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The POLYPHEM Project: An Innovative Small-Scale Solar Thermal Combined Cycle

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Abstract. The POLYPHEM project is a research and innovation action funded by the European Union's H2020 program. The project started in April 2018 and will end in March 2022. It is implemented by a European consortium of 4 research centers and 5 industrial partners. The aim of this project is both to increase the flexibility and improve the performance of small solar tower power plants. The POLYPHEM concept consists in implementing a combined cycle formed by a solarized micro gas-turbine and a Rankine organic cycle machine, with an integrated thermal storage device between the two cycles. The need for cooling is minimal. Developed from a technology already patented by CNRS and CEA, the pressurized air solar receiver is integrated in the micro-turbine cycle. The thermal efficiency targeted for the receiver is 80% with a cost of 400 €/kW. The innovative thermal storage uses thermal oil and a single thermocline tank with a technical concrete filler material. The main expected impact of this project is to enhance the competitiveness of low-carbon energy production systems through the technology developed. The expected progress is a better fitting of electricity generation to variable local needs and an overall conversion efficiency of solar energy into electricity of 18% for an investment cost of less than 5 €/W with low environmental impact. By 2030, the cost of electricity production targeted by the POLYPHEM technology is 165 €/MWh for an annual direct normal irradiation of 2600 kWh/m^2/year (North Africa and Middle East) and 209 €/MWh under 2050 kWh/m^2/year (Southern Europe). In addition to decentralized power generation, other applications are considered for the deployment of this technology used in poly-generation: industrial heat production, solar heating and cooling, desalination of seawater or brackish water. A prototype plant of 60 kW$_{el}$ with a thermal storage of 1300 kWh is designed, built and installed on the site of the experimental solar tower of Themis in Targasonne (France). The objective of the project is to validate the technical choices under test conditions representative of actual operating conditions.

THE CONCEPT OF POLYPHEM

As described in Fig.1, the overall concept underpinning the POLYPHEM project is to bridge together two thermodynamic cycles with an intermediate storage system to make a combined cycle with unique flexibility. In this way, three innovative ideas bear the POLYPHEM concept:

- Coupling a small-scale organic Rankine cycle (ORC) with an open Brayton cycle (µGT) to make a novel kind of combined cycle.
- Integrating a low-cost thermal energy storage (TES) between both cycles.

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- Integrating a high temperature solar receiver in the top cycle.

The resulting concept is a solar-driven combined cycle featuring a small-scale CSP plant of next generation. Competing technologies featuring steam cycles are not suited for small scale power generation with high conversion efficiency and limited water consumption. Five technology bricks are integrated to form the complete system: the solar field and tower, the hybrid solar micro gas-turbine, the thermal energy storage system, the organic Rankine cycle and the control and regulation system.

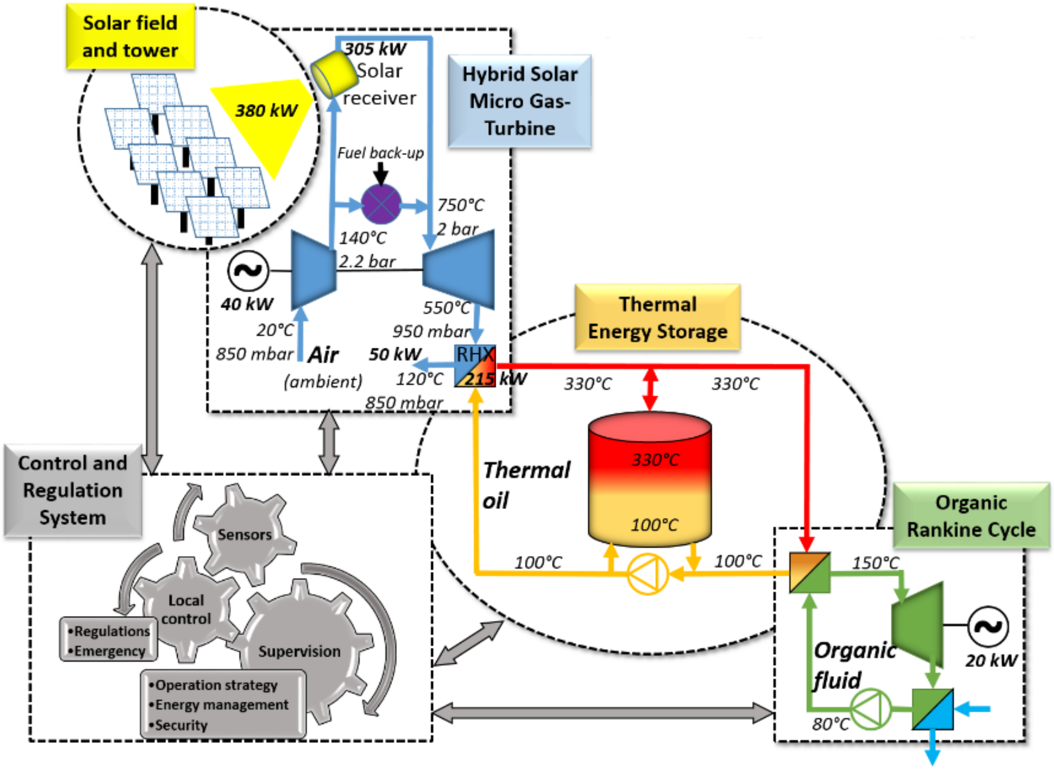

FIGURE 1. The POLYPHEM overall concept

Solar Field and Tower

In small-scale CSP plants currently in operation solar heat is produced by a line focus concentrating technology, parabolic trough (PT) or linear Fresnel (LFR). These optical components are modular and reliable, but they face limitations of low concentration ratio and low optical efficiency (100 suns, <55%). An alternative highly efficient concentrating system is the single parabolic dish. This latter, taken at its maximum size of 500 m^2, like the SG4 Big Dish developed by the Australian National University [1], offers optical performance (83.1%) higher than that of a small tower. However, such a large dish is 24% more expensive than a solar tower [2] and the complex design and operation of the µGT that would result from the moving focal area attached to the parabolic mirror is a great limitation of this technology for small CSP plants with integrated storage.

The solar tower technology offers a high optical efficiency (>60%). It totals 1 GW of installed capacity worldwide with large utility-scale CSP units. POLYPHEM is based on the utilization of a solar tower with a small solar field of about 700 m^2. Downscaling the solar field to 700 m^2 and the tower to about 20 m increases the concentration and the efficiency (>70%). Small solar tower technology is being currently studied at different research institutions. CSIRO, CENER and CyI have demonstrated that reducing the size of the heliostats allows significant potential of cost reduction [3]. CENER and Tekniker have developed a cost-effective small heliostat in the EU H2020 project CAPTure [4] illustrated in Fig.2-a. In this latter, several small towers are installed, a solar-driven micro gas-turbine is implemented in each tower and the heat rejected at each engine exhaust is collected in a single thermal storage unit. This option will be considered for scaling-up the POLYPHEM concept in the MW range. IMDEA has designed an ultra-modular 500 m^2 heliostat field [5] illustrated in Fig.2-b. Other concepts of small heliostats have been recently developed worldwide, like the self-calibrating 1.4 m^2 heliostat proposed by the company e-Solar [6] and the Helio100 project of the Stellenbosch University [7] illustrated in Fig.2-c. The optimized height of the tower needed for the development of POLYPHEM at industrial scale is about 20 m. Pylons designed for wind energy systems serve as reference for small solar towers.

(a) Cost effective heliostat (Courtesy of Cener &Tekniker)

(b) Small heliostat of IMDEA (Courtesy of IMDEA & RioGlass)

© Helio100 solar facility (Courtesy of Stellenbosch Univ.)

FIGURE 2. Examples of small-scale heliostat fields and downsized heliostats under development

The prototype plant of POLYPHEM will be installed and tested in the solar tower experimental platform Themis in France (42°30'05.62" N, 1°58'27.72" E, elev. 1665 m). This platform features a heliostat field of 5800 m^2 and a 100 m tower, under an average DNI in the range 1700 – 2000 kWh/m^2/y (see Fig.3). This research facility operated by CNRS provides concentrated solar beam in the range 100 – 600 kW/m^2 for power up to 4000 kW, far above the requirement of POLYPHEM.

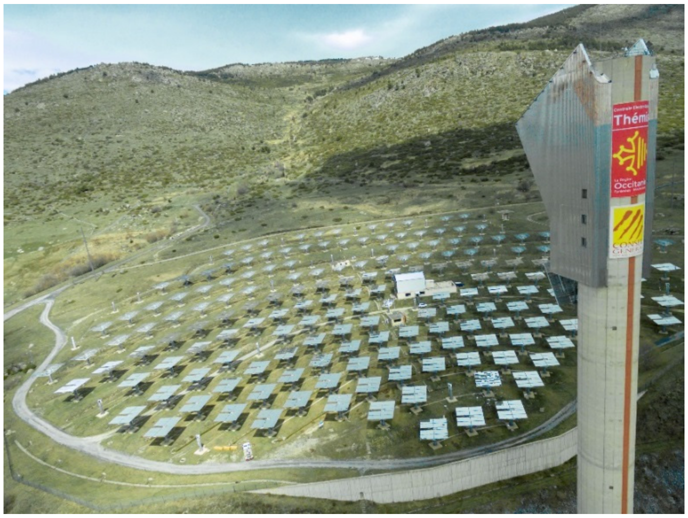

FIGURE 3. Solar tower experimental platform Themis, France (photo credit: CNRS)

Hybrid Solar Gas-Turbine: High Temperature Compressed Air Solar Receiver Integrated into the Gas Cycle

The integration of a solar receiver into an air Brayton thermodynamic cycle has been envisaged through research projects intended to develop the so-called "Hybrid Solar Gas-Turbine" (HSGT) technology for CSP plants from small-scale [230 kW in SOLGATE project, 2001-2003, and 100 kW in SOLHYCO project, 2006-2010] to medium-scale [5 MW in SOLUGAS project, 2010-2014]. Although the high conversion efficiency and potential cost competitiveness of these technologies has been demonstrated by simulation works [8], the limitation for market penetration is the high construction cost and the absence of storage. HSGT technology for small-scale power generation is still under development through current projects by research institutions [SUNDISC, University of Stellenbosch, South-Africa] or by industry [WILSON-247, Wilson Solar Power, USA]. The SUNDISC concept implements a dual pressure solar receiver (Hybrid Pressurized Atmospheric Receiver) and a thermal energy storage unit with atmospheric air and rock bed [9]. An air/water steam generator completes the concept to drive the bottom steam Rankine cycle. The WILSON-247 concept features a recuperated micro gas-turbine and a low-pressure volumetric solar receiver that reheats the exhaust gas which is used as heat source in the recuperator. A packed bed and low-pressure thermal storage unit allows for increased collection of solar energy in the receiver and a continuous power generation is claimed [10, 11]. The concepts proposed need to be proven with experimental works.

Several works have been done for modelling and predicting the expected performances of various configurations of hybrid solar combined cycle power plants [12, 13]. All these works consider utility-scale power plants. The concept of Brayton-ORC combined cycle with a high temperature thermal storage integrated to the topping Brayton cycle has been considered in simulation works [14]. The authors predict the best annual power block efficiency for this configuration (46.1%) when compared to other ones. The experimental validation of these complex concepts is still pending.

The concept of POLYHEM implements the HSGT technology in which the conventional fuel is substituted by solar energy in the gas-turbine (air Brayton cycle) through the integration of the solar receiver in the gas cycle. The solar receiver is cooled by the pressurized air. Its development addresses many issues: material issues resulting from the high temperature, fluid distribution issues linked to the compact shape and complex design, fluid flow issues related to the pressure drop and heat transfer issues to get a high efficiency. CEA and CNRS have recently collaborated on the development of advanced high temperature pressurized air solar receivers [15, 16]. The core technology developed is a bundle of thin Nickel-based alloy tubes (diameter <8 mm) arranged in parallel rows and embedded into a highly conductive material (Copper alloy). An external thin plate of Nickel-based alloy prevents oxidation and corrosion of the Cu-alloy (Fig. 4). The assembly of metallic materials by hot isostatic pressure technics has been proven and mock-ups of absorber modules have been successfully tested [17].

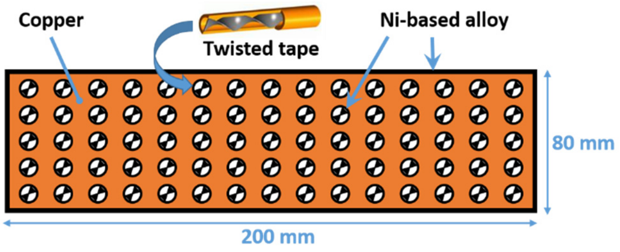

FIGURE 4. Cross-section of solar absorber module

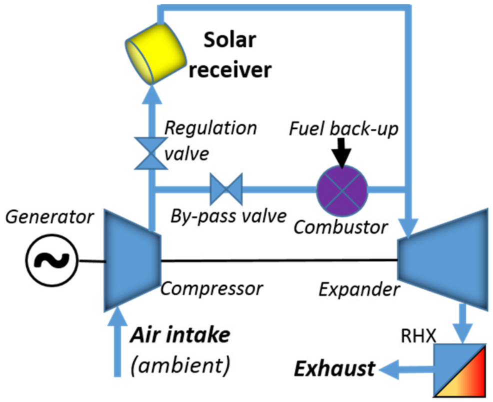

FIGURE 5. Hybrid solar configuration of the µ-GT in POLYPHEM

The R&D on the solar receiver in POLYPHEM project will focus on scaling-up this concept to achieve the design of a cost effective real-size receiver (380 kW, 80% efficiency and cost target 0.4 €/W) incorporating optimized manifolds to reduce the pressure drops. The design of the receiver will be optimized to meet the specific and demanding requirements of the project in terms of temperature range – air temperature increases from 140°C at the inlet up to 750°C at the outlet- and thermal cycling. The modular approach proposed in POLYPHEM properly addresses the issue of thermomechanical stresses and achieves elevated thermal performance [18].

The top cycle of the prototype plant will use the micro gas-turbine Garett GT30-67. Fresh air is sucked from the outside at atmospheric pressure and it is compressed up to 3.5 times (compression ratio) by the compressor which rotates on the same shaft as the expander turbine. In a conventional gas-turbine the combustor heats the compressed air up to the turbine inlet temperature by burning a standard fossil fuel. In the POLYPHEM hybrid concept (Fig.5), the air issued from the compressor stage will be directed to the solar receiver where it will be heated by solar energy. The hot air at high pressure will then return back to the expander (turbine) where power is generated on the shaft. The exhaust gas (air mixed with combustion products) are released from the turbine at high temperature (>500°C) and atmospheric pressure. In POLYPHEM the combustor of the gas-turbine will be conserved in parallel to the solar receiver (e.g. by-pass configuration) for the needs of start-up and for other purposes like full load operation in hybrid mode. Former research projects brought the solarisation of other gas-turbines to the experimental proof of concept [SOLGATE, EU-FP5, 2001-2003] and to the validation in lab [SOLHYCO, EU-FP6, 2006-2010]. However the modifications needed are specific to the technology of the engine and to the technology of the solar receiver. Both components will be installed in the focal area at the top of the tower in order to minimize the pressure loss -by reducing the length of tubing- and the dead volume of air. KAEFER has already worked on the Garett GT30-67 and masters its technology. The recovery heat exchanger (RHX) is attached to this brick and is interfaced with the thermal energy storage brick. This key component bears an important idea of the concept which is the heat recovery at the exhaust of the gas-turbine and the transfer of the recovered solar heat to the next step of the conversion chain: the thermal storage. The RHX will be tailored to match the high temperature on the gas side (550°C – 180°C) and the temperature of the storage fluid (100°C - 330°C). The pressure drop in the gas will be low (<5%) so the efficiency of the turbine will remain high. A recuperated solarized gas-turbine would certainly provide a higher conversion efficiency but without storage no flexible power generation would be available in this case.

Thermal Energy Storage: Thermocline with Oil and Concrete Filler

The two engines making the combined cycle operate at different temperature ranges: 750°C and more for the gas-turbine and less than 140°C for the ORC. The thermal energy storage (TES) system interfaces with both engines. It must match both temperature ranges and offer a storage capacity of 1300 kWh. Moreover, the POLYPHEM concept seeks for inexpensive technology. The proposed solution is to use a liquid heat transfer fluid (HTF) stored in a single tank under a thermal stratification mode (thermocline). A solid filler material inside the tank allows for reduced amount of HTF and for almost constant thickness of the temperature gradient zone. Thermal oil working at atmospheric pressure combines the good heat transfer properties and ease of use offered by many liquids with the low requirement for the non-pressurized tank. The R&D work about the thermal storage in POLYPHEM is presented into more details by E. Rojas et al. in [19]. Thermal oil suited for application in the range of temperature considered in the POLYPHEM project has been successfully tested by CNRS [20]. CIEMAT and CEA have already engaged collaborations on thermal models applied to such storage systems [21] and have tested them at prototype scale in the range 150 kWh to 2 MWh [22]. The extended utilization of concrete as filler material and as construction material will be promoted in POLYPHEM in order to achieve low cost target for the TES. A concrete tank erected on insulating concrete foundations is the preferred option to pave the way for large capacity storage tanks. ARRAELA has dedicated substantial efforts to develop various concrete grades suited for high temperature applications and has enlarged the structural role of concrete materials to include a thermal role, either as storage or insulating media. Both thermal energy storage tank and ORC engine will be installed at the bottom of the tower.

Organic Rankine Cycle

The ORC plays an essential role in the concept: it produces power in a flexible mode and it imposes boundary conditions to the TES through the heat exchanger oil/organic fluid. The main advantage of ORC is the elevated temperature of the condenser which allows for a simple and low-cost dry cooling system. Another remarkable feature is the constant conversion efficiency of the ORC when it is operated at full load or part load. The flexibility is therefore improved without decreasing efficiency. The small-scale ORC considered in the project is suited for reusing lost thermal energy rejected at low temperature by industrial processes. The integration of such an engine in the POLYPHEM concept needs to adapt the heat exchanger for the energy input to properly interface with the thermal storage discharging circuit.

Control and Regulation

The control and regulation system of POLYPHEM is transverse to the other bricks. It is entirely specific to the project and needs a complete development to embrace all the aspects of the operation and to organize them into a consistent and efficient tool. The solar field, the solar receiver, the gas-turbine, the thermal storage system and the organic Rankine cycle engine need a local control and regulation suited for each of these individual components. The integration of these components in the hybrid solar combined cycle configuration needs a high level of control and regulation which will assure the operation of the overall POLYPHEM system in transient modes and flexible power generation scenario. For example, the regulation of the turbine inlet temperature (TIT) in various operation modes is critical to adequately balance the load on the generator. The flame-out must be carefully prevented, the start-up of the engine should be in fuel-only mode and the transition to solar-only or hybrid solar mode must be covered by the control system.

Cost and Efficiency Targets

The cost and efficiency targets of the main components are indicated in Table 1 below.

TABLE 1. Cost and efficiency targets of the main components of Polyphem prototype plant

Component	Efficiency target	Cost target
Solar field	0.8	100 €/m^2
Solar receiver	0.8	400 €/kW$_{th}$
Solarized micro gas-turbine	0.2	1500 €/kW$_{el}$
Organic Rankine cycle	0.08	2500 €/kW$_{el}$
Thermal energy storage	-	28 €/kWh

METHODOLOGY

The POLYPHEM project approach consists in four main topics related to specific work packages of the work plan:

- Research to improve the performances by modelling and by carrying out experimental work on key components such as the pressurized air solar receiver, the recovery heat exchanger and the thermal energy storage. This step includes the modelling and numerical simulation of fluid dynamics, heat transfers, thermodynamic cycles, as well as the experimental measurements at laboratory scale. Research work will also assess the environmental impact of these innovative components from the early stage.
- Integration of the sub-systems to form the complete solar-to-electric conversion chain. The layout will be optimized to meet the requirements of various applications.
- Manufacturing of the components, engineering and construction of the prototype plant, implementation at the Themis solar tower facility.
- Testing and validation of the feasibility of manufacturing, validation of the operation in realistic solar conditions and determination of the appropriate range of operation strategies.

In addition, cross-cutting activities are carried out in other specific work packages:

- Modelling and performance assessment of the system, including the development of optimization tool and life cycle assessment. The overall system will be modelled to estimate the cost of electricity.
- Assessment of the deployment of the demonstrated and qualified technology in appropriate markets and areas
- Communication, dissemination and exploitation of the results.
- Management and coordination of the project.

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