

EVALUATION OF A HYBRID SOLAR / GAS COMBINED HEAT AND POWER SMALL SYSTEM

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ABSTRACT

The use of solar thermal collectors for electricity production is a way to contribute to the Portuguese objective of reaching 39% of electricity production from renewable energy sources, until 2010. This is also in accordance with the objectives of the European Union and the Kyoto Protocol.

The system in analysis is powered by solar energy and supplemented by a natural gas boiler, specially for periods when solar radiation is low. Use of the system would result in significant savings in primary energy consumption and a reduction in CO₂ emissions to the environment. The solar collectors are of the heat pipe type.

In this work, the behaviour of a combined heat and power cycle producing 6 kW of electricity was simulated. The heat rejected in the cycle condenser is used for space heating/cooling in buildings. Several refrigerants have been considered for the cycle and methanol presented the best performance. The contribution of solar energy (solar fraction) was evaluated for the climatic data of Lisbon (Portugal).

The energy and economic potential of the system is compared to the conventional alternative.

1. Introduction

Existing large-scale plants for power generation are usually located far away from centres of population. This precludes efficient utilization of a reasonable proportion of the waste heat produced. Moreover, current technology limits these power stations to a maximum efficiency of about 40%, which, after the transportation of electricity through the grid, is reduced to about 30%, [1]. This means that vast quantities of fossil fuels are burnt with unwanted pollutants entering the atmosphere.

The solar radiation availability in Portugal is excellent when compared with other European countries. The annual average number of sun hours ranges from 2200 to 3000 in Portugal, while in Germany, for instance, it ranges from 1200 to 1700, [2]. However, this resource has been poorly utilized in Portugal.

The utilization of solar energy with conventional energy sources, for combined heat and power for buildings, reduces pollutant emissions and offers energy savings.

Solar thermal electricity was not achieved until the 1980s. However the technology had been under development for about 140 years, [3]. It started with Mouchot and Pifre, [4], in France in 1882, and continued by extraordinary pioneers such as Ericsson, [5], in 1888, Eneas in 1901, [6], Shuman in 1903, [7], and Francia in 1961, [8], and in 1968, [9]. In the 1980s, the first large trough, dish and tower array were installed in response to the challenges of the 1970s oil crises. After the 1980s, the number of publications about solar electricity decreased, following the oil price falling.

Spencer [10], [11], [12] presented a review of small solar-powered heat engines up to 1989.

Best and Riffat, [13], in 1995 and Wolpert and Riffat, [14], in 1996, simulated a solar powered Rankine cycle. The electricity surplus could be stored in the form of hydrogen using the electrolysis of water. When a shortfall of electricity occurs or when

little or no solar energy is available, hydrogen could be converted back into electricity via a fuel cell. They analysed four fluids: R134a, R152a, Klea32 and Care 30. R152a required a smaller area of solar collector to satisfy the electrical demand. However, the environment impact of Care 30 was negligible and it was the recommended fluid.

Yamamoto et al, [15], have investigated theoretically and experimentally the performance and characteristics of a closed type Organic Rankine cycle using working fluids such as HCFC-123 and water. HCFC-123 gave the best characteristics over other candidates such as water and methanol. The experimental results showed a maximum cycle efficiency of 1.25%.

Nguyen et al., [16], in 2001 and Oliveira et al., [1], in 2002 developed a novel hybrid solar / gas system intended to provide cooling/heating and electricity generation for buildings. The system was based on the combination of an ejector heat pump cycle with a Rankine cycle. The system used pentane as working fluid and the experimental results were an average cooling cycle COP around 0.3 and an electricity production efficiency between 3% and 4%.

Freepower, [17], commercialises a CHP system that produces 6 kW of electricity. The fluid in the Rankine cycle is a hydrofluoroether. The micro-turbine efficiency is 73%, and the operating temperature is 165°C at 11.6 bar (turbine inlet). The system has an electricity efficiency of 10 to 15% and could be driven by solar energy.

The system under analysis is a micro-CHP system that uses solar energy collected by hybrid heat pipe solar collectors and supplemented by a natural gas boiler. The hybrid solar collectors receive energy from two sources: from solar energy and from boiler exhaust gases that circulate below the collector plate. A major difficulty of the present solar micro-CHP system is that its initial cost is still relatively high, similar to

the cost of PV panels. However, when supplemented by a gas burner, it has the advantage of producing electricity during periods of low solar radiation.

2. Micro-CHP system

Micro Combined Heat and Power is the decentralized production of electricity and heat in micro-turbines, fuel cells, Stirling engines, small internal combustion engines or hybrid systems (micro-turbine / fuel cells), with an electrical power up to 150 kW.

The micro-CHP system under analysis has an electric power of 6 kW and produces 110 kW of heat, that could be used to heat or cool an office or commercial building, where the ratio heat / power is usually high.

The system in figure 1 is composed by two cycles: the primary cycle where the working fluid expands in the turbine, and the secondary cycle with the hybrid solar collectors and boiler. The solar collectors are named hybrid, since they use boiler exhaust gases to complement solar energy, [18]. A heat exchanger transfers heat between the two circuits. The water pressure in the secondary cycle is about 2 bar. The turbine has an electrical output of 6 kW and an isentropic and mechanical efficiency of 70%. The pump has an efficiency of 80%. The turbine inlet temperature, point 1 in the figure 1, is 100°C with 5°C of superheating (saturation pressure of 95°C). This temperature is compatible with the maximum temperature achieved in the solar collectors. The collector efficiency reduces with the increase in temperature: to achieve higher temperatures it would be necessary to use evacuated tubes and / or concentrating collectors, [18]. The condenser pressure outlet is 1 bar with 5°C of subcooling, corresponding to a condenser temperature of about 50°C. The heat rejected could be used for building heating or cooling (in this case with an absorption heat pump).

Several refrigerants were analysed for the primary cycle: n-pentane, HFE7100, methanol and ciclohexane. Organic fluids are desirable for such low temperature applications, due to their high molecular weight and positive slope of the saturated vapour curve in the temperature-entropy plane, both attributes simplifying the design of the expander [19].

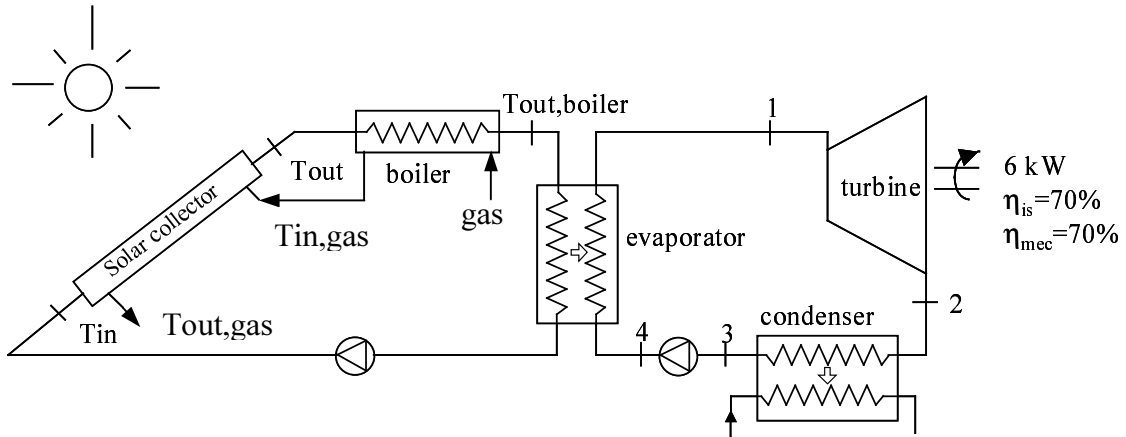


Figure 1 Micro-CHP system.

Table 1 presents the evaporator input heat, Q_{evap} , the condenser output, Q_{cond} , the electrical efficiency (equation 1), η_{elec} , the second law efficiency (equation 2), η_{II} , and the cycle efficiency (equation 3) for all refrigerants. The second law efficiency represents the system approximation to an isentropic process. The cycle efficiency presents values of about 98%, since the turbine is adiabatic and heat losses from piping are neglected. Definitions used for efficiency calculations are:

$$\eta_{elec} = \frac{P_{elec}}{Q_{evap} + P_{pump}} \quad (1)$$

$$\eta_{II} = \frac{\eta_{elec}}{\eta_{Carnot}} \quad (2)$$

$$\eta_{cycle} = \frac{P_{elec} + Q_{cond}}{Q_{evap} + P_{pump}} \quad (3)$$

Table 1 Refrigerants analysed and cycle results.

Refrigerant	Psat @ T =95°C	Qevap	Qcond	η_{elec}	η_{II}	η_{cycle}
n-pentane	527 kPa	133.1 kW	124.7 kW	0.045	0.077	0.982
HFE 7100	276 kPa	146.2 kW	137.8 kW	0.041	0.070	0.982
methanol	296 kPa	118.9 kW	110.4 kW	0.050	0.086	0.979
ciclohexane	153 kPa	127.7 kW	119.2 kW	0.047	0.080	0.980

The refrigerant that presents the best performance is methanol, with an electrical efficiency of 5.0%. This fluid is toxic and inflammable, with a minimal impact on the environment.

Figure 2 shows the temperature-entropy diagram for the methanol in the primary cycle.

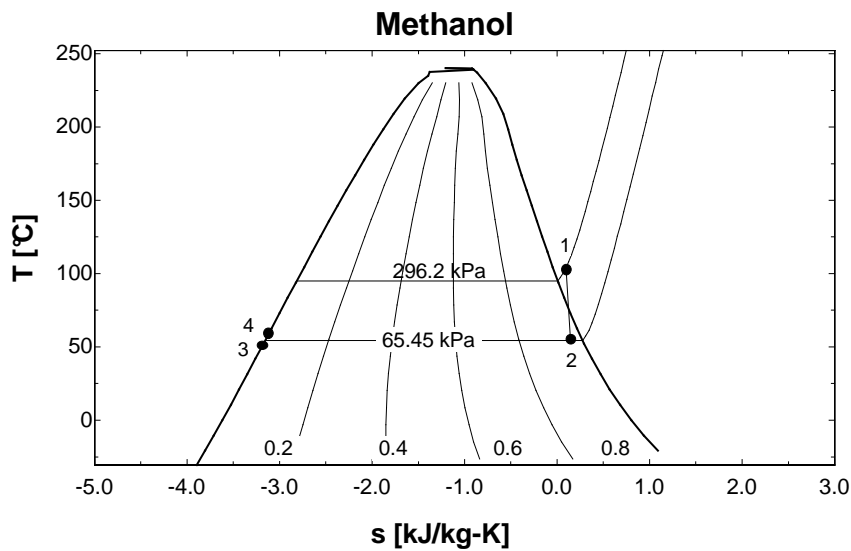


Figure 2 Temperature-entropy diagram of methanol.

3. Economic analysis

Energy savings can be calculated by comparing the micro-CHP system with a conventional system. This would be to consume electricity from the grid (6 kW), and

use a gas burner to obtain 110 kW of heat. Table 2 presents energy cost data for building applications in Portugal.

Table 2 Energy cost data for building applications in Portugal.

Electricity cost	Natural gas cost
12.51 €/month + 0.1013 €/kWh	6.09 €/month + 0.4862 €/m ³ (0.0462 €/kWh)

The initial costs of the system opposed to the conventional system are: solar collector costs, which depend on collector area, turbine, condenser, pipework and valves, pumps, instrumentation and methanol (see table3).

Table 3 Capital costs for micro-CHP system.

Hybrid solar collectors [20]	350 €/m ²
Turbine [17]	1034 €/kW = 6204 €
Condenser [21]	650 €
Pipework and valves [21]	650 €
Pumps [21]	750 €
Instrumentation [21]	800 €
Methanol (8 l)	50 €

Life cycle savings (LCS) are defined as the difference between the life cycle cost of a conventional system and the life cycle cost of the solar plus auxiliary energy system, [22], including initial costs (investment) and operating costs (energy and maintenance). Figure 3 shows LCS of the micro-CHP system as a function of solar collector area for a period of 15 years, with the climatic data for Lisbon (Portugal). The annual average solar fraction, ratio between solar energy input and total evaporator heat input in the system, is also presented. The system is viable even without solar collectors,

which means that the investment in the CHP system (turbo-generator mainly) is compensated by the savings in energy costs. The larger LCS occurs for a relatively high collector area of 240 m², which corresponds also to a large investment.

Table 4 presents monthly (integrated) values of solar fraction with a collector area of 191 m², the area for which there is no energy excess under the most favourable conditions – August at noon (maximum incident solar radiation of 1006 W/m²). A maximum of 21% is obtained in August and a minimum of 7% in December and January.

The system was considered to operate 24 hours per day, everyday, during 365 days/year. During the summer period the heat produced could be used to drive an adsorption cooling machine.

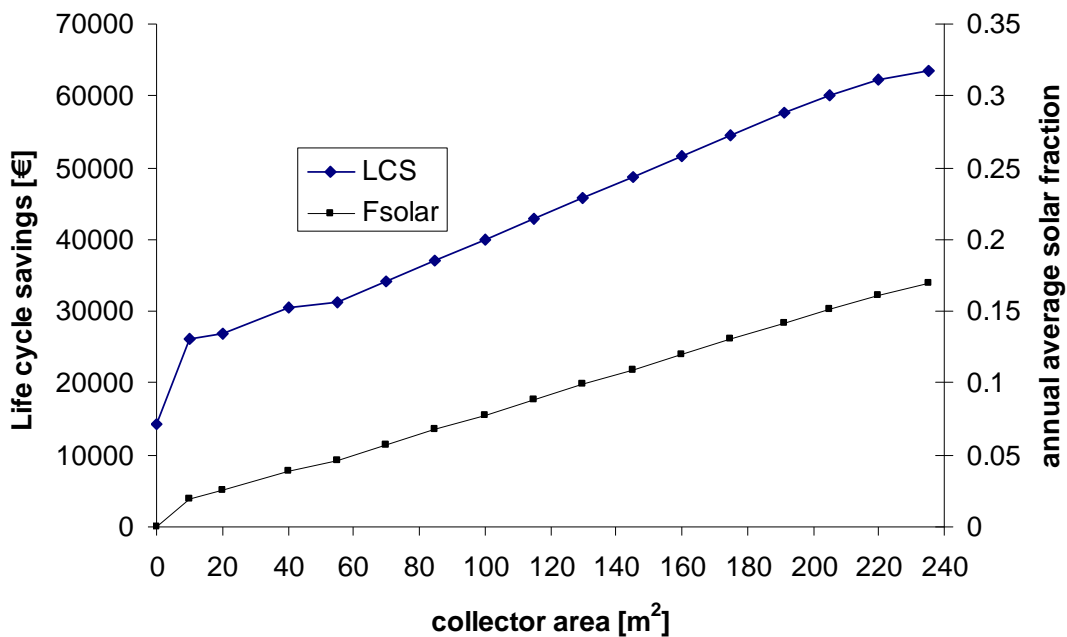


Figure 3 Life cycle savings of the micro-CHP system for a period of 15 years and annual average solar fraction

Table 4 Average monthly solar fraction for the system in Lisbon with area of 191m².

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Set	Oct	Nov	Dec
0.07	0.09	0.12	0.14	0.17	0.17	0.20	0.21	0.18	0.16	0.11	0.07

The system payback period depends on components' costs. Considering the costs in table 3, the payback period can be calculated through:

$$C = E \left[\frac{1}{j-i} \left(1 - \left(\frac{1+i}{1+j} \right)^n \right) \right] \quad (4)$$

Using the values of table 5, a payback period of 8.5 years is obtained for 191 m² of solar collector area. For 50 m² the payback period is 7.0 years.

Table 5 Payback period.

C, Initial cost	75954 €
E, Energy savings	91849 €/year
j, Interest rate	2.4%
i, inflation rate	2.3%

4. Environmental viability

To evaluate the environmental viability, the CO₂ emissions of the micro-CHP system were calculated and compared with a conventional system. The specific CO₂ emission of natural gas, without considering boiler efficiency, is 1891 g CO₂/m³, [23]. Figure 4 shows CO₂ emission savings of the micro-CHP system. The conventional system emits CO₂ to produce 110 kW of heat and to produce electricity. The electricity in Portugal comes 75% from thermal plants (fuel) with an average efficiency of 30%. The other

25% come from hydropower (renewable source) For a solar collector area of 191 m² the CO₂ emission savings are about 51.3 tons per year.

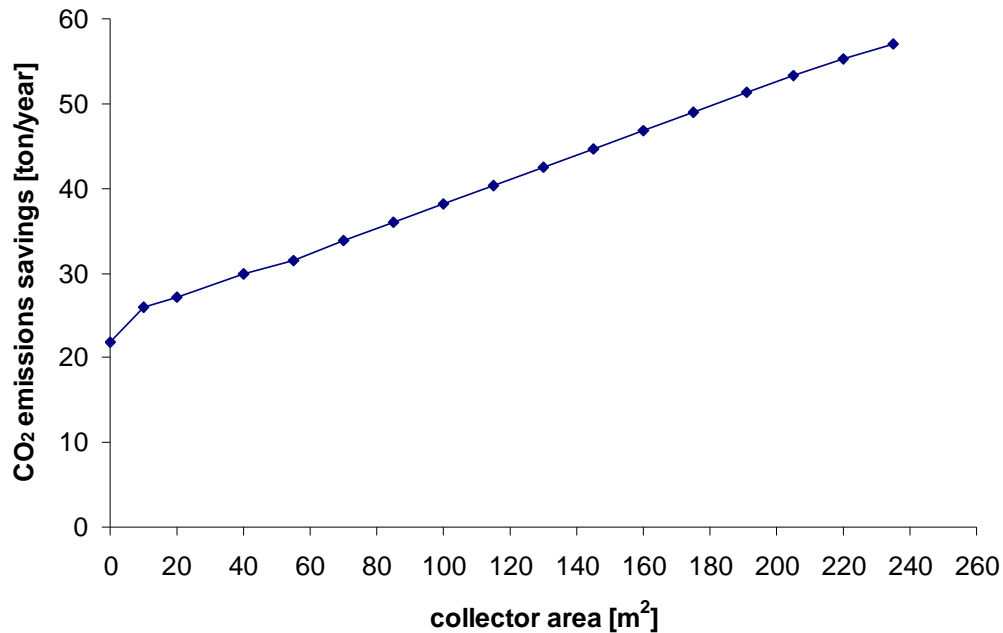


Figure 4 CO₂ emissions savings of the micro-CHP system.

5. Conclusions

A micro-CHP cycle producing 6 kW of electricity was evaluated. The heat rejected in the cycle condenser is used for space heating or cooling in buildings. Several refrigerants in the cycle have been simulated and methanol presented the best performance.

The contribution of solar energy to system energy needs was quantified under Lisbon climatic conditions. The life cycle savings is positive even without solar collectors, this means that the system is always feasible. The average monthly solar fraction ranged from 7 % to 20%.

The estimated payback period – about 8.5 years – is smaller than the estimated system life time, which means an worthy investment. Besides, the system could save about 51 tons of CO₂ per year when compared to the conventional situation.

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References

- [1] A C. Oliveira, C. Afonso, J. Matos, S. Riffat, M. Nguyen and P. Doherty, A Combined Heat and Power System for Buildings Driven by Solar Energy and Gas, *Applied Thermal Engineering* **22**, 587-593 (2002).
- [2] Manuel Collares-Pereira, *Energias Renováveis, a Opção Inadiável*, Sociedade Portuguesa de Energia Solar, Lisboa, 2000.
- [3] D. Mills, Advances in Solar Thermal Electricity Technology, *Solar Energy* **76**, 19-31 (2004).
- [4] A. Pifre, A Solar Printing Press, *Nature* **21**, 503-504 (1882).
- [5] J. Ericsson, The Sun Motor, *Nature* **38**, 321 (1888).
- [6] A. Eneas, U.S. Pat. 670, 1910, 917.
- [7] F. Shuman, The Most Rational Souce of Energy: Tapping the Sun's Radiant Energy Directly, *Sci. Am.* **109**,350 (1913).

- [8] G. Francia, Un Nouveau Collecteur de L'énergie Rayonnant Solaire: Theorie et Verifications Experimentales, United Nations Conference on New Sources of Energy, pages 554-588, Rome, 1961.
- [9] G. Francia, Pilot Plants of Solar Steam Generation Systems, Solar Energy **12**, 51-64 (1968).
- [10] L. C. Spencer, A Comprehensive Review of Small Solar-Powered Heat Engines: Part I. A History of Solar-Powered Devices Up to 1950, Solar Energy **43**(4), 191-196 (1989).
- [11] L. C. Spencer, A Comprehensive Review of Small Solar-Powered Heat Engines: Part II. Research Since 1950 – “Conventional” Engines Up to 100kW, Solar Energy **43**(4), 197-210 (1989).
- [12] L. C. Spencer, A Comprehensive Review of Small Solar-Powered Heat Engines: Part II. Research Since 1950 – “Unconventional” Engines Up to 100kW, Solar Energy **43**(4), 211-225 (1989).
- [13] F. G. Best and S. B. Riffat, Miniature Combined Heat and Power System, Renewable Energy **6**(1), 49-51 (1995).
- [14] J. L. Wolpert and S. B. Riffat, Solar-Powered Rankine System for Domestic Applications, Applied Thermal Engineering **16**(4), 281-289 (1996).
- [15] T. Yamamoto, T. Furuhashi, N. Arai and K. Mori, Design and Testing of the Organic Rankine Cycle, Energy **26**, 239-251 (2001).
- [16] V. M. Nguyen, P. S. Doherty and S. B. Riffat, Development of a Prototype Low-Temperature Rankine Cycle electricity Generation System, Applied Thermal Engineering **21**, 169-181 (2001).
- [17] <http://www.freepower.co.uk>.

- [18]] J. Facão, A. C. Oliveira, Simulation of the Thermal Behaviour of a Hybrid Heat Pipe Solar Collector, Proceedings SET2002 Conference (1st Int. Conf. on Sustainable Energy Technologies), ISBN 972-95806-9-3, 2002.
- [19] K. Koai, N. Lior and H. Yeh, Performance Analysis of a Solar-Powered / Fuel-Assisted Rankine Cycle with a Novel 30 hp Turbine, Solar Energy **32**(6), 753-764 (1984).
- [20] S. B. Riffat, Hybrid-CHP – An Hybrid Combined Heat and Power System, EU Research Contract n° ENK5-CT-2000-0080, 2003.
- [21] A. C. Oliveira, An Integrated Hybrid Solar / Gas System for Buildings, Final Report, The European Commission, Joule III, 2000, Contract: JOR3-CT97-0183.
- [22] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes, John Wiley & Sons, Inc, second edition, 1991.
- [23] T. J. McCann, 1998 Fossil Fuel and Derivative Factors, March 2000.

Nomenclature

C	initial cost, €
E	energy savings, €
F _{solar}	solar fraction
h	enthalpy, J/kg
i	inflation ratio
j	interest ratio
LCS	life cycle savings, €
P	power, W
P _{sat}	saturation Pressure, Pa
Q	heat flux, W
s	entropy, J/(kgK)
T	temperature, K

η efficiency

Subscripts

II second law

cond condenser

Carnot Carnot

elec electrical

evap evaporator

in inlet

in,gas inlet gas

is isentropic

mec mechanical

out outlet

out,boiler outlet boiler

out,gas outlet gas

pump pump