Thermoeconomic Analysis of Advanced Solar-Fossil Combined Power Plants[*]

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Abstract

Hybrid solar thermal power plants (with parabolic trough type of solar collectors) featuring gas burners and Rankine steam cycles have been successfully demonstrated by California's Solar Electric Generating System (SEGS). This system has been proven to be one of the most efficient and economical schemes to convert solar energy into electricity. Recent technological progress opens interesting prospects for advanced cycle concepts: a) the ISCCS (Integrated Solar Combined Cycle System) that integrates the parabolic trough into a fossil fired combined cycle, which allows a larger exergy potential of the fuel to be converted. b) the HSTS (Hybrid Solar Tower System) which uses high concentration optics (via a power tower generator) and high temperature air receivers to drive the combined cycle power plant. In the latter case, solar energy is used at a higher exergy level as a heat source of the topping cycle. This paper presents the results of a thermoeconomic investigation of an ISCCS envisaged in Tunisia. The study is realized in two phases. In the first phase, a mixed approach, based on pinch technology principles coupled with a mathematical optimization algorithm, is used to minimize the heat transfer exergy losses in the steam generators, respecting the off design operating conditions of the steam turbine (cone law). In the second phase, an economic analysis based on the Levelized Electricity Cost (LEC) approach was carried out for the configurations, which provided the best concepts during the first phase. A comparison of ISCCS with pure fossil fueled plants (CC+GT) is reported for the same electrical power load. A sensitivity analysis based on the relative size of the solar field is presented.

Key words: Integrated solar combined cycle system, solar thermal power plant, multiple pressure level steam generator, exergy loss

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1. Introduction

Integrated Solar-Fossil Power Plants (ISFPP) represent, both economically and energetically, a promising alternative for the conversion of solar energy while offering a guarantee of a minimum power supply independent of the level of solar radiation (Favrat, 1995; Allani and Favrat, 1991; Allani et. al., 1996). Their performance is however strongly dependent on the intensity of the solar input. Taking account of the classical thermoeconomic criteria (performances/costs), several integration concepts and technology options are used (Buck et al., 1998):

- The SEGS plants (Solar Electric Generating System between 30 and 80 MW each) in California are based on cylindrical-parabolic concentrators and gas boilers used to drive simple steam Rankine cycles (Kolb, 1997). The efficiency of SEGS plants, particularly when using a substantial amount of fossil fuel, is lower than modern Combined Cycle Plants (CC).

- Concepts such as PAESI[1] (Allani et. al., 1996; Allani et al., 1998) or ISCCS-Nevada in USA (Pilkingston, 1996) use a fuel-fired gas turbine topping cycle and convert these SEGS plants into Integrated Solar Combined Cycle Systems (ISCCS). Major advantages of the latter are, among others, a better conversion efficiency in fossil fired mode and an improved equipment amortization (Pilkingston, 1996). In these two latter cases, solar energy is used at a lower exergy level with a temperature limited by the stability of the solar heat transfer fluid, even though another concept using direct evaporation on the collectors has been proposed (Dagan et al., 1992; Goebel, 1997),

- The HSTS (Hybrid Solar Tower System) uses high concentration optics (via a power tower generator) and high temperature air receivers to drive the combined cycle power plant. In this case, solar energy is used at a high exergy level as a heating source for the topping gas turbine cycle (Price et. al., 1996; Worner et. al., 1995).

For all these cases, the electricity costs tend to be very high compared to conventional thermal power plants.

This paper focuses on a simplified thermoeconomic analysis and optimization of the synthesis, design and operation of an advanced ISCCS. It is realized in a two-step approach:

a) In the first step, a mixed approach using pinch technology principles coupled with a mathematical programming optimization algorithm is applied to minimize heat transfer exergy losses respecting the off design operating conditions of the steam turbine (cone law) and define the optimized configurations of plant process.

b) In the second phase, an economic analysis based on the Levelized Electricity Cost (LEC) approach is carried out for the configurations that showed the best results during the first phase.

This method has been developed and applied for the PAESI project but it may be applied to any ISCCS including a steam cycle with n different pressure levels.

2. Thermodynamic Optimization and Results

2.1 Methodological approach and Results

As explained above, ISCCS are power plants which combine the thermal energy from the combustion gases of the gas turbine and from the thermal oil of the solar collectors to drive the steam cycle. Following discussions with the Tunisian Electricity Company (STEG) and to minimize overall risks for a first plant it was decided early in the project to aim at a plant of 80 to 125MW. Furthermore considerations of reliability and previous time-dependent simulations formed the basis for a decision to use two gas turbines in the proposed combined cycle power plant. As a result, the PAESI plant application includes in particular:

a) a solar field corresponding to a maximum heat rate capacity of about 200 MW with maximum temperature of the thermal oil limited to 390° C,

b) two gas turbines of the 25 MWe class with flue-gas temperature of approximately 540°C,

c) a train steam turbine with a maximum capacity of about 80 MWe.

The cooling media is sea-water at an average temperature of 25°C. The live steam cycle parameters depend on the gas turbine operating modes and on the important variations of solar supply. The challenge of pinch technology application to ISCCS is these highly variable operating conditions linked to the availability of solar radiation (variable hot composite). A methodology to determine how to get the cold composites corresponding to optimized concepts for different operating conditions is the first objective. A general thermodynamic approach using pinch technology principles coupled with a mathematical programming optimization algorithm is applied.

Figure 1 gives a schematic block diagram of the planned ISCCS and of the basic formulation. The optimized variables are the pressure levels and steam mass flows (independent variables) corresponding to a minimization of the heat

[1]PAESI stands for "Projet d'Aménagement Energétique Solaire Intégré"

transfer exergetic losses in the steam generators (objective function) at each solar operating mode (0% night, 100% summer day). Calculations can be applied for any steam cycle with a single or n different steam pressure levels, a minimum pinch for all the pressure levels is respected (critical pinch constraints). With the aim of a strategy that maximizes the yearly electricity production the plant will operate continuously, except for the maintenance periods, and the main part of the electricity will be produced under night operating conditions.

Heat tranfert exergy loss (Objective fonction)

$$L = \sum_i \dot{M}_i T_a c_i \ln \frac{T_{i,out}}{T_{i,in}} + \sum_k T_a \left(\dot{M}_{b,k} \cdot \frac{\Delta h_{b,k}}{T_{b,k}} + \sum_{j \neq b} \dot{M}_j \frac{\Delta h_{j,k}}{\Delta T_{j,k}} \ln \frac{T_{j,out}}{T_{j,in}} \right)$$

Critical pinch points

$$\Delta T_{x,k} = \frac{\Delta H_{x,k} + \sum M_i c_i T_{i,out}}{\sum M_i c_i} - T_{b,k}$$

Law of cone
Steam turbine operating conditions

$$\dot{M}_{s,k} \cdot \frac{\sqrt{\frac{v_{s,k}}{P_{s,k}}}}{\sqrt{1 - \left(\frac{P_{out,k}}{P_{s,k}}\right)^{\frac{n+1}{n}}}} = K_{0,k}$$

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Gas Turbine        Oil Solar
  Cycle              Cycle

Heat Recovery     Heat Solar
   Steam             Steam
 Generator         Generator

       Steam Cycle
       Power Plant
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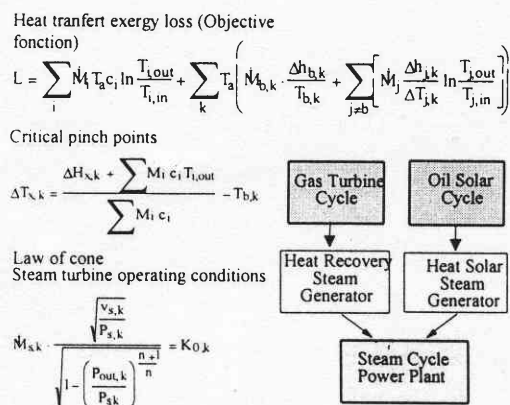
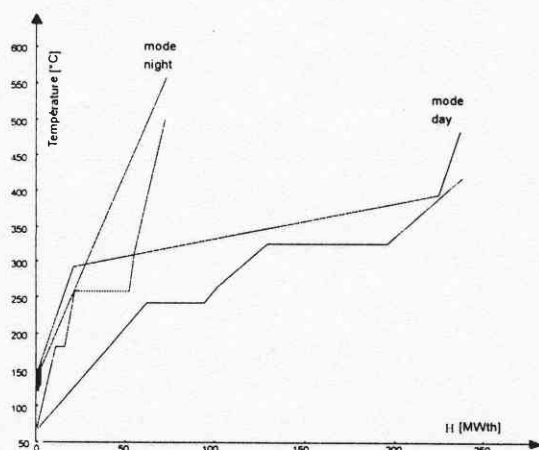Figure 1. Thermodynamic optimization model

Figure 2. Optimized composites for two extreme operation modes: CC-night and ISCCS-day

Steam turbine cone parameters of the law of cone (Traupel, 1982) corresponding to the night conditions are chosen and maintained fixed during the optimization of the steam pressure levels at the other operating regimes (cone law constraints). Figure 2 shows the composites (hot and optimized cold composites) for the two most extreme conditions (Kane and Favrat, 1999) (0% solar supply at night operation mode, 100% solar at a peak summer day operation mode). The reduced slope of the central part of the hot composite mainly corresponds to the solar

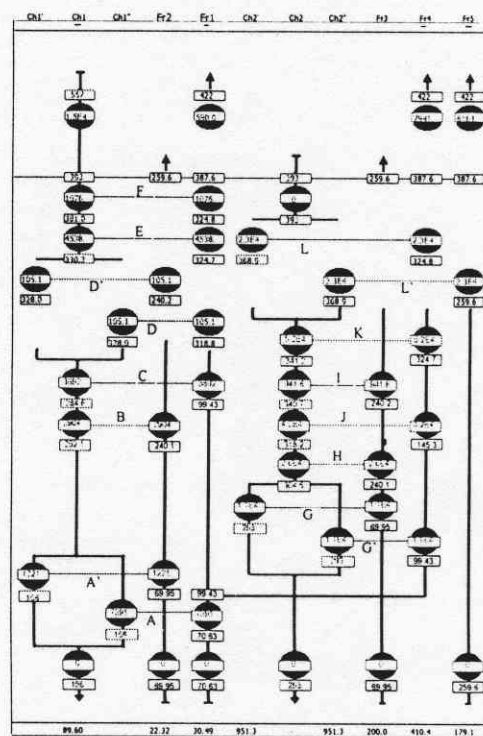posite mainly corresponds to the solar thermal oil contribution, which disappears at night.

Figure 3. Heat exchanger networks

However the detailed distribution of steam mass flows between the various heat recovery lines is still unknown. An iterative procedure to adjust the new so-called "stream interaction factor" for each water or steam stream is described and then applied to determine the mass flows in the steam generators of the two supply streams (solar thermal oil and combustion gases) of the PAESI power plant (Kane and Favrat, 1999). From the resulting steam streams, the standard heat exchanger design procedure of pinch technology is applied, with a separate design of the network above, respectively below the pinch temperature level, suitable for the extreme operating modes (multiple base case design approach). The subnetwork of Figure 3 is finally obtained for the 100 to 125 MWe PAESI plant and corresponds to the flowsheet shown in Figure 4.

This approach allows a structured search for the most promising heat exchanger networks during the predesign phase. In addition, an environomic[2] optimization based on a superstructure generated by the present approach is currently under development.

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[2] environomic is a term illustrating the fact that environmental costs corresponding to the main emissions are simultaneously accounted for, together with the energetic and economic factors.
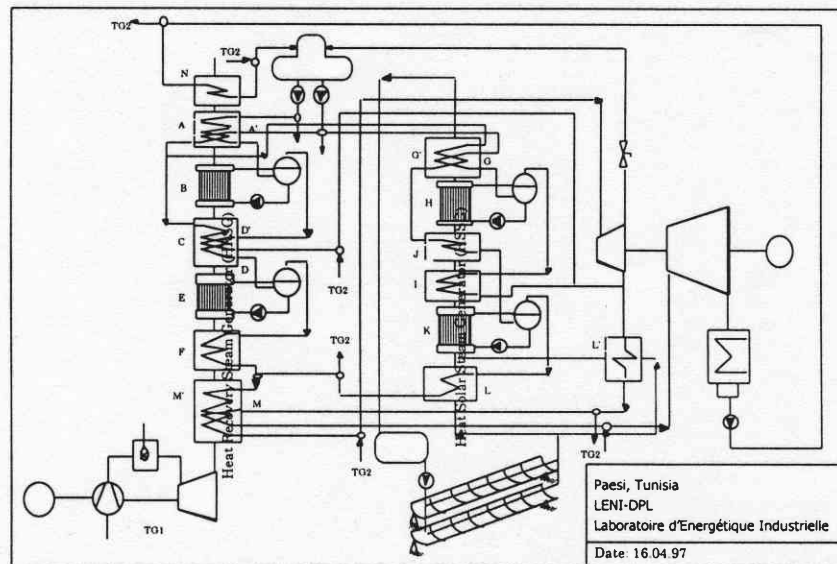
Figure 4. Flowsheet of the alternative of an ISCCS with the highest efficiency and dual pressure steam generator

2.2 Performances comparison

Calculations were carried out for different configurations of steam turbines and for different operating modes of the ISCCS (only one gas turbine in operation when 100% of the solar capacity are available):
- SPL simple cycle: Operation with one evaporation pressure level of all steam generators (HSSG, HRSGs) with a reheater only based on solar thermal power, so that the moisture content at the turbine exhaust remains within the acceptable limits. For that configuration, the plant will have to operate at night without the reheater due to the lack of solar radiation.
- SPL advanced cycle: Operation with one evaporator pressure level of all steam generators with two stage moisture separators in the expansion through the steam turbine in order to avoid unacceptable moisture content in the steam at the turbine exhaust. No need of energy (solar or fossil) for reheating. This option corresponds to a smaller size of the low-pressure parts of the steam turbine because of the reduced mass flow, resulting in an improved efficiency at night operation. However the various heat recovery units (Solar steam generator and HRSGs) work independently in parallel for different operating conditions.
- DPL advanced cycle: Double Pressure Level operation of all steam generators with two reheater types (solar and gas) working in line. This case, shown in *Figure 4*, presents a network, which includes interlaced heat exchanger tubes at the same temperature level in the HRSGs.

The diagram in *Figure 5* shows a comparison of the calculated steam cycle efficiencies for the different designs as a function of the available solar capacity.

It may be seen that there is a significant increase in efficiency from the so-called SPL simple cycle to the more sophisticated designs SPL and DPL advanced cycles.
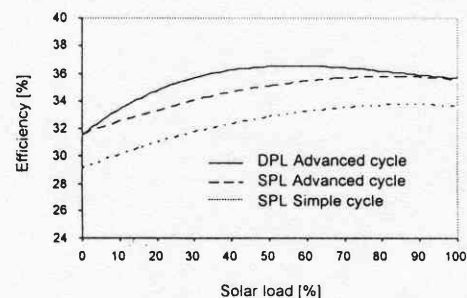

Figure 5. Calculated steam cycle efficiencies

The comparatively low efficiency at 0% solar load is due to the fact that the steam turbine operates in deep part load (about 29% of the maximum load) as long as there is no additional steam provided by the solar plant. In this case, the electric-mechanic efficiency of the steam turbine group is about 89% against 98% at the nominal point (Allani et al., 1998). This is the price that has to be paid for the advantage of having only one steam turbine running throughout the year (starting up and shutting down a second "solar steam turbine" every day would make the plant difficult to operate and might reduce the availability of the system). Alternatives like the lowering of the shaft speed at night together with the use of power electronics to adjust the delivered current frequency might also be considered.

TABLE I. INFLUENCE OF SIZE OF SOLAR FIELD AND SUBSIDY IMPACT ON THE ISCCS'S VIABILITY

Plant type		ISCCS Base case		ISCCS Medium solar	
Size of Solar Field	[m2]	450 000		280 000	
Total Insolation	[kWh/m2]	1 950		1 950	
Net capacity	[MW]	125		100	
Total Investment Cost including	[Mio US$]	235		190	
- *solar field with HTF system*	*[Mio US$]*	*110*			
- *power block*	*[Mio US$]*	*63*			
- *auxiliaries*	*[Mio US$]*	*12*			
- *engineering*	*[Mio US$]*	*15*			
- *site and infrastructure*	*[Mio US$]*	*9*			
- *land*	*[Mio US$]*	*6*			
- *contingencies*	*[Mio US$]*	*20*			
Specific Investment Cost	[US$/kW]	1 880		1 900	
Administration and O&M costs:					
- power plant	% of invest.	6			
- Solar field	[MUS$/y]	1.61			
Average fuel cost	[US$/kWh]	0.01			
Discount rate	%	4			
Annual Power Production	[GWh/y]	607		580	
Annual Gas Consumption	[GWh/y]	1000		1050	
CO$_2$ Emissions	[to/y]	200'000		210'000	
Solar Share	[%]	24.3		14.5	
Power Plant Fuel Efficiency	[%]	61.0		55.0	
IBRD-subsidy (assumed)	[Mio US$]	50	0	50	0
Internal Rate of Return (IRR)	[%]	5.7	2.5	10.1	5.0
Levelized Power Cost – Fossil	[US¢/kWh]	4.0	4.0	4.0	4.0
Levelized Power Cost – Solar	[US¢/kWh]	9.5	12.6	8.5	13.7
Levelized Power Cost	[US¢/kWh]	5.4	6.1	4.8	5.5

The results of the SPL and DPL advanced cycles are similar at 0% (night operation) and at 100% (summer day operation) solar load. At medium solar load the design DPL advanced cycle shows by far the best performance. Taking into account that the power plant is operating in this domain for approximately 1500 hours per year (against a total of about 7500 h) the influence of this difference on the annual plant performance has been estimated to be about 1% (between SPL and DPL advanced cycles). For this reason the economic calculations and sensitivity analysis shown below have been carried out considering the SPL advanced cycle, which presents the simplest operation and regulation system. The average annual electrical energy production is estimated to be 607 GWh and can be used to calculate a theoretical plant factor based on the total installed power of 125 MW.

3. Cost Analysis

The Levelized Electricity Cost (LEC) approach including capital investment, financing and operating cost is used to characterize the economic viability. The cost evaluation is valid in real terms (constant cost 1997) and a real dis-

count rate of 4% has been assumed. To calculate the Internal Rate of Return (IRR), a constant real power price of 5.7 US¢/kWh has been considered[3].

3.1 Influence of the size of the solar field

For the base case (corresponding to 200 MW of solar heat power supply), the size of solar field has been fixed to 450 000 m^2 with a solar collector cost[4] of $245/m^2 including the HTF system. This is based on the assumption that the World Bank (IBRD) would contribute with a subsidy of the order of US $50 millions. For the investment cost used in the analysis, when this subsidy is considered it has been deducted from the investment costs for the total plant. In order to provide more general data, detailed sensitivity calculations have been carried out to investigate the influence on the economics of the project of reducing the size of the solar field. The results of

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[3] This is the price that might be paid by the STEG (Tunisian Power & Gas Company) to independent power producers.
[4] Buck et al., 1998 cite specific prices some 20% lower at $200/m2 but we have not been able to confirm these low figures. The same authors predict a further decrease to $140/m2 by 2005, which would of course considerably change the economics.

these calculations are summarized in TABLE I. More detailed information is shown on *Figures 6 to 8*.

As may be seen from TABLE I, the ISCCS-Base Case with a solar field of 450 000 m² has a high solar share of 24.3% but an IRR of only 2.5% (no subsidy case) to 5.7% (with IBRD-subsidy of 50 Mio US$).

As an alternative the option "ISCCS-medium solar" with a smaller solar field of 280,000 m² is also shown. This latter option still offers a relatively high solar share of 14.5% and an IRR of 10.1% (an IRR of 10 % is considered as a minimum in terms of economic feasibility of a power plant project).

If the subsidy is neglected, the production cost of the solar power is in a range from 12.5 to 17 US¢ / kWh according to the size of the solar field (*Figure 7*). This is still a very good result compared to other solar power technologies. It is important to note that these results are very sensitive to the unit cost of the solar collectors.
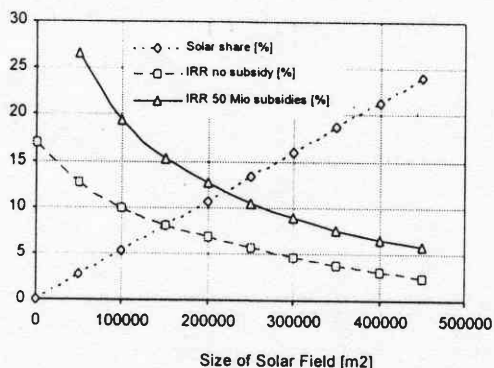

Figure 6. *IRR and solar share versus size of solar field. Annual power production 540 to 600 GWh.*
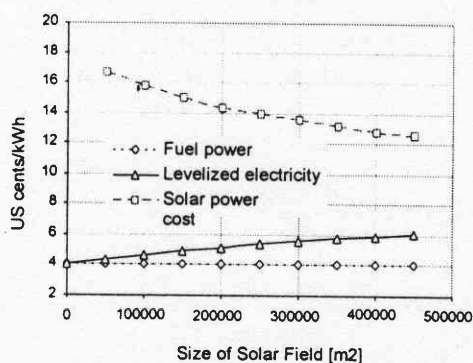

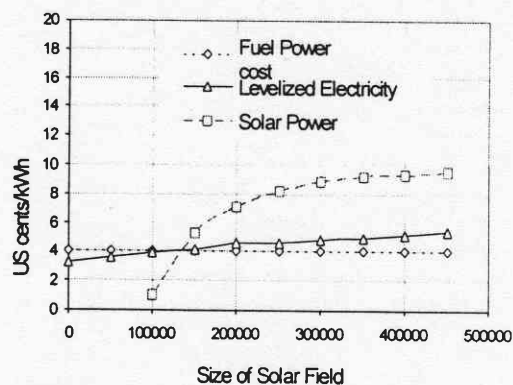Figure 7. *Power costs versus size of solar field, without subsidy. Annual power production 540 to 600 GWh*

Figure 8. *Power costs versus size of solar field, with subsidy. Annual power production 540 to 600 GWh*
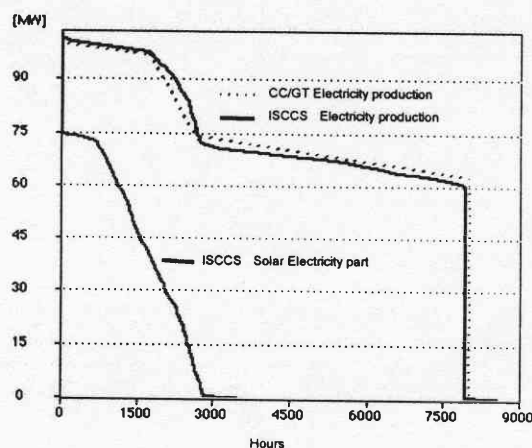

Figure 9. *Cumulated curve of the Electricity production*

3.2 Comparison with a pure fossil fired equivalent power plant (CC+GT)

TABLE II below shows the financial analysis for a rough comparison case representing a fossil fired power plant of a similar size.

To provide a similar cumulated curve (*Figure 9*) of the electricity production, the pure fossil system is represented by a combined cycle block of 75 MWe for the base load and an additional 25 MWe gas turbine simple cycle for the peaking hours.

TABLE II also shows the data for the pure fossil fired plant corresponding to the case where the additional 84 500 tons of CO_2 per annum emitted are penalized by an internalization of CO_2 costs of 2.5 US¢ / kg. The latter has been taken from the literature (Goswami, 1995).

TABLE III. ISCCS COMPARISON WITH A COMBINED CYCLE PLANT[5]

Plant type		ISCCS Medium solar	CC with CO2 penalty	CC no CO2 penalty
Size of Solar Field	[m2]	280 000	0	0
Total Insolation	[kWh/m2]	1'950	0	0
Net Capacity	[MW]	100	100	100
Total Investment Cost	[Mio US$]	190	100	100
IBRD-subvension (assumed)	[Mio US$]	50	0	0
Specific Investment Cost	[US$/kW]	1 900	1 000	1'000
Annual Power Production	[GWh/y]	580	600	600
Annual Gas Consumption	[GWh/y]	1050	1400	1400
CO_2 Emissions	[to/y]	210 000	284 500	284 500
Plant Factor	[%]	66.0	68.6	68.6
Solar Share	[%]	14.	0	0
Power Plant Fuel Efficiency	[%]	55.0	47.0	47.0
Internal Rate of Return (IRR)	[%]	10.1	10.2	12.5.
Levelized Power Cost	[US¢/kWh]	4.80	4.89	4.54

The resulting IRRs are as follows: 12.5 % (No CO_2 penalty assumed) and 10.2% (with CO_2 penalty assumed). Both of the resulting IRRs are in a much higher range than the ISCCS-base case IRR presented on TABLE I. But the ISCCS-medium solar with a subsidy of 50Mio US$ may be competitive when compared to a fossil fired plant with a similar size CC. However the most realistic comparison scenario is either with a subsidy for solar and no internalization of CO_2 cost or solar without subsidy and internalization of CO_2 cost. In the latter case the unit cost of CO_2 would have to be doubled for the ISCCS medium solar option to become economically competitive at the present price of solar collectors. Nevertheless ISCCS represent at present the most economical way to reliably convert solar energy into electricity.

4. Conclusion

Modeling and thermodynamic optimizations based on a pinch technology approach were developed for the synthesis, design and operation of advanced solar-fossil combined power plants. The design method can be applied to any ISCCS, including a steam cycle with single or multiple steam evaporation pressure levels. Calculations were carried out for different configurations of steam turbines and for different operation modes of an 80 to 125 MWe ISCCS.

Taking account of annual plant performance and the simplicity of the operations, the LEC approach is applied to an ISCCS concept (called SPL advanced cycle) with an economic sensibility analysis. Results show that the solar electricity costs are still high and depend consid-erably on the size of the Solar Field (ISCCS Levelized Electricity Cost with 15 to 24% of annual solar share is about 20% to 30% higher than similar size Combined Cycle Plant). However solar collector cost reduction and credits for reducing emissions, both of which are expected in the near future (Buck et al., 1998; Pilkingston, 1996), will offer new opportunities for intermediate power ISCCS. For example, calculations show that for a subsidy of 50Mio US$ and taking account of 2.5 US ¢/ kg of additionally emitted CO_2, those hybrid solar thermal power plants may already be competitive against conventional fuel fired power plants.

Nomenclature

CC	Combined Cycle
DPL	Double Pressure Level
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
HSSG	Heat Solar Steam Generator
HSTS	Hybrid Solar Tower System
ISCCS	Integrated Solar Combined Cycle System
ISFPP	Integrated Solar-Fossil Power Plants
LEC	Levelized Electricity Cost
PAESI	Projet Pilote d'Aménagement

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[5] Note that several of these data are site specific (Laakarit in Tunisia), see also footnote 4 regarding the cost uncertainties for the solar field

Energétique Solaire Intégré
SEGS	Solar Electric Generating System
c	constant pressure specific heat [MJ.kg^{-1}.K^{-1}]
h	Mass enthalpy [MJ/kg]
Ko	Cone mass flow constant [-]
L	Heat transfer exergy loss [MW]
M	Mass flow rate [kg/s]
n	Polytropic factor [-]
P	Pressure [Pa]
T	Temperature [K]
v	Mass volume [m^3.kg^{-1}]

Subscripts:

a	ambient
b	saturated zone
i	heat transfer fluid (gas or solar oil)
j	exchanger type
k	pressure level (high or low)
s	superheat vapor

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