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Novel system for distributed energy generation from a small scale concentrated solar power

Luigi Crema[1,*], Fabrizio Alberti[1], Ewa Wackelgard[2], Barbara Rivolta[3], Sebastian Hesse[4], Lorenzo Luminari[5], Drummond Hislop[6], Brian Restall[7]

[1] Fondazione Bruno Kessler, REET Unit, Via alla Cascata 56/C, 38123 Trento, Italy

[2] Department of Engineering Sciences, Uppsala University, Uppsala, Sweden

[3] Department of Mechanics, Politecnico di Milano, Milano, Italy

[4] Narva Lichtquellen GmbH + CO; Brand-Erbisdorf, Germany

[5] El.Ma. Electronic Machining srl, Riva del Garda (TN), Italy

[6] Sustainable Engine Systems Ltd, London, UK

[7] Projects in Motion Ltd., Naxxar, Malta

* Corresponding author. Tel.: +39-0461-314922; fax: +39-0461-314930
E-mail address: crema@fbk.eu

Abstract

The present work describes 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. 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. This CSP m-CHP will provide electrical power, heating and cooling for single and multiple domestic dwellings and other small buildings.

The developed system 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. Some good results have already been achieved, while developments on several technology subcomponents will be finalized through first part of 2013.

Two Cer.Met. have been modelled, realized and tested. The up scaled receiver, in form of Cer.Met. coating based on TiO2 – Nb, has been confirmed an absorptance of 0.94 and emittance of 0.1 (@350°C). A second Cer.Met. coating based on SiO2 – W has demonstrated an absorptance of 0.93 and emittance of

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0.09 (@350°C). A full-evacuated solar tube has been designed and realized, with absorber of 12 mm in diameter and length in 2 meters.

The system is provided of a concentration ratio 12:1, and a single module is 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, has the selective absorber on a tube of 12 mm in diameter. A very thin glass mirror has been developed (< 1 mm). The overall mirror reflectivity has been measured, the verified value is 0,954.

Research has proposed a high energy density, double acting Stirling engine, provided of innovative heat exchangers realized through Selective Laser Melting process. The engine is a low speed (250 RPM), high pressure (130 Bars) and compact solution able to be run at 300°C and generate 3,5 kW nominal power.

The solar technology has actually entered the proof-of-concept stage. A solar plant has been installed in Malta, by Arrow Pharm company, supplying the industrial process of generated steam at 180°C and 3.5 absolute pressure. The solar collector's efficiency is close to 47% in presence of 900 W/m2 of direct solar radiation.

During 2013, solar evacuated tubes with innovative Cer.Met. coating, together with new thin glass mirrors will upgrade the demonstration site, together with a new and innovative low temperature difference and high energy density Stirling. By end-2013, the system will be demonstrated, with the overall objective to achieve a minimum of 65% in solar collectors' efficiency at 300°C, and 12 – 15% of overall electrical efficiency by the Stirling cycle.

The actual work is part of a FP7 European Funded project, DIGESPO [1].

Keywords: small scale csp, micro combined heat and power, distributed energy generation

1. Introduction

Distributed energy generation is a strategic topic for next generation energy society. Its importance is outlined in several scientific, societal, politic and economic surveys and papers. Above all, it is indicated as a major topic by the European Technology Platform Smart Grids in the Strategic Research Agenda 2020. An essential contribution to distributed energy generation comes from domestic applications.

The actual marketable solar systems for domestic and distributed applications (PV and Solar thermal) suffer indeed 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).

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 behavior 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 (~ 320 °C) from the new CSP collectors;
- 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 such m-CHP solar technology, which integrates a cooperation between seven main partners distributed along five European countries.

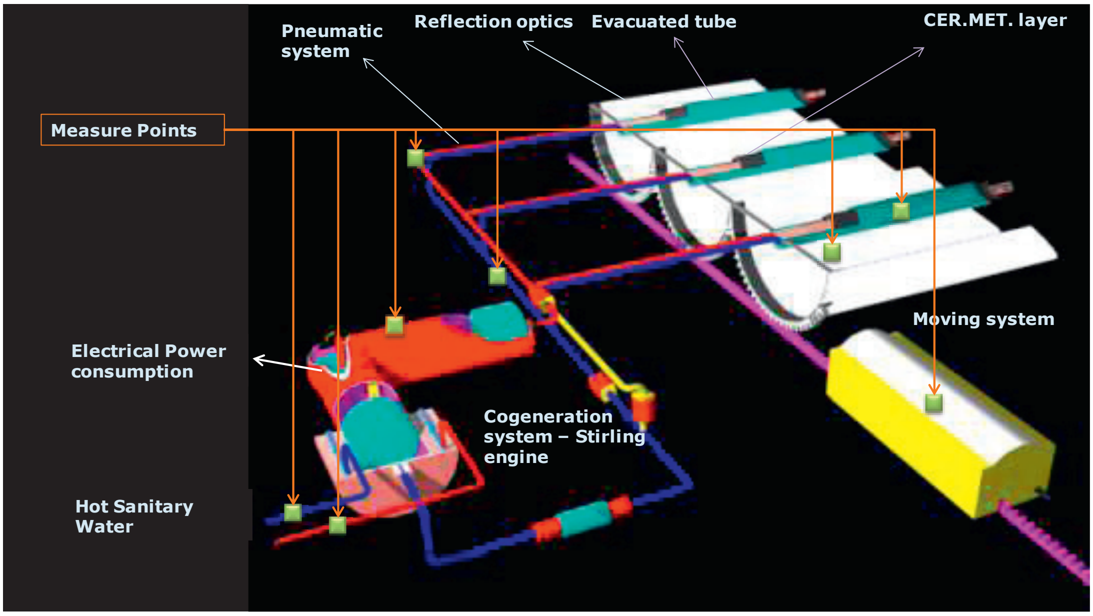

Fig. 1: Schematic picture of the m-CHP system under development within DiGeSPo project

2. Innovation outline and motivation

2.1 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 minimize solar re-radiation back to atmosphere. At the same time to increase the conversion efficiency at temperatures up to 250-350°C. The absorber target performance are absorbance greater than 0.93 and emittance smaller than 0.06.

Concentration optics and tracking system: modeling 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 (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 maximizes 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: Modeling and optimization 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, based on a pre-engineering realized 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 conversion efficiency for the engine/generator of 20-22%, with air-cooling if required.

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, commercial impact on the market and prescribed standards. A test bench has been equipped with sensors to measure performance parameters. The final prototype will integrate sensors with the control system, to provide feedback and to control all security options. All the sensors have been chosen in order to meet the precision requirement defined by the UNI EN 12975-22006 standard, which is the guideline for efficiency testing and certification of solar collectors.

A first thermoregulation unit, also referred as “Steam Centralina”, is the system installed by the demonstration site, properly designed for the steam generation from solar thermal power system. It is capable to set a fixed temperature, 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, which is used to generate steam by thermal power transferred by the thermal oil, an electrical heater, which will be used mainly during start-up of the system to reduce viscosity of the mineral oil. A magnetic seal pump drives the thermoregulation loop.

A second thermoregulation unit, also referred as “m-CHP Centralina”, is the system designed to decouple the testing for the solar collector and the engine (see Fig. 2). It is capable to set a fixed temperature in the system, as the previously described unit. 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. A magnetic seal pump (PRC-1) drives the thermoregulation loop, while a secondary pump (PRC-2), which rotation velocity is controlled with an inverter, sets the flow delivered to the system. 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. In the expansion tank, a secondary water heat exchanger (FT-C) controls the temperature. This 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.

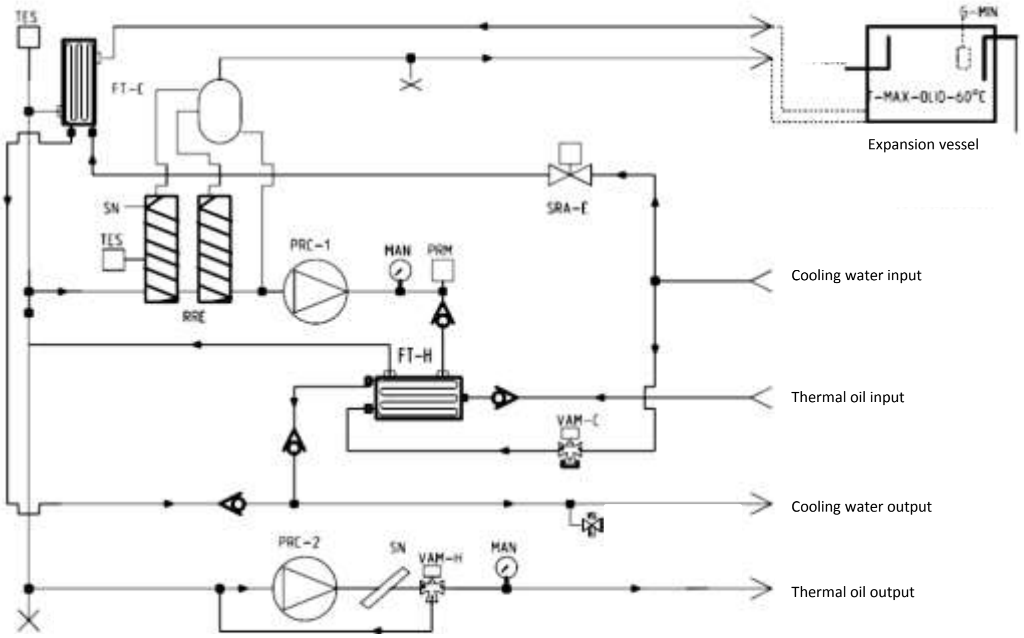

Fig. 2: thermoregulation unit layout ("Centralina"). The system is designed to test solar collector efficiency and engine performance up to 320 °C

The demonstration of the technology has started in a high impact and visibility location in the middle of the Mediterranean area (ArrowPharma Ltd. 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 CO2 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€/kWh$_e$ by 2020 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 can be achieved in several ways. Most attractive is integration with gas-fuelled m-CHP, for which there are several options;
- the small scale will ensure reliability and durability, 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.

3. Results

At the present stage of the project, some promising outputs have already been achieved. Hereafter some results are presented on main technological issues.

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 [2].

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 Fe, Co, Ni, Y, Nb, Mo, W, Pt, Ce, Sm, Tb, Dy, Er, Tm, Yb as metal component. In addition, Al_2O_3 was modelled with Mo, W, Ni, and Ta_2O_5 with W, Pt and Ta.

One clear result is that the 4f-element Cer.Met. (e.g. specifically Dy) showed in general a lower absorbance (for about the same emittance) compared to the 3 d – element Cer.Met. Another systematic result is that TiO_2 as matrix gives a lower absorbance than SiO_2 and ZrO_2. However the differences are small, the best result for in the titanium oxide group (Ce-TiO2) 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-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 absorbance by 0.02 to 0.03 units. Two Cer.Met. 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 best candidates from the modelled group are: W-Al_2O_3, W-SiO_2 since W is proven to maintain stable performances at high temperatures.

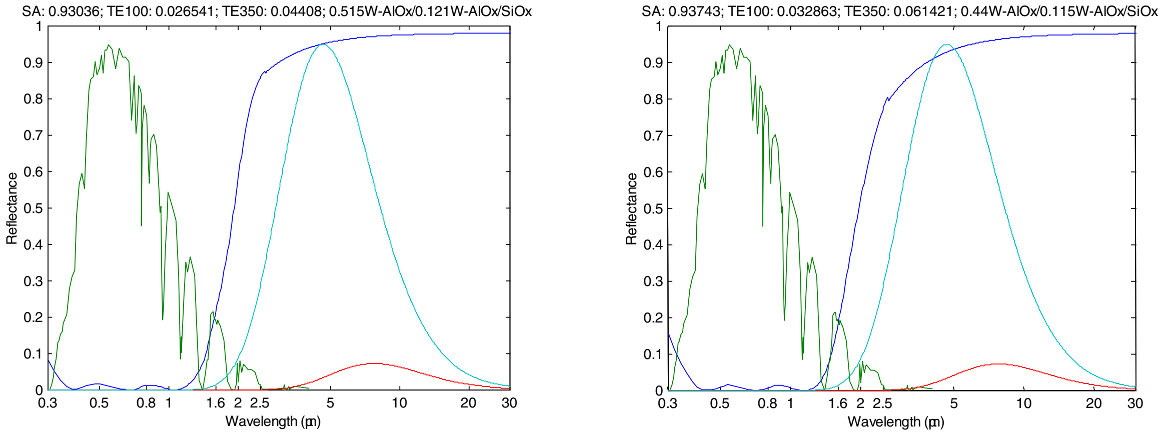

Fig. 3: Two spectra of best Cer.Met. candidates from theoretical modelling (W-AlOx/SiOx)

Numerous solutions for the absorption pipes studied are possible since the absorption pipe is a compromise between achieving different operational requirements. Numeric models have been used to find a good compromise since they provide the possibility to calculate the essential output parameters in relation to the input parameters. The first prototype was a 12 mm (external diameter) coaxial-coated tube, which will use a commercial absorption layer (Figures 4 and Figure 5 below). Finally, an absorber pipe made from stainless steel had been realized, with a molybdenum protection layer, coated with the best Cer.Met identified and developed by above analysis.

Fig. 4: 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:

- The potential problem arising from thermal stress dilation and glass cracks has been resolved by the use of a coaxial tube [3];

Fig. 5: a) Details from the first series of tube. b) The coating has been deposited directly on the stainless steel tube

- Line losses arising from convection and conduction are greatly reduced with a level of vacuum below 0.02 Pa. This feature has been experimentally tested and proven;
- For the first prototype, a Cer.Met layer from ALMECO-TINOX is used. The second series of test tubes have a molybdenum layer, which will further limit the emissivity of the coating. Final measured performances are transmittance 0.94 and emissivity 0.06 @ 350°C.

3.2 Concentration optics

The system is 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, has the selective absorber on a tube of 12 mm in diameter. A very thin glass mirror has 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 Figure 6 are evidenced the 4 optical modules.

Fig. 6: 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 included two separate engine solutions, and one solution to the heat exchanger problems, that will be used for both engines.

Fig. 7: Engineering of a high energy density Stirling engine

Fig. 8: Photo of the High Energy Density Stirling engine proposed by FBK

The investigated solution in a new ***Stirling engine*** (Figure 7 and 8), improved of latest available materials and technologies and 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 [4].

3.4 Demonstration activities

Demonstration activities has started in Malta on July 20th, 2012. The demonstration plant, in its first version, is composed of 16 vacuum tubes provided of the new design and coated of Almeco-Tinox standard TiAlN coating. 16 parabolic trough are realized integrating Alanod aluminum mirrors and the overall system is controlled in 1 axis tracking mode (azimuth). Therminol 66 is the thermal fluid and the first described thermoregulation unit is connected to the solar plant generating steam (2,5 Bars at 160°C) for Arrow Pharm plant. The system is provided of a remote control system, able to properly manage all subcomponents and run the plant in automatic or manual mode. Figure 9 illustrates main sampled parameters.

Best efficiency provided by the solar system has been 47% at 200°C and direct solar radiation of 880 W/m².

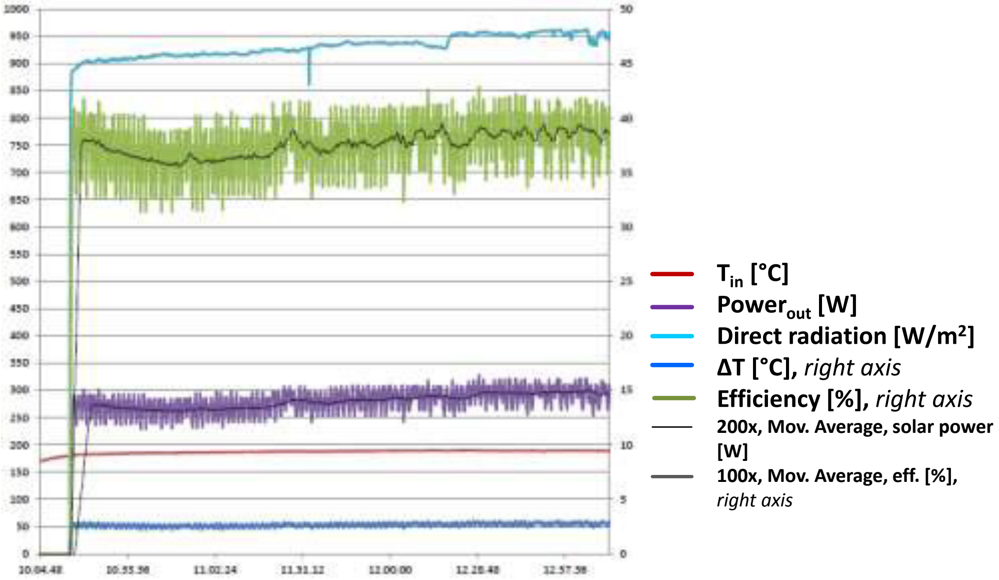

Fig. 9: Sample data and trend lines from the demonstration plant in Malta

In Figure 10, photos of the demonstration site are reported.

Fig. 10: View of the demonstration site in Malta, installed by Arrow Pharma company

4. Conclusions

The presented work has started first tests and demonstration activities during July 2012. The evacuated tubes has been integrated of a more performing Cer.Met. coating. The engine has been manufactured and it is under testing. On the next months, full characterization of the proposed technology will be completed.

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.

5. References

[1] DiGeSPo project (2011) "Distributed generation from a small size concentrated solar power". http://www.digespo.eu/ , last accessed 10.08.12;

[2] Wackelgard at al, (2010). "New development of spectrality selective Solar absorbing coating for low and intermediate temperature applications". World Renewable Energy Congress 11, September 2010, Abu Dhabi;

[3] Mientkewitz, G. Schaffrath, W., NARVA (2010). Solarabsorberrohr. Patentanmeldung, 21.10.10;

[4] Bejan A. , (1996), "Entropy generation minimization: The new thermodynamics of finite-size devices and finite-time processes". J. Appl. Phys. 79 (3), 1191 – 1218.