Distributed CHP Generation from small size concentrated Solar Power

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Abstract
The distributed cogeneration of energy is one of the leading arguments for the improvement of renewable energy share in the energy consumption at European level. The actual work describe the realization of a modular 1-3 kWe, 3-9 kWth micro Combined Heat and Power (m-CHP) system based on innovative Concentrated Solar Power (CSP) and Stirling engine technology.
This CSP m-CHP will provide electrical power, heating and cooling for single and multiple domestic dwellings and other small buildings.
It integrates small scale concentrator optics with moving and tracking components, solar absorbers in the form of evacuated tube collectors, a heat transfer fluid properly investigated, a Stirling engine with generator after the development and testing of two main solutions, and heating and/or cooling systems; it incorporates them into buildings in an architecturally acceptable manner, with low visual impact.
The work is part of a European Funded project (DiGeSPo) in the CALL ENERGY-2009-1.

Keywords: distributed generation, m-CHP, Stirling engine, Cer.Met. coating

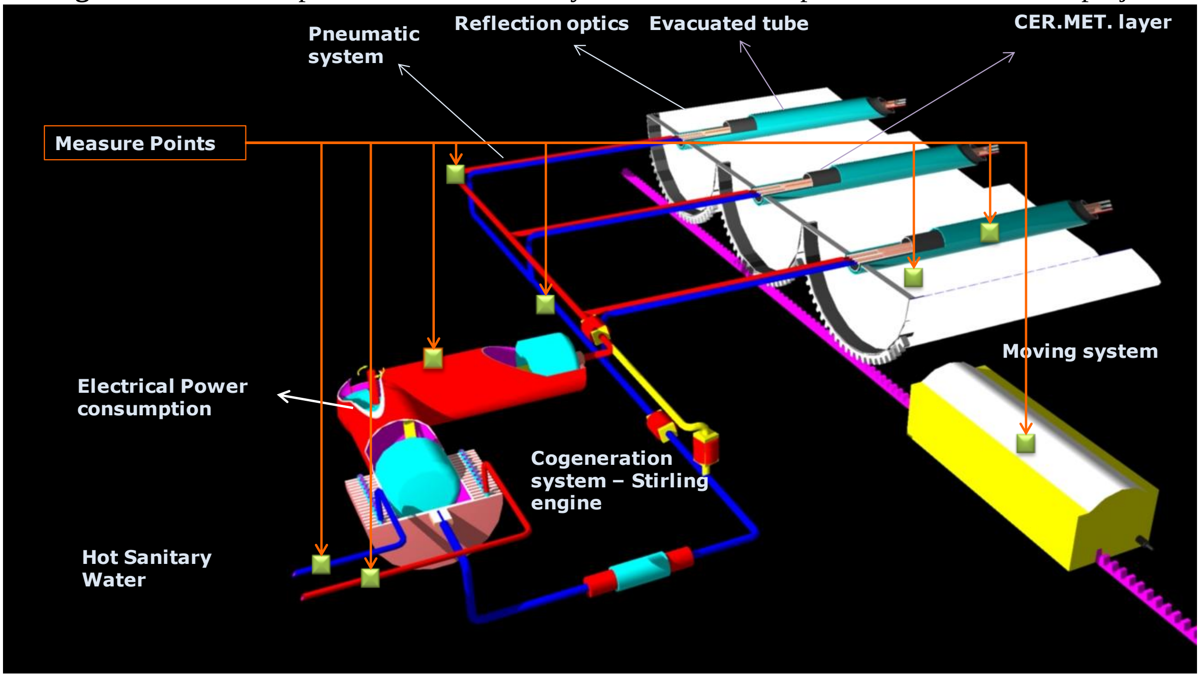
1. Introduction
The cogeneration of energy at distributed level is one of leading argument in large part of energy policies related to renewable energy resources and systems. The actual marketable solar systems for domestic and distributed applications (PV and Solar thermal) suffer of notable limitation: i) the low overall (electrical) efficiency of PV systems create a small collected energy from available space, sometimes restricted in surface to few square meters, ii) the stagnation temperatures on solar thermal collectors actually limiting the diffusion of solar thermal systems, iii) fixed and not retrofittable systems may generate energy in intermittent way not aligned with the auto consumption profile of domestic spaces.
The development of a new cogeneration system, based on a compact concentrated solar power is therefore highly required, realized compatibly with the market levelized energy cost (LEC).
This paper will describe the first phases of development of such m-CHP solar technology, which integrated a cooperation between seven main partners distributed along five European countries.
Such system (see Fig. 1) integrates small scale concentrator optics with moving and tracking components, solar absorbers in the form of evacuated tube collectors, a heat transfer fluid, a Stirling engine with generator, and heating and/or cooling systems; it incorporates them into buildings in an architecturally acceptable manner, with low visual impact. Four main themes have led to the development of this proposal:

- improvements in glass technology allow the adaptation of large parabolic trough solar concentrator technology for much smaller scale systems, down to the single domestic dwelling;
- recent studies on ceramic-metal (Cer.Met.) coatings suggest that they can provide improved optical behaviour and material durability for absorbers inside evacuated tube collectors, at

higher temperatures than previously possible, leading to lower emittance and higher efficiencies, with very low costs at high production volumes;

- modified Stirling cycles and new compact heat exchanger technology can improve the costs and performance of small heat engines, so that they can operate with higher proportions of Carnot efficiency on the intermediate temperatures (~ 350 °C) from the new CSP collectors;
- the high cost and low power efficiency of gas-fuelled m-CHP systems, combined with increases in natural gas prices, both absolute and relative to electricity prices, can under-mine the financial viability of gas-fuelled m-CHP. There is an urgent need for alternative m-CHP systems, of which solar m-CHP , whether separately or as a hybrid, is an option with high potential.

Figure 1. Schematic picture of the m-CHP system under development within DiGeSPo project



2. Methodology

2.1 The multidisciplinary approach

The CSP m-CHP technology under development requires a multidisciplinary approach and regards a series of themes below described on the main objectives for the related research.

Selective absorber (Cer.Met. coating): R&D on an innovative coating for the solar absorber inside the evacuated tube collector. A new nano-technology-based Cer.Met. layer (ceramic-metal) will be used to minimise solar re-radiation back to atmosphere and increase the conversion efficiency of solar radiation to heat energy in the thermal vector fluid at temperatures up to 250-350°C. The general efficiency target is to have an absorbance greater than 0,93 and an emittance smaller than 0,06.

Concentration optics and tracking system: modelling and development of the optical sub-system. It comprises a very high efficiency, low profile parabolic trough reflector using new, chemically treated, flexible and low cost thin glass mirrors, with concentration ratio of 8-10:1, a tracking system (both mechanical and electronic control components). The efficiency target is a reflectance higher than 0,93 (averaged on solar spectrum) and an impact factor higher than 0,93.

Thermal fluid: R&D on a suitable single or two phase fluid that maximises heat transfer efficiency from the Cer.Met. layer to the Stirling engine; reducing the NTU deficit, Number of Transferred Units (of heat), to a minimum. The thermal fluid must adapt at the defined heat engine cycle and must be compatible with the hydraulic circuit of the evacuated solar collector.

Full solar collector: Modelling and optimisation of an existing evacuated tube collector It uses a low iron, glass tube with a nanoparticle-based anti-reflective coating (actual certified transmittance of the glass: 0,96), an absorber with the improved, new high temperature Cer.Met. layer; integration of the complete collector system to the input/output of the thermal vector fluid. The overall efficiency target is 75% (heat to fluid/radiation to concentrator).

Heat engine: modelling, development and assessment of two novel engine options that will provide higher efficiencies than existing engines at the target temperatures. One is a valved Stirling-cycle engine, based on a pre-engineering realized by Allan J. Organ, an external collaborator with the project partners [1]; the second is a rotary, modified Stirling cycle engine based on scroll compressor technology. Both will use novel, extremely compact heat exchangers based on new manufacturing technology, offering higher efficiency and lower cost. Both will be matched to the low/medium temperatures and different cycle conditions, with a target power conversion efficiency for the engine/generator of 27-28%, with air-cooling if required.

2.2 Full system integration and demonstration activities

Integration of the sub-systems into complete formats suitable for initial prototype production and testing, and compatible with later large scale industrial production and commercial impact on the market. Finally the objective will be the development of a small scale distributed/domestic CSP m-CHP system in the 1-3 kWe range, complete with high quality optics, moving, tracking, collector and absorbing units; with a low visual impact that will readily be accepted by the architectural profession and the building industry. The targets are hot and cold end temperatures for the engine of 300°C and 40°C respectively, theoretical Carnot efficiency of 46%; achievement of about 60% of Carnot efficiency; and overall system efficiency of circa 20% (power generated/solar radiation).

The demonstration of the technology will be located in a high impact and visibility location in the middle of the Mediterranean area (Hilton Hotel in Malta).

2.3 Methodological approach to the technological development

The technology under development addresses directly the above issues with the intention to make available solar cogeneration systems for the distributed scale, by respecting specific contents/scopes, as follows.

- improving the efficiency of key components: the efficiency of the following sub-systems will be improved: small scale parabolic trough concentrators, solar absorbers inside evacuated tube collectors, heat transfer to the prime mover, and the prime mover (modified Stirling engine) itself;
- improving CSP's environmental profile by: vastly increasing its potential market and the CO_2 savings that result; locating the CSP plant on roof-tops to eliminate the need for extra land; and reducing or even eliminating the use of water for cooling: final heat rejected by engine is used for heating and/or cooling the building, because the high efficiency of the engine, together with the use of highly compact heat exchangers, particularly the cooler, allows significant reductions in the temperature of reject heat, compared with existing Stirling engines;
- employing new coatings and nano-technology: self-cleaning nano surfaces on the concentration mirrors reduce maintenance costs and increase reflective efficiency; Cer.Met coatings on the absorber increase energy conversion efficiency;
- providing large reductions in both capital and maintenance costs: approaching the EU's target of 6-9 cent€/kWhel by 2020 [2] is one of the main project drivers. It will be achieved by innovation in component and sub-system design ; by later mass production; by eliminating land and water costs; by the use of reject heat for heating and/or cooling on-site; and by almost eliminating transmission costs;
- hybridisation with other fuels can be achieved in several ways. Most attractive is integration with gas-fuelled m-CHP, for which there are several options;
- reliability and durability will be ensured by the small scale, low profile design, by transferring lessons learnt in the large scale sector to the small scale sector and by the use of proven evacuated tube technology.

2.7 Overall efficiency

The overall efficiency, for a parabolic trough collector, is given by Eq. 1.

$$\eta = F_R\left[\eta_0 - U_L\left(\frac{T_i - T_a}{G_B C}\right)\right] \qquad (1)$$

Where F_R is the heat removal factor, η_0 is the collector optical efficiency, U_L is the solar collector overall heat loss [W/m^2K], T_i is the collector input temperature [K] and T_a is the ambient temperature [K], G_B is beam radiation and C is the collector concentration ratio.

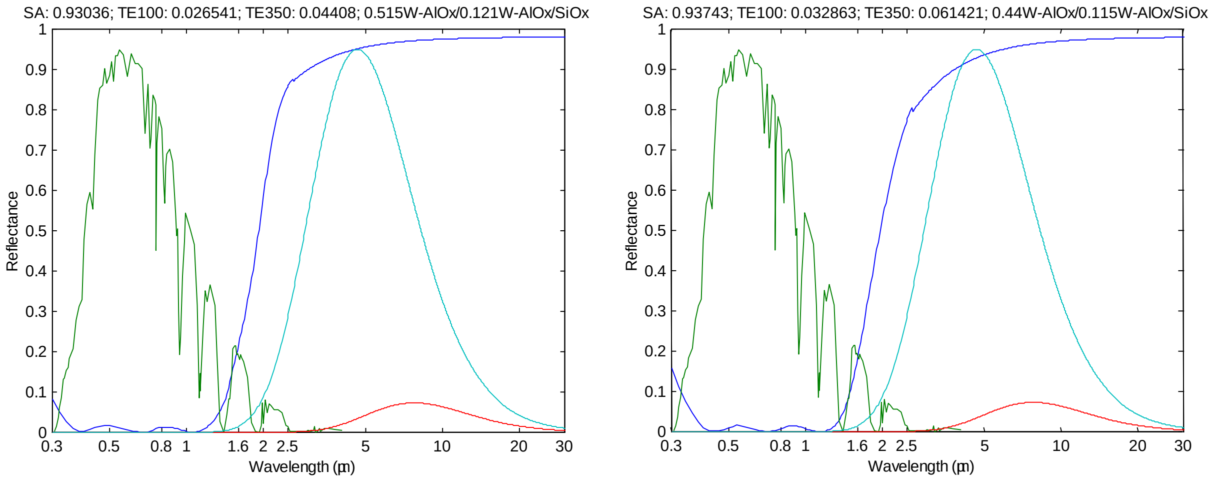
3. Results

On the starting development phases related to the project, some good results have already been achieved. Some details are yet under modelling and development. Indeed some results are presented on the main technological issues.

3.1 Selective absorber (Cer.Met. coating)

A theoretical modelling on sample candidates has been performed at Angstrom Laboratories in Uppsala University. The modelled results have provided indications on the best candidates.
From theoretical calculations using the commercial software SCOUT, it has been modelled a number of coatings. It has been used a Cer.Met. structure of three layers (two cermets and one antireflection) using the oxide matrix TiO2, SiO2, ZrO2 and Fe, Co, Ni, Y, Nb, Mo, W, Pt, Ce, Sm, Tb, Dy, Er, Tm, Yb as metal component. Also Al2O3 was modelled with Mo, W and Ni and Ta2O5 with W, Pt and Ta. One clear result is that the 4f-element cermets (en specifically Dy) showed in general a lower absorptance (for about the same emittance) compared to the 3 d – element cermets. Another systematic result is that TiO_2 as matrix gives a lower absorptance than SiO_2 and ZrO_2. However the differences are small, the best result for in the titaniumoxide group (Ce-TiO2) has absorptance/emittance 0.955/0.097 compared to the best result (0.964/0.096 for Y-ZrO_2 or 0.963/0.091 for Ta-SiO_2). The worst result of all modelled is 0.907/0.097 for Dy-ZrO_2. The limitation here has been a little higher in the emittance than set by the delivery condition. Lowering the emittance to the delivery of 0.06 gives a lower absorptance by 0.02 to 0.03 units. Two cermets have been modelled for the lower emittance than for W-Al_2O_3 0.937/0.06 and for W-Al_2O_3 0.935/0.05.
The candidates from the modelled group are: W-Al_2O_3, W-SiO_2 since W is proved to be relatively stable in temperature.

Figure 2. Two spectra of best Cer.Met. candidates from theoretical modelling (W-AlOx/SiOx)



3.2 Concentration optics

The system will be provided of a concentration ratio 40:1, and a single module will be 200 cm long, 40 cm wide and 20-25 cm high. Two or more modules can readily be combined. The evacuated solar tube, located on the focus, will have the selective absorber on a tube of 10 mm in diameter. A very thin glass mirror have been developed (< 1 mm) (compared to 4 mm in CSP trough collectors), shown in Figures 8-9, chemically treated to provide flexibility at ambient temperature, with a multi-layered structure of silver for reflection and protective coatings. In Fig. 1 it has been measured the mirror reflectivity, equal to about 0,95 and accounting for the overall mirror efficiency. In Fig. 2 is visible a first prototypal realization under manufacturing by a project partner (ELMA).

Figure 3. Reflectance spectrum from thin glass mirror

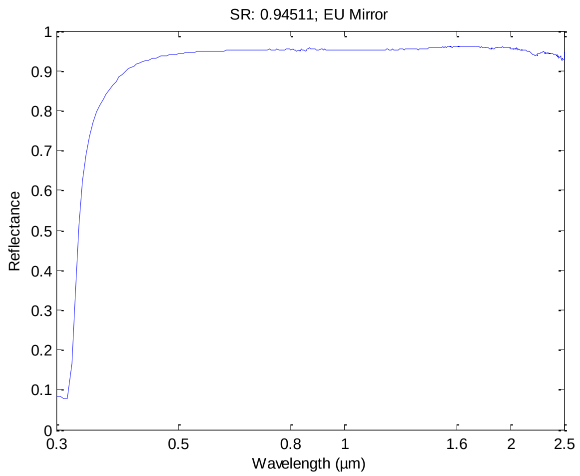


Figure 4. first prototypal realization of the optical system

3.3 Heat engines

Research will focus on solutions to the technical and cost problems that are delaying commercialisation of the Stirling engine, whether in m-CHP or other applications. The development phase will includes two separate engine solutions, and one solution to the heat exchanger problems, that will be used for both engines.

Figure 5. Modified valved Stirling cycle

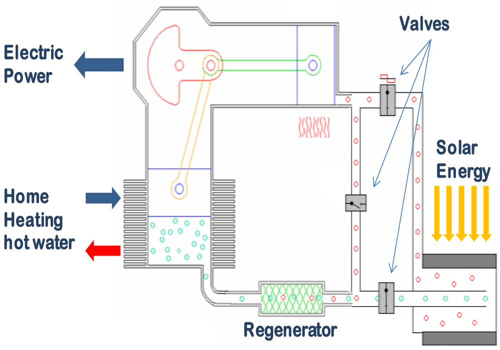
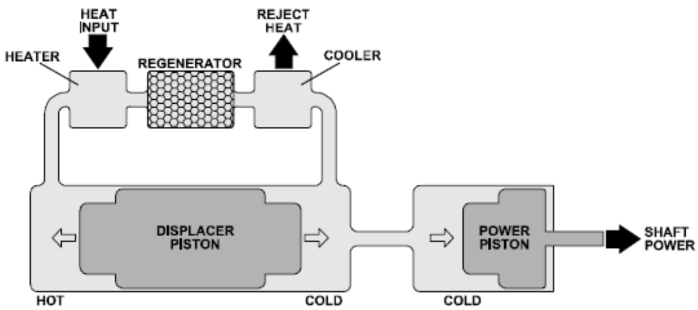


Figure 6. Rotary Scroll engine



FBK's "injection Stirling" (patent pending [2]) includes four main innovations.

Use of valves to increase power efficiency: the valves isolate compression and expansion volumes from the rest of the gas circuit, and eliminate work lost in compressing or expanding against back-pressure. They also allow the charge gas to by-pass the heater and cooler after expansion and compression respectively. This reduces the heat load on each heat exchanger and, as a result, reduces their size, internal volumes and costs. Valves have long been accepted as a method of approaching optimal thermodynamic cycle conditions, but the very high hot end temperatures (600-700oC) of combustion–based engines has prevented progress. The much lower temperatures (250-350oC) of solar m-CHP significantly reduce the design and materials constraints on valving.

Dead volume reduction while increasing heat exchange area: due to the separation between the hot source and the hot cylinder, there is the possibility to increase the heat exchange area while avoid increased dead volumes that would cause a lower engine efficiency.

Single working fluid: FBK will use a single working fluid with two functions: transfer of heat from solar collector to engine; and as the engine's working fluid. This eliminates the engine heater and further reduces costs.

Control on the thermodynamics of the cycle: by synchronizing the valves' functioning it will be possible for the engine to run at almost constant efficiency, even at times of relatively low solar radiation. This is achieved by adjusting the mass transfer rate to ensure constant temperature at the hot cylinder.

Another development will regard a new and compact scroll engine. In contrast to the Stirling engine, a heat engine based on mass-produced orbiting scroll compressor technology will have uni-directional, near-steady state charge gas flow (fig 2). This addresses issue (a): heat exchangers can be specified optimally for most of the cycle, and the anomalous heating and cooling can be eliminated.

Issue (b) is addressed by new manufacturing techniques for compact heat exchangers, that provide complete freedom of 3-D design and "build to shape" manufacture of complex, thin-walled, voided components. These allow the manufacture of very compact heat exchangers, with surface area densities of 20,000 m_2/m_3 or more (the Stirling heater is normally <1000 m_2/m_3), pure counterflow heat transfer, surface enhancement and varying duct cross-section, in high performance materials. Several functions (eg combustion air pre-heat, combustion, heating) can be incorporated in a single component. This helps to overcome the heat transfer imbalance across the heater tube walls, reduces costs, size, weight and materials use, and increases thermodynamic efficiency.

4. Conclusions

The presented work will come on concrete development phase on next months and a full first version working prototype will be realized by the half of 2011. Other developments will regards an enhanced thermal fluid, possibly realized integrating metal oxide nano particles and the evacuated solar tube.

Particularly the tubes are under modelling to define the better profile for the internal metal tube (coaxial or u-tube).

The actual work is part of a European Funded project, the best valued within the specific topic of CSP in the call FP-Energy-2009-1.

The impact strategy for such technology is addressed in four main issues: ***First*** is the contribution to "improvements in the optical and thermal efficiency of the solar components, power generation efficiency (including hybridization with other fuels), and operational reliability". *Second* is the scope for hybridization with other fuels. *Third* is a large reduction in capital and maintenance costs. ***Fourth*** is improvements in the environmental profile of CSP.

There are three additional impacts. *First* is the creation of a new and extremely large market for small scale CSP systems, down to the size of the individual household. *Second* is the application of the innovations, particularly in the engine, to other solar CSP applications. *Third* is the application of the engine innovations to non-solar carbon saving applications.

Finally ***DiGeSPo*** project will provide a new technology system, with the potential for an extremely high impact in the field of energy production from renewable sources.

5. References

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[2] As reported in Concentrated Solar Power (CSP) technical page on European Community website: http://ec.europa.eu/research/energy/nn/nn_rt/nn_rt_cs/article_1116_en.htm.

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