

Analysis of a Micro-Cogeneration System Using Hybrid Solar/Gas Collectors

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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 and hybrid: they act as a boiler economizer, as boiler exhaust gases circulate below the absorber plate, increasing the energy input and collector efficiency. The behaviour of a combined heat and power cycle producing 6 kW of electricity was simulated. The heat rejected in the cycle condenser can be used for space/water heating or cooling of 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), for two applications: a pool complex and an office building. The energy and economic potential of the system was compared to the conventional alternative.

Keywords: hybrid solar collectors, micro-cogeneration, economic analysis

NOMENCLATURE

<i>c</i>	cost of energy unit (€/kWh)
<i>f</i>	annual solar fraction (-)
<i>I</i>	incident solar radiation (W/m ²)
<i>IC</i>	initial cost (€)
<i>LCC</i>	system life cycle costs (€)
<i>LCS</i>	system life cycle savings (€)
<i>q̇</i>	heat flux per unit area (W/m ²)
<i>s</i>	selling value of unit energy (€/kWh)
<i>T</i>	temperature (K)

Greek symbols

Δt	operating time (hours)
η	efficiency (-)

Subscripts

<i>a</i>	ambient
<i>ad</i>	additional
<i>b</i>	boiler
<i>cog</i>	cogeneration
<i>col</i>	collector
<i>conv</i>	conventional
<i>el</i>	electricity
<i>fm</i>	fluid mean = (inlet+outlet)/2
<i>gas</i>	gases
<i>in</i>	collector inlet
<i>ng</i>	natural gas
<i>out</i>	collector outlet

1. INTRODUCTION

Existing large-scale plants for power generation are usually located far away from centres of population. This prevents 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%. This means that vast quantities of fossil fuels are burnt with unwanted pollutants entering the atmosphere.

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. 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.^[1] It started with Mouchot and Pifre in France in 1882,^[2] and continued by extraordinary pioneers such as Ericsson in 1882,^[3] Eneas in 1910,^[4] Shuman in 1913,^[5] and Francia,^[6] 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, [7, 8, 9], presented a review of small solar-powered heat engines up to 1989.

Best and Riffat, [10], and Wolpert and Riffat, [11], 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 occurred 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, [12], 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., [13], and Oliveira et al., [14], 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, [15], commercialises a combined heat and power (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 can be driven by solar energy.

The system analysed in this work 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 drawback of the present solar micro-CHP system is that its initial cost is still relatively high. However, when supplemented by a gas burner, it has the advantage of producing electricity and heat during periods of low solar radiation, with a high average efficiency and a low energy cost.

2. HYBRID SOLAR COLLECTORS

In the framework of a European research project, [16], a new concept of solar thermal collector was developed. It uses circular heat pipes (20) embedded in the absorber plate. They are heated by two different sources: solar energy transmitted through the transparent cover (double glazing) and hot gases circulating below the plate. Figure 1 shows the collector schematically. Each collector has a useful collecting area of 2.4 m². Water (or another working fluid) is heated in the condenser zone of the heat pipes. Double glazing was chosen according to the application in view: water outlet temperatures around

100°C, in order to drive the power cycle; for these conditions, double glazing is always preferable to single glazing. The collector plate has a selective coating.

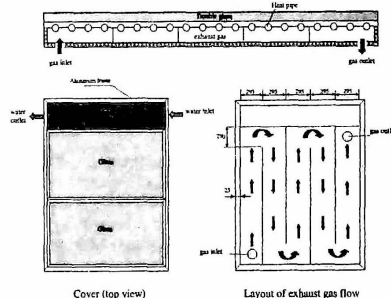


Figure 1: Hybrid solar/gas collector.

The conversion of solar energy to process heat with temperatures between 100 and 150°C normally requires evacuated tube collectors or concentrating systems. However, the hybrid solar collectors are of the flat-plate type, with the advantage of lower cost and easier handling.

The hybrid solar collector was modelled, [17], and the model was validated with experimental results, [18]. Solar collector efficiency was correlated through

$$\eta_{col} = 0.78 - 2.49 (T_{fm} - T_a) \quad (1)$$

for operation without circulation of gases (solar input only).

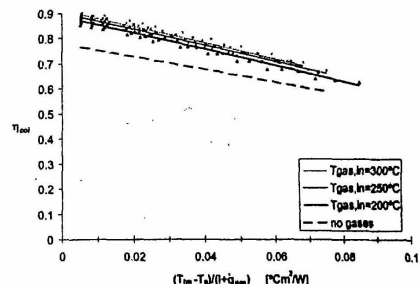


Figure 2: Efficiency for the hybrid solar collector.

The gases are coming from a boiler exhaust. Usually a gas boiler is used as energy back-up for a solar system. In this case, the hybrid collectors also act as a boiler economiser, partially recovering some of the heat carried in the boiler flue gases. This increases collector and overall performance. Figure 2 represents the hybrid collector efficiency, which depends on temperature, solar radiation intensity and recovered heat flux. Water flow rate was fixed at 20 g/s/m², and gas flow rate was also fixed, by imposing a constant velocity (3 m/s). As can be seen, collector

efficiency is higher than without gases, by up to 12% (absolute value), even for large temperature differences (fluid-ambient). The temperature of gases also affects collector efficiency: a higher temperature leads to a higher recovered heat flux, but also to higher collector plate temperature and losses. The efficiency increases moderately with gas temperature.

3. MICRO-COGENERATION SYSTEM AND PERFORMANCE RESULTS

Micro-generation is the decentralized production of electricity, through different means (micro-turbines, fuel cells, Stirling engines, small internal combustion engines, PV cells), with an electrical power output up to 50 kW. Micro-cogeneration, or micro-CHP, is the combination of micro-generation with useful heat.

The micro-CHP system under analysis uses a micro-turbine and electric generator with a power output of 6 kW. Such small turbines are recently available in the market, and have typical overall efficiencies around 70%,^[15]. The system is represented in Figure 3, and is composed of two cycles: the primary cycle where the working fluid expands in the turbine and condenses in the condenser, and the secondary cycle with the hybrid solar collectors and boiler. A heat exchanger transfers heat between the two circuits.

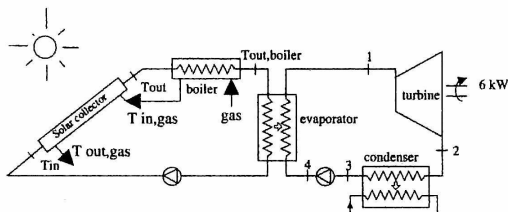


Figure 3: Micro-CHP system.

The water pressure in the secondary cycle is about 2 bar. The turbine inlet temperature, point 1 in Figure 3, is 100°C with 5°C of superheating (saturation pressure of 95°C). This temperature is compatible with the maximum temperature achieved in the collector/boiler circuit. At condenser outlet the fluid is at 1 bar with 5°C of subcooling, corresponding to a condenser temperature of about 50°C. The heat rejected in the condenser can be used for water heating or building heating or cooling (in this case with an adsorption heat pump). Micro-generation systems driven at low/medium temperatures (100°C in this case) have the disadvantage of generating an amount of heat which is much higher than the generated power. 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.

Several refrigerants were analysed for the primary cycle: n-pentane, HFE7100, methanol and cyclohexane. It was found that methanol led to the best results, with an electricity generation efficiency of 5.0% and a primary cycle efficiency of 98%. This fluid

is toxic and inflammable, with a minimal impact on the environment. For the above conditions, the system produces 110 kW of heat (119 kW input in primary cycle).

Potential system applications are those in which thermal energy needs are much larger than electricity needs. In many applications the electricity generated may not be sufficient: in this case additional electricity should be bought from the grid. As it is the case with most cogeneration systems, in order to maximise the system economic viability, it is more interesting to apply it when thermal energy needs are present throughout the year, particularly heating needs. One such application is to swimming pool complexes, where water heating (and space conditioning) needs last through the whole year, and are much higher than electricity needs (only for water pumping or artificial lighting). Another possible application is to office buildings, where heat can be used during the cold season for space heating (floor heating, for instance), and used during the hot season to drive an adsorption chiller (which can produce chilled water from hot water temperatures above 50°C). In office buildings the small amount of electricity produced would be a contribution to the building electrical consumption.

The CHP system was modelled, assuming constant operating conditions for the primary cycle (using methanol). The driving temperature is assured by the combination of hybrid collectors with a boiler (secondary cycle). A constant electricity and thermal output were therefore assumed. For the boiler, burning natural gas, an efficiency of 90% was assumed, with exhaust gases temperature of 200°C. The boiler supplies only the energy needed after collector output, which means that its contribution depends on collector efficiency and collector area. In order to quantify system performance, a solar fraction was calculated, defined as the percentage of energy needs (load) supplied by free sources (solar plus recovered heat). Figure 4 shows annual solar fraction results for the climatic conditions of Lisbon, Portugal, using the Test Reference Year climatic file (hourly data).

Solar fraction increases more or less linearly with collector area, as no energy excess occurs: from the hourly calculations performed, an hourly fraction of 100% would occur on the 26th of August at 1 pm, for a collector area of 202 m². An area up to 200 m² was considered for the calculations. The difference between the solar fraction for the pool and for the office building is due to a different system operating time: while in the pool an operation of 24 hours per day was assumed throughout the year (except one week per year used for maintenance), in the office building an average operating time of 12 hours per day – during normal working hours – was considered. Therefore, the solar fraction is higher for the office building (about twice), since the load is about half the one for the pool (which has a double system operating time), with virtually the same solar contribution.

Figure 5 presents the variation of another system parameter with collector area: the average (annual) system efficiency, defined as the ratio between useful

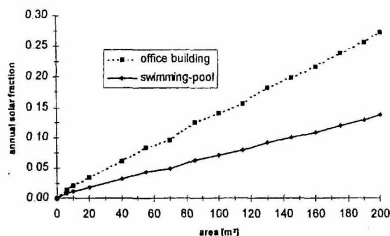


Figure 4 System annual solar fraction as a function of collector area, for the two applications (office building and swimming-pool).

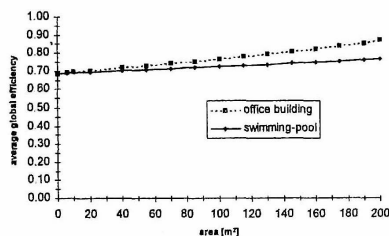


Figure 5 Average (annual) system efficiency as a function of collector area, for the two applications (office building and swimming-pool). Energy provided by the system – electricity and heat – and spent (paid) energy – gas in the boiler and electricity for pumping (this last one is a very small part). The annual efficiency is generally higher than 70%, increasing with collector area, and may reach values higher than 80%. It is higher for the office building application, due to the higher solar collector contribution.

4. SYSTEM ECONOMIC ANALYSIS AND ENVIRONMENTAL ASSESSMENT

In order to evaluate the economic interest of the micro-cogeneration system, both initial costs and energy costs were calculated. They were compared with the cost of a conventional solution, which consists in buying electricity from the grid and using a boiler to produce thermal energy.

The initial cost of the system – additional cost, compared to the conventional situation – includes the cost of the micro turbine/generator (6200 €), heat exchangers (including condenser and evaporator), pumps, valves, instrumentation and working fluid, besides the hybrid collectors cost. Note that the boiler exists in both situations and, therefore, is not considered as an additional cost. The additional cost was estimated to be 9754 €, ^[17] plus collector cost which depends on collector area. The collector cost was estimated at 350 €/m².

Energy costs were also calculated, with the objective of estimating system life cycle savings (LCS). These are defined as the difference between the life cycle cost of a conventional system and the

life cycle cost of the micro-generation system, including initial cost and operating costs (energy and maintenance).

Energy costs depend on the costs of electricity and fuel (in this case, natural gas). In this work, the costs for the Portuguese situation were considered. Electricity cost varies throughout the day. For a total power between 20.7 and 41.4 kVA and the applications considered, the average electricity cost is 0.061 €/kWh for the pool and 0.071 €/kWh for the office building (consumption during working hours). For small electricity producers, it is also possible to sell the electricity to the national grid, up to a maximum of 50% of the total produced. According to the present legislation, the average sale value is 0.10 €/kWh for the pool (24 hours/day) and 0.11 €/kWh for the office building (12 hours daily). This means that, in the present situation, it is more favourable to sell half of the electricity produced and to consume the rest. Two situations will be considered: total consumption and 50% consumption.

The cost of natural gas depends on the annual consumption. For the Portuguese situation and large consumers (industry or services), it may vary between 0.038 €/kWh and 0.032 €/kWh. It is lower for higher consumption, which is the case of the swimming-pool.

The life cycle cost (LCC) for the conventional situation can be expressed as

$$LCC_{conv} = 6 \cdot c_{el} \cdot \Delta t + \frac{110}{\eta_b} c_{ng} \cdot \Delta t \quad (2)$$

while the life cycle cost for the micro-generation system is

$$LCC_{cog} = IC_{ad} + \frac{119}{\eta_b} (1-f) \cdot c_{ng} \cdot \Delta t - 6 \cdot 0.5 \cdot (s_{el} - c_{el}) \cdot \Delta t \quad (3)$$

considering that 50% of the electricity may be sold to the grid.

The micro-cogeneration system needs a higher thermal input, but part of which is supplied through free sources (solar plus recovered gas), and has no net electricity consumption (neglecting pump consumption) – it may consume the same amount sold to the grid.

Life cycle savings are obtained by subtracting (3) to (2). Figure 6 shows LCS for a system life of 15 years, for the office building and pool applications, as a function of collector area. It was assumed that 50% of the generated electricity is sold to the grid. LCS are always positive. The use of decentralised electricity generation (without any collectors) is already favourable, compared to centralised generation. But the use of the hybrid collectors increases LCS significantly, even for small collector areas. The increase in collector area has a higher impact in the case of the office building, due to higher gas and electricity costs per energy unit. For the pool application, the increase in collector area is not very interesting, because the initial cost increases without a significant increase in LCS: the recommended

collector area is low (10 to 20 m²). For the office building a higher area is justifiable.

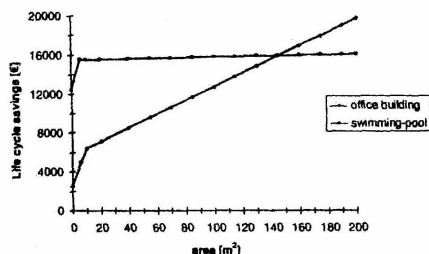


Figure 6 Cogeneration system life cycle savings as a function of collector area, for the two applications – for 15 years and 50% of the generated electricity sold to the grid.

Figure 7 compares the consumption of 50% of the generated electricity (50% sold) with the consumption of 100%, for the pool application. When no electricity is sold the LCS are negative if no collectors are used. Only the use of the hybrid collectors leads to positive LCS.

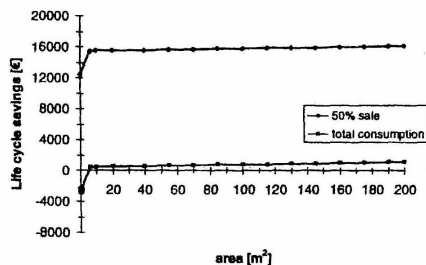


Figure 7 Cogeneration system life cycle savings as a function of collector area, for the pool application – for 15 years and comparing 50% of the generated electricity sold to the grid with total consumption.

Figure 8 compares the same two situations for the office building application. In this case, the collector area should be higher than 40 m² in order to have positive LCS, if all electricity is consumed. Note that the difference between 50% and 100% consumption is much lower for the office building: about 8000 € compared to about 15000 € for the pool.

Since energy prices are very volatile, the effect of an increase in natural gas cost (energy unit) was assessed. As Figure 9 shows, for the pool application, an increase of 10% in the cost of natural gas leads to a higher effect of collector area in LCS. LCS are higher for a collector area above 100 m². A higher natural gas cost justifies a higher collector area. The same conclusion is valid for the office building. In this

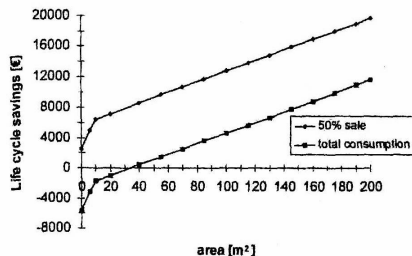


Figure 8 Cogeneration system life cycle savings as a function of collector area, for the office building application – for 15 years and comparing 50% of the generated electricity sold to the grid with total consumption.

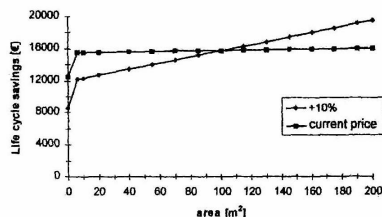


Figure 9 Cogeneration system life cycle savings as a function of collector area, for the pool application – for 15 years, 50% of the electricity sold and comparing current natural gas prices with prices increased by 10%. Analysis the cost of one unit of electricity was maintained, as electricity prices are more stable.

Another economic parameter that was assessed was the system payback period. As known, it represents the period for which energy savings compensate the additional initial cost. The cogeneration system payback period depends on the application (pool or office building) and also on collector area. They are lower for the pool application, varying between 6.9 years (10 m²) and 11 years (100 m²). For the office building they vary between 10.4 years (10 m²) and 11.5 years (100 m²). These values are valid for 50% of the electricity sold.

The environmental impact of the cogeneration system was also assessed, by calculating savings in CO₂ emissions. The comparison is made with the conventional situation, for which 25% of the spent electricity is coming from hydro sources and 75% from fuel thermal plants (30% efficiency) – average situation in Portugal. The specific CO₂ emission of natural gas, without considering boiler efficiency, is 1891 g CO₂/m³, [19]. As Figure 10 shows, emission savings are always positive, even without collectors (decentralized generation only). For a collector area of 6 m², and the pool application, 23 tons are saved per year, while for 200 m² savings reach 50 tons/year.

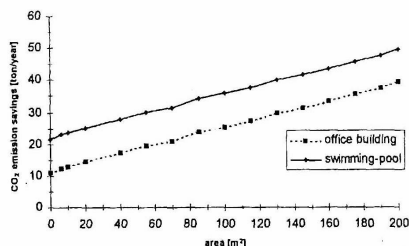


Figure 10 Savings in CO₂ emissions as a function of collector area, for the two applications.

5. CONCLUSION

A novel concept of solar collector was developed and applied to a micro-cogeneration system. Besides using heat pipes, the collector can recover heat from a boiler exhaust, with hot gases circulating below the absorber plate. As shown, this increases energy input and collector efficiency. The hybrid collectors, supplemented by a natural gas boiler, are able to provide hot water to drive a micro-cogeneration system, using methanol as working fluid, producing 6 kW of electricity and 110 kW of heat.

The heat generated by the system can be used for water/space heating or space cooling, if coupled to an adsorption heat pump. Two applications were simulated: heating of a swimming-pool and heating/cooling of an office building. The average (annual) system efficiency is high – between 70 and 85%, depending on solar collector area.

The micro-cogeneration system economic potential was assessed. It was found that the application to a swimming-pool leads to the higher life cycle savings. It was also found that a relatively low collector area (10 to 20 m²) leads to a significant increase in those savings. It was also concluded that, under the Portuguese specific conditions, it is more favourable to sell the generated electricity to the grid (maximum of 50%) than to consume it. For application to an office building, the use of the hybrid collectors may be decisive to economically justify the CHP system (if all electricity is consumed). In this case, a collector area above 40 m² is recommended.

A major drawback of the present solar micro-CHP system is that its initial cost is still relatively high – estimated cost of 23754 € for a collector area of 40 m². Its payback period varied, for the different applications and situations, between 6.9 and 11.5 years. The system initial cost and payback period will be reduced with a higher dissemination of the system, reducing collector and micro-turbine costs. Also the foreseen increase in energy prices (both electricity and natural gas) shall increase the economic interest of the system.

The environmental impact of the system was also assessed. It was found that it can save 22 to 50 tons of CO₂ per year for the pool application and 12 to 40 tons of CO₂ per year for the pool application, depending on collector area.

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