NOVEL m-CHP GENERATION FROM SMALL SCALE CONCENTRATED SOLAR POWER

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1. INTRODUCTION

The development of a new cogeneration system, based on a compact concentrated solar power is highly required both for industrial and distributed applications, realized compatibly with the market levelised energy cost (LEC) and with the overall objective to achieve in short medium term a grid parity. 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;
• high energy density Stirling engine 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 (~ 300 °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.

This paper will describe the first phases of development of the solar technology, where seven main partners from five European countries are collaborating.

![Fig. 1 - Schematic picture of the m-CHP system under development within DiGeSpo project](image)

2. METHODOLOGY

2.1 Multidisciplinary approach

The CSP m-CHP technology under development requires a multidisciplinary approach on a series of themes below described.

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 efficiency targets are absorptance greater than 0.93 and 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 12:1, a tracking system (both mechanical and electronic control components). The efficiency target is a reflectance higher than 0.93 and an impact factor higher than 0.93.

**Thermal fluid:** R&D on an enhanced 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.

**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 80% (heat to fluid/radiation to concentrator).

**Heat engine:** modeling, development and assessment of two novel engine options that will provide higher efficiencies than existing engines at the target temperatures. One is a high energy density Stirling engine, by Fondazione Bruno Kessler; 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 electrical efficiency of 20-22%.

2.2 System integration and Demonstration of the technology

Sub-components are integrated into complete formats suitable for initial prototype characterization, and compliant with later large scale industrial production. The final prototype will integrate sensors with the control system, to provide feedback and to control all security options.

A thermoregulation testing unit, also referred as “Centralina”, is in between the solar collectors and the engine (see Fig. 2). It’s capable to set a fixed temperature in the system, thanks to a PID controller, which regulate the rejection or insertion of heat power in the system. The main components are a water heat exchanger (FT-H), which is used to extract power during solar collector’s efficiency testing, and an electrical heater (RRE), which will be used for Stirling engine performance characterization and preheating purpose. The thermoregulation loop is driven by a magnetic seal pump (PRC-1), while the flow delivered to the system is set by a secondary pump (PRC-2), which rotation velocity is controlled with an inverter. This configuration allows a better control on the response of the system and avoid the risk of oil degradation.
To avoid the contact of hot oil with atmospheric air, which can lead to oxidation of the fluid starting at 70 °C, an open expansion tank is located upon the unit. The connecting leg act as a thermal insulator and the system is open to atmosphere and not pressurized. Temperature in the expansion tank is further controlled with a secondary water heat exchanger (FT-C), which is automatically activated if a temperature sensor is triggered. Total power is 14 kW for electrical heater and 25 kW for the cooler heat exchanger.

![Fig. 2 - thermoregulation unit layout (“Centralina”). The system is designed to test solar collector efficiency and engine performance up to 320 °C](image)

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

2.3 System modelling and qualification, energy balance and overall efficiency

The proposed technology is able to convert direct solar radiation into electrical and thermal energy. The energy flow has been characterized and the different energy conversions / transfers have been partly verified and partly theoretically confirmed.

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

\[ \eta = F_R \left[ \eta_0 - U_L \left( \frac{T_i - T_a}{g_0 C} \right) \right] \]  

(eq. 1)

Where \( F_R \) is the heat removal factor, \( \eta_0 \) is the collector optical efficiency, \( U_L \) is the solar collector overall heat loss [W/m²K], \( T_i \) is the collector input temperature [K] and \( T_a \) is the ambient temperature [K], \( g_0 \) is beam radiation and \( C \) is the collector concentration ratio.

The fluid dynamic of the overall system has been modelled and tested. The mass flow rate for the pump is calculated in relation to maximum thermal power at the input of the system. The solar field is composed by 4 units, each with four parabolas 2 x 0.4 m. The data used in the calculation are: \( I = 850 \text{ W/m}^2 \) (maximum direct solar radiation); \( A = 2 \cdot 0.4 \text{ m} = 0.8 \text{ m}^2 \) (parabola area); \( n = 16 \) (total number of parabolas); \( \approx 0.8 \) (maximum thermal efficiency expected for the solar collector @ 300 °C and 850 W/m²). During calculations the oil is assumed at 300 °C, with a density of 809 kg/m³ and specific heat capacity (\( C_p \)) of 2.51 kJ/kg·K. Maximum power transmitted to the fluid is calculate in a on conservative way, by assuming a perfect thermal efficiency for solar collectors, as indicated in Eq. 2:

\[ P_S = \eta_{optimal} \cdot I \cdot A \cdot n = 10.8 \text{ kW} \approx 11 \text{ kW} \]  

(Eq. 2)

This value can be used to select pump size, which must provide sufficient flow in order to control temperature rise inside the collectors. It is assumed that the flow is equally distributed on solar field, which is composed by 16 tube in parallel. Simulation on heat transfer phenomena shown that maximum bulk (345 °C) and film temperature (375 °C) is avoided (Solutia Inc., 2010) when a velocity of at least 0.4 m/s is imposed inside the collector tube (Fig. 7). This value correspond to a flow rate as from Eq. 3:

\[ \dot{m}_L = n \left( \frac{D_p}{2} \right)^2 \cdot \rho \cdot \pi \cdot n = 0.212 \text{ kg/s} = 15.8 \text{ l/min} \]  

(Eq. 3)

Temperature rise is calculate as reported in Eq. 4:

\[ \Delta T = \frac{P_S}{\dot{m}_L \cdot C_p} = \frac{11}{0.212 \cdot 2.57} = 20 \text{ °C} \]  

(Eq. 4)

Under such flow regime the oil in the solar field is heated from 300 °C to 320 °C. See Fig. 3 for temperature distribution in function of the inlet velocity and inlet temperature.

![Fig. 3 - Maximum bulk (blue dot) and film temperature (green dot) for the fluid in the solar collector, as a function of flow rate, solar irradiation and inlet temperature](image)

A lower temperature rise and film temperature can be achieved by increasing the flow rate. A flow rate of 32 l/min can reduce outlet temperature to 305 °C (see Eq. 5).
Simulation show that a minimum velocity should always be imposed inside the collector, in order to avoid losses in thermal efficiency for the solar collector (Fig. 4). The efficiency is reduced when velocity is below 0.1 m/s, which correspond to a flow rate of about 4.2 l/min (see Eq. 6).

\[ m_{\text{MIN}} = \pi \left( \frac{D_i}{2} \right)^2 \cdot v \cdot \rho \cdot n = 0.0556 \text{ kg/s} = 4.13 \text{ l/min} \]  
(Eq. 6)

The simulation program enable the analysis and prediction of the thermal behaviour of coaxial vacuum tubes under different working conditions. The software algorithms allow the realization of parametric studies, where various input variable (such as temperature fluid at inlet, solar irradiation, outside temperature and wind conditions) can be varied, in order to calculate the efficiency and find the optimal operational configuration. An example of the parameters taken in consideration is presented in Fig. 5.

On the extreme end of the hydraulic circuit, thermal energy enters a heat engine for energy cogeneration. The thermodynamic design of the cycle for the heat engine has used different tools in order to find the optimal parameters for main components of the engine, including pistons, the regenerator and heat exchanger. The starting point has been Schmidt analysis and the Beale number, from which qualitative parameters can be extracted.

\[ B_n = \frac{W_o}{P V F} \]  
(Eq. 7)

Where \( B_n \) is the Beale number, \( W_o \) is the power output of the engine [W], \( P \) is the mean average gas pressure [Bar], \( V \) is swept volume of the expansion space [m³], \( F \) is the engine cycle frequency [Hz].

Increasing the cycle efficiency has the disadvantages of increasing mechanical losses from friction, and leaves with the option of increasing instead the pressure. Other engines realized for medium temperature application are designed for low speeds (Cool Energy, Boulder CO), in order to achieve good efficiency and reduce mechanical losses. A low speed engine can also operate more quietly and with less noises. Initials parameters derived from the Beale number have been used to perform the iterative simulations based on such input parameter. It has been used a codex developed by Urieli and Berchowitz (Urieli and Berchowitz, 1984) to simulate the thermodynamic cycle. Those method results in sinusoidal varying temperatures in the working spaces, temperature drop between the compression space and cooler, temperature drop between the heater and the expansion space, non-constant working fluid temperatures over the cycle, and pressure losses across the cooler, regenerator, and heater, as shown in Fig. 6.
The energy flow, including all sub-components, from direct solar radiation to thermal and electrical energy generation, is reported in Fig. 7.

![Energy flow and efficiency loss/gain through the CSP modules and the thermodynamic cycle](image)

### 2.4 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.

- improving the efficiency of key components: 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 CO2 saving 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;
- employing new coatings and nano-technology: Cer.Met coatings on the absorber increase energy conversion efficiency;
- providing large reduction in both capital and maintenance costs: approaching the EU’s target of 6-9 cent/kWh 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;
- hybridization with other fuels such as integration with gas-fuelled m-CHP;
- 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.

### 3. RESULTS

Some good results have already been achieved. Some others are yet under development. Indeed some details are presented on the main innovation topics.

#### 3.1 Selective absorber (Cer.Met. coating) and evacuated solar tube

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 (Wackelgard et al., 2010).

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 Cer.Met. and one antireflection) using the oxide matrix TiO$_2$, SiO$_2$, ZrO$_2$ and some metallic component. Also Al$_2$O$_3$ was modelled with Mo, W and Ni and Ta$_2$O$_5$ with W, Pt and Ta.

![Two spectra of best Cer.Met. candidates from theoretical modelling (W-AlOx/SiOx)](image)

One result is that the 4f-element Cer.Met. showed in general a lower absorbance (for about the same emittance) compared to the 3d – elements. Another systematic result is that TiO$_2$ matrix gives a lower absorbance than SiO$_2$ and ZrO$_2$. However the differences are small, the best result for titanium oxide group (Ce-TiO$_2$) has absorbance/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-ZrO₂. Two Cer.Met. have been modelled for the lower emittance than for W-Al₂O₃ 0.937/0.06 and for W-Al₂O₃ 0.935/0.05.

Numerous solutions for the absorption pipes have been studied for the identification of the best candidate. Mathematics models have been used to find a good compromise. The first prototype will be a 12 mm (external diameter) coaxial coated tube, which will use a commercial absorption layer developed by ALMECO-TINOX (Figures 9 and Figure 10 below). The final prototype will either be an absorber made by stainless steel, with a molybdenum protection layer, coated with the Cer.Met identified by above indicated analysis.

**Fig. 9 - First series of coated tube from Tinox**

A proposed technology has been designed and realized for a first series of tests. Some of the main conclusions achieved include:

- Market analysis has shown a lack of products for concentrated receivers in the small -mid size range. The solution available on the market cannot reach good efficiencies at the indicated working conditions;
- The potential problem arising from thermal stress dilation and glass cracks has been resolved by the use of a coaxial tube (Mientkewitz G., Schaffrath W., 2010);
- A fundamental parameter for collector efficiency is the vacuum quality. Line losses arising from convection and conduction are greatly reduced with a level of vacuum below 0.02 Pa;
- For the first prototype a Cer.Met layer from ALMECO-TINOX is used. The second series of test tubes will have a molybdenum layer which will further limit the emissivity of the coating;
- The actual concentration ratio has been based on similar values obtained by similar medium to large scale technologies, so a scale factor has been applied both to the dimension of the optics and that of the receiver;
- The first tube will have a diameter of 12 mm.

**3.2 Concentration optics**

The system will be provided of a concentration ratio 12:1, and a single module will be 200 cm long, 40 cm wide and 20-25 cm high. Two or more modules can be combined. The evacuated solar tube, located on the focus, will have the selective absorber on a tube of 12 mm in diameter. A very thin glass mirror have been developed (< 1 mm), chemically treated to provide flexibility at ambient temperature, with a multi-layered structure of silver for reflection and protective coatings. The overall mirror reflectivity has been measured, the verified value is 0,954. In Fig. 11 are evidenced the 4 optical modules after manufacturing by a project partner (ELMA).

**Fig. 10 - Details from the first series of tube. The coating has been deposited directly on the stainless steel tube**

**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.

**Fig. 11 - first prototypal realization of the optical system**

**Fig. 12 - Engineering of a high energy density Stirling engine**
The first investigated solution in a new Stirling engine (Fig. 12), improved of latest available materials and technologies and with overall objective of realizing a high energy density, light weight, efficient engine. The thermodynamic cycle has been investigated and defined theoretically respect some border conditions set for the engine itself. The engine configures as a high pressure double acting Stirling. Peak power from the current solar field under realization is estimated to be 10 kW. The target efficiency for the cogeneration unit is 20 % in electrical conversion and 65 % in the overall efficiency (including thermal), which is recuperated as hot sanitary water for heating and domestic consumption. The load profile for a solar energy application has a typical non-constant curve, which should be followed by the engine. The heat power extracted by the engine should be adjustable, otherwise the fluid in the collectors is cooled/heated, and the source temperature is perturbed. The power can be reduced or increased by a factor of 2-3 by acting on the engine speed. Due to technological constrain, both on materials and fluid, the maximum temperature has been imposed to 320 °C. The cold sink is water for heating purpose, at temperatures in the range from 40 °C to 60 °C. The target mechanical output is 3 kW. The engine is required to be adjustable to lower nominal power, down to 1 kW, in order to be scalable with the input source, which is a function of the solar field dimensions. The nominal output power for the engine can be increased or reduced by a factor of 10 by managing the charge pressure. The heat exchangers has been optimized through a entropy minimization analytical model (Bejan A., 1996).

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. 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 (see Fig. 13 for example). These allow the manufacture of very compact heat exchangers, with surface area densities of 20,000 m²/m³ or more (the Stirling heater is normally <1000 m²/m³), pure counter flow heat transfer, surface enhancement and varying duct cross-section, in high performance materials. Several functions (i.e. 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.

3.4 Variable speed control

The Stirling (or Scroll) engine is provided and instrumented with all necessary on-boars sensors for the monitoring of performances, fault detection, identification and solution in real-time during operability. At the same time they’re required for the engine characterization and verification of the overall system efficiency, measure of the energy and mass balance through the engine itself. Main sensors included in the Stirling are pressure and temperature, mainly used for the characterization of the thermal cycle. Sensors are sampled through an A/D board, included of an encoder connected to the drive control (DS2000 by MOOG Industries), in feedback loop with the measures themselves. The engine provides also a three-phases power line from the integrated generator. The generator is a 48-pole, 3-phase alternator using permanent magnet (PM) excitation, nominally designed to operate at 480rpm, but rated for operation until 600 rpm. The electric power at the output has 500 VDC in open circuit, and 420 VDC at 7.15 A at full load, generating 3000W of nominal power. The drive control is used for the engine start-up, speed regulation and electrical power regeneration.

The Overspeed Protection Box is an additional and independent device included in the overall control system. The box is an additional safety tool in case of fault of the main drive DS2000, and for extreme faults out of the potential direct control of DS2000. It’s an electromechanical protection that brakes the engine and slow it down preventing major damages in case of load loss contemporarily to a fault status of DS2000. The objective of the Protection Box will be to maintain the engine below its maximum speed of 600 RPM.

DC load/Inverter has the purpose of conversion of direct voltage in alternate and deliver it to the grid. During the engine characterization the load for the Stirling engine is composed of a programmable electronic device, while during demonstration activities it will be replaced by an inverter for on-grid electrical generation.

During the monitoring, the control system will sample input information from the hot sided of the thermo – fluidic system until the power generation. The measure
of the thermal energy transferred by the thermal oil to the Stirling is in direct relationship with the rated output power from the Stirling engine itself. Specific temperature and flow sensors are included in the side of the thermal oil for the quantification of the energy balance. Similarly, on the cold side, the transferred heat is monitored to account the amount of energy from the Stirling (Scroll) engine to the hot water storage tank.

The PC/PLC control unit is used for the acquisition of the sensor measures and for the activation of relative commands, together with their elaboration and handling. The unit will be equipped with a PC user interface for interpretation of the measured values and for implementation of controls in automatic or in manual mode. All the measures are saved in a data logger for a post processing of sampled values. A complete description of the system is illustrated in Fig. 14.

![Fig. 14 - Architecture for the variable speed control of the engines](image)

### 4. CONCLUSIONS

The presented work will has started first tests and demonstration activities. On the next months full characterization of the proposed technology will be completed. Other developments will regards an enhanced thermal fluid, possibly realized integrating metal oxide nano particles and thermal oil used in the hydraulic circuit. The evacuated tubes will be integrated of a more performing Cer.Met. coating. The engines will be manufactured and characterized by the half of 2012.

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


