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Lesson Learned During the Designing and Construction Phases of the ORC-PLUS Thermal Energy Storage System of 20 MWh

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Abstract. A limitation to the expansion of medium sized Concentrating Solar Power (CSP) plants is represented by the lack of technical solutions of Thermal Energy Storage (TES) systems specialized for this size of CSP plants and validated in a relevant industrial environment. In order to make the medium sized CSP systems more competitive than PV systems, the TES system has to allow the operators of the solar power plant to adjust the electricity production for matching consumer demand, so enabling the sale of electricity during peak demand periods for boosting plant revenues. At the same time, there is the need of lowering the TES system weight in the capital costs of the overall system. The ORC-PLUS (Organic Rankine Cycle - Prototype Link to Storage Unit) Project aims to realize a demonstrator of a TES system optimized for a medium sized CSP plant coupled with an ORC (Organic Rankine Cycle) turbine of 1 MWe. In this paper, the difficulties encountered during the manufacturing and commissioning operations of the TES system and their potential impact on capital costs will be reported.

INTRODUCTION

The deregulation of the electric power generation market and the currently evolution of the environmental regulations inspire the next development of distributed utilities close to local power loads. This trend will allow to reduce the oversizing of the power grid and the costs of the transmission and distribution of the electric power. In this frame the Concentrating Solar Power (CSP) plants of few Megawatts, coupled with advanced TES systems, will play an important role since they have all the characteristics to closely track both demand and potential growth in local electrical power loads; in addition, respect at other systems, they can be easily integrated in local district heating.

It is for these reasons that, in the last years, has been evaluated the possibility to employ the Organic Ranking Cycle (ORC) systems as heat engines to produce electric energy in little CSP applications. The ORC systems are a good technological option because they are characterized by a high reliability and the possibility to implement the system with remote control. However, one of the major technical limits in the diffusion of the ORC systems in the

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sector of the CSP application is represented by their low operative temperatures of work. This limit requires the development of TES systems with different characteristics from those employed in the large CSP plants, where it is possible to reach higher operative temperatures.

In this frame, the H2020 ORC-PLUS Project aims to develop at pilot level an innovative TES system able to extend the power production of an existing solar thermal power plant in Benguerir (Morocco), by using the linear Fresnel collectors technology as solar field and an ORC turbine with a rated output of 1 MWel as power unit. The Heat Transfer Fluid (HTF) used by the existing CSP plant is an environmentally friendly mineral oil working in the range 180°C - 300°C. The goal of the project is to adjust the layout of the plant to integrate the innovative storage system, with a size of 20 thermal MWh customized on the features of the plant, and to extend the power production of the CSP plant at rated output up to four hours during the evening hours, in order to cover characteristic power peak load of the local Medium Voltage grid.

The targets of the project are the validation of a form of decentralized power system based on the CSP technologies specialized for the Morocco territory, and the demonstration of the capability to use a TES system in this scale of plant. Such experiences could also be beneficial for other arid areas of the Mediterranean region where the power peak load represents a serious problem of management of the local power supply and there is not enough capacity of other renewable power systems (e.g. hydraulic station) to regulate the fluctuations of the power in such grids.

In the case under exam, two different thermocline TES systems have been taken into consideration as possible candidates for the final configuration of the CSP power plant. As first technological option, it was examined the possibility to utilize a storage system which uses internal heat exchangers with mineral oil (Delco Term Oil) as HTF, and a low melting point molten salts mixture "NitCal-K" (solar grade $KNO_3.5Ca(NO_3)_2 \cdot 10H_2O$ [1]) as a Heat Storage Material to exploit the energy of its sensible heat. As second technological option, it was examined the possibility to build a thermal storage system directly charged by the HTF, which can also be used as Heat Storage Medium (HSM) since its vapor pressure is below the ambient pressure, and its price is much cheaper than synthetic oils. In this second case, to further reduce the cost and to increase the energy density, a cheap solid filler material has been inserted in the storage tank with the additional advantage of reducing the required amount of thermal oil needed in the tank. Three different TES prototypes, in a scale of 1/100 (200 kWh)in comparison to the pre-industrial TES system, have been designed and built by CIC, ENEA and F-ISE to help for the identification of the most suitable TES technology to the present case (see Fig. 1).

(a) (b) (c)

FIGURE 1. TES prototypes, (a) low melting point (NitCal K) molten salt ENEA TES prototype, (b) Oil-Pebbles CIC TES prototype, (c) molten salt F-ISE TES prototype.

ECONOMIC EVALUATION OF THE TES SOLUTIONS

During the first two years of the Project, the ORC-PLUS consortium analyzed, at a prototype and model level, two different thermocline TES systems. The first TES system analysis used a low melting point (90°C – 100°C at ambient pressure) molten salts mixture (NitCal-K solar grade) as Heat Storage Material (HSM), whilst the second one used magnetite pebbles and oil as HSM. Both systems had mineral oil as Heat Transfer Fluid (HTF). At the end of the second year of the Project, ENERRAY Spa, on the base of the information supplied by scientific partners, elaborated a preliminary economic comparison of the two aforesaid TES technologies. The preliminary economic evaluation was calculated by ENERRAY applying the usual procedure for an EPC contractor. The costs are the results of the sum of the direct costs and the production costs, where the direct costs obtained by summing the supplies expenses, services, subcontracts. The production costs Comprised the contingency & risk provision among other costs. The preliminary economic evaluation, as shown in Table 1, has highlighted that the solution based on thermocline oil with magnetite pebbles, for the case in the exam, is cheaper than the solution based on thermocline with low temperature melting salts. This difference is due in one hand to the lower cost of the magnetite material, and the lower quantity of HSM. On the other hand, the solution based on the molten salts is disadvantaged by the max operation temperature of the HTF used in the solar field.

TABLE 1. Preliminary economic evaluation.

	Thermocline based on Oil + Magnetite (Volume of the TES: 203 m^3)	**Thermocline based on NitCal K Molten Salt** (Volume of the TES: 250 m^3)
Centrifugal pumps, valves, expansion tank,	50,00 k€	12,00 k€
HTF + HSM (tank content)	359,52 k€ (640 t magnetite + 67t HTF)	507,96 k€ (500 t molten salts +15t of HTF)
Storage tank	350,00 k€	434,60 k€
Total	**759,5k€**	**954,56 k€**

This preliminary economic comparison has been utilized by ORC-PLUS Consortium to choose the TES technology more fit at the case under evaluation and to indicate at ENERRAY (Engineering, Procurement, Construction, Commissioning of the project) the technical system to engineer for the demonstrator plant. After this step ENERRAY, with the support of the scientific partners of the project, has designed and manufactured a pilot scale TES system based on the oil and magnetite thermocline option.

TES Materials Characterization

The economic analysis was supported by intense activity of material characterization to identify the best solutions of HSM and container materials to employ in the manufacturing of two TES technology solutions. In particular for the container materials, the compatibility with the oil and the Hitec XL was tested against TES tank materials proposed by the industrial partners among those available in the market (Carbon Steel A516, Stainless steel AISI 304, Stainless steel AISI 304). The selection of filler materials for the TES system based on pebbles and oil was done among the following materials individuated after a literature review including Electric Arc Furnace slags: EAF-Slag, Basic Oxygen Furnace slags: BOF-Slag, High density Concrete, Magnetite, River Rock and excavation Mine Rocks in Morocco [2]. Among the studied materials, BOF-Slag, Magnetite and River Rock have been considered as the most promising candidates for effective thermal energy storage, on the base of their thermo-physical characteristics. Table 2 summarizes the results of the tests of durability and compatibility analysis between HSM and HTF.

TABLE 2. tests of durability and compatibility analysis between HSM and HTF

Container material	**Delco Term Oil**	**Hitec XL**
CS A 560	Oxidation (40 μm)	Oxidation (40 μm) in the absence of water Strong corrosion in the presence of water
AISI 304	Small oxidation (4 μm)	Fully compatible
AISI 316	Small oxidation (4 μm)	Fully compatible
Filler	**Delco Term Oil**	**Hitec XL**
Magnetite	Fully compatible	Fully compatible
River Rock	Fully compatible	Fully compatible
BOF-Slag	Fully compatible	Fully compatible

Thanks to the thermo-mechanical properties the magnetite and its compatibility with the HTF according to Table 2 (no visible degradation after thermal cycling test), this material was selected as HSM material of reference for the pilot thermocline TES solution.

LESSON LEARNED DURING THE DESIGNING AND CONSTRUCTION PHASES

The final design of the pilot plant was elaborated addressing the design through technological choices that allow to activate the possible chains of domestic production and small CSP-related services, that have to be activated to create local jobs. ENERRAY Morocco SAS, to reinforce this aspect, has performed a process of selection of local companies with up to EU standards and requirements.

The design phase was supported by a risk analysis to identify the major technological risks. The risk analysis was elaborated by the subcontractor FICHTNER. The analysis, for the part related at TES construction, identified the following major potential risks:

- Technology risks.
- Contractual / scope situation for the construction in Morocco.
- Health and Safety risks during the different phases of TES construction.
- Unexpected Expenses during Construction (Cost Risks).

After the construction and installation of the TES system, a post–risk analysis was elaborated to assess the possible vulnerabilities of the TES technology that can affect the process of manufacturing and installation.

Technology Risks and Problems Encountered

The process design of the TES was elaborated on the base of the outcomes of the simulation performed by scientific partners and the experimental data got during the preliminary tests on the TES prototypes. No particular problems were encountered for this activity.

The mechanical design was made on the base of the following parameters: wind and seismic loads, weight of the magnetite pebbles, minimum and maximum temperatures of operation and ratcheting load. This last parameter was the one that most influenced the sizing of the shell ring thickness and in particular the lower part of the tank.

The mechanical sizing from the point of view of use of constructive calculation software did not present particular problems, but presented some problems related to the unusualness of their application and lack of “standard" design protocols. This problem led to the use of high safety coefficients, corresponding mainly to the use of higher thickness shell rings with consequently increase of the costs.

The survey of market on potential magnetite suppliers has found that on the European market, the choice was essentially limited to one supplier (Norway company), this means that it is not possible to achieve an optimization of the magnetite cost. During the construction of the TES it was also noted that the product is supplied with a high percentage of particles <2mm. This fact obliges the manufacturer, before filling the tank, to perform a “sifting” of the product (in the case of ORC-PLUS 526 t). This process involved an increase in costs, an increase in tank construction time (about 1 month) and a reduction in the amount of filler available on site for tank filling operations (around 14%).

Contractual/Scope Situation for the Construction in Morocco

The shell rings of the TES tank were made of P355 NH EN 10028-3, a steel suitable for working in the temperature ranges between the room temperature and 300°C. This material could not be found on the Moroccan market and this caused delays in the realization of the TES. The thickness of the plates used for the construction of the tank was at the maximum limit of the capacity to weld on site for this reason, and unlike what was originally planned, it was decided to realize the tank in the workshop, this involved:

- An increase in the manufacturing quality of the tank as it was possible to carry out an additional series of checks.
- The need to operate an exceptional transport between the workshop and the installation site.
- A dimensional study was necessary for the realization of additional eyebolts on the TES tank, those were required for the lifting and positioning of the tank in site, which was done with the use of two cranes (see Fig. 2).

Health and Safety Risks During the Different Phases of TES Construction

No particular issue of Health and Safety was observed during the operation of construction and installation of the tank. This thanks also the design choices operated during the preliminary phase of the project. As preventive measure, and to overcome possible safety and environmental concerns related to the HTF, a containment wall was built around the tank. The chosen heat transfer fluid and filling material also have a low safety and environmental risk improved the final system safety level.

Unexpected Expenses During Construction (Cost Risks)

Unexpected processing has led to an increase in tank construction costs of around 14%. Problems such as the need for special fitting for the instrumentation setup, increase of tank wall thickness at the bottom part to overcome ratchetting effects, lower magnetite particle size than expected which required special sieving process are among the main issues that were encountered during the system implementation.

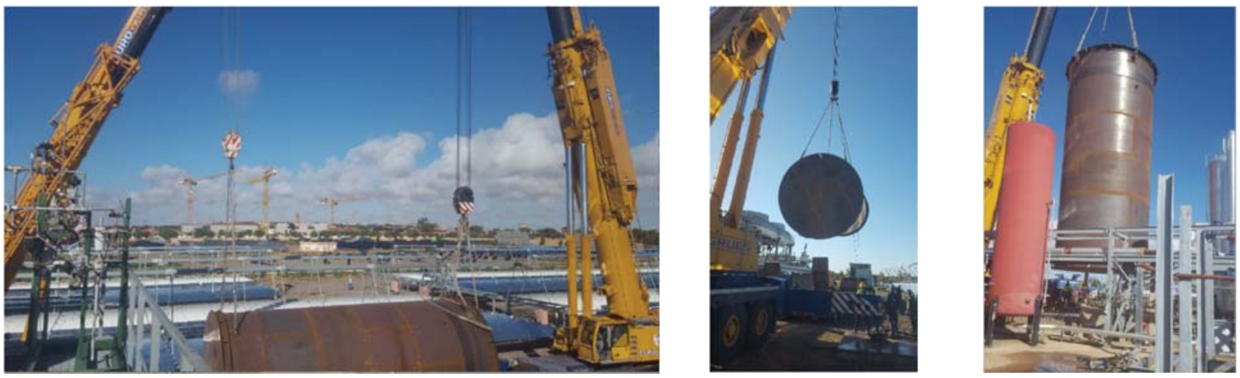

FIGURE 2. Some steps of the installation of the TES tank.

TES Description

In Table 3 the main mechanical features of the manufactured TES system are shown.

TABLE 3. main specifications of the ORC-PLUS pilot TES

Description	Value
Content of magnetite filled	452400 kg
Volume of magnetite filled	156 m^3
Content of Magnetite envisaged by the project	526641 kg
Design magnetite height/magnetite height after the filling	9,12 m/8,7 m
Tank volume	165 m^3
HTF volume for TES (20°C)	70 m^3
HTF volume over magnetite top surface	8,071 m^3
Tank insulation type/density/ thickness	Rockwool / 120 kg/m^3 / 0,200m
Specific weight of the Magnetite (after the screening process)	2,9 kg/m^3
Total height of tank without ceiling	10,590 m
Diameter of tank	4,72 m
Expansion area	0,8 m
Nitrogen height	0,100 m

Due to the reduction of magnetite quantity uploaded in the tank, which was the consequence of magnetite sieving process (see Fig.3), it was estimated that, in contrast with design values, the energy storage size TES decreased by about 15 %.

(a) (b) (c)

FIGURE 3. magnetite supplied (a) state of the magnetite pebbles supplied on site, (b) systems employed to sieve the supplied magnetite pebbles, (c) tank filling operation.

The main features of the ORC-PLUS pilot plant are shown in table 4.

TABLE 4. Main features of the ORC-PLUS pilot plant.

Type solar receiver tubes	Evacuated receiver tube
Solar field Mirror surface	4900 m^2
Heat-Transfer Fluid type	DelcoTerm®Solar E 15
Cooling system	Direct dry cooling

CONCLUSION

The post risk analysis applied during design and construction phases, has not shown any vulnerability for the technology under exam. The unexpected expenses during construction for problems encountered have been limited at 14% respect at preliminary economic analysis. This difference can be justified with high rate of innovation of the technology and especially by decision, at the design stage, to apply engineering solutions that fit to the local technical constrains and available components; all the manufacturing and installation works have been done by local subcontractors, without any technical problems.

The limit represented by the presence of only one supplier of magnetite pebbles at European level can be overcome with the fact this material is very common and abundant outside of Europe. In addition, it is necessary to underline that the market survey was targeting materials with reduced particle size and not all suppliers could supply the desired particle size.

The data collected during the design and manufacturing process have shown that this size of TES represent a technological limit (ratcheting problem). To achieve higher storage capacities, it is more appropriate to employ more storage tanks in parallel.

On the basis of the above, it is possible to affirm that this type of TES is a possible good technological option to support the diffusion of the mid-size CSP plants in the smart grid applications, this statement can be strongly confirmed once the tests in operational conditions will be launched and completed.

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