ECOS'01 July 4-6, 2001 ISTANBUL
Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems
First International Conference on Applied Thermodynamics (6B/4)

Small Hybrid Solar Power System

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Abstract

This paper introduces a novel concept of mini-hybrid solar power plant integrating a field of solar concentrators, two superposed Organic Rankine Cycles (ORC) and a (bio-)Diesel engine. Turbines for the Organic Rankine Cycles are hermetic scroll expander-generators. Sun tracking solar collectors are composed of rows of flat mirror bands (CEP) arranged in a plane, which focus the solar energy onto a collector tube similar to those used in SEGS plant in California. The waste heat from both the exhaust gases and block cooling of the thermal engine are also heat sources for the ORCs. Such units are considered to meet electricity, cooling and pumping needs of remote settlements in the sun belt areas or on special sites requiring low temperature heating such as swimming pools or greenhouses. The thermal engine guaranties a minimum level of both power and heat availability at night or during cloudy periods.

Laboratory tests, made with the superposed ORCs only, confirmed adequate operational characteristics with good performances over a broad range of conditions. A few preliminary tests on the site of the solar power plant when coupled with the engine confirmed a reasonable behavior and the interest of the concept even at part load or during sharp variations of the thermal supply. The performances are satisfactory for a hybrid solar plant of this power range (10 to 25 kWe) and working so far with rather low temperature solar supply (165°C). First Law electric efficiencies of conversion referred to the fossil fuel supply only (total electricity produced/fuel supply) are of the order of 35% at part load and up to 47% with peak solar radiation. These results are encouraging particularly when one considers that excellent prospects exist for further increasing the supply temperature. However further in-situ tests are required to fully explore the behavior and performance of the complete power plant over a broad range of conditions.

Keywords: Hybrid solar thermal power plant, solar concentrators, turbine scroll, thermal engine, Organic Rankine Cycle.

1. Introduction

Drawbacks of solar power generation are:

- the low density of solar radiation requiring large collector areas,
- high investment costs partly due to the use of specific technologies produced in small series and,
- the lack of reliability and the fluctuations of the solar supply, which are highly dependent on the meteorological conditions.

Recent technological progress opens new perspectives for Integrated Solar Fossil Cycle Systems (ISFCS). In the context of increasing global environmental concerns these offer the possibility to accelerate fossil fuel substitution (even if only partial), and therefore reduce emissions, while ensuring adequate power availability (Favrat, 1995; Allani et al., 1996).

On the basis of classical thermo-economic criteria (performance/cost) several integration options are commonly cited (Buck et al., 1998), which include:

- Concepts like the SEGS power plants in California (Kolb, 1997) with electric powers between 30 and 80 MWe, which are based on cylindro-parabolic concentrators with additional fossil fuel burners or natural gas boilers to supply a steam cycle;
- Concepts called ISCCS for Integrated Solar Combined Cycle Power Systems, such as PAESI (Allani and Favrat, 1991; Kane and Favrat 1999, 2000) or ISSCS-Nevada, USA (Pilkingston, 1996, Goswami, 1995) based on efficient combined cycles to have an optimal fuel conversion efficiency and reduce electricity production costs (by as much as 42 %) compared to the present SEGS plants (Kolb, 1997); and
- Concepts using high efficiency parabolic solar concentrators with an integration of the solar heat at a level of exergy sufficient to preheat or to fully heat the gas of a gas turbine cycle ideally in a combined cycle or to supply heat for endothermic fuel reforming (Price et al., 1996; Worner et al., 1995).

It is important to note that these advanced concepts have been designed for multi-megawatt plants aiming at a centralized production with the associated power transport losses and costs and with limited possibilities to use the waste heat (cogeneration to meet either heat and/or cold demand). The present paper addresses the same type of ideas but for small Hybrid Solar Power Systems (HSPS) of a few kWe to a few tens of kWe but with easy cogeneration opportunities for hot water production, absorption refrigeration or thermal desalination. A small hybrid prototype of power plant of 10 to 25 kWe has been designed and implemented in the frame of a project called SPS (Solar Power System). This plant integrates two rows of solar collectors, two superposed 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. The nominal electric power of the engine is 15 kWe. This paper discusses the design parameters and options, the results of laboratory measurements of the power unit subsystem and the preliminary in situ demonstration of the full plant.

2. Design of the SPS prototype

In a hybrid solar thermal power plant the electricity production efficiency is strongly dependent on the way the fossil fuel unit is integrated. The term hybrid is often used to characterize such systems and the solar production part of the total electricity production is a design parameter. It can go from a relatively small proportion (5 to 15%), as in the large ISCCS planned so far, to a significant part if the plant can be shut down during part of the night. Independent from the night operational strategy adopted, the integration of an engine allows:

- a leveling of the heat supply in spite of solar radiation fluctuations,
- a faster startup by preheating of the solar network in engine cogeneration mode, and
- an extension of the hours of operation of the solar part late in the afternoon when the solar radiation decreases.

A major difficulty if we want to use close to standard components for the power unit is the different exergy levels of the heat sources. The additional problem is the large number of parameters linked to the choice of the operational sequences to meet a given demand, which complicate the design and optimization of these systems[1]. Considering the main application target of supplying isolated villages preference was given to using hermetic components for the ORCs, which allow a factory charge of working fluid and reduced on-site maintenance.

The design is a tradeoff between:

- the percentage of solar versus fossil fuel energy supply for a given demand and environmental objectives,
- the increase of the thermodynamic cycle efficiency, the expander characteristics and the increased losses of the solar collectors as collector temperature raises,
- the energetic efficiency and the control complexity (reliability, robustness, cost, training requirements, etc.).

For the SPS project a decision was made to rely on earlier work, which demonstrated the use of expanders modified from standard hermetic scroll compressor units[2] with potentially low costs as most components are produced by thousands worldwide. The major limitations of the latter are the limited pressure range and the built-in volume ratio for efficient operation. Hence the proposal to preferably use two

[1] A structured thermoeconomic optimization will be published separately (Kane, 2001).
[2] Based on an earlier successful demonstration (Zanelli et Favrat, 1994; Favrat, 1995, Kane et al., 1999)

superposed ORCs each working with a different fluid, which allows working:

- at a range of pressure levels and pressure ratios close to the optimum expander efficiencies and unit volumes,
- independently with one or the other cycle in function of the solar condition or of the heat demand requirements (Favrat, 1995; Kane et al. 1999).

Figure 1 shows the simplified flowsheet of the SPS prototype of power plant.

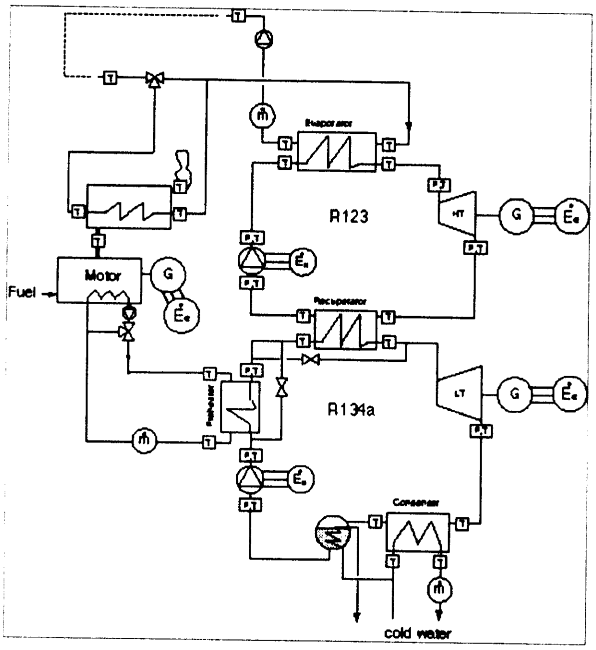

Figure1. Simplified flowsheet of the SPS power unit

For this prototype unit (Figure 2) the chosen fluids are HCFC 123 for the topping cycle and HFC 134a for the bottoming cycle.

Topping ORC (HCFC123)

The vapor produced in a (plate) evaporator is either bypassed (during warm-up) or expanded in the high temperature scroll unit HT. The discharged vapor is cooled and condensed in a condenser-evaporator (plate) heat exchanger where it communicates its energy to heat, evaporate and superheat the bottoming cycle fluid. Liquid HCFC123 is then pumped by a (membrane piston) pump to feed the boiler of the topping cycle. The nominal power of the HCFC123 scroll expander-generator is 5 kWe corresponding to a 53 cm^3/rev discharge volume (suction volume in compressor). The built-in volume ratio is 2.3. In the present setup the boiling temperature varies between 120°C and 150°C in function of the solar radiation.

Bottoming ORC (HFC134a)

The heat recovery from the topping cycle allows the evaporation of the fluid of the bottoming cycle (HFC 134a). The flowsheet is almost identical to the one of the topping cycle with however an additional heat exchanger to recover heat from the engine cooling network. The possibility exists to test the latter either in series as a liquid preheater or in parallel to the evaporator. Because of the additional heat rate from the engine the lower temperature scroll expander is oversized compared to its high temperature counterpart with, in the present design, a nominal power of 8 kWe (exhaust volume of 72 cm3/rev) for the same built-in volume of 2.3. Note that step in nominal power is essentially dictated by the range of compressor sizes available on the market.

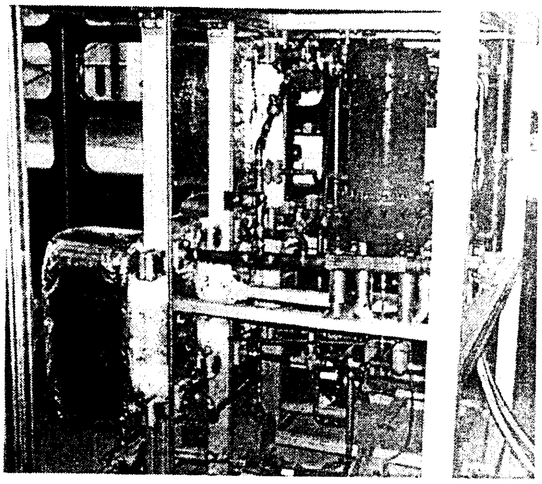

Figure 2. Power unit with two superposed ORCs tested in laboratory

Although previous laboratory tests had been conducted with a separate oil pump to lubricate the expander bearings, a simplification is made here by circulating the oil with the refrigerant. An oil separator at evaporator exit (not represented in Figure 1) recovers the oil to be injected within the hollow expander shaft using the pressure difference available. This arrangement allows operation in the wet expansion domain (Kane et al., 1999) with limited risks in the event of inadequate control or disturbances of short duration. The efficiency of the separator does not need to be high as some amount of oil is desirable at the expander inlet to contribute to seal the inner gaps during the expansion.

The concept is designed to take advantage, in the future, of an expected increased capability of the turbine of the topping cycle to deal with higher inlet temperatures (>150°C) and therefore increase cycle performance. This is in line with the choice of solar concentrators and of a vacuum insulated collector tube. For simplicity of operation at the prototype stage pressurized water is being used but a later switch to thermal oil allowing much higher temperatures at moderate pressures is planned. The originality of the concentrators is that they are made of a series of flat mirror bands of calculated and different widths, which can be assimilated to a Fresnel mirror. Each of the mirror bands is fixed with hold-down clip which allows an handy change in case of breakage. Moreover the open structure with air gaps reduces the wind forces[3].

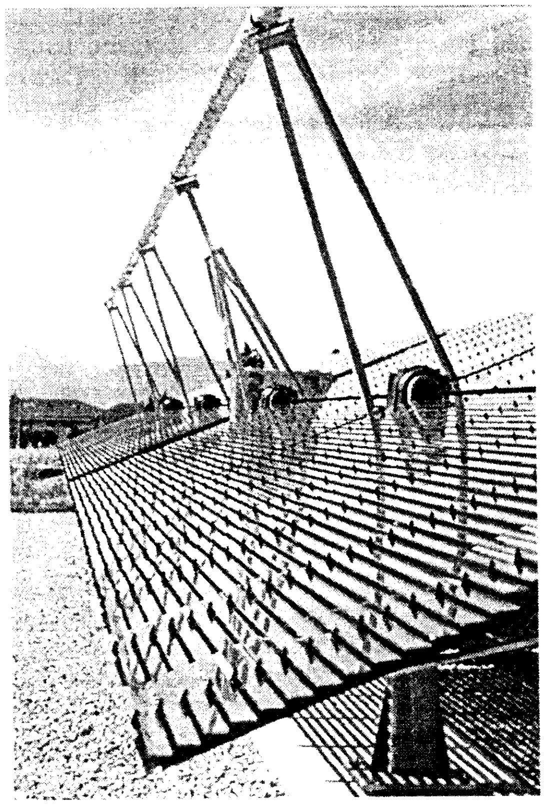

Figure 3. view of one of the two solar collector lines

The two lines of collectors installed by a local company are oriented North-South with a tracking system from East to West. They have an active collection area of 100 m^2 (Fig 3). The collected heat rate is of the order of 60 kWth for a solar radiation of 1000 W/m^2.

Because of the need for frequent operation at part load both for the ORCs and the engine, pumps for the ORC are variable speed and the engine has to have a reasonable efficiency at part load. As gas turbines are both not yet available in the expected power range and not efficient at part load, choice was made to use a 3 cylinder Diesel engine of 15 kWe. A good complementarity among renewable energy sources could be the use of biodiesel in the future, although no tests have yet been made. Figure 4 shows the composites for a case with 50 kWth delivered by the solar collectors and an operation of the Diesel engine at full power. These composites show the main integration elements, which are:

- (a and a') : recovery of 19.3 kWth at around 75°C on the engine block cooling and boiling at 68°C of one part of the bottoming cycle flow (HFC134a).
- (b et b') : boiling at 146°C of the HCFC 123 of the topping cycle using the high temperature heat source made of the solar energy as well as of the heat recovered from the combustion gases of the engine.
- (c et c') potential to recover 15 kWth from about 580°C to 160°C to complement the heat collected by the solar panels.

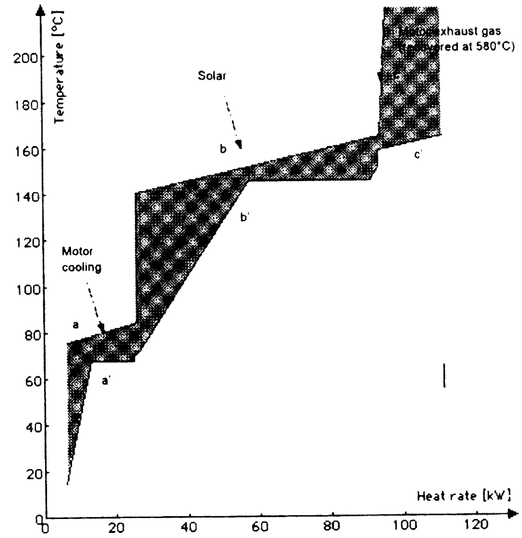

Figure 4. Diagram of the composites corresponding to a case with engine at its nominal capacity of 15 kWe and 50 kWth of solar heat rate

Needless to say, the composites are modified as the solar radiation and the motor load vary.

3. Experimental results

The first series of tests has been made with the two superposed ORCs alone using electrically heated thermal oil to supply heat to the evaporator of the topping cycle. The bottoming ORC was only supplied through the evaporator-condenser without additional heat supply to replace the engine block heat recovery. The objective was to determine the operational feasible range of heat supply to the topping cycle. The supply temperature as well as the heat rate, which was adjustable in order to simulate various solar heat supplies.

A second series of tests done in the laboratory included the integration of the engine block cooling heat but without the heat recovery from the gases. A third and limited series of tests has been made in situ with the full integration of

[3] the one line of collectors already built in December 1999 at the time of one of the most severe storm of last century survived without any damage

the engine and of the solar collectors. It allowed a preliminary validation of the concept of hybrid power plant even though those tests occurred late last fall with a rather week solar radiation. For each of the tests the cold source was water at 7°C with a flow regulation to adapt the condenser temperature of the bottoming cycle. The measured data included the boiling and condensing pressures of both ORCs, the temperatures and pressures at the inlet and outlet of the main components and the electric power at each of the generators as well as the net electricity output. In addition flowmeters and temperature measurements on the hot and cold streams allowed the determination of the energy balance of the cycles.

3.1 Laboratory tests of the superposed ORCs

The total power range of the laboratory tests was from 3 to 10 kWe. The performance of the cycles can be expressed according to two slightly different First Law definitions:

- Cumulated electric power produced by the two expanders divided by the sum of the heat and the pump electricity supplied or
- Net electrical output (difference between the output of the expanders and the electricity supplied to the pumps) divided by the heat supply. Figures 5 and 6 show the variations of efficiencies as well as the power output in function of the heat supplied to the evaporator of the topping cycle for a temperature of heat supply varying between 130°C and 165°C.

The overall superposed cycle efficiency up to 14%, is satisfactory for this low power range (up to 10 kWe) and the relatively low supply temperature (up to 165°C). Note that for these peak values the corresponding Carnot efficiency is of the order of 30%. Figure 7 shows the variation of the exergy efficiency in function of the supply heat rates. Those exergy efficiencies are good when compared to data published with other ORCs working within a comparable temperature range (see VDI-Verlag, 1984).

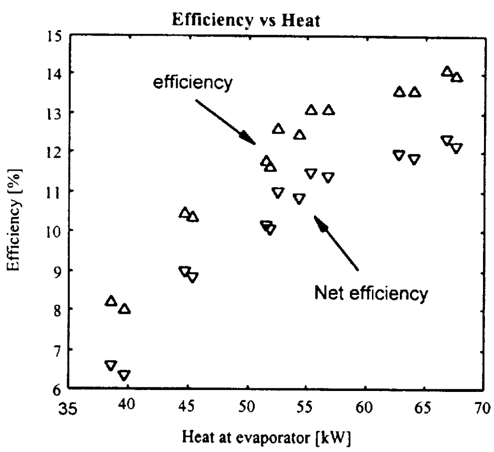

Figure 5. Efficiencies of the superposed ORCs as for various supply heat rates

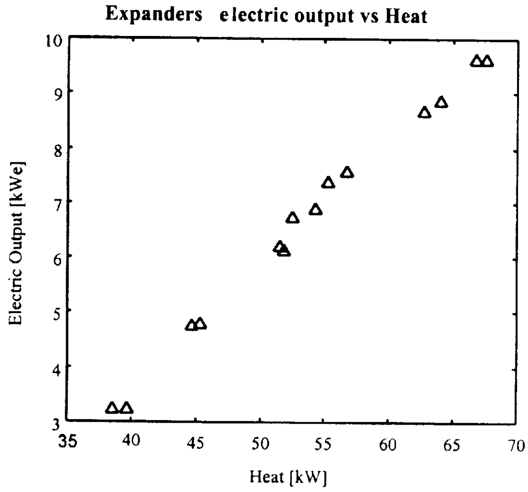

Figure 6. Electric power outputs for various supply heat rates

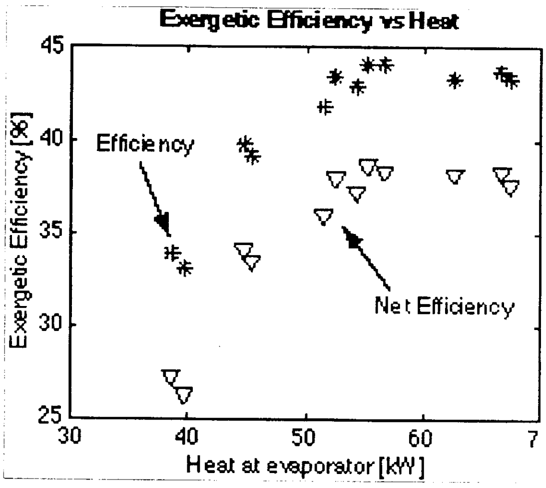

Figure 7. Exergy efficiencies of the superposed ORCs for various supply heat rates.

Note that the efficiency decrease at low supply heat rates can be explained by the losses linked to the inadapted pressures at the expander of the bottoming cycle (see Figure 8). This is due to the fact that, for simplicity, the two generators are directly connected to the grid without any variable speed electronics. This simple and cheap approach imposes gliding pressures with variable loads. Moreover the high amount of oil mixed with the refrigerant increases the boiling temperature in the end phase of evaporation moving the pinch point there. This phenomenon is well known in heat pumps and is accompanied by a significant drop in heat transfer with a corresponding drop of the evaporation pressure. This is particularly negative at the evaporator-condenser where the resulting temperature difference is excessive. Solutions to improve this situation are: change of evaporator-condenser type (falling film shall-in-tube instead of plate evaporator), introduction of expander speed regulation, separation of the oil at the discharge of the bottoming cycle with a separate oil pump, etc.

Nevertheless these preliminary tests on the superposed cycles allowed a demonstration of the robustness of the present concept, providing some insight on the control characteristics required for an automated operation of the power plant.

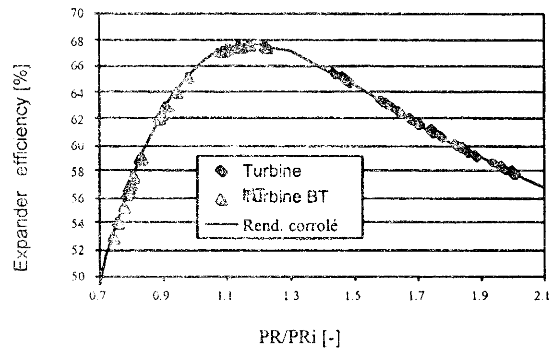

Figure 8: Electric isentropic efficiencies and operating range of the expanders

3.2 Laboratory tests with the ORCs and the integration of the heat supply from the engine block cooling

For simplicity and safety reasons[4] the coupling of the engine with the ORCs was done only through the recovery of the engine block cooling. This was not a major hindrance as the laboratory thermal oil heater had enough power available to simulate the supply from both the solar collectors and the combustion gas cooling over the whole range of expected conditions. The heat rate from the engine block cooling was of 18 kWth for an operation of the engine at 12.8 kWe. *Figure 9* shows the variation of the power output from the expanders in function of the topping cycle supply temperature with or without the engine. Note the substantial increase of the system's performance particularly at lower heat rates. This is due to a better adaptation of the pressures at the bottoming expander as a result of the block heat supply. This improvement is however limited by the capacity of the pump and the pinch occurring at the end of evaporation.

3.3 In-situ tests of the complete hybrid power plant

Because of construction delays and tests of individual components, in situ tests could only be made at the end of October with solar radiations lower than 500 W/m^2 as typical for Switzerland at that period. The maximum heat rate available from the 100 m^2 solar collectors was of the order of 25 kWth. This results in an operation of the ORCs at partial load even with the engine operated close to its nominal value (12.8kWe with 18kWth on block cooling and 12 kWth on the recovery from the combustion gases). Operating conditions and results are summarized in Table 1. The fuel conversion efficiency (net electric power produced over fuel rate) referred only to the fossil fuel supplied is of the order of 35%, in spite of the strong penalty on the ORCs at low load. Figure 10 illustrates the low level of load during these tests. Note that the peak efficiencies to be expected at full solar supply would be of the order of 47% with expanders operating at full capacity (10 kWe). However those results are incomplete and a new test campaign is planned in 2001 over the whole range of operation.

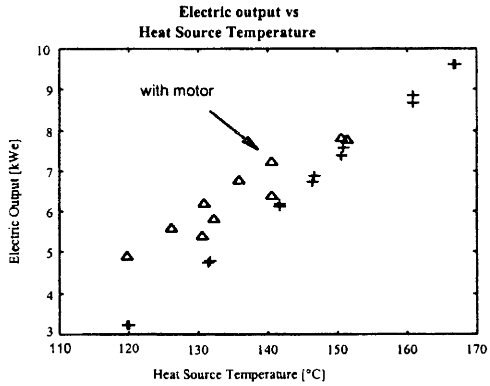

Figure 9: Electric power produced by the expanders (with or without engine operated at 13 kWe power output)

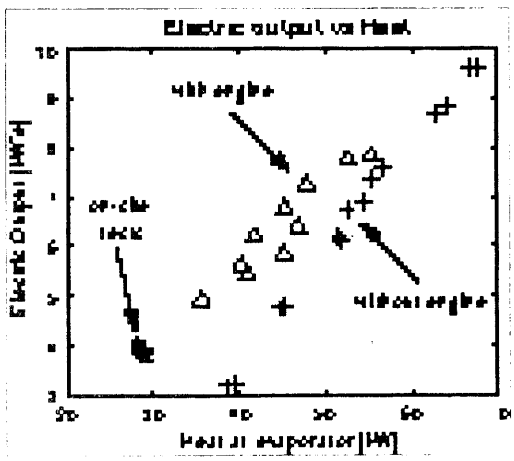

Figure 10: Electric power produced by the expander s(with or without engine

These initial points are first attempts to validate the concept, which, so far, meets the early expectations.

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[4] in the lab, thermal oil was used instead of pressurized water and an accidental contact between thermal oil and combustion gases was to be avoided.

Table 1: Electrical power produced by the expander-generators (with or without engine)

	HT Cycle	LT Cycle	Engine
Source temperature(°C)	120/125		Electrical power 12.8 kWe
Evaporation pressure (bar)	8	11.5	
Condensation pressure (bar)	3.4	5	Heat rate from combustion gases 12 kWth
Heat rate (kW)	28 (evaporator)	25 (recuperator) + 18 (preheater)	
Electrical power (kWe)	1.3	2.5	Exchanger inlet gas temperature 580 °C

4. Conclusions

A novel concept of a mini hybrid solar power plant has been partly demonstrated both in the laboratory and in situ for a limited number of points. Indications so far confirm the robustness of the concept, which should be well adapted to cogeneration in isolated settlements, particularly in the sun belt regions. Laboratory tests have shown an adequate behavior over a broad range of conditions including in the presence of large variations of thermal supply. The integration of a thermal Diesel engine to the superposed Organic Rankine Cycles of the thermal solar plant has been successful with reasonable efficiencies considering the relatively low power range of such a pilot plant. Replacing fuel supply by bio-Diesel, which still has to be demonstrated, would provide a fully renewable solution with power availability largely independent from atmospheric conditions. The modular nature of the concept with other potential applications of the power units for waste heat recovery should contribute to lower the production costs and improve economic viability although this aspect was not specifically addressed in the present study. Measured fuel efficiencies at part load are of the order of 35% with peak fuel efficiencies up to 47% at peak solar supply. Improvements aiming at reducing internal losses have been identified.

However more in situ tests are required to further assess the full potential of the concept and further characterize the improvement paths in particular for a fully automated operation. Several power plant components deserve further studies and this is particularly true for the evaporator-condenser and the pumps of the ORCs. Furthermore the likelihood of the future availability of higher temperature turbines or expanders exists to further enhance the potential of such integrated plants. An additional path could be to envisage substituting the thermal engine for a fuel cell (most likely solid oxide fuel cell) when available in the future with their excellent part load characteristics.

Acknowledgments

The authors would like to acknowledge the financial support provided by the Swiss Federal Office of Energy.

Nomenclature

HSPS	Hybrid Solar Power System
ISCCS	Integrated Solar Combined Cycle System
ISFPP	Integrated Solar-Fossil Power Plants
PAESI	Projet Pilote d'Aménagement Energétique Solaire Intégré
SEGS	Solar Electric Generating System
SPS	Solar Power System

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