Levelized Cost of Heat for Linear Fresnel Concentrated Solar Systems

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Levelized cost of heat for linear Fresnel concentrated solar systems

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Abstract

In this paper, a deep investigation upon levelized cost of heat (LCOH) produced by small-scale solar linear concentrating Fresnel collectors (CSLFC) is proposed. Solar industrial process heat applications have temperature requirements from about 60°C to 260°C. CSLFCs can effectively integrate conventional fossil fuel thermal systems. The study is addressed to assess technology cost projection needed to achieve competitive LCOH. So, on the basis of a framework specifically developed for these economic assessments, the best investment scenarios, in terms of industrial application, geographical location and technical design solutions, where to effectively apply the technology of CSLFC, are highlighted.
The analysis has been focused on specific cost of several existing CSLFCs associated with declared performances at different operating temperatures. Two main classes of CSLFC with different total efficiency (optical and thermal) corresponding to various design solutions and specific cost were selected. The expected performances in the whole application temperature range have been evaluated through Glayx Tech proprietary simulation code, including optical and thermal unsteady analysis.
A huge database coming from full CSLFC simulation varying latitude, yearly DNI, operating fluid, outlet temperature, thermal storage options, has been collected. CLSFC design and performance requirements are the key-choice to achieve competitive LCOH: the use of high efficiency – high cost components is not always rewarding in terms of final LCOH and must be attentively decided basing on site, irradiation, heat quality and LCOH target. In this perspective, CLSFCs are the most promising for industrial small scale heat applications since they show the greatest potential to reduce manufacturing costs.

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1. Introduction

The concentrated solar power (CSP) sector is experiencing a big challenge despite the growth of investment in recent years [1]. Two main factors in the energy landscape are threatening the global deployment of CSP sector.

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First, the declining cost of other forms of renewable energy (photovoltaic and wind first of all) is attracting a large share of global investment in the renewable energy sector [11][12]. Second, the shale gas revolution in conjunction with the development of international trade of liquefied natural gas and the subsequent low gas prices with the establishment of a global gas market are changing the strategy of energy utilities reshaping their energy mix production. At the same time, cost reduction in the large scale CSP generation has not been completely achieved and, so far, only the power tower technology and the linear Fresnel technology seem able to maintain their potential cost reduction roadmap [4][7]. Large scale CSP power generation is still attractive for its ability to store energy but its global attractiveness seems to be at the end of its “golden era”. Indeed, several global energy players, such as Siemens, are leaving the playing field.

Big research and industrial efforts have been made in the deployment of cost effective CSP large power station. At the same time the huge market of process heat has been considered only marginally in the deployment of small scale solar concentrating collectors [8], i.e. having a reflective mirror surface lower than 500 m^2.

In 2009 global energy demand for heat represented 47% of final energy use [2]. More than 55% of the whole process heat demand in Europe is below 400°C and more than 30% is below 100°C. Considering only the process heat demand of industrial productions, almost 100% is below 260°C. This market represents a tremendous opportunity for the whole sector to learn and deploy affordable solution which can also be learning lessons for the most technological challenging CSP market [3].

As a consequence, this work is primarily addressed to investigate the possibility of future diffusion of concentrating solar linear Fresnel collectors applied to heat generation. A deep analysis on current technology state has been developed, mainly comparing different design solutions of existing commercial system in terms of specific cost and total efficiency. In particular, a selection of High-Efficiency and Low-Efficiency standards has been carried out and used as a benchmark in evaluation of design solutions.

Glayx Tech proprietary computational code has been used to determine expected production from the different systems at several sites, latitudes, irradiation values, heat quality in term of inlet/outlet fluid temperature. Besides, the achieved efficiency values were compared with specific cost to determine the Levelized Cost of Heat LCOH from solar source and then compared to LCOH currently available from standard fossil fuel (i.e. Methane).

The analysis of resulting data enforces the idea that CSLFC systems have potential capacity to enter the market of process heat production only passing through an accurate selection of design solutions and their concrete added-value; the choice of the system efficiency must be paired with analysis of site, heat quality and competitive cost.

Nomenclature

CF	yearly capacity factor
CRF	capital recovery factor
CSLFC	concentrating solar linear Fresnel collectors
DNI	Direct Normal Irradiation, [kWh/m^2]
Eth	thermal energy produced in one year, [kWht]
HEF	high efficiency system
LCOH	Levelized Cost of Heat, [€/kWh]
LEF	low efficiency system
OCC	overnight capital cost, [€/MW]
OMC	fixed O&M cost, [€/MW]
fc	fuel cost, [€/kWh]
hr	heat rate
i	discount rate
n	number of annuities received

2. Linear Fresnel collector: technology and market overview

One of main CSLFCs system key-factor to be competitive in the market of the renewable systems is related to design robustness and cost-effective specific solutions. The components of the whole system can be divided for simplicity at least into four different typologies, namely reflective mirrors, frame structures, collector tube and tracking system.

Reflective mirrors include reflective materials and support frame of mirroring surfaces. Frame structures are obviously required to sustain the mirrors and the absorber tube. Collector tube includes the collector itself as far as secondary reflector, surrounding frame and coating. Tracking system refers to control system components including actuators, electronic devices, sensoring.

Table 1. CSFLFCs commercial solutions

Typology	Commercially Available Solutions	Efficiency Difference (1-low to 5-high)	Specific Cost Difference (1-low to 5-high)
Reflective Mirrors	High-reflective flat glass; Thermally-Curved glass; Reflective Aluminum plates; Aluminum sandwich	2	4
Frame Structures	Pre-assembled customized steel profile; Commercial Anodized extruded Aluminum profiles	N.A.	2
Collector Tube	Vacuum tube with selective coating on tube; unpressurized isolating air; selective coating in ambient air; secondary reflector	5	5
Tracking System	Closed-loop / Open loop control system; Rotational electrical motors; Linear actuators	2	3

Market overview on existing CSLFCs systems currently available has been summarized for each type as reported in Table 1.

For each typology, available solutions have been investigated in terms of specific capital cost, estimated failure rate (in relation with higher yearly maintenance cost) and efficiency @200°C fluid (when applicable). Only commercially available solutions have been considered and relevant technical data given by manufacturers have been assumed in order to compute system global efficiency. More details upon internally-developed computational code are given in Section 3.

For each category, all evaluated solutions have been compared in order to understand how the specific subcomponent contributes to the final system efficiency and cost: results are shown in Table 1, columns 3 and 4 respectively.

The most critical design choice in CSFLFCs results to be the collector tube: this subcomponent has a strong impact on the thermal efficiency of the system, and the different solutions have a relevantly different specific cost. It is important to point out that the specific costs have been determined as the sum of initial capital cost and O&M yearly cost. For instance, considering vacuum tube collector solution compared to a simple selective-coated collector, component capital cost difference is quite limited due to recent larger commercial diffusion of vacuum tube technology, but maintenance costs are significantly higher [6].

The analyzed solutions of Reflective Mirrors have limited influence on CSLFCSs optic efficiency since most of dispersed solar energy is due to sun positioning during the year, self-mirroring and unsettled surface cleaning. However, mirrors have relevant impact on total system cost. As a result, market tendency is addressed to implementing lowering-cost solutions among those available [9].

The whole analysis results in the determination of two CSLFCs system efficiency classes, not corresponding to any specific commercially available system from a single manufacturer:

High-efficiency system (HEF): it includes all the components having maximum specific efficiency, namely high-reflective Aluminum mirrors and vacuum tube with selective coating. It virtually represents the maximum-efficiency system achievable using commercial solutions currently available.

Low-efficiency system (LEF): it includes the design solutions associated to lower specific efficiency, namely standard glass mirrors and collector tube within external ambient air.

Fig. 1 shows total CSLFC cost for LEF and HEF as a result of single subcomponent incidence. As expected, there is an important difference due to the contribution of the collector tube, which implies a significant cost increase in the HEF.

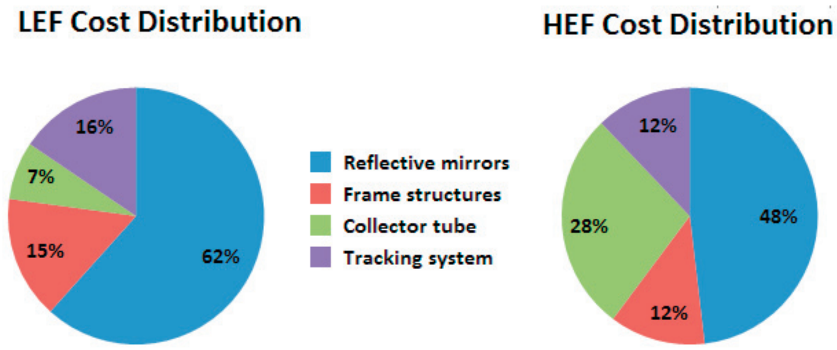

Fig. 1. Cost distribution for LEF and HEF systems

3. Simulation code

The expected performances in the whole application temperature range have been evaluated through Glayx Tech proprietary simulation code. The code was subdivided in two parts, dealing with the optical and thermal efficiency, respectively. The logical process implemented is shown in Fig. 2.

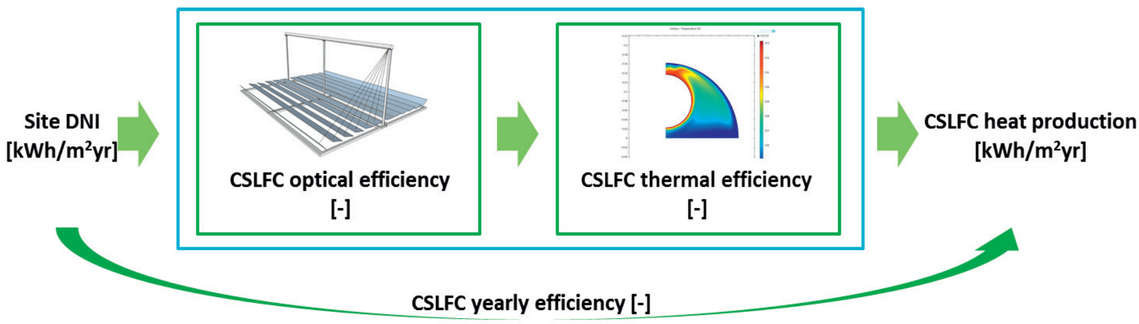

Fig. 2. Glayx Tech proprietary code functional scheme

Once specified a geographical location and a set of geometrical parameters defining a CSLFC configuration, as well as the DNI values for the selected location, the optical code computed the optical efficiency of the system. In other words, it was possible to compute the amount of energy collected at the receiver during an established amount of time (e.g. one year). Such result represented an input for the thermal code which, exploiting the knowledge of operating fluid, thermal storage options, air temperature and wind speed, is able to compute the thermal efficiency of the system. Trivially, the overall efficiency of the analyzed CSLFC was obtained as the product of the optical and thermal efficiencies. Finally, the unit cost was obtained as the ratio between the overall cost of the system and the total energy produced, using suitable assumptions and methodologies, as described in Section 4.

3.1. Optical efficiency

The first step was the choice of a geographical location. This results in values of latitude, longitude and altitude. Then, once chosen a period of time for the analysis (whole year, single months, single days), such data were the input for *SolarAzEl*, a free *Matlab*® software by D. Koblick, which provides the azimut and elevation angles of the sun relative to that site for the selected period of time, with a proper level of time discretization. The second set of optical code input data was represented by the geometrical configuration of the CSLFC: this includes parameters like number of mirrors, their width and length, their spacing, the dimensions of the receiver and the secondary reflector and their positioning relative to the mirrors. Then, for each day of the selected period of analysis, using the selected time discretization (e.g. one minute), the software computed:

- solar radiation incidence angle;
- angular position for each mirror;
- shadow on each mirror due to the secondary reflector;
- shadow on each mirror due to the adjacent mirror;
- direction of each light beam reflected from each mirror;
- amount of each mirror surface reflecting directly in the receiver, in the secondary reflector, or outside both of them;
- amount of the so-called "extremity effect" (not all the reflector length is exposed to the light beam reflected from the mirrors, because of the direction of the solar beam which is generally spatial [10]).

Meteonorm tool was used to create a database of DNI values for the selected location at each time step. Thus, the total optical efficiency for the selected period was computed as the ratio between the sum of the energy obtained at the reflector and the sum of the energy theoretically available. The inclusion of the DNI value in the computation allowed to consider each value of efficiency associated to its amount of DNI, for instance distinguish between time steps having same optical efficiency but different DNI, as to obtain a scientifically meaningful result.

As an example, results for the optical efficiency for five different geographical locations at different latitudes using the same CSLFC are shown in Fig. 3. Data relative to a whole year are compared to those obtained considering only the summer months. Low latitudes represent an advantage for two main reasons: first, the better position of the sun (e.g. less extremity effect), second, the higher amount of DNI during the most favourable optical conditions. The second effect is most probably the reason why CSLFC at latitudes slightly higher than zero perform better than if at zero latitude. However, a system working only in summer is obviously not convenient from the point of view of the total amount of energy collected. Anyhow, it is worth to point out that there is a significant difference between the optical efficiency of the same CSLFC in Lamu, Kenya, -2°S Latitude, 67%, and Stuttgart, 49°N Latitude, Germany, 50%.

Lastly, it was observed that the material of mirrors does not have a significant effect. On the other hand, it is very important the cleaning frequency of the mirrors [11].

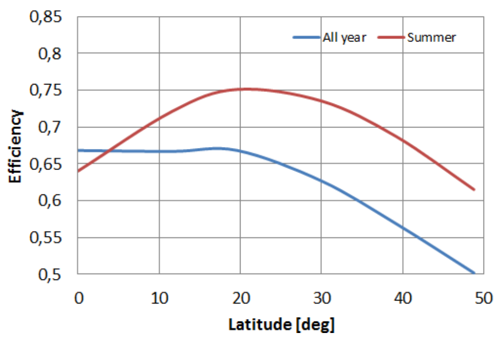

Fig. 3. Optical efficiency for different latitudes.

3.2. Thermal efficiency

The amount of energy collected computed with the optical part of the Code was used as the input data for the computation of thermal efficiency.

Differently from computations of optical efficiency, where all regulating parameters (i.e. geometric design, geographical position and reflective mirror characteristics) were set up as variables, the determination of thermal efficiencies associated to commercially available design solutions required the implementation of specific computational model.

The efficiency values were evaluated using a steady-state simplified thermodynamic model and the thermal results were validated using a multi physics software based on the finite element method. For this reason, each design configuration has been rebuilt within FEM model and heat transfer coefficients for the single specific arrangement were computed and collected in a proper database. In particular, convection and irradiation transfer coefficients were determined at different operating temperatures, geometrical frames as far as collector type [13]. Table 2 reports general fluid conditions used in the simulations.

The steady-state model was then integrated in time through implicit method solved by iteration; hourly values available in *Meteonorm* database for each simulation site were used to compute hourly heat fluid flows for the whole reference year (or different time frame), even exploiting available ambient temperature, radiation and wind values at the specific location [14].

Table 2. Computation assumptions

Fluid	Superheated water
Pressure	15 bar-g
Ambient Temperature, Radiation and Wind	From database, hourly values
Outlet Temperature	80-200°C
Inlet-Outlet Temperature Difference	15°C
Considered Yearly days	365

Fig. 4 shows HEF thermal efficiency behavior as a function of outlet fluid temperature, as achieved through the application of the Glayx Tech proprietary code mentioned above.

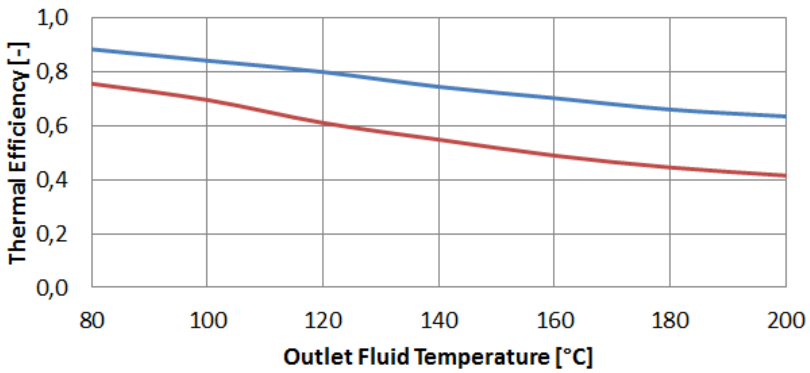

Fig. 4. Thermal Efficiency for HEF and LEF systems

4. Levelized cost of heat (LCOH)

4.1. Definition of LCOH

The levelized cost of heat (LCOH) is the cost of generating heat for a particular system at a particular temperature of the working fluid. It is an economic assessment of the cost of the heat-generating system including all the cost over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital. A net present value calculation is performed and solved in a proper way, such thatthe project's net present value is zero for the value of the chosen LCOH [5]. Hence, LCOH is defined by the following formula

$$LCOH = \frac{OCC \cdot CRF + OMC}{8.76 \cdot CF} + fc \cdot hr$$

CRF is defined by:

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1}$$

LCOH is the minimum price at which heat must be sold for a heat generating system, at a defined maximum temperature of the working fluid, to break even. Typically LCOH is calculated over 20 year lifetime, and it is given in units of currency per kilowatt-hour, for example \$/kWh or €/kWh or per megawatt-hour.

When comparing LCOH for alternative systems, it is important to define the boundaries of the 'system' and the costs included in it. In this paper R&D expense, tax, costs of impacts on public health and environmental damage were not considered. At the same time any possible supporting policies or government subsidies were included in the calculation.

A key issue is the decision about the value of the discount rate *i*. The value chosen for *i* can often 'weight' the decision towards one option or another, so the basis for choosing the discount rate must be carefully evaluated. The discount rate depends on the cost of capital, including the balance between debt-financing and equity-financing, and an assessment of the financial risk.

4.2. LCOH for fossil fuels

In this paper we considered only LCOH obtained using natural gas, which is nowadays the most used fuel in industrial applications. As already mentioned the shale gas revolution and the international trade of liquefied natural gas are creating a global market with actually Henry Hub gas prices at 4 \$/MMBtu. Outlook for natural gas price foresees a price in the near future not exceeding 5 \$/MMBtu with the possibility that prices will be globally homogeneous in few years.

Currently, LCOH from natural gas results to be in the range 0.03-0.05 €/kWh within EU countries. Gas prices in USA are lower with LCOH between 0.02 – 0.04 €/kWh.

4.3. LCOH for CSLFC

In calculating LCOH for small linear concentrating Fresnel collector we considered an independent generating system for the sake of simplicity. In reality basically all solar heating systems are coupled with standard fossil or biomass fuelled heating systems in order to have continuous operation. The level of integration between solar and standard generating system is related to many factors as DNI, heating storage capacity, etc. A comprehensive LCOH analysis should include also these parameters.

LCOH formula can be simplified in the following way:

$$LCOH = \frac{OCC \cdot CRF + OMC}{Eth}$$

Proprietary simulation code has been used to compute LCOH assuming 20 years system life-time, 1.3 c€/kWht O&M cost and 6% loan interest rate on 20 years duration and compared to fossil fuel fired LCOH. All computations and results were obtained considering a reference “small scale” plant of 500m^2 reflective mirrors.

For example, the results obtained for a given location (Cagliari, 39°N latitude, Sardinia, Italy, yearly DNI 1703 kWh/m^2yr), for two different industrial applications (T=140°C for laundry and T=200°C for dairy) and no storage system required, are shown in Fig. 5. In this case, for industrial heat applications @140°C, the LCOH of LEF CSLFC can be competitive with natural gas LCOH if specific cost is lower than 230 €/ m^2, while HEF keeps 30% additional cost margin. This margin is increasing to 40% for industrial heat application @200°C, conveying the idea that CSLFC design and performance requirements are the key-choice to achieve competitive LCOH.

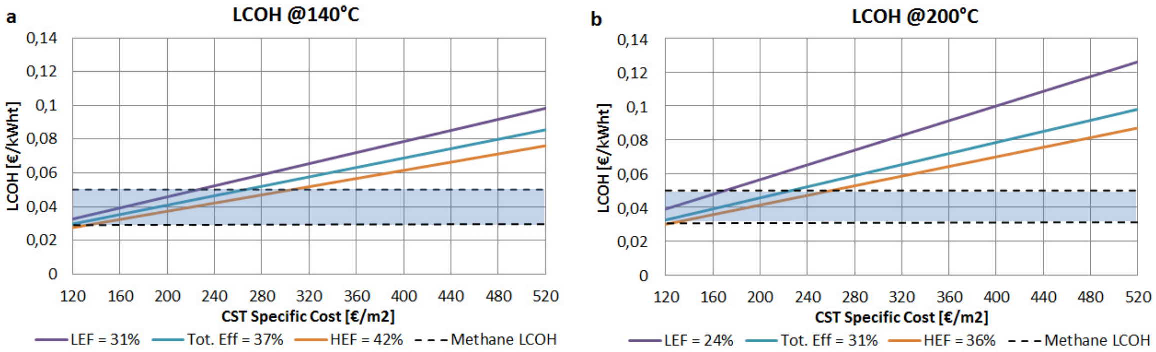

Fig. 5. (a) LCOH at T = 140°C; (b) LCOH at T = 200°C

Fig. 6 shows the relevance of specific site DNI in achieving a cost-effective LCOH; data are referred to 200°C operating temperature of the working fluid assuming a reference latitude of 35°N. Considering absolute specific cost values, the effect of higher irradiation has higher impact on HEF systems performance if compared to LEF systems. It can be inferred that HEF systems get competitive advantage with growing site DNI more than LEF do.

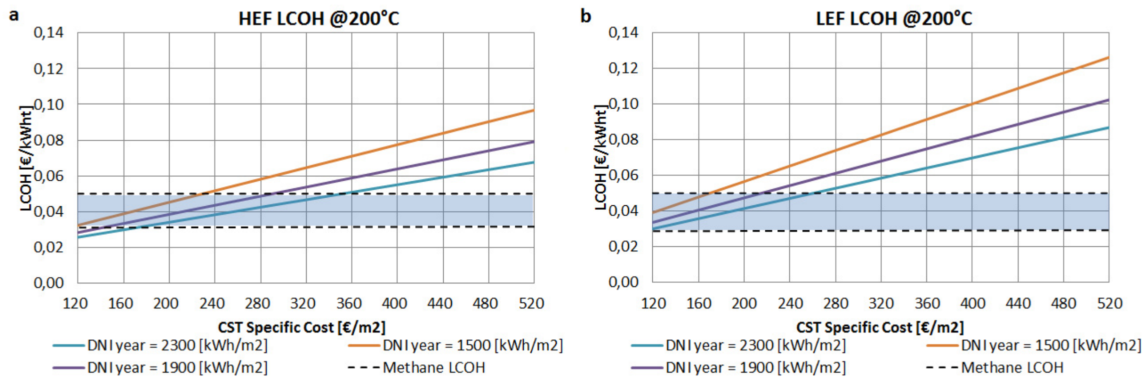

Fig. 6. LCOH at T = 200°C at latitude of 35°N for (a) HEF systems; (b) LEF systems

In Fig. 7, Fig. 8 and Fig. 9 the allowable area of specific cost - total efficiency coupled values of any CSLFC - is reported for T = 200°C at three different DNI, for a LCOH in the range 0.03-0.05 €/kWh. It must be highlighted that all CSLFCs systems having total efficiency higher than 40% and specific cost below 150€/m^2 yield their LCOH at lower values than 0.03 €/kWh, at least in sites having yearly DNI greater than 1900 kWh/m^{2}yr. From market overview, it seems that such environment can be available in the near future, opening promising perspectives for the technology in huge market areas like India (1900 kWh/m^{2}yr average in many industry districts), Brasil (over 2000 kWh/m^{2}yr) and UAE (over 2100 kWh/m^{2}yr). In this perspective, CSLFCs appear the most promising for industrial small scale heat applications since they show the greatest potential to reduce manufacturing costs.

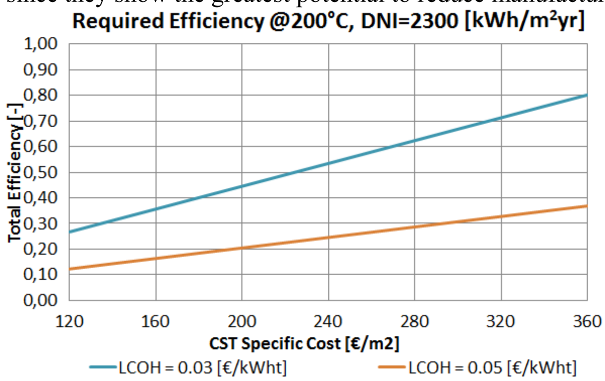

Fig. 7. Required CSLFC efficiency as a function of specific cost, @200°C, DNI= 2300 kWh/m^{2}yr

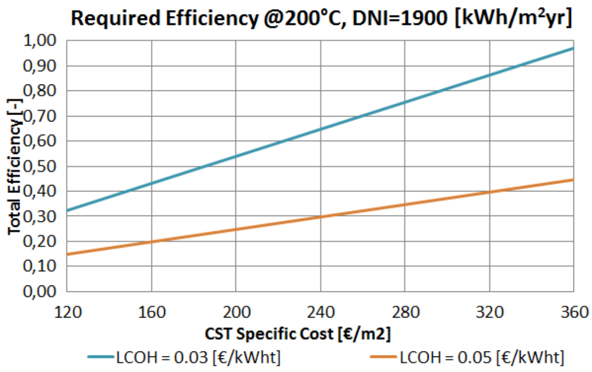

Fig. 8. Required CSLFC efficiency as a function of specific cost, @200°C, DNI= 1900 kWh/m^{2}yr

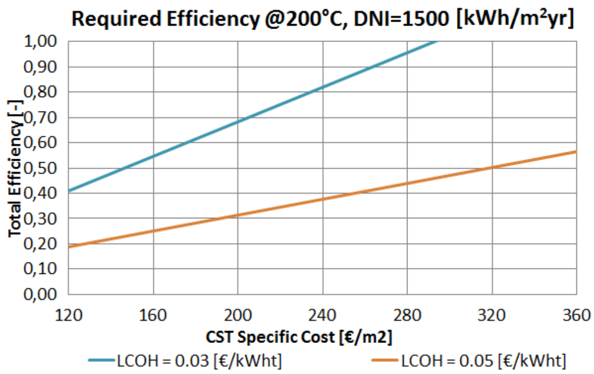

Fig. 9. Required CSLFC efficiency as a function of specific cost, @200°C, DNI= 1500 kWh/m^{2}yr

5. Conclusions

Industrial process heat market is still an unexplored huge market for small scale concentrating collectors. The low natural gas price scenario, which today energy markets are exploiting, is posing high competitive pressure on solar generated heat with T>130°C. Small scale (<500m^2) linear Fresnel collectors are suitable, among concentrating collectors, for cheap industrial process heat.

A proprietary simulation code and a database coming from full CSLFC simulation have been realized. Simulations were carried out varying latitude, yearly DNI, operating fluid, outlet temperature and thermal storage options. Then, LCOH of CSLFC have been calculated and compared with LCOH of natural gas. The results show that industrial process heat from CSLFC can compete with natural gas even in the actual low gas price scenario and without any government subsidy with specific cost under 150 €/m^2 and DNI larger than 1900 kWh/m^{2}yr. This level of cost can be achieved with simple and robust design and economy of scale that only a mature market can assure. A more detailed analysis should consider that CSLFC have to be integrated in standard gas fired boiler, and the resulting overall LCOH value will be between the solar and the fossil value.

There are still good margins of lowering LCOH of CSLFC working on mirror cost, O&M costs, building cost and at the same time keeping a good total efficiency (optical and thermal). Modular design and ease of installation can play a significant role about the wide spreading of the technology and its integration with standard gas-fired burner for industrial process heat, especially in region with high DNI.

Finally, as already mentioned, the concentrated solar sector is experiencing a though competitive landscape. Applications in industrial process heat open a huge market that can encourage the widespread of the technology, also assuring the economy scale needed by the concentrated solar power generating sector to lower the levelized cost of electricity and be competitive with other renewable energy and fossil fuel.

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