Multicriteria Optimisation of Small Hybrid Solar Power System

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Abstract: A new concept of small hybrid solar power system (HSPS) has been successfully demonstrated in the context of a project called SPS (Solar Power System). This plant integrates two rows of solar collectors, two superposed Organic Rankine Cycles (ORC) each equipped with a scroll hermetic expander-generator and a heat engine. In operation with solar energy only, the heat is supplied by a thermal fluid (presently pressurized water) heated in the vacuum insulated focal tubes of sun following, flat concentrators made of series of thin plate mirrors (CEP). In hybrid mode additional heat is supplied by heat recovery from the exhaust gases of the engine in series with the solar network and by a separate network recovering heat from the cooling of the engine block at an intermediate temperature level. This paper presents the results of a multi-criteria optimization of a 22 kWe HSPS, including aspects such as energy performance, economic and financial analysis, and environmental aspects. The so called mini-maxi methodological approach with genetic algorithm is used considering three principal criteria such as the energy efficiency of the superposed ORCs, the minimal cost of the installation and the minimum emission of CO_2. Taking into account of the solar radiation time dependence, the electricity supply variation and the change of configuration (night and day operation), the performance analysis is based essentially on the yearly energy simulation in which the off-design physical models of components are considered. A comparison of HSPS with pure fossil fuelled Plants (DEPU-Diesel Engine Power Unit) is reported for the same electrical power load curve, with an economic sensitivity analysis. Results show that the solar electricity costs are still high and depend considerably on the size of the Solar Field (the HSPS Levelized Electricity Cost with 5 to 16% of annual solar share is about 17% to 49% higher than a similar size Diesel Engine Power Unit). However, a reduction of CO_2 emission up to 26% could be obtained when replacing the Diesel Engine Unit by a similar HSPS. Those hybrid solar thermal power systems may already be competitive if a tax of about 42 Swiss cts /kgCO_2 would be considered.

Keywords: Hybrid solar thermal power plant, solar concentrators, turbine scroll, thermal engine, Organic Rankine Cycle, mini-maxi muticriteria optimization, genetic algorithms.

1. Introduction

Electricity generation from low temperature heat sources generally imply the use of so-called organic fluids working in Rankine cycles equipped with vapour turbines or expanders. Hence the name of Organic Rankine cycles (ORC) used in this context. Those fluids have thermodynamic properties, which are adequate for this application, such as their low specific volume, high molar mass as well as a saturated vapour slope which is often positive in a Log P-h diagram, which prevents condensation at the end of the expansion. This last factor simplifies the design of the turbines for applications in the mid to large power range (some hundreds of kWe and more). Only a few studies both theoretical and experimental (Prigmore and Barber, 1975; Giampaolo et al., 1991; Wolpert and Riffat, 1996; Yamamoto et al., 2001) have been done in the low power range going from a few kWe to a few tens of kWe. The main limitations in the latter power range are the unavailability of turbines or expanders with adequate efficiencies, in particular when having to cope with reasonably high expansion ratios and variable operating conditions. Economic considerations also considerably restrain the possibility to use dedicated technological developments with high specific costs considering the low initial production quantities. This therefore tend to favour the exploration of the potential of adaptation of components produced in large quantities for other duties like is done in this paper. Moreover there exists a strong incentive to avoid as much as possible open systems with shaft seals, which are sources of leakage and a burden on the maintenance. Those are the considerations, which initiated our work on hermetic scroll expander-generators (Zanelli et Favrat, 1994) for low power ORC units. The expander-generators, which we presently use, are obtained by modifications of actual hermetic compressors produced at large scale for refrigeration and air-conditioning worldwide, hence with low specific costs. These units are not only hermetic but, provided an adequate oil management is introduced, present the advantage of a weak sensitivity to liquid fractions, which could result from an imperfect evaporation and two-phase expansion.

One of the major limitations of standard scroll compressor units is the low built-in volume ratio, which restricts the efficient expansion ratio to values lower than typically 8 within a pressure domain from 25 to 3 bars. However this can be compensated by considering superposed ORCs using each a different fluid to keep a high specific power within the pressure range of the scrolls and avoid sub atmospheric pressures (Favrat, 1995; Kane et al. 1999). This solution allows an efficiency improvement compared to single cycles, while avoiding the large specific volume of equipment required at the lower end of a two-stage, single fluid cycle, which is another potential alternative. The small and modular ORCs open the possibility of not only converting solar energy in hybrid solar power plants, in particular in developing countries, but also of converting waste heat or heat from small boilers. In this context the feasibility of a small pilot power plant (HSPS: Hybrid Solar Power System), of 22 kWe nominal power has been demonstrated within the project SPS (Solar Power System). This hybrid plant includes two superposed cycles each equipped with its own expander-generator (figures 1 and 2). The hot source is provided by sun following solar concentration linear collectors with vacuum insulated tubes. The concentrators are made of series of thin plate mirrors (CEP) of different width and fixed at calculated angles on linear supports to offer a reduced wind resistance and allow an easy replacement in case of failure. The thermal source is complemented with the heat from both the combustion gases and the block cooling of a cogeneration Diesel engine of 13 kWe. This integrated power plant mainly designed for demonstration purposes has been tested both in the laboratory using heat from a thermal oil boiler and then on site where pressurized water was used in the collector tubes. Information relative to the design choices and the description of the preliminary tests have been presented in earlier papers (Kane et al., 1999; Kane et al., 2001). Some of the in-situ results (Martin et al., 2002; Kane 2002) will be briefly commented underneath. The present study also deals with the formal design and operation optimisation, accounting for energetic, economic and environmental considerations. The original method used is based on a formulation for a mini-maxi multicriteria optimization using genetic algorithms[1]. Results are presented for various solutions of optimal configurations.

2. HSPS prototype and results

In-situ tests have been done over a period of several months from May to October 2001 on a site at EPFL (Lausanne, Switzerland). This allowed performances to be measured over a broad and variable operational range of conditions. Direct sun radiation varied from day to day between 500 and 800 W/m^2 for a collector area of 100m^2. When used, the power range of the engine varied between 11 and 13 kWe, due in particular to variations in the air temperature, and gave a heat recovery of the order of 20 kWth on the engine block and 7 kWth on the exhaust gases. For all tests covering a cumulated duration of 110 hours, the power plant produced about 800

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[1] The approach is part of a global methodology developped in a recent thesis (Kane, 2002) for the systemic optimisation of hybrid thermal solar power plants in general.

kWh including 500 kWh from the turbines. Some of the operational conditions as well as the results obtained for two operational modes (solar only and hybrid) are summarized in Table 1 and Table 2.

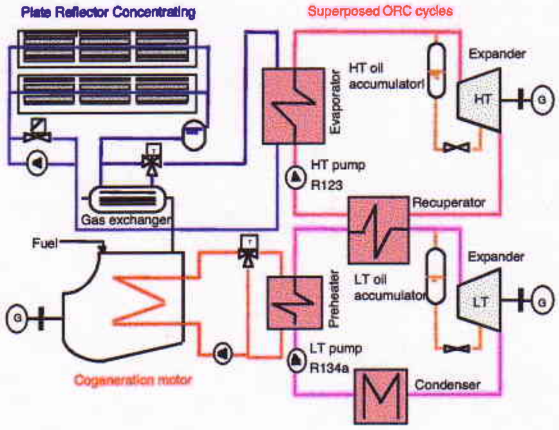

Figure 1: Simplified flowsheet of the HSPS power plant

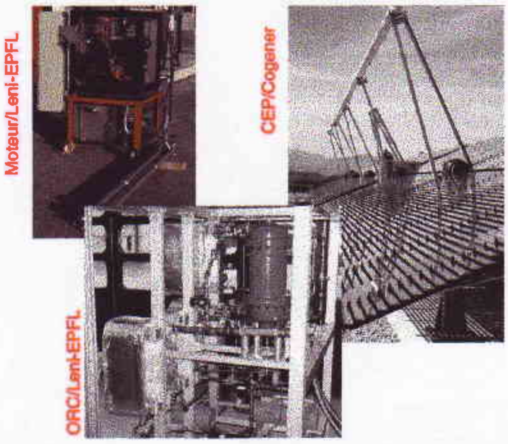

Figure 2: Components of the SPS power plant

Solar				
	Direct solar radiation	:	500…800	W/m2
	Collector area	:	100	m2
Motor				
	Electrical power	:	11…13	kWe
	Engine cooling rate	:	20	kWth
	Cooling temperature	:	82.5	°C
	Combustion gas hest rate	:	5…7	kWth
Superposed ORCs				
	Hot source temperature	:	120…150	°C
	Cold source temperature	:	7…9	°C
	Condensation pressure	:	5...6.5	bar
SPS power plant				
	Number of hours of test	:	110	Hours
	Electricity produced	:	800	kWh

Table 1: In-situ test conditions and number of produced kWh (Site EPFL-Lausanne)

Dates	-	29.05.01	14.08.01
Direct solar radiation	(W/m2)	833	742
Operating mode	-	solar	hybrid
Total elecvtricalpower	(kWe)	6.52	18.57
Turbine electrical power	(kWe)	6.52	7.32
Motor electrical power	(kWe)	0	11.25
Cycle energy efficiency (1st Law)	(%)	13.7	13.67
Cycle exergy efficiency	(%)	46.57	57.26
Overall system efficiency	(%)	7.74	15.88
Fossil efficiency	(%)	-	41.1

Table 2: In-situ test results for 2 operational points (mode solar only and hybrid, Site EPFL-Lausanne)

Considering the fact that there are different input temperature levels for the ORCs, it is best to express them exergetically for both operational modes (solar only without engine input or hybrid mode with engine). Curves of ORC exergy efficiencies and electrical energy produced by the scroll turbines are given in Figure 3 and Figure 4. The exergy efficiency is the ratio between the net electrical power and the heat exergy (or exergy transformation) of the various heat inputs to the superposed cycles according to:

$$\eta_{ORC} = -\frac{\dot{E}_T - \dot{E}_P}{\dot{M}_{pw} \cdot \Delta k_{pw} + \dot{M}_{cw} \cdot \Delta k_{cw}} \qquad (1)$$

The two distinct curves obtained in hybrid mode correspond to series of measures with different values of solar radiation. Even if a number of improvement opportunities have been detected, the performance reached are encouraging for a thermodynamic conversion cycle in this power range and with such a low level of temperature. The superposed cycle exergy efficiency reached a maximum value of 48% in solar mode only and 57% in hybrid solar mode. The decrease of exergy efficiency observed in hybrid mode can be attributed to losses linked to an increase of the condensing pressure. The latter is due to a limitation of the cooling flow, which was observed following construction works which affected the cooling network.

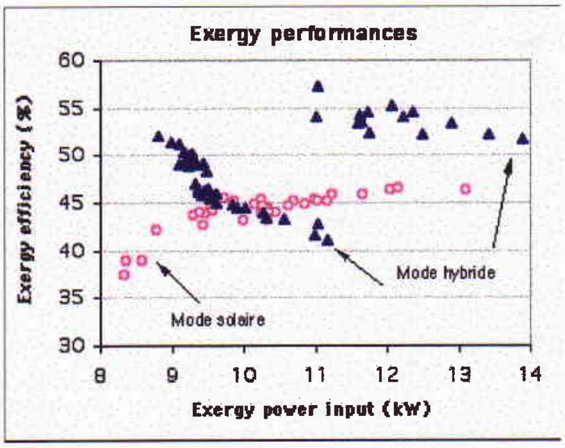

Figure 3: Exergy efficiency

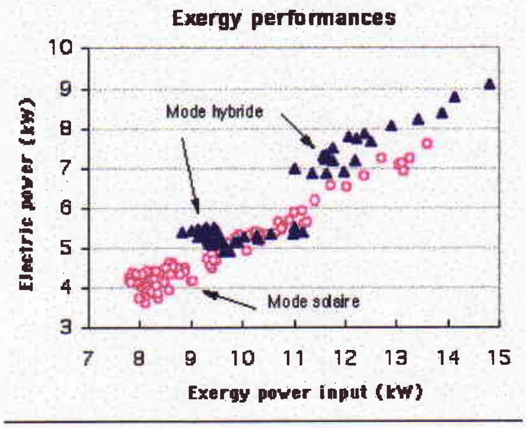

Figure 4: Electrical power delivered by the scroll expanders

It is interesting to note that the energy efficiency (First Law) in hybrid mode and referred to the fuel only (total electrical power/fuel LHV) reaches 41.1%, which represents an increase of 50% compared to the electrical efficiency of 27% of the original Diesel unit. However the solar electrical efficiency alone (ORC electrical power/solar radiation) is of the order of 7.7%, which is 35% lower than the 12% initially, expected.

It is important to note that the tests reported here have been realised in very partial operational conditions of the cycles. Figure 4 illustrates the load level of the turbines (9 kWe maximum for an installed power of 12 kWe). These operations at partial loads are due to an over sizing of the turbine relative to the solar field and to the fact that the solar field did not yet achieve the expected efficiencies, about 53% only for an initial value estimated at 75% (corresponding to 60 kWth direct solar radiation of 800 W/m^2). Moreover the characteristics of the heat exchangers and particularly the evaporator-condenser are very sensitive to oil trapping. The minimum pinch is located at the end of evaporation, which inherently limits the heat transfer capacity. Nevertheless these tests did allow the experimental validation of the concept of hybrid solar plant HSPS and its interest for the solar thermal electric conversion.

3. Multicriteria optimisation and Results

The tests of the SPS prototype allowed the identification and model validation of the most significant operational parameters (Kane, 2002). However the actual size of the different components (motor, turbine) as well as the type and number of installed turbines are not optimal when considering the yearly operation. This is due to the fact, in the timing of this particular project, the optimisation tools were not yet ready when the prototype power plant had to be designed and built. For example the configuration with one turbine by stage was chosen for simplicity as the night operation (coupling of cogeneration engine and superposed ORCs) was not a major objective at the time. But further optimisation is seen as an important element for the future progress of this type of plants.

3.1 Methodological approach and optimization

The idea of a multi-objective optimisation is applied to determine one or several efficient solutions, which can serve as a basis for trade-off analysis between several different criteria. In many cases in energy systems, the objectives present different trends or even opposite trends in function of the evolution of the different key variables. A typical example in power plant design is to look for a compromise between objectives such as: to maximise the efficiency while keeping costs and emissions as low as possible. Such a compromise can be obtained either by comparing[2] values of objectives obtained for a large number of decision vectors or based on the optimisation of a **utility function** which groups all the objectives in a single scalar criterion. In many cases of the literature the method of weighted functions is used (Lightner et Director, 1981; Steuer et Choo, 1983; Li et Yang, 1996). It consists in using a utility function, which is made of the algebraic sum of the different objectives, each associated with its own predetermined weight. An adequate adjustment of the weighting parameters allows the identification of several feasible solutions (dominating solutions, pareto optima). In this work we use a so-called **minimaxi formulation** based on canonic weights. According to this formulation the optimisation is done on the basis of a utility function, which is represented by the normalized distance between an ideal point of reference (R) and another feasible point (F) (Lightner et Director, 1981):

$$f(\mathrm{x}) = \sum_{\mathrm{i}} \omega_{\mathrm{i}} \cdot \frac{f_{\mathrm{i}}(\mathrm{x}) - f_{\mathrm{i,opt}}}{f_{\mathrm{i,vnp}} - f_{\mathrm{i,opt}}} \tag{1}$$

where:

- ω_i : priority level relative to the objective $f_i(x)$.
- x : vector of independent variables $\in$ to the decision space Ω.
- $f(x)$: utility function.
- $f_i(x)$: $i^{ème}$ objective function $\in$ to the function space $f(\Omega)$.
- $f_{i,opt}$: optimal value of the objective function $f_i(x)$.
- $f_{i,vnp}$: non-preferred value of the objective function $f_i(x)$.

ω_i being a reference coefficient assigned to each objective to define its priority level compared to the other objectives (Hiller et Lieberman, 1990). Hence the order of priority is identical for all objectives if all the ω_i parameters are chosen equal to unity. The aim of the optimisation is then to minimise $f(x)$ in the space of functions. It is necessary to distinguish between the decision space Ω, describing all vectors of the independent variables from the space of the objective functions $f(\Omega)$. A point in the space of functions $f(\Omega)$ can correspond to a unique decision vector (feasible solution) or to several different points in the space of the vectors of the decision variables (non-feasible solution). For example the ideal reference point ($R=f_{1,opt}, f_{2,opt}, \cdots f_{k,opt}$) represented, in the solution space, by the best scores of all the considered objectives is a non-feasible solution as the optimal value of each individual objective corresponds to a unique decision vector. Similarly the point ($P=f_{1,vnp}, f_{2,vnp} \cdots f_{k,vnp}$) represented by the worst scores of the objectives (boundary non preferred solutions) is also not feasible.

The optimisation consists then in the search of the feasible solutions, which are the closest as

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[2] the operator of comparaison is itself a function.

possible from the ideal reference point (or the most far away from the non preferred boundary). Figure 5 describes the iterative structure of the multiobjective optimisation.

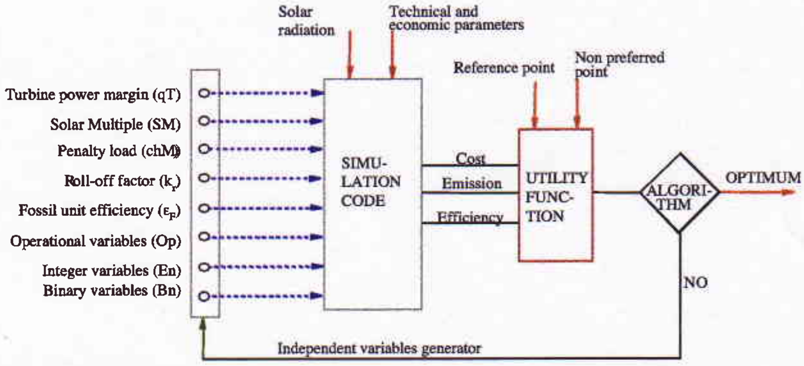

Figure 5: Iterative structure of the multiobjective optimisation undertaken

The main objectives considered in this study, are the minimisation of the costs of equipments (CAE), the minimisation of CO_2 emissions (q_{CO2}) and the maximisation of the yearly energy efficiency of the superposed cycles (ε_{ORC}). As expected these three criteria show different trends relative to the decision variables. The decision vector is made of different groups of variables:

- The **variables associated with the size of components** represented by the thermal margin of the turbine, the so-called solar multiple.
- The **integer variables** corresponding to the type and number of turbines implemented at each ORC. These turbines can be chosen among three different types: T1, T2 and T3. Each type corresponds to a different serial model and hence to a different catalogue of machines. The maximum number of turbines per ORC stage is limited to two, which can only be set in parallel and not in series.
- The real variables of the load curve of the fossil unit (roll-off coefficient, penalisation load), of the sizing of the heat exchangers (pinches) and of the operation of the thermodynamic cycles (boiling and condensation pressures, subcooling and superheating temperatures).

By optimising separately each of the three objectives (CAE, q_{CO2}, ε_{ORC}), we get the three extreme decision vectors (X_{CAE}, X_{CO2}, X_{ORC}) and their corresponding scores which form the ideal reference. To determine the limit point of the non-preferred objectives, the simulation is then successively launched for the vectors (X_{CAE}, X_{CO2}, X_{ORC}). The worst score is then noticed for each objective. On the basis of these two points, characteristics of solar radiation, and of the economic parameters (economic life time, interest rates, amortisation, etc.), the simulation code calculates all the thermodynamic points of the hybrid cycle and sizes all equipments. It also determines the energetic, economical and environmental performances of the whole power plant and gives back the values of the different objectives (score). The utility function is established and the optimisation at this stage is reduced to searching a new decision vector X_{OPT} that minimizes the Euclidian distance relative to the ideal point of reference (R). For each iteration step, the values of the independent variables are modified on the basis of characteristic rules of the algorithm being used, in this case a genetic algorithm. The optimisation constraints are managed at the level of the simulation model. The latter allows the avoidance of penalty functions, which are traditionally slowing convergence. The advantage of such a process is that at the end of the optimisation, the engineer has optimal solutions for each individual objective as well as one or several solutions, which are compromises. There are no intrinsic limitations on the number of objective functions, which can be considered by opposition to multiobjective optimisation based on a criterion of comparison of the different scores.

3.2 Performance analysis and Results

The multicriteria optimisation model presented above has been applied to an HSPS of 22 kWe. The yearly energy performance is calculated on the basis of the hypothesis of a solar profile by correlation (Kane, 2002) and of a classification of the direct solar radiation in the plan of a sun following N-S collector field. The region of Gabes in Tunisia[3] (Minder, Cogener 1996) has been chosen as an example. The quantity of emitted CO_2 and the efficiency of the ORCs are averaged over a full year, optimising in each case, the load curve with a maximum electric power constraint of 22 kWe. The Diesel fuel considered has a lower heating value (LHV) of 11.86 kWh/kg and a density of the order of 840 kg/m³. The engine cooling water is supposed not to exceed a temperature of 90°C although there exists engines which could tolerate higher temperatures. Input temperature limits of the ORCs are of the order of 170°C for the hot source and 10°C for the cold source. At night, the power unit is supposed to work only with the lower temperature cycle, which works with R134a. The transition to the superposed cycle mode from the single ORC mode is supposed to take place when the input heat rate at the evaporator reaches 50% of the nominal value. However and even if the simulation model includes an option to operate with variable speed turbines (case of an isolated region), we limit our considerations in this paper to turbines directly linked to the electric net which corresponds to a speed of the order of 3000 rpm. Table 3 shows the corresponding optimum values of objectives.

Objectives			decision vectors			
Name	Symbol	Units	X_{CAE}	X_{CO2}	X_{ORC}	X_{OPT}
Equipment cost	CAE	(kCHF)	118.5	149.9	206.6	157.5
Amount of CO2 emitted	q_{CO2}	(to)	120.3	100.8	115.9	101.0
ORCs efficiency	ε_{ORC}	(-)	8.83	10.84	12.35	11.23

Table 3: values of the objectives for an HSPS-22kW
(Site of Gabes-Tunisia, G_{max}=900 W/m²)

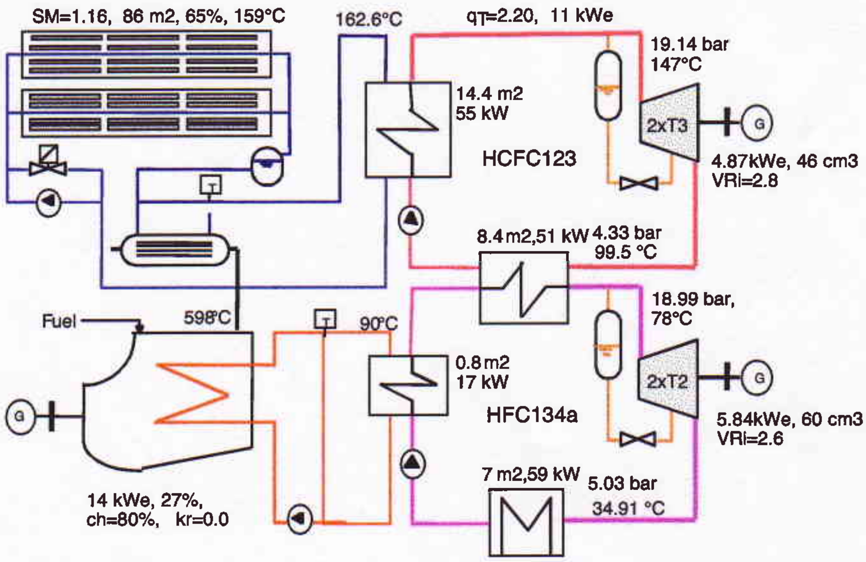

Figure 6: optimum configuration minimaxi (multi-criteria optimisation, HSPS-22kWe)

The final optimal solution X_{OPT} (minimaxi optimum) corresponds to a configuration with two turbines per cycle, type T3 for the high temperature cycle and T2 for the low temperature cycle.

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[3] This site was chosen in relation with another hybrid combined cycle project called PAESI (Projet d'Aménagement Energétique Solaire Intégré) which has also been used to test the optimisation methodology described in this paper.

Figure 6 shows the capacity of the different components and the thermodynamic conditions for daylight operation.

One such configuration is favourable from the energy efficiency point of view by minimising the efficiency drop at part load, but is of course far from being the most economical with present day economics. Tableau 4 shows the investment costs for this minimaxi optimum in comparison with optima obtained for each of the other criteria.

Figure 7 shows the distribution of the different costs for the minimaxi optimum.

Investments		Optima			
Name	Units	CAE	q_{CO2}	ε_{ORC}	Trade-off
Type of power plant	-	HSPS	HSPS	HSPS	HSPS
Yearly collected solarenergy	(kWh/m2)	1934	1817	1647	1647
solar field	(m2)	49	81	137	86
Capacity	(kWe)	22	22	22	22
Type of fuel	(-)	Diesel	Diesel	Diesel	Diesel
Solar unit (CAEs)	(CHF)	44'575	69'262	110'924	73'225
Fossil unit (CAEm)	(CHF)	20'553	19'662	22'286	20'156
Energy conversion unit (CAEu)	(CHF)	53'357	60'956	73'384	64'122
Civil Engineering (g)	(CHF)	6'970	8'817	12'153	9'265
Assembly and Engineering (v)	(CHF)	13'939	17'633	24'305	18'530
Total investissement cost (CTI)	(CHF)	139'394	176'330	243'052	185'297
Specific cost	(CHF/kWe)	6'458	8'174	10'803	8'543

Tableau 4: Investment cost optima
(multi-objective criterion, HSPS-22 kWe, Site Gabes-Tunisia)

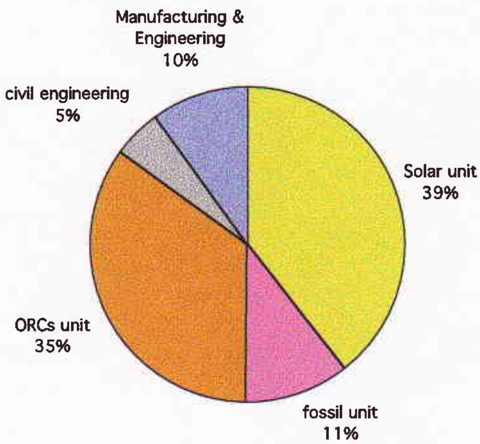

Figure 8: Distribution of the investment costs
(optimum minimaxi configuration, HSPS-22 kWe, Site Gabes-Tunisia)

We can see the significant impact of the solar field and of the ORCs on the global HSPS cost. The solar unit represents in it already 39% of the total equipment costs. The ORC power unit represents 35% for a maximum power rating of 11 kWe compared to only 11% for the motor Diesel unit rated at 14 kWe[4]. It is however important to note that the cost values used for the ORCs are determined from two different prototypes (ORC-10kWe, 1999 and ORCNC-21kWe,

[4] The total rating is 25 kWe (11 kWe for the superposed ORC and 14 kWe for the engine). However, the nominal operational power is 22 kWe accounting for the fact that the engine is operated at partial load in the daylight mode.

2001). Note that no effort was made to improve the present pumps, which at present have a higher unitary cost than the scroll expander-generator themselves and therefore offer a potential for improvement. Moreover a unitary solar collector price of 850 CHF/m^2 pour 86 m^2 has been considered. This price is determined on the basis of cylinder-parabolic LES3 collectors, which are commercialised for large power plant and negatively corrected by a factor of scale (Kane, 2002). Actual price of the solar field was higher (Allani et al. 2002)

The specific cost depends on the configuration and on the component sizing. It is of the order of 8543 CHF/kW for the minimaxi optimum of an HSPS of 22 kWe. This results from a tradeoff between the most economical (hence the least efficient) (6458 CHF/kW, 8.83%) and the most expansive and efficient solution (10803 CHF/kW, 12.35%). The specific cost increases with the size of the solar field. For the most efficient solution we have a total solar field of the order of 137 m^2 instead of 49 m^2 obtained for the minimum cost solution. The maximum energy solution corresponds to a solar multiple SM of 1.20, corresponding to a design radiation of 775W/m^2 compared to the maximum value of 900W/m^2. The incident solar energy is in this case of the order of 1647 kWh/m^2/y compared to a maximum solar radiation available of 1934 kWh/m^2. Table 5 shows the optima of the unitary production costs for the different configurations resulting from the multi objective optimisation. An economic lifetime of 20 years is considered for the reimbursement of capital at an interest rate of 4.5%. A fund to renew defective material is established at 100% on the basis of the reserve capital generated by the project. The return for such a fund is done at the market rate of 3% and over an amortisation period of 20 years. The unit price of Diesel fuel is taken equal to 0.62 CHF/kg.

Mean unitary cost		Optima			
Nom	Units	Costs	CO2	ε_{ORC}	Trade-off
Type of plant	-	HSPS	HSPS	HSPS	HSPS
Yearly collected energy from solar	(kWh/m2)	1934	1817	1647	1647
Solar field	(m2)	49	81	137	86
Rating	(kWe)	22	22	22	22
Type of fuel	(-)	Diesel	Diesel	Diesel	Diesel
Hours per year	(hours)	8'759	8'759	8'759	8'759
Yearly electricity production	(kWhe/y)	170'124	153'561	178'551	154'798
yearly solar contribution	(%)	5.3	10.3	15.8	10.8
yearly contribution of waste heat	(%)	14.4	15.2	15.9	15.2
yearly fossil contribution	(%)	80.3	74.5	68.2	74.0
Fuel Consumption	(kg/y)	38'332	32'124	36'808	32'170
CO2 emissions	(kg/y)	120'253	100'818	115'898	100'963
Reduction of CO2 emissions	(%)	17	24	26	24
Capital cost (Zt)	(CHF/y)	16'002	20'243	27'902	21'272
Depreciation (CRM)	-	4'410	5'578	7'689	5'862
Reimbursement and interest (CPA)	-	10'716	13'556	18'685	14'245
Assurances and Taxes (TTA)	-	877	1'109	1'529	1'166
Subsidy (CTS)	-	0	0	0	0
Operation and Maintenance (OM)	(CHF/y)	29'690	27'411	33'151	27'821
Resources (Rs)	-	23'766	19'917	22'821	19'945
Maintenance (KM)	-	5'924	7'494	10'330	7'875
Mean yearly cost (Costma)	(CHF/y)	45'692	47'653	61'053	49'093
LEC	(CHF/kWh)	0.269	0.310	0.342	0.317

Table 5: Optima of the unitary production costs
(multiobjective criterion, HSPS-22 kWe, Site Gabes-Tunisia)

Figure 9 shows the evolution of the unitary cost (LEC) as well as the CO_2 emission reduction rate (τ_{CO2}) for each of the solutions, the latter being defined as the amount of CO_2 (q_{CO_2}) which is not emitted compared to the emissions ($\overset{o}{q}_{CO_2}$) of a fossil reference plant satisfying the same load curve:

$$\tau_{CO2} = \left(\overset{o}{q}_{CO_2} - q_{CO_2}\right) / \overset{o}{q}_{CO_2} \qquad (2)$$

As expected the trend indicates a unitary cost (LEC), which increases with the solar coverage (yearly solar electricity produced). The latter reaches 16% for the most efficient solution, corresponding to a LEC of the order of 34 Swiss cts/kWhe, which is 49% higher than the LEC of a simple reference Diesel engine following the same load curve (DEPU-Diesel Engine Power Unit, 22kWe, 23 Swiss cts/kWh[5]). Consequently a maximum rate of emission reduction of 26% is reached for this most efficient solution (X_{ORC}).

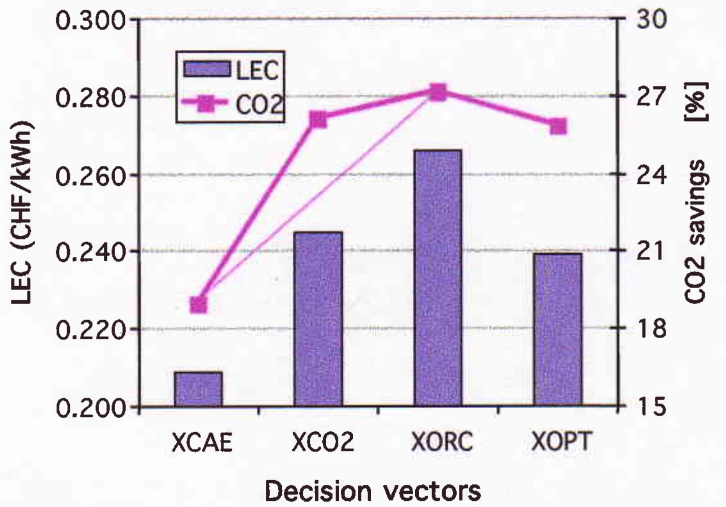

Figure 9: Unitary cost LEC and amount of avoided CO_2 emissions

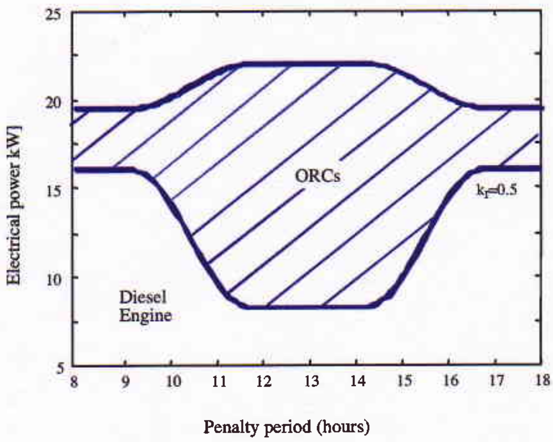

Figure 10: Daily load curve (criterion energy efficiency, ε_{ORC})

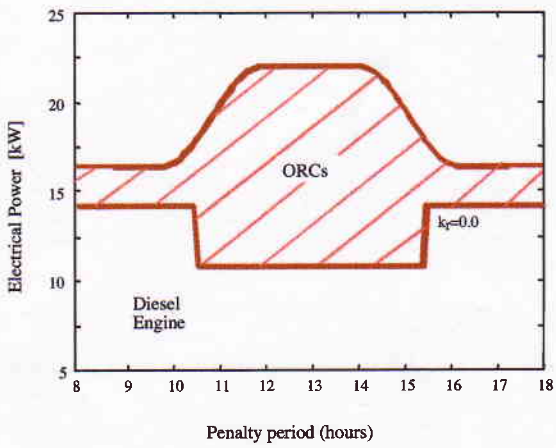

Figure 11: Daily load curve (criterion minimum emission, q_{CO2})

It is worth mentioning that the optimum for the absolute CO_2 emissions (q_{CO_2}) corresponds to a configuration with a smaller fossil unit, here a smaller cogeneration engine, but does not necessarily represent the solution with a lower emission in relative terms (Figure 10 and Figure 11). This result can be explained by the fact that the reference for CO_2 also varies in function of

[5] The calculation of the LEC for the DEPU-22kWe is done with the same hypotheses than the HSPS-22kWe power plant.

the load curve. An interesting conclusion is that a tax of the order of 42 Swiss cts/kg$_{CO2}$ would be required in the present economics to ensure the competitiveness of an HSPS 22 kWe compared to a Diesel of the same size (not accounting for any tax for additional pollutants).

4. Conclusions

A prototype unit of an original concept of mini-solar hybrid plant has been manufactured and tested within the framework of a project called SPS (Solar Power System). Performances of the thermodynamic cycle are satisfactory considering the low temperature and power ranges and the fact that obvious improvement measures have been identified. The First Law efficiency of electricity production in hybrid mode is of the order of 41% when considering only the fossil fuel input (total electrical power/ LHV of the fuel). This already represents an efficiency increase of close to 50% compared to the Diesel engine alone. However due to an over sizing of the turbines and a lower solar collector efficiency than expected, the conversion operated at very partial load and the efficiency in mode "solar only" was only of 7.74%. The latter is 35% below the expected performance for operations, which would be closer for the expected nominal values.

Simulating a continuous operation of the hybrid plant over a full year (day and night), one multicriteria optimisation based on a mini-maxi formulation and using genetic algorithms was done for a power plant HSPS of 22 kWe. Such an approach allowed the determination of various optimal configurations in function of extreme criteria (thermodynamic, economical and environmental) as well as a trade-off solution. Results show that the solar electricity conversion costs stay relatively high and considerably depend on the relative size of the solar field. For example the LEC of a HSPS-22kWe plant with 6 to 16% of solar contribution is about 17 to 49% more expansive that a reference fossil unit (DEPU-Diesel of 22 kWe, 23 Swiss cts/kWh), which would satisfy the same load profile. However future potential reduction of the costs of the solar field, identified improvements of the ORCs as well as the introduction of credits for the reduction of CO_2 emissions should open new prospects for hybrid solar power plants. Nevertheless, at present, a tax of the order of 42 Swiss cts/kg$_{CO2}$would be required to ensure the competitivity of an HSPS-22 kW with 16% solar compared to Diesel of the same power.

Nomenclature

CAE	Cost of Equipment	
CEP	Extra-Plats Solar Collector	
DEPU	Diesel Engine Power Unit	
HSPS	Hybrid Solar Power System	
ORC	Organic Rankine Cycle	
SPS	Solar Power System	
LHV	Lower heating value	(kJ or kJ/kg)
$\dot{E}_P$	Electric power delivered to the pump	(kW)
$\dot{E}_T$	Electric power delivered to the turbine	(kW)
$f(x)$	Utility function	
G	Direct solar radiation	[W/m^2]
$\dot{M}_{pw}$	Pressurized water mass flow of the hot source	(kg/s)
$\dot{M}_{cw}$	Coolant water mass flow from the engine to the preheater	(kW)
q_{CO2}	Yearly amount of emitted CO_2	[kgCO_2/an]
q^o_{CO2}	Yearly amount of emitted CO_2 from a reference power plant	[kgCO_2/an]
ω_i	Priority level with regards to the objective $f_i(x)$.	
x	Vector of independent variables $\in$ to the decision space Ω.	
Δh_{pw}	Enthalpy difference on the pressurized water heating the evaporator	(kJ/kg)
Δh_{cw}	Enthalpy difference on the water cooling the condenser	(kJ/kg)
Δk_{pw}	Coenthalpy difference (exergy) of the water to the evaporator	(kJ/kg)

Δk_{cw}	Coenthalpy difference (exergy) of the coolant to the preheater	(kJ/kg)
ε	First Law efficiency	[-]
η	Exergetic efficiency	[-]
τ_{CO2}	Reduction rate of emissions of CO_2	[-]
τ_{CSA}	Yearly solar contribution to electricity production	[-]

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