Competitivness of a Solar Boiler based on Fresnel Technology

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***Abstract*—Produce a superheated steam for industrials process represents one of the advantageous applications of solar concentrator based on Linear Fresnel Reflector (LFR). Fresnel Solar Boiler falls in this category and produces either steam or hot liquid (heat transfer fluid) by concentrating sunlight.**

It can be integrated in several industrial processes including enhanced oil recovery (EOR), cooling, agro-food processes, water desalination and chemical processes. The target industry is the agro-food one.

In this context, this work focuses on the study of the economic competitiveness of solar boilers based on Fresnel technology. The aim is to show when this technology can be economically competitive according to the DNI level and the fossil fuel price.

To achieve this purpose, Total payback period is simulated for several scenarios, eventually without storage and with 2 hours storage system and compared, subsequently, with boilers already existing in the market e.g. Heavy Fuel Boilers, Diesel Boilers etc.

Results from the study have shown that the energy produced and the payback periods are conditioned by DNI level, while the payback period varies between 2 and 9 years depending on the chosen scenario and to the climatic conditions.

***Keywords*—CSP; Linear Fresnel technology; Fresnel Solar Boiler; Heat storage; Total payback; CAPEX.**

I. INTRODUCTION

Actually, fossil fuels such as oil and natural gas represent the primary energy sources in the world. However, it is anticipated that these sources of energy will deplete within the next 40-50 years [8].

Moreover, environmental damages such as global warming, acid rain are caused by the production of emissions from these sources.

Knowing that steam systems are a part of almost major industrial process, all industrial are called to reduce their emissions and to produce, in a sustainable way, by utilizing a variety of renewable energy resources which are less harmful to the environment such as solar energy, wind etc.

Solar energy includes many technologies and represents an excellent solution to get rid of environmental problems. Furthermore, it offers several financial and strategic advantages for producing steam used in industry.

Solar plants are a relatively new technology, with significant development potential. They offer an opportunity to sunny countries comparable to that of wind farms for coastal countries.

The most promising areas for the implementation of these technologies are those of the southwestern United States, South America, much of Africa, the Mediterranean countries and the Middle East, the desert plains of India and Pakistan, China, Australia, etc. [10].

The concentrating solar power (CSP) includes several technologies:

- **Parabolic Trough system (PTC):** use parabolic reflector that have filled pipes running along their center. The mirrored reflectors are titled towards the sun and focus sunlight on the pipes to heat the oil inside. The hot oil is then used to boil water, which make steam to run conventional steam turbines and generators [9].

- **Power tower systems:** also called central receivers, use many large, flat heliostats to track the sun and focus its rays onto a receiver. The receiver sits on top of all towers in which concentrated sunlight heats a fluid. The hot fluid can be used immediately or stored for later use [9].

- **Solar Dishes (SD):** The SD system consists of a parabolic dish shaped concentrator that reflects sunlight into a receiver placed at the focal point of the dish. SD systems require two-axis sun tracking systems and offer very high concentration factors and operating temperatures. However, they have yet to be deployed on any significant commercial scale [4].

- **Linear Fresnel Reflector** (LFR): The linear Fresnel reflector technology receives its name from the Fresnel lens, [7] which was developed by the French physicist Augustin-Jean Fresnel for lighthouses in the 18th century [7].

It uses flat or slightly curved mirrors to concentrate sunlight and to reflect it to a linear receiver. Its applications address direct human needs such as water and food, assistance of other energy energy-consuming industries such as Oil & Gas, petrochemicals and mining, and temperature regulation needs [10].

LFR has worldwide successful applications, for instance: the linear Fresnel collector of Giovanni Francia Solarmundo [11], Fresnel prototype in Liège/Belgium, etc. [6].

It is considered as the youngest CSP technology and aroused an increasing interest in the last decade. This interest is mainly due to its cheapest cost relatively to the PTC technology. The considerable economic advantages of Fresnel collectors (LFR) are principally related to their constructive simplicity. Additionally, Fresnel solar fields permit higher land use efficiency than any other type of solar fields [10].

NOMENCLATURE

Symbols

A_{fs}	Annual fuel saving
A_r	Reflecting surface
A_{tot}	Total area
$B_{l,s}$	Boiler lifecycle saving
C_{lr}	Land requirement cost
$C_{O\&M}$	Cost for operation and maintenance
C_{sb}	Solar boiler cost
G_c	Gross capacity
$G_{c,ann}$	Annual gross capacity
I	Inflation
L_r	Land requirement
$N_{bh,f}$	Number hour per day of fossil boiler
$N_{bh,s}$	Number hour per day of Solar boiler
P	Pressure
P_f	Fuel price
Q_f	Collected energy by the fluid
Q_m	Total incident energy on the mirror field
Q_r	Incident energy on the receiver
S_{ap}	total reflective surface aperture of the solar field
S_f	Solar field
$S_{f,l}$	Solar field lifecycle
S_p	Storage price
T	Temperature
$T_{f,in}$	Solar field inlet temperature of the fluid
$T_{f,out}$	Solar field outlet temperature of the fluid
T_{pb}	Total payback period
t_{pb}	Total payback period without O&M cost
W	Watt (physical unit)

Greek letters

η_b	Boiler efficiency
η_{op}	Solar boiler optical efficiency
η_{the}	Solar boiler thermal efficiency

Abbreviations

CAPEX	Capital Expenditure
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiation
EOR	Enhanced Oil Recovery
LHV	Lower Heating Value
LFC	Linear Fresnel Collector
LFR	Linear Fresnel Reflector
O&M	Operation and Maintenance
PTC	Parabolic Trough collector
SD	Solar Dishes

If these advantages are sufficiently strong, then Fresnel power plants represent an interesting alternative to parabolic trough power plants.

The Fresnel Solar concentrator is among the applications that fall into the category of energy production system from renewable resources as it aims to generate heat for direct use in a wide spectrum of industrial process.

It provides an interesting temperature margin, which allows it to be adaptable to many types of industrial applications, particularly those employing steam, hot water or hot air in their process.

The Fresnel solar concentrator (Fig.1.) consists of the following elements:

- A field of flat or slightly curved mirrors fixed on metal supports. Each of these mirrors can continuously rotate around its axis to concentrate sunlight in the receiver;
- A receiver consisting of a tube covered with a selective surface (absorber), a secondary reflector and a rear and lateral insulation;
- A hydraulic circuit for transporting the produced heat to the place of use;
- A storage system;

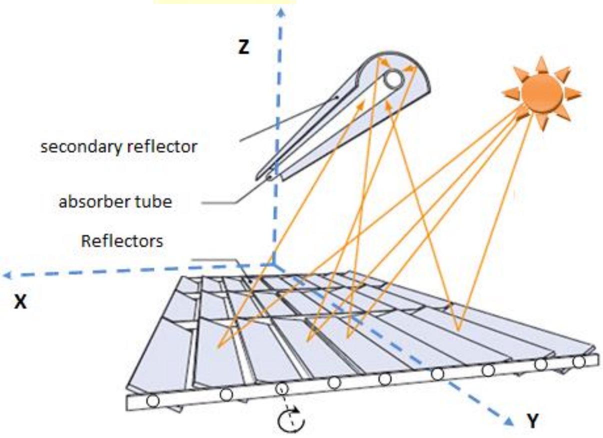

Fig. 1 Fresnel system description

Solar Boiler offers considerable economic advantages which will be analyzed in this study. It can also be combined with other source of energy such us a biomass.

To demonstrate the possibility of Solar Boiler integration, we target the agro-food industry, especially drying applications such as agricultural products (apricots, grapes, figs...), drying phosphates, drying and preheating of building bricks, and other food industrial applications.

The integration of Solar Boiler can be made within two scenarios that will be discussed in this paper:

- Industrial customer already having a fossil energy boiler ,
- Industrial customer looking for a new installation.

These case studies are investigated with: no storage system and 2 hours storage system. Based on the construction of our first prototype in Green Energy Park of Benguerir-Morocco the solar boiler cost ranges considered here varies between 100€ /m^2 and 250€ /m^2 and the assessment is made in term of the total payback period. Of course, the only constraint for the customer is the availability of the necessary land required by the solar field.

Fig. 2 Fresnel solar boiler prototype in Green Energy Park of Benguerir Morocco

Furthermore, and based on the DNI level for different countries, a study was conducted to emphasize the climatic conditions and the fossil fuel price effect on Total payback period.

II. OPTICAL AND THERMAL MODELING

Predicting the energy yield of a solar field is a crucial task in this study. It is required to compare different case studies and to investigate the influence of the climatic conditions.

The total solar power produced is calculated based on the following expression:

$$Pw = A_r \eta_{op} \eta_{th} DNI \qquad (1)$$

With:

$$\eta_{op} = \frac{Q_r}{DNI\ S_{ap}}$$

$$\eta_{thermal} = \frac{Q_f}{Q_r}$$

. The Optical efficiency is defined as the ratio of incident energy on the absorber tube and the total incident energy on the aperture of the reflective surface. It is calculated by using OPSOL code based on Monte-Carlo/ray-tracing algorithm. This code was developed in the framework of CHAMS1 project [2].

Whereas, the thermal efficiency is defined as the ratio of the collected energy by the heat transfer fluid and the incident energy on the absorber tube. Its calculation is based on the global heat balances applied on different component of the receiver (secondary reflector, glass, absorber tube, heat transfer fluid, air cavity,…) taking into account the heat transfer by conduction, convection and radiations. The different equations are integrated and solved in *THERSOL* code [1].

Note that the optical efficiency is dependent on the geographical location, and the thermal efficiency is dependent on the ambient temperature. Then, the reference value of the global efficiency of the solar field varies between 0.4 and 0.45. More details concerning the development and the validation of OPSOL and THERSOL codes can be found reference [1], [3].

Because of the solar energy intermittency, the storage system is needed. The technology considered here is based on thermocline storage on a rock bed [5]. Its sizing involves several parameters such as thermal power, rock diameter, etc. Likewise, it offers a cheap and simple way correcting fluctuations of the Solar Boiler plant energy produced.

III. METHODOLOGY

We looked for the Total payback period of Fresnel Solar boiler that would conduct to underline the effect of the DNI and to compare this technology with the boilers already existing in the market.

The payback period represents the length of time required to recover the investment cost of solar boiler based on Fresnel technology. It is considered as an important determinant to undertake the project. The Total payback period is the ratio of the cost of project and the annual cash inflows. It is calculated as:

$$T_{pb} = \frac{C_{O\&M}\, t_{pb} + CAPEX}{A_{fs}\, P_f} \qquad (2)$$

With:

$$CAPEX = C_{sb} A_{tot}$$

$$t_{pb} = \frac{CAPEX}{A_{fs}\, P_f}$$

$$A_{fs} = \frac{100\, G_C}{0.01\, \eta_b\ LHV}$$

Project cost includes capital expenditure (CAPEX) and operation and maintenance cost whereas the annual cash inflows takes account the annual fuel saving and fuel price.

On the basis of these assumptions we assume that the better investment is the one with the shorter payback period, what drives us to minimize, as possible, the project cost.

A. *Case variations*

Motived by the early development stage of the prototype designed in CHAMS 1 project, solar boiler competitiveness is assessed by including two scenarios:

Scenario A: considering an industrial customer already having a fossil fuel boiler operating full time 24h/24h. Three boilers category are considered:

- Case A.1: heavy fuel boiler,
- Case A.2: diesel boiler,
- Case A.3: gas boiler.

Scenario B: we supposed that a manufacturer intend acquiring a new steam production for partial use, among the most effective solutions, a Biomass boiler. Based on this, we will compare Biomass boiler with the Fresnel Solar one.

The second study focuses the effect of DNI level on the total payback period.

B. Parameters of comparison

In what follows, we will present an overview of the technical and economic parameters used during the assessment. As far as climatic conditions effect concerned, the DNI data related to the target country will lead to different payback period. Concerning the solar boiler integration, for scenario A, the chosen country is Morocco particularly with Meknes as reference area (33°53'36''North, 5°32'50''West, 531m Latitude), besides two operation periods are investigated:

- Fresnel field will replace the boiler 8 hours per day without storage system,
- Fresnel field will replace the boiler 10 hours per day including 2 hours storage system.

The different simulations parameters used are summarized in Table I.

Table I. Simulation parameters used in different scenario

Parameters	**Solar field**	**Heavy fuel boiler**	**Diesel boiler**	**Gas boiler**	**Biomass Boiler**
DNI ($kWh/m^2/year$)	2372	-	-	-	-
Thermal power (kWth)	1 000	1 000	1 000	1 000	500
Efficiency (%)	-	88	88	88	75
PCI (kWh/T)	-	11 160	12 444	13 986	5 233,5
Fuel Price (€/T)	-	318	798	1 000	66
O&M cost (% CAPEX)	3	3	3	3	5

IV. RESULTS AND DISCCUSION

A. Case studies

1) Case A.1: Heavy fuel boiler

In Morocco, heavy fuel supplies a quarter of the country's needs. It is considered as the cheapest fuel used in the industry. In the last three years, its price, in the Moroccan market, is about 318€ /T. As far as DNI concerned, the annual DNI is about 2372 $kWh/m^2/year$ (According to Meteonorm database for Meknes region). For the Solar boiler, the reference cost is fixed to 100 €/m², the simulation results are summarized in Table II. By referencing to the heavy fuel, these results show clearly that the implementation of Fresnel Solar Boiler allows a return on investment in about 4-9 years.

Note that the payback is affected if the storage system is considered. The corresponding CAPEX increase significantly and in the opposite, the Boiler lifecycle saving is ameliorated (80 %).

Table II. Technical economic comparison between a solar Fresnel concentrator and heavy fuel boiler

Data	**No storage**	**With 2 hours storage**	**Units**
Generation capacity of the LFR project			
Gross capacity	1000	1000	kWth
Number of hours per day	8	10	Hour
Annual Gross capacity	2920	3650	MWh/year
Yearly DNI	2372,5	2372,5	kWh/m2/year
Land requirement and orientation			
Reflecting surface	2862	3675	m²
Total area	3721	4778	m²
Solar field orientation	**North-South**		
Project lifecycle			
Solar field lifecycle	20	20	year
Steam			
Pressure	175		°C
Temperature	9		bars
Economic analysis			
CAPEX Turnkey solar boiler cost	372093	591438	€
O&M cost	11163	17743	€/year
Annual fuel saving	297	446,0	T
Payback period without O&M cost	3,9	4,2	year
Total payback period	4,4	4,7	year
Boiler lifecycle saving	4,1	6,1	month/year

This expansion in the CAPEX is not related to the tank storage price, but it is influenced by the increase of the corresponding solar field surface. This shows that the use of storage system to increase the autonomy of the solar field may be wasteful.

Therefore, the storage can be used efficiently only to compensate the temporary fluctuations in DNI during the day, in this case the storage tank will increase the CAPEX by 10%.

Besides, we observe that the increase of Solar boilers cost conducts to significant increase of the Total payback period (Fig. 3) which lead to conclude that for a customer already producing steam with a heavy fuel boiler, Solar boiler cost value mustn't exceed 100€/m^2.

The solar boiler becomes very cost-effective if the CAPEX is maintained lower than 150 €/m^2, in this case our system can be compared economically to the PV system considered as the mature technology.

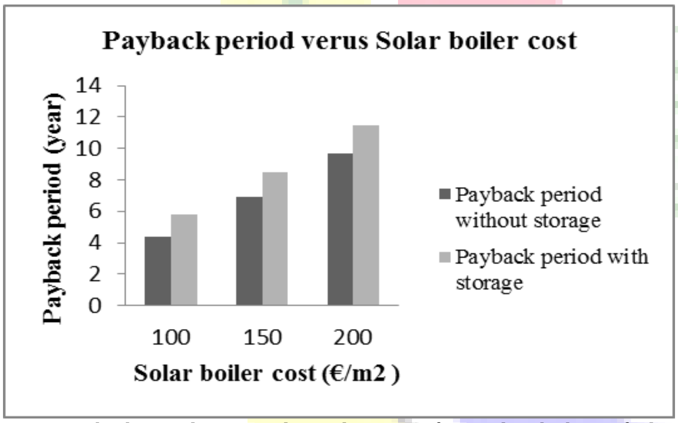

Fig. 3 Payback period versus Solar Boiler cost (referenced to the heavy fuel boiler)

2) Case A.2: Diesel boiler

Actually, diesel boilers are presented as being a cost-efficient heating option for many industrials because they are very efficient and have relatively low running costs.

Indeed its high LHV which can be profitable for steam production. However, diesel cost, in Morocco, is considerable and reaches 797.27€/T. For The simulation, the Solar boiler cost is fixed at 100 € /m^2.

The different results are shown in the following table.

Unlike the previous case, the cost of the gasoil influences slightly the payback period. The increase of payback period according to the solar boiler cost is less significant. These results show also, that the investment on solar field, for a customer producing heat with a diesel boiler is profitable with a return on investment around 2 years without storage system and 3 years including a storage system.

Table III. Technical economic comparison between a solar Fresnel concentrator and diesel boiler

Economic analysis			
Data	**Without storage**	**With 2h storage**	**Units**
CAPEX Turnkey solar boiler cost	372093	591438	€
O&M cost	11163	17743	€/year
Annual fuel saving	267	400,0	T
Payback period without O&M cost	1,8	1,9	year
Total payback period	1,8	2,0	year
Boiler lifecycle saving	4,1	6,1	month/year

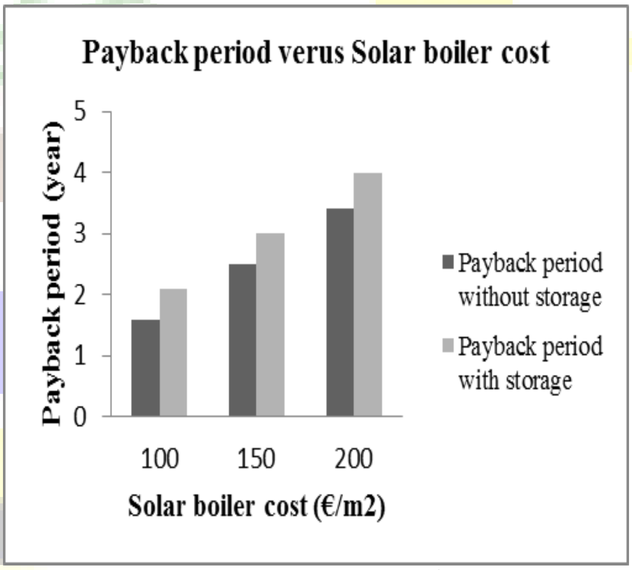

Fig. 4 Payback period versus Solar Boiler cost (referenced to the diesel boiler)

3) Case A.3: Gas boiler

The gas boiler considered here is the propane one. For all industrials, the unavoidable question is the fuel price. In general, propane price fluctuate unpredictably which can be considered a real concern for a boilers working full time.

In what follows the results reached, for the Solar boiler, the cost is fixed at 100€/m^2 (Table IV).The return on investment is around 2 years without storage system and 3 years including a storage system.

These results show, obviously, that the implementation of solar field either with or without storage system is very cost-effective.

Table IV. Technical economic comparison between a solar Fresnel concentrator and gas boiler

Economic analysis			
Data	**Without storage**	**With 2h storage**	**Units**
CAPEX Turnkey solar boiler cost	372093	591438	€
O&M cost	11163	17743	€/year
Annual fuel saving	237	355,9	T
Payback period without O&M cost	1,6	1,7	year
Total payback period	1,6	1,7	year
Boiler lifecycle saving	4,1	6,1	month/year

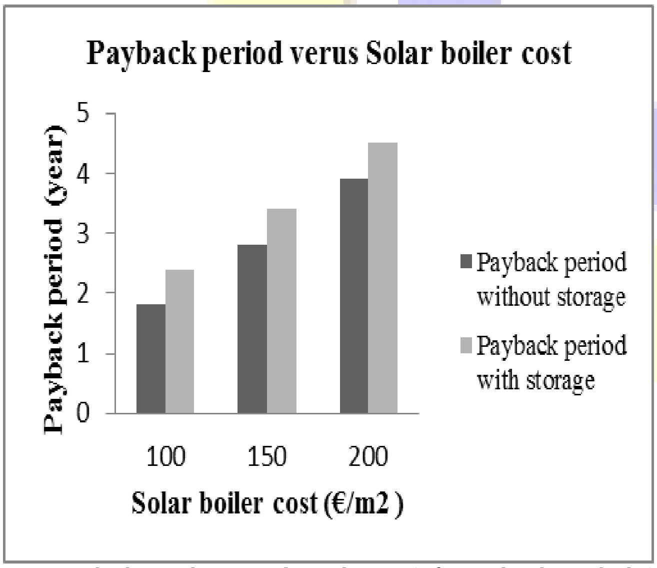

Fig. 5 Payback period versus Solar Boiler cost (referenced to the gas boiler)

4) Case B: Biomass boiler

Biomass is the name given to any organic matter which is derived from plants. Several biomass fuels can be used such as wood from forests, crops, seaweed, material left over from agricultural and forestry processes, etc.

The target Biomass Boiler, considered here use Pomace olive, usually available in the area producing olive oil like Meknes region in Morocco. The comparison results are summarized in table V.

Results lead to conclude that the Fresnel Solar boiler with 2 hours storage system becomes beneficial than Biomass Boiler after only 4 years (cumulative expenditure in table V) which accentuates the competitiveness of this technology.

Table V. Technical economic comparison between a solar Fresnel concentrator and biomass boiler

Technical Economic analysis			
Data	**Biomass Boiler**	**Solar Boiler with 2h storage**	**Units**
Gross capacity	1825	1825	MWh/year
Reflecting surface	-	1829	m^2
Total area	-	2377	m^2
CAPEX	285000	412145	€
O&M costs	14250	12364	€/year
Fuel costs	30686	0	€/year
Total expenditure (1st year)	329936	424509	€/year
Total expenditure (2nd year)	374872	436873	€/year
Total expenditure (3rd year)	419808	449237	€/year
Total expenditure (4thyear)	464744	461601	€/year
Total expenditure (5thyear)	**509680**	**473965**	€/year

B. Effect of climatic conditions on total payback period

Actually, climatic conditions such as DNI level, temperature and dust represent challenges for any CSP implementation since they affect directly the solar field efficiency and then the capital expenditure (CAPEX).

The DNI level represents the most important factor. It affects directly the total payback period. The purpose of this section is to highlight the DNI level effect on total payback period.

To achieve this goal, a study was conducted for different countries in the Mediterranean areas. Based on data given by Meteonorm (Table VI), total payback period was calculated for Egypt, Spain, Italy and Mali.

Table VI. DNI and Heavy fuel price data related to several area

Area	DNI (kWh/m2/year)	Heavy Fuel Price (€/T)
Meknes (Morocco)	2372	318
Aswan (Egypt)	2571	743
Malaga (Spain)	1962	1358
Palermo(Italy)	1938	1788
Bamako (Mali)	1976	1030

The simulation results are presented in Fig. 6 and Fig. 7

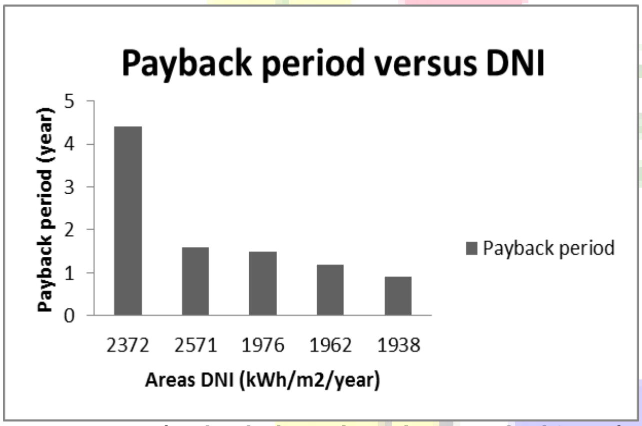

Fig. 6 Variation of total payback period according to DNI level (case of Morocco, Egypt, Mali, Spain, Italy)

If we take the case of a heavy fuel boiler as reference, we can see easily that the payback period is significantly linked both to the insolation (DNI) and the heavy fuel price.

The results illustrate, obviously, that the DNI impacts directly total payback period; the decrease of the DNI leads to an increase of the capital expenditure (CAPEX), as a consequence the total payback increases.

This can be explained by the fact that more the DNI is high, less reflecting surfaces are needed. Then we can conclude, that DNI level represents important criteria for any Solar boiler investment.

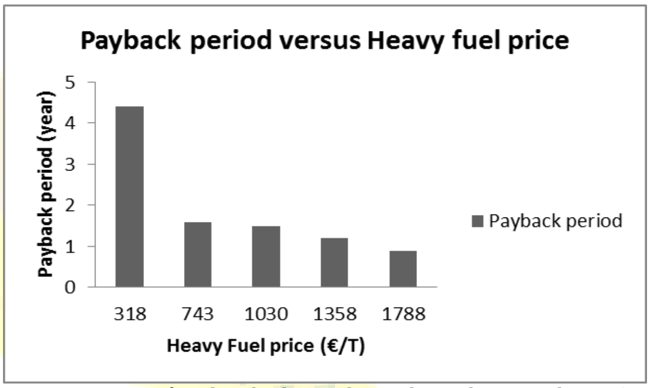

Fig. 7 Variation of total payback period according to heavy Fuel price (case of Morocco, Egypt, Mali, Spain, Italy)

More than this, the payback period is also conditioned by the heavy fuel price. The increase of this later conducts to a major decrease of payback period.

Furthermore, the areas with a high DNI represent excellent candidates for solar investment, especially, solar boiler based on Fresnel technology. Nonetheless, as revealed earlier, the price of fuel used represents an essential key factor of investment and must be taken into account.

V. CONCLUSION

Concentrated Solar Power (CSP) technology is classically used for electricity purpose i.e. it is used for producing electricity by generating thermal energy and converting it to electricity.

However, the produced energy can be used directly in industrial processes requiring low-to-medium temperature levels. Among the CSP technologies, Linear Fresnel Reflector (LFR) represents a very interesting technology in industrial processes using heat at medium temperature.

Energy from Solar Boiler based on Fresnel technology could be obvious excellent alternative energy source since its competitiveness is pinpointed in this paper.

In spite of climatic conditions effect, implementation of Solar Boiler based on Fresnel technology, for countries with high DNI, allows making a reasonable return of investment around 25% of total lifecycle of the solar field.

Moreover, it offers convincing advantages either for industrials producing steam with a fossil fuel or industrials looking for a new installation. The Solar boiler payback varies between 4-5 years for an industrial producing with a heavy fuel boiler, whereas the payback is around 3 years for industrial producing steam with Diesel or Gas boiler. These results represent a success factor of Solar boiler investment.

The solar field allows both of them reducing radically energy bill and then the dependence on fossil fuel price fluctuations. For instance, to produce 1000 kWth the annual fuel saving for an industrial producing steam with a heavy fuel boiler reaches 394 T, 313 T for Diesel boiler and 278 T for Gas boiler.

It allows, also, significant diminution of operating and maintenance cost i.e. For a 1825 Mwh/year gross capacity, the O&M cost for a Solar boiler is 12364 €/year unlike the Biomass boiler which required 14250 €/year for operation and maintenance, besides and after the payback period, the energy bill concern only O&M cost.

Likewise, it permits to increase the lifecycle of already installed boiler and decrease the CO2 emission which can be significant versus the worldwide strategies of using renewable energy and the emission limits legislated.

ACKNOWLEDGMENT

This work has been carried out thanks to the support of IRESEN (Morocco) and KIC InnoEnergy in the framework of SIROCCO project.

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