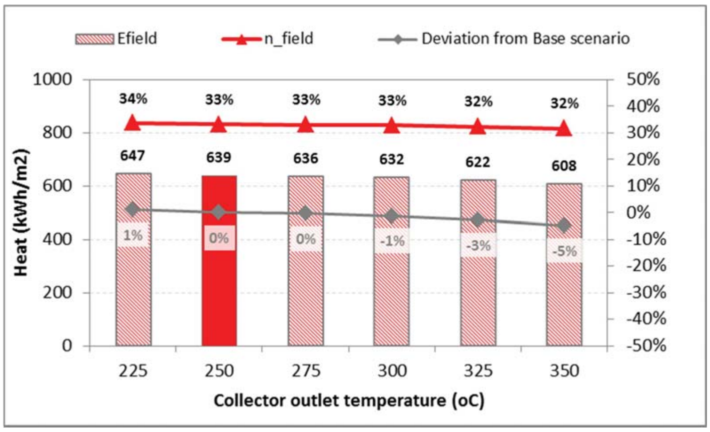

Fig 12: Effect of the Outlet temperature from the solar collectors with constant inlet temperature of 200oC at the system energy solar field heat (Efield) production and the solar field efficiency (n_field)

5.3.4 Variable 4 - Solar aperture area

In this parametric set, the effect of the solar aperture area at the system energy performance was investigated. In total 7 cases were simulated from area of 528 m^2 to 2,112 m^2 with a step of approximately 250 m^2.

Starting from the base scenario of 1,056 m^2, the decrease of the aperture area leads to almost equivalent reduction. For example area of 528m2 which is 50% less than the base scenario (1056m^2) leads to solar fraction of 22% which is reduced by 49%.

On the other hand, the increase of the solar aperture area offers limited increase of the solar fraction. For example the increase of the solar area by 40% (1,478m^2) leads to increase of solar fraction only by 21% (from 42 %to 51%).

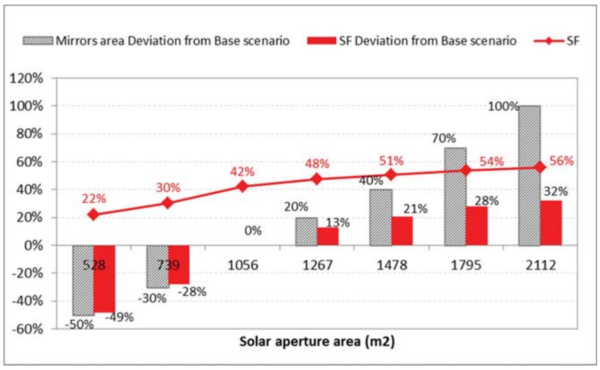

Fig 13: Effect of the solar aperture area at the system solar fraction (SF)

5.3.5 Variable 5 - Series distance expressed in multiples of the collector aperture width

In this parametric set, the effect of the series distance expressed in multiples of the collector aperture width (2.3m) at the system energy performance was investigated. In total 6 cases were simulated from series distance of 1 to 4 multiples with a step of approximately 0.5.

The series distance of 1 multiply (2.3m) leads to ground coverage of 100% but the energy production is reduced by 34% compared to the base scenario of 2.5 (5.75m). Series distances of 2 to 3 multiples have limited effect at the energy production (-4% to 2%) and the ground coverage lays between 33% and 50%. Respectively, the series distance of 4 multiples lead to increase of energy production only by 5% but the ground coverage is 25%.

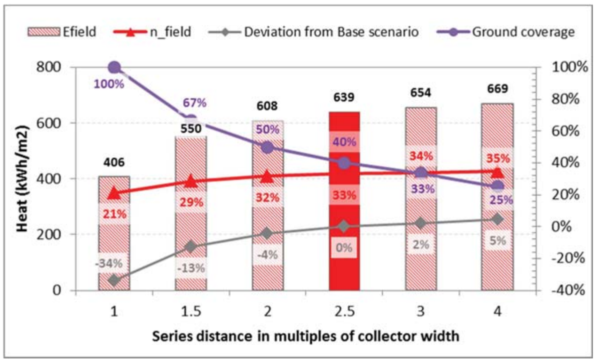

Fig 14: Effect of the series distance expressed in multiples of the collector aperture width at the system energy solar field heat (Efield) production and the solar field efficiency (n_field)

6. Economic assessment

The overall system budget accounts for 573 k€, with the solar collectors absorbing the highest percentage. The figures of the major system components are based on recent quotations while the rest are based on estimations from previous projects.

The main analysis assumptions are the following: 1% / year efficiency system reduction, 4% operation and Maintenance cost,75% conventional system efficiency, 1 €/lt oil cost and 10% increase rate of energy cost.

Based on the above considerations, the simple payback period time is calculated at 7 years.

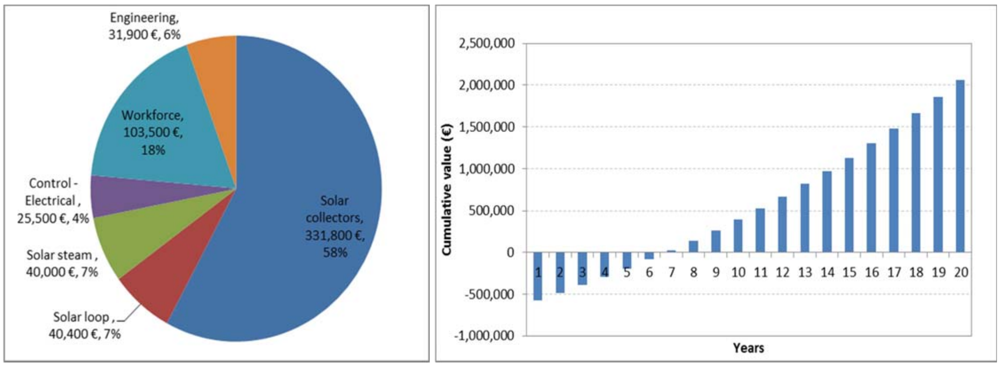

Fig 15: System economic figures

7. Conclusions

Present study attempted to present a techno-economic evaluation of a concentrating solar system for steam production at a food industry in Kalamata. The solar system consisted of the parabolic trough collectors (1 056m^2), the thermal storage (4.7tn of thermal oil) and the solar steam boiler (530kW). The field orientation was North – South, the series distance of the parabolic trough collectors was 5.75m and the thermal oil operation temperature was in the field is 200 - 250^{o}C. A parametric analysis of the above parameters was performed in order to investigate their effect in the system performance.

According to the energy simulation for the base scenario, the solar fraction (SF) was 42%, saving energy of 655MWh per year which corresponds to oil savings of 87.3 tn and 213tn CO_2 emissions. Of the 700kWh/m^2 heat production of the parabolic trough collectors 89% (620kWh/m^2) were actually delivered to the system. Regarding the economic potential of the system, the initial cost was 573 k€, the annual Operation and Maintenance cost was 4%, and the oil cost was 1 €/l, resulting to a simple payback of the system, without any subsidy, of 7 years. Considering the cumulative value at the end of the system lifetime (20 years) the present study indicates that the concentrating solar systems can play an important role at the energy saving in the sector of process heat in Greece.

8. References

Drosou, V., Tsekouras, P., Oikonomou, T., Kosmopoulos, P., Karytsas, C., 2014, The HIGH-COMBI project: High Solar Fraction Heating and Cooling Systems with Combination of Innovative Components and Methods, Journal of Renewable & Sustainable Energy Reviews 29, 463-472

Drosou, V., Karagiorgas, M., Travasaros, C., 2011, The Greek Solar Thermal Market and Industrial Applications, Proceedings of World Sustainable Energy Days, Conference Solar Process Heat, Austria

ECOHEATCOOL Intelligent Energy for Europe Program, 2006, Solar heating for industrial processes.

European Commission, 2009 Market Observatory For Energy, Europe's energy position markets and supply, ISBN: 978-92-79-14175-1

European Union, 2013, Eurostat Pocketbooks, Energy, transport and environment indicators, ISBN 978-92-79- 33105-3

Greenius software, 2016, Version 4.3.1 http://freegreenius.dlr.de

Tsekouras, P., Christodoulaki R., Tsekouras, G., Lamaris,V., Lamaris,P., 2014, Techno-economic assessment of a concentrating linear Fresnel system for steam production, IHT – 10th Conference on Renewable Energy Sources, Greece

Tsoutsos, T., Karagiorgas, M., Zidianakis, G., Drosou, V., Aidonis, A., Gouskos, Z., Moese, C., 2009, Development of the applications of solar thermal cooling systems in Greece and Cyprus. Fresenius Environmental Bulletin, 18(7b), 1367-1380