INCREASING THE COST EFFECTIVENESS OF CSP TECHNOLOGIES THROUGH THE DEVELOPMENT OF A NEW CLFR "ETENDUE MATCHED" COLLECTOR

Luís Guerreiro[1], Diogo Canavarro[2] and Manuel Collares-Pereira[2]

[1] University of Évora, BES Renewable Energies Chair. Casa Cordovil, 7005-651 Évora, Portugal, lguerreiro@uevora.pt
[2] University of Évora, BES Renewable Energies Chair

Introduction

A new CLFR "Etendue Matched" is a promising CSP technology to achieve a better cost effectiveness with a lower levelized cost per m^2. This new technology can significantly reduce shading and blocking existing in a conventional LFR (Chaves, 2009; Chaves, 2010), while at the same time optimizing primary and secondary concentration to the limits allowed by first principles in optics. A preliminary evaluation of the optical and thermal performance has been performed (Canavarro, 2010, Horta 2011), and a configuration for a full scale CSP power plant proposed, with two secondary receivers (Fig.1), i.e a multiple receiver solution.

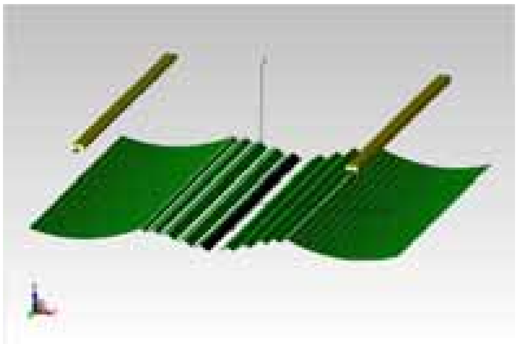

Fig. 1: New CLFR "Etendue Matched" proposed

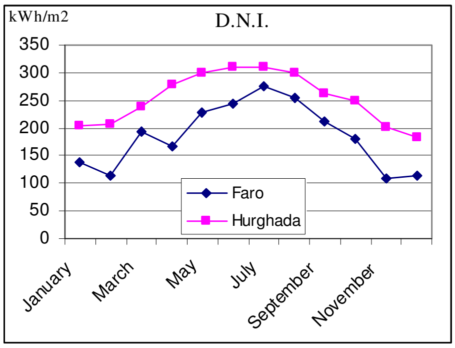

Fig. 2: Yearly DNI for the locations considered

Simulation Model

In the last 10 years several CSP plants have been built, more than 90% of them are PTR plants. In Spain, due to the tariff scheme, most plants are 50MW plants, some of them have now several years of operation with well monitorized data.

Performance data for LFR and PTR systems come from simulations and from real data available; one example is the paper by Hoyer et al (Hoyer, 2009) reporting the overall system efficiency as well as overall losses (shading, blocking, reflection, thermal, optical receiver) Hurghada, Egypt (27ºN), Guadix,Spain (37ºN) and Faro,Portugal (37ºN) for both Linear Fresnel (overall efficiency of 9%) and Parabolic Through (overall efficiency of 15%) collector types.

In order to evaluate the new CLFR-EM concept, first a simulation model has been developed for the optical optimization of the primary and secondary mirrors using the software TracePro (Canavarro, 2010) and afterwards for the thermal optimization using an FEM model simulating the energy balance in the receiver using the *Navier Stokes* equations (Horta, 2011) with a finite element approach to the convection occurring inside the secondary TERC, together with the definition of heat flow boundary conditions enabling a complete analysis of the different heat loss terms affecting system performance at any given operating temperature.

The model developed was first applied to PTR and LFR collectors for Hurghada and Faro. Losses calculated were within +/-2% of the ones reported by Hoyer et al., which can be considered a validation of the calculations involved. With the model calibrated both in the optical and thermal aspects, these tools were applied to the evaluation of the performance to be expected from the optically optimized CLFR "EM" configuration which is the object of this paper. A ray trace study was performed defining the heliostat positioning in order to take advantage of the new Etendue Matched concept patented (Chaves et al., 2009) and described in detail in Chaves, 2010. This way, shadowing and blocking effects were minimized, and the irradiance level was studied in order to evaluate how the configuration for the receiver, TERC type, should be, having the aim of increasing the concentration factor up to 60x (Fig. 3-4). Apart from the reduction of losses and higher concentration factor, this configuration has the extra advantage of enabling a lower height for the optimal position of the receiver to about 6m height against the usual 14-16m of a conventional LFR type collector, with the same width. This feature reduces the investment costs, but also the operational risk failure.

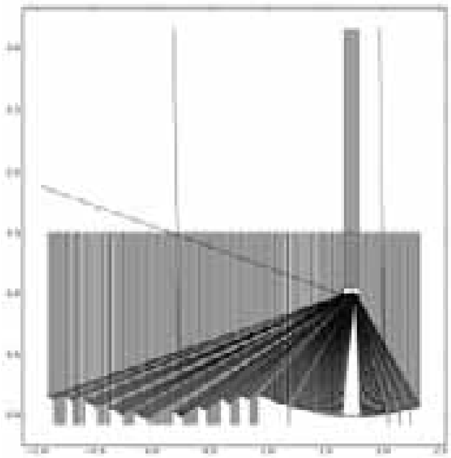

Fig. 3: New CLFR "Etendue Matched", ray-trace study, one half only

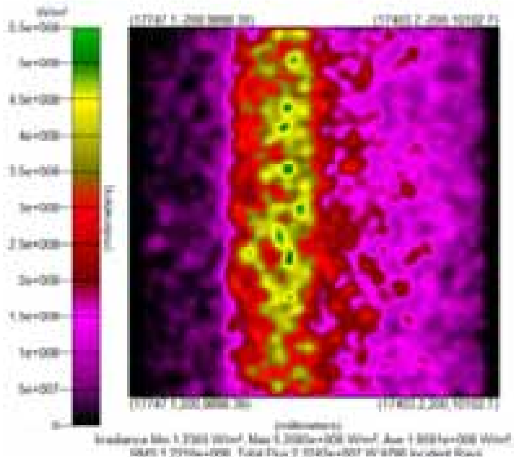

Fig. 4: CLFR "Etendue Matched", radiation concentration

The thermal efficiency calculation, it was made for a non-vacuum cavity with selective coated tubes with a diameter of 50mm, placed side by side. The energy input considered was the equivalent of an incident direct radiation (d.n.i.) of 900W/m², ambient temperature of 25°C and wind velocity of 1m/sec. In Fig.5 the velocity and temperature fields are showed for a temperature of 400ºC in the fluid. The results obtained report a 70% optical efficiency per mirror surface area (considers losses of 4% due to non-specular effect) equivalent to 63% per soil surface area, resulting in a value of 0.16 W/m²/°C for the heat loss coefficient F´Ul at 400ºC (Horta, 2011).

$$\eta = F'\eta 0 - F'Ul(T - Tamb)/Icol$$

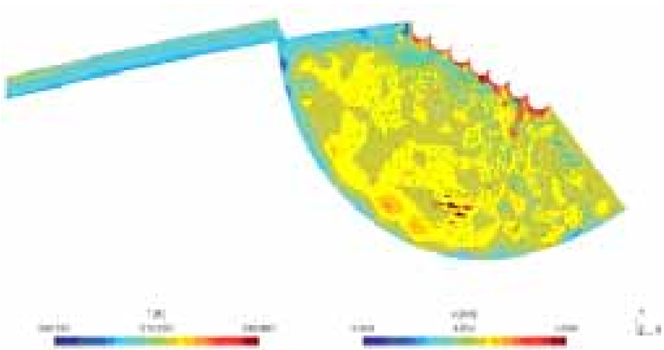

Fig. 5: CLFR-EM, receiver thermal and velocity field

kW/m				
Q_{aper}	Q_{proj}	Q_{util}	η	η^*
41.88	37.54	26.35	0.63	0.70

Fig. 6: CLFR-EM, receiver thermal losses and efficiency

The data obtained suggests that due to the increase in the concentration factor, operating temperatures above 400ºC, up to 500ºC in the thermal fluid can be achieved with good efficiencies.

Model Application

With the model described in the previous section, and using Meteonorm weather data, energy production for the two locations previously mentioned was computed for three different technologies: conventional PTR and LFR as well as for the new CLFR-EM concept.

In the calculation, a slight energy dumping effect (of 1%) was considered, that is, in all cases the plant was dimensioned to produce only slightly more energy than the rated peak output power of 50MW.

Technology	Optical eff. (%)	Losses coef. (W/m2/ºK)	Operating temp. (ºC)	Pipping Losses (%)	Turbine eff. (%)
CLFR EM	74	0.16	450	8	37.5
PTR	78	0.16	400	16	36.5
LFR	66	0.30	270	5	25.0

Table 1: Data considered in the energy output calculation

Month	CLFR -EM (kWh/m2) Soil area	CLFR -EM (kWh/m2) Mirror área	LFR (kWh/m2) Soil area	LFR (kWh/m2) Mirror area	PTR (kWh/m2) Soil area	PTR (kWh/m2) Mirror area
Jan	33,48	37,21	30,18	41,16	26,48	52,96
Feb	32,55	36,17	27,55	37,56	26,21	52,43
Mar	63,97	71,07	51,80	70,63	52,19	104,37
Apr	60,76	67,52	48,24	65,78	49,57	99,13
May	88,78	98,65	68,99	94,07	74,21	148,43
Jun	98,26	109,18	75,89	103,49	83,55	167,09
Jul	110,35	122,62	85,36	116,40	93,25	186,51
Aug	93,11	103,46	73,27	99,91	77,27	154,55
Sep	73,06	81,18	58,70	80,04	59,54	119,08
Oct	54,75	60,83	45,56	62,13	44,58	89,15
Nov	28,09	31,21	25,03	34,13	22,09	44,18
Dec	25,12	27,91	23,14	31,55	19,70	39,40
Total	**762,29**	**846,99**	**613,70**	**836,86**	**628,63**	**1257,27**

Table 2: Thermal Energy output for Faro for the 3 different technologies

Technology	Mirror area (m2)	Soil area (ha)	Annual energy production (GWh)
CLFR EM	300 000	36	79
PTR	220 000	66	72.5
LFR	450 000	68	85

Table 3: Mirror area, soil occupation and energy production in each case, Faro, with 1% dumping

Final figures for overall system energy efficiency, both in Faro and Hurghada is summarized in Table 4.

Technology	Optical efficiency (per mirror area)	Overall system efficiency (per mirror area)	
		Faro - PT, 37°02'N	Hurghada – EGY, 27°13'N
CLFR – EM	74 %	11.8%	13%
PTR	78 %	14.8%	16.4%
LFR	66 %	8.5%	9.1%

Table 4: Optical efficiency and overall system efficiency

Month	CLFR -EM (kWh/m2) Soil area	CLFR –EM (kWh/m2) Mirror area	LFR (kWh/m2) Soil area	LFR (kWh/m2) Mirror area	PTR (kWh/m2) Soil area	PTR (kWh/m2) Mirror area
Jan	58,80	65,33	49,45	67,43	48,29	96,57
Feb	70,91	78,79	57,18	77,97	57,17	114,34
Mar	90,24	100,27	71,33	97,27	72,24	144,49
Apr	111,53	123,93	86,18	117,52	92,35	184,71
May	124,01	137,78	94,97	129,51	107,15	214,31
Jun	127,48	141,65	97,75	133,29	111,69	223,38
Jul	130,67	145,19	99,85	136,16	113,60	227,20
Aug	121,31	134,79	93,22	127,12	102,41	204,83
Sep	101,64	112,93	79,64	108,60	82,07	164,14
Oct	84,66	94,07	68,31	93,15	68,53	137,07
Nov	66,19	73,55	54,26	73,99	53,42	106,84
Dec	55,44	61,60	46,82	63,85	44,76	89,53
Total	**1142,88**	**1269,87**	**898,97**	**1225,87**	**953,70**	**1907,40**

Table 5: Thermal Energy output for Hurghada for the 3 different technologies

Considering the data presented in Table 2 and 5 and the efficiencies described in Table 4, the electricity output for Faro and Hurghada was calculated (Fig 7 and 8) in kWh/m2 of mirror surface area, being respectively 263 and 394 kWh/m2 per year for the CLFR-EM system.

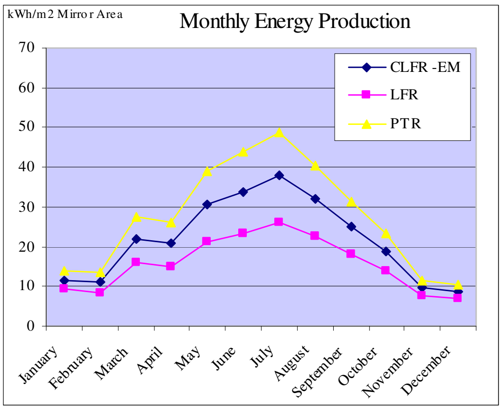

Fig. 7: Electricity produced per mirror area, Faro

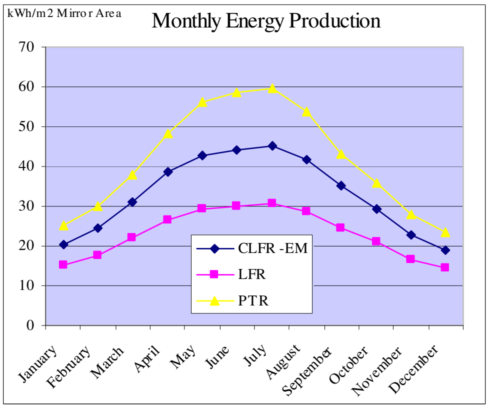

Fig. 8: Electricity produced per mirror area, Hurghada

In the Iberian peninsula, in practice it is economical to size collector fields for a number of operating hours equivalent at full power between 2000 and 2300h considering no thermal storage.

If a choice is made for 2220 hours, there will be an oversizing of the collector field with respect to that in Table 3, of about a factor of 1.4X (420 000m2) resulting in a production of 111 GWh for the CLFR-EM in Faro, and resulting in an energy dumping of about 12%.

For PTR the equivalent choice would yield an oversizing of about 1.53X (336 000m2) for the same production and comparable energy dumping.

This dumping effect might be eliminated either by delivering to the grid more than the rated 50MW whenever necessary, or by taking advantage of a possible thermal storage facility, a concept that is more and more critical for solar thermal plants.

These results show that CLFR-EM overall efficiency can be up to 13% for Hurghada where LFR would only achieve 9,1%. This is due to the optimized optical efficiency through the reduction of shading, blocking and TERC design upgrade which enables a higher concentration factor with the corresponding increase in the operating temperature. Comparing with PTR collectors the efficiency is still lower, however, when the comparison is made in terms of costs (per installed power or mirror surface), then CLFR-EM is more advantageous than PTR.

Cost evaluation

In order to confirm the simulated data, and due to the interest in this concept manifested by several companies, a demonstration plant at the University of Evora will be installed and monitored, (see Fig. 1). It will have a total heliostat surface of 530m2, and will demonstrate only optical and thermal performance. The high operating temperatures demand tubular receivers with selective coatings that were not yet possible to find in the market. The decision was reached to use, instead, evacuate tubular receivers and limit the demonstration to temperatures around 400ºC. Standard receiver tubes available in the market specific for CSP plants (PTR70) was used for the calculations, with a thermal losses factor (with a factor ~60 concentration) of 0.12 W/m²/°C (NREL, 2009), lower than the initially considered due to vacuum. The configuration of the cavity was also re-evaluated reporting a slight decrease in the optical efficiency due to the 1-tube configuration, however this reduction is counter balanced with the lower thermal losses of the receiver, thus the overall system efficiency is considered to be the same (at 400ºC) as the one calculated in detail with results presented in the previous section. Additionally, the planning of a 50MW CLFR-EM plant (420.000 m^2) was evaluated with a procurement phase for a cost estimation considering relevant players in the market (Table 7).

	CLFR-EM, demonstration plant	CLFR-EM, 50MW plant
Number heliostats, rows [-]	24	24 x 12
Total receiver length [m]	24 x 2	1455 x 2 x 12
Collectors in a row [-]	8	485
Row width [m]	0,55; 0,9; 1,2	0,55; 0,9; 1,2
Avg. distance bet. rows [m]	0,3	0,3
$\eta_{opt,0}$ [-]	0,74	0,74
Receiver type	PTR70	PTR70
HTF-medium	Therminol VP1	Therminol VP1
Solar field location	Evora,PT (40ºN); North-South	Evora,PT (40ºN); North-South
Other settings	Thermal loop w/ heat dissipation	Power block w/ turbine η=37,5%

Table 6: Plant configuration considered in the cost analysis

<table>
<tr><td rowspan="2"></td><td colspan="2">CLFR – EM
(mirror area of 420.000m²)</td><td colspan="2">PTR
(Morin et al, adapted for 336.000m²)</td></tr>
<tr><td>Total cost [MEuro]</td><td>Cost [Euro/m²]</td><td>Total cost [MEuro]</td><td>Cost [Euro/m²]</td></tr>
<tr><td>Receiver</td><td>7,2</td><td>17</td><td rowspan="4">93</td><td rowspan="4">275</td></tr>
<tr><td>Reflector</td><td>5,2</td><td>12</td></tr>
<tr><td>Base structure</td><td>40</td><td>95</td></tr>
<tr><td>Control system</td><td>3,3</td><td>8</td></tr>
<tr><td>Thermal Block</td><td>40</td><td>95</td><td>40</td><td>119</td></tr>
<tr><td>Comissioning and others</td><td>3,8</td><td>9</td><td>30</td><td>90</td></tr>
<tr><td>Overall Cost (50MW)</td><td>99,5</td><td>237</td><td>163</td><td>484</td></tr>
<tr><td>Cost per Wp installed</td><td colspan="2">2,0</td><td colspan="2">3,3</td></tr>
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Table 7: Cost estimation for CLFR-EM and PTR systems for a 50MW plant with similar electricity production for Faro, PT

To evaluate the opportunity of an investment in a CLFR-EM plant in a Southern European location, an economic evaluation was performed computing the project NPV and its IRR considering following assumptions: Investment costs= 99,5MEuro, maintenance costs= 2MEuro/year, system availability=100%, electricity selling price=0,27Euro/kWh for 25 years, WACC=10%. Results are presented in Table 8.

NPV	62 M.Euro
IRR	19.9%
Pay back time	7.5 years

Table 8: Economic project valuation

In order to evaluate the impact of possible changes in the expected scenario, a sensitivity analysis was performed considering different scenarios (best, better, expected, worst, worse) for 3 different cases:

Case 1: Initial investment costs (receiver, base structure, etc.). Variation of +20%; +10%; 0%, -10%; -20%

Case 2: Overall system efficiency. Variation of +10%; +5%; 0%, -5%; -10%

Case 3: Feed-in electricity tariff. Variation of 0%, -5%; -10%; -15%; -20%

Case	NPV "Best" [M.Euro]	NPV "Worst" [M.Euro]	IRR range
1	88	37	17,8% - 21,8%
2	101	32	17,3% - 22,1%
3	62	15	14,4% - 19,9%

Table 9: Economic project valuation for 3 different cases

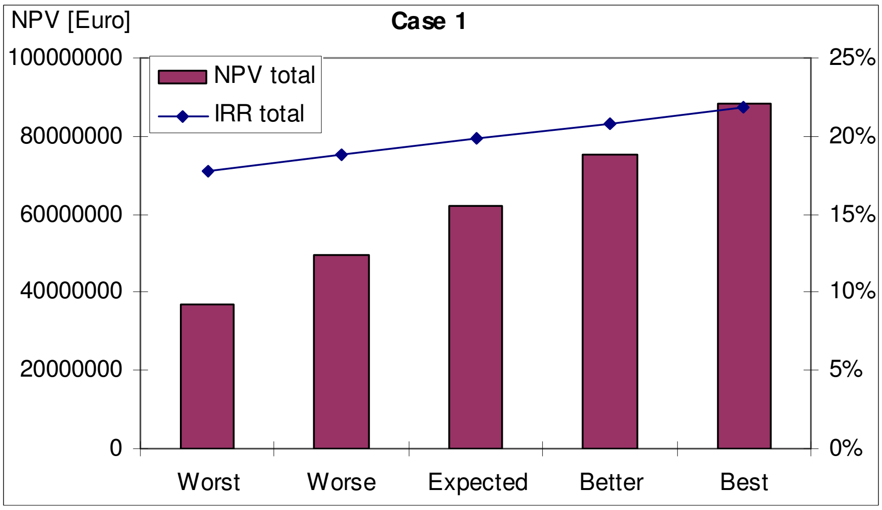

Fig. 9: Case 1, NPV and IRR

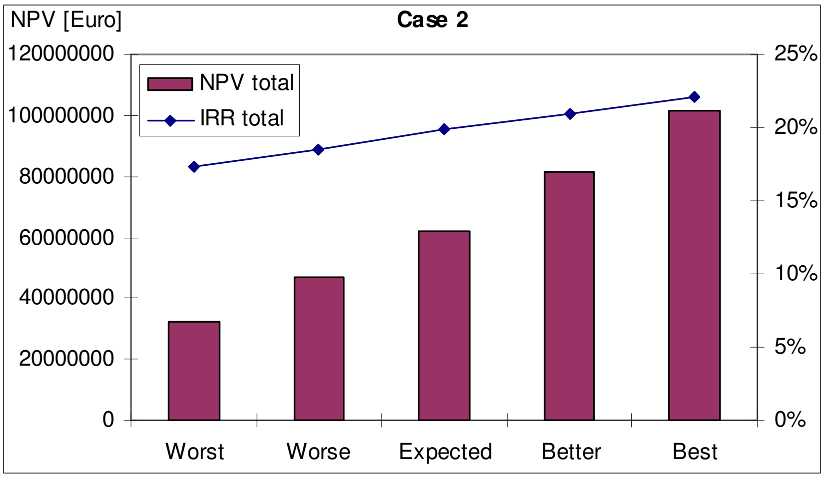

Fig. 10: Case 2, NPV and IRR

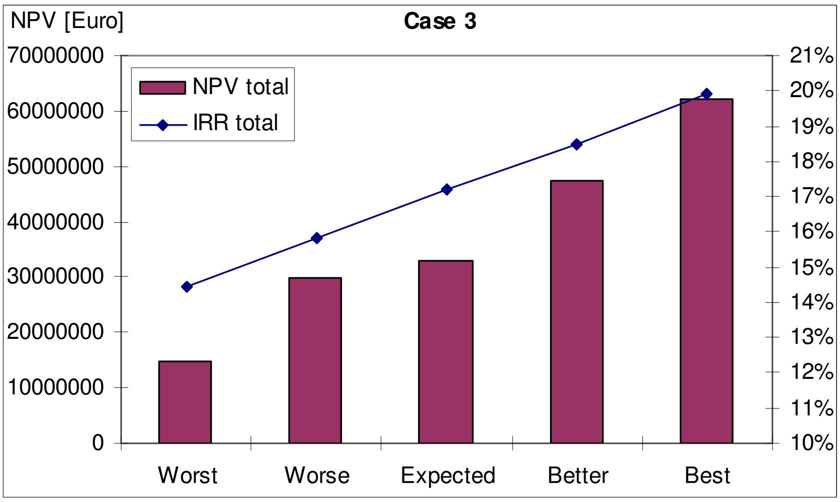

Fig. 11: Case 3, NPV and IRR

The results show that in the scenarios analyzed the IRR varies in a range between 14,4% and 22,1%. The three cases have different impact on the project evaluation. Case 1 is dependent on the market size and number of players which enhances competition, it is foreseen that with the rising number of CSP facilities, this cost will tend to decrease (experience and scale economies).

Case 2 is dependent on technological improvements and its implementation pace. If initiatives like Desertec will move forward, the market size will increase significantly and therefore increasing R&D spending and learning curve will drive efficiency values higher.

Case 3 is dependent on the economic framework and to the existence of a guaranteed feed-in tariff. Theses values are always dependent on the solar radiation available, and are foreseen to be reduced in the future, due both to CSP technology economies of experience and to the pressure of cutting this kind of benefits. For this reason, only scenarios with same or reduced feed-in tariff were analyzed. The outcome shows that with a reduction in the tariff down to 0,21 Euro/kWh, the IRR is reduced to 14%. This is close to the lowest acceptable value for the cost of capital considered, and is therefore considered to be the lowest point for a still attractive investment under the current difficult scenario of the international capital markets.

The analysis performed considered that the investment was done by a company already with CSP technology and experience, with a WACC of 10%. For a new player, WACC would be increased due to its higher business risk, β, making the investment a more riskier one.

Concluding the sensitivity analysis, the two more relevant variables were considered (investment costs and feed-in tariff) and assuming different probabilities of occurrence for the various scenarios a global value for the NPV and IRR was calculated (Fig.12). The probability of occurrence was 20% for the expected scenario, 15% for each combined scenario "better" vs. "worse" and 5% for the more extreme combined scenarios.

Feed-in Tarif		Initial investment costs: Worse	Initial investment costs: Expected	Initial investment costs: Better	
Worse					
	NPV total	10 279 798	29 779 681	49 279 565	7 444 920
	IRR total	14.0%	15.8%	17.9%	
	Pay back	8	8	8	
	Probability	5%	15%	5%	
Expected					
	NPV total	25 940 288	33 013 394	40 086 500	16 506 697
	IRR total	15.3%	17.2%	19.3%	
	Pay back	8	8	8	
	Probability	15%	20%	15%	
Better					
	NPV total	39 733 703	65 643 691	91 553 600	16 410 923
	IRR total	16.6%	18.5%	20.7%	
	Pay back	8	8	7	
	Probability	5%	15%	5%	
	NPV total	6 391 722	20 916 185	13 054 633	40 362 540 Euro

Fig. 12: Sensitivity analysis with probabilities for different scenarios

To finalize the evaluation, a comparison between CLFR-EM and PTR technologies was made, considering the investment costs mentioned in Table 7, analyzing the sensitivity to the value of the feed-in tariff for an IRR=14% in both situations (Table 10). Although it can be argued that the costs considered by Morin et al are somewhat high for the current state of the art of the PTR systems, it is evident the difference in profitability of both concepts, meaning that with the pressure for a reduction in the feed-in tariff, the CLFR-EM concept has a good perspective for becoming an important technology in a near future.

	CLFR-EM [Euro/kWh]	PTR [Euro/kWh]
IRR = 14%	0,21	0,305

Table 10: Feed-in tariff for 25 years for systems with 2200h of yearly production

An identical calculation for Hurghada (EGY) yields a tariff at least 30% lower in both cases, all else being equal, not just because solar radiation (and the number of equivalent operating hours) is 30% higher, but, in the case of CLFR-EM, the overall conversion efficiency is higher, in particular because of the lower latitude. This analysis will be the topic of a future paper.

As a final calculation, and in spite of the fact that a sensitivity analysis was carried out with respect to several variables, in particular to cost, it is interesting to use the tools developed to perform a final estimate, a one shot estimate of what tariff one would obtain if a more substantial cost reduction can be achieved in the future, due to the usual learning curve, scale effects, optimum control, optimization of collected versus dumped energy, etc., items not included in the analysis done above. For this, supposing a Capex cost reduction of 35% can be achieved, i.e. if a value of 1.3 Euro/Wp is considered for the CLFR-EM technology, the equivalent tariff to the one found in Table 10 (same IRR of 14%, same investment conditions, same location, etc) would lead to a tariff lower than 0,15Euro/kWh.

Conclusion

Efficiency and economic results of a new CLFR-EM system have been presented. Overall efficiency shows a potential increase from 8.5% (9,1%) for LFR conventional systems to 11.8% (13%)for the new CLFR-EM system for sunny locations like Faro, PT (Hurghada, EGY). This higher efficiency associated with investment costs similar to the conventional LFR makes the new CLFR-EM attractive. Comparing with the standard PTR technology, the CLFR-EM has a lower output in kWh/m2 of mirror area, however is much more compact in the soil usage, and globally the cost of the kWh produced is lower than the PTR cost. The calculations for the tariff supporting an IRR of 14% indicate a value around 0,21Euro/kWh for a sunny location in Southern Europe (Faro, PT). The same calculation yields a higher value of 0,305 Euro/kWh for PTR technology. This result depends on real performance data and should be confirmed; thus a demonstration plant is currently being planned for Evora, PT where real performance data will be obtained, with the support of the utility company group EDP. It is clear that identical calculation for a sunnier location, like Hurghada (EGY) will yield a lower tariff value (at least 30% lower), all else being equal.

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