



SolarPACES 2013

Status of the development of a new High Temperature Thermal Energy Storage System (HTTESS) for CSP-power plants

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Abstract

Thermal Energy Storage-Systems (TES-System or TESS) are already acknowledged to be highly needed to optimize the electricity yield of CSP-power plants and to improve the economics of CSP-projects and to reduce electricity prices. Furthermore for many electricity grid operators it is important to have spinning reserves in the grid and dispatchable power available.

It has been the task of enolcon to develop a new TES-System realizing a step change which is by its principle simple, robust with regard to execution and operation, and which is reducing the electricity costs of CSP-power plants. Furthermore such system shall be open to future developments of CSP-systems with regard to increasing steam temperatures and steam pressure. Such TES-system shall be commercially available for large scale application already in year 2014/2015.

As a result enolcon has invented in year 2010/2011 a TES-System using ambient air as heat transfer fluid and stones/rock as storage medium. The key elements of the enolcon-TES are the open cycle using always ambient air with an air-air-heat exchanger and the arrangement of the storage material in such way to minimize the pressure losses and the own electricity consumption. The development is progressing in a structured way by studies, engineering works, TES-pilot plants, isothermal air flow test plant for the verification of the CFD-calculations, and since end of 2012 by the operation of a high temperature TES-module with all features of the large scale modules. The actual status of the TESS-development and the key results of the charging and discharging of the high temperature TES-module TESS002 is presented following.

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Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.

Keywords: Energy Storage; High Temperature Thermal Energy Storage

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1. Introduction and Background

HTTESS or in the following TES (Thermal Energy storage)-systems are an important element of large scale CSP power plants. As proven technology molten salt is used as storage medium. Such molten salt storage systems require a huge amount of salt (approx. 30000 t for a ‘conventional’ 50 MWel CSP power plant with a storage capacity of approx. 8 hours). To melt the salt for the filling of the tanks a gas amount of approx. 100.000 MWh is necessary. In addition such molten salt systems require huge tanks, pumps, substructures, heat exchangers, piping, valves, measurement systems, isolation etc. etc. which need to be designed in a way that the salt will not freeze and that at the same time no corrosion will interfere the operation of the CSP plant and maintenance is possible. Just for melting the salt and to fill the tanks special boilers and material handling equipment is required. The **overall investment costs** for a complete molten salt TES-plant (including engineering, salt, filling of tanks and system, gas consumption, tanks, foundation/civil works, heat exchangers, pumps, etc.etc.) are for a 8 hours storage period for a 50 MW-CSP power plant at approx. 65 – 85 million €. This can be translated into specific TES-costs of approx. 60 – 80 € per kWh_{th}. It is obvious that in the near future such molten salt TES-systems will start to become a hindering cost element to get the LCOE further down.

Even if there are several companies working on improvements of molten salt TES-systems in many directions-which enolcon is doing as well – only the implementation of a **new TESS-technology** can bring the LCOE further down.

Enolcon has recognized that fact in the year 2009 and started in a structured way to look for such new system. The approach of enolcon was a ‘practical approach’, meaning to set up specification criteria with the target to have a commercial TES-system available within a reasonable short period of a few years. The concept has been presented during the IRES-conference in November 2011 [1].



Figure 1: Main criteria for a new TES-system

Based on these criteria enolcon has chosen a fixed bed system consisting of cheap storage material for an own development of a long term HTTESS (> 3 hours storage time).

The novel approach of the whole new enolcon-TESS is the use of air as heat carrier medium in an open cycle and recovering the rest heat of the air leaving the storage material via an air-air-heat exchanger to the incoming air. This means that always ambient air will be feed into the system, then pre-heated via the air-air-heat exchanger and then heated up with heat from the solar field via a heat exchanger (air - Steam/water, or air - salt, or air-thermal oil) in the **charging mode**, shown in figure 2. From there the air flows through the storage material containers heating up the storage material (pebble stones or rock or solid bed-mixtures). The ‘cooled’ air (still has a certain level of temperature of more than 150 °C) flows through the air-air-heat exchanger and is pre-heating the incoming air. Finally the air leaves the whole system to the atmosphere at a temperature level of between 70 – 120 °C.

The storage efficiency depends on the design of the air-air-heat exchanger and can reach more than 90 % ($heat_{in} : heat_{out}$).

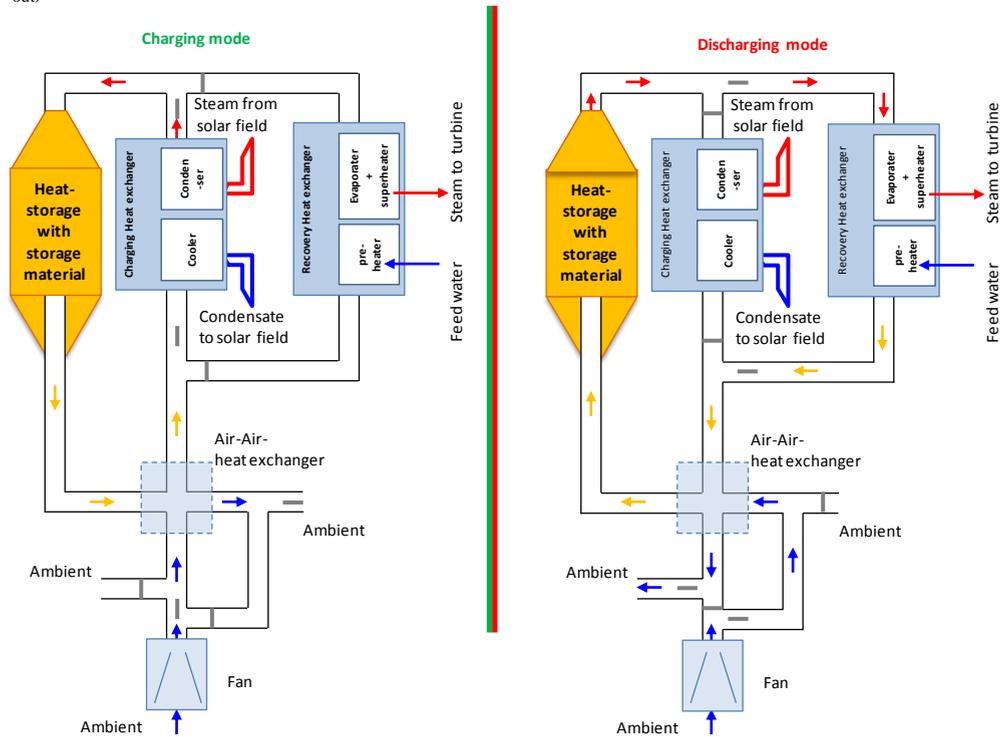


Figure 2: enolcon-TESS-process, charging and discharging mode

For the **discharging of the TESS** some valves will direct the air through the storage material containers and then the hot air will produce steam in a standard heat recovery steam generator. To overcome the temperature reductions of the heat exchangers and heat losses a standard supplementary firing system might be installed providing for heat in the amount of 5 – 15 % of the total heat used for the electricity production.

As usual the challenge of such system are just the details, for example to keep the pressure loss low in order to reduce the electricity own consumption of the air fan. The key element of the measurements at TESS001 has been to find out the pressure loss through a layer of stones, gravel etc. with a thickness of 1.20 m under certain conditions (air velocity in front of the stones, temperature etc.). The theoretical model according to Ergun [2] and Breuer [3] haven been used for such pressure loss calculation and compared with the measurements (see figure 3). It has been found out, that the pressure loss will stay in a low level of less than 7.5 – 25 mbar even through such a 1.20 m thick layer when applying air velocities of approx. 0.5 – 1.5 m/s entering the solid bed. The theoretical models and the results of TESS001 have been confirmed by pressure loss measurements at the TESS002-plant (red dots).

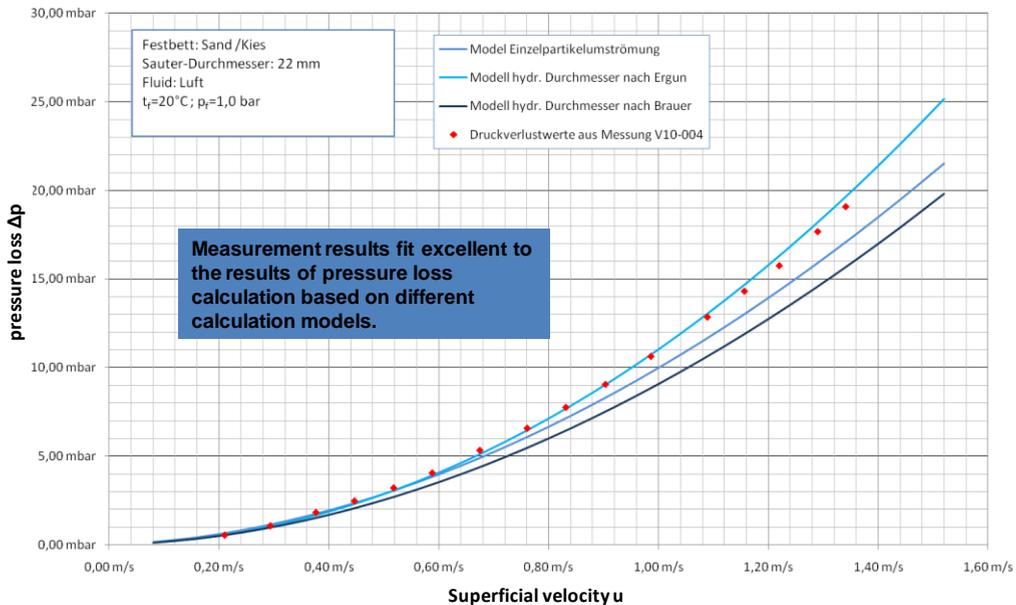


Figure 3: Comparison of theoretical pressure losses with measured data (red dots)

As a consequence one special item of this new concept is the arrangement of the solid bed in providing a big surface in the storage containers to reduce the air velocity through the stones and subsequently the pressure loss. The pressure loss through the whole enolcon-HTTES-system (heat exchangers, channels, solid bed) sums up to the range of only between 45 – 70 mbar. Taking the air mass into account necessary for such TES-system the calculation leads to an electrical own consumption of the whole CSP-power plant for the fan of approx. 4 – 8 % and is therefore in principle in the same level as it is the case for molten salt storage systems.

To keep the pressure loss low the storage material is packed in many modules/containers each having several solid bed-‘walls’. Once a module is charged the air will be directed to the next module. The question which material (sand, rock, gravel etc.) fits best is more an economical optimization question less about technical feasibility. All this materials can in principle be used. However, the heat capacity and the thermal conductivity of the material, and the Sauter-diameter [3] are also important parameters within the design progress (layer thickness, number of modules, fan power).

Enolcon made several application concept studies and used the software Epsilon Professional for the heat-and-mass-balance calculation [4]. As an example a ‘solar pure’ concept for a 50 MW_{el}-CSP power plant and 24 hours base load operation is indicated in figure 4. In this concept the basis is a CSP-power plant with direct steam generation and steam parameters of 550 °C at 100 bar. The disadvantage of the temperature loss between the steam and the maximum achievable temperature of the air have been reduced by applying several superheater loops and the desuperheating in steam/air heat exchangers, shown in the q,T -diagram of figure 5. The total air mass flow during 8 hours charging is 640 kg/s resulting in a total fan consumption of approx. 2,6 MW_{el}. During 16 hours discharging the electrical production is at 35 MW_{el} and the related electrical fan consumption is at approx. 1,7 MW_{el} with an air mass flow of 335 kg/s.

Due to the flow rates, the air channel diameters will be in the same size than flue gas channels behind big gas turbines or before entering a heat recovery steam generator.

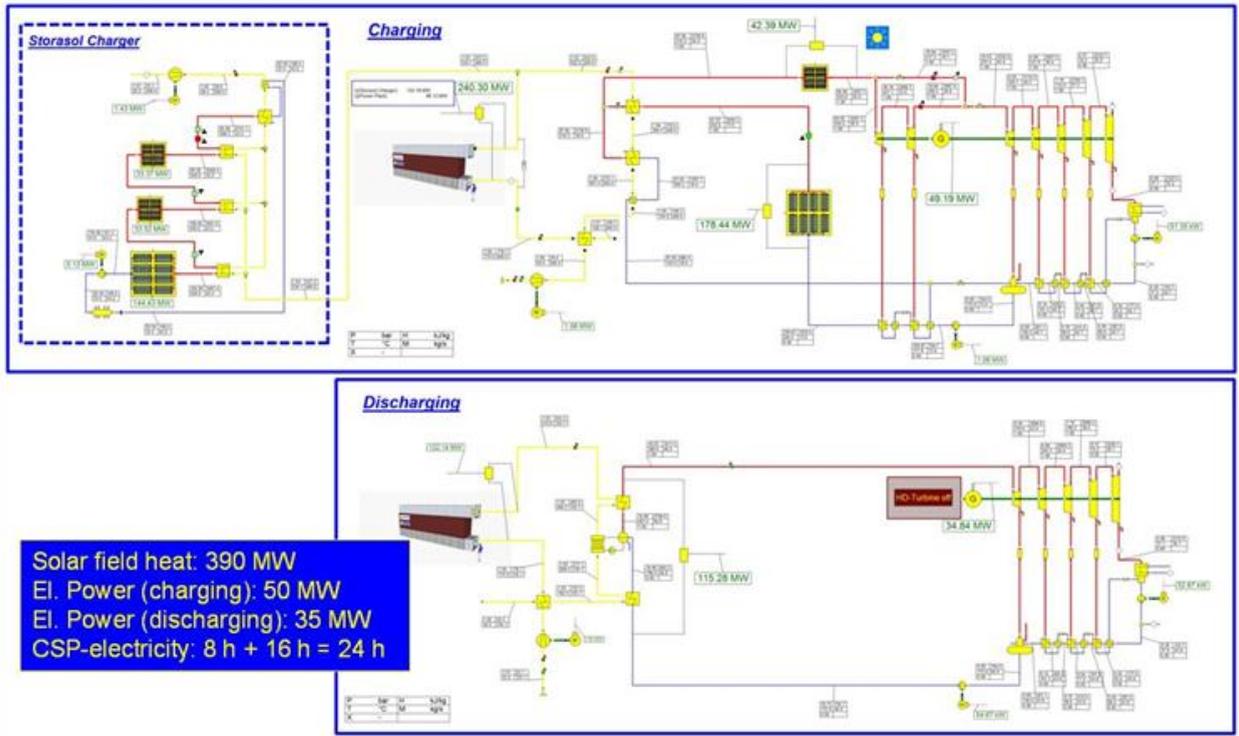


Figure 4: Example concept for application of the HTTES in a direct steam generation CSP-power plant (solar pure) based on [4]

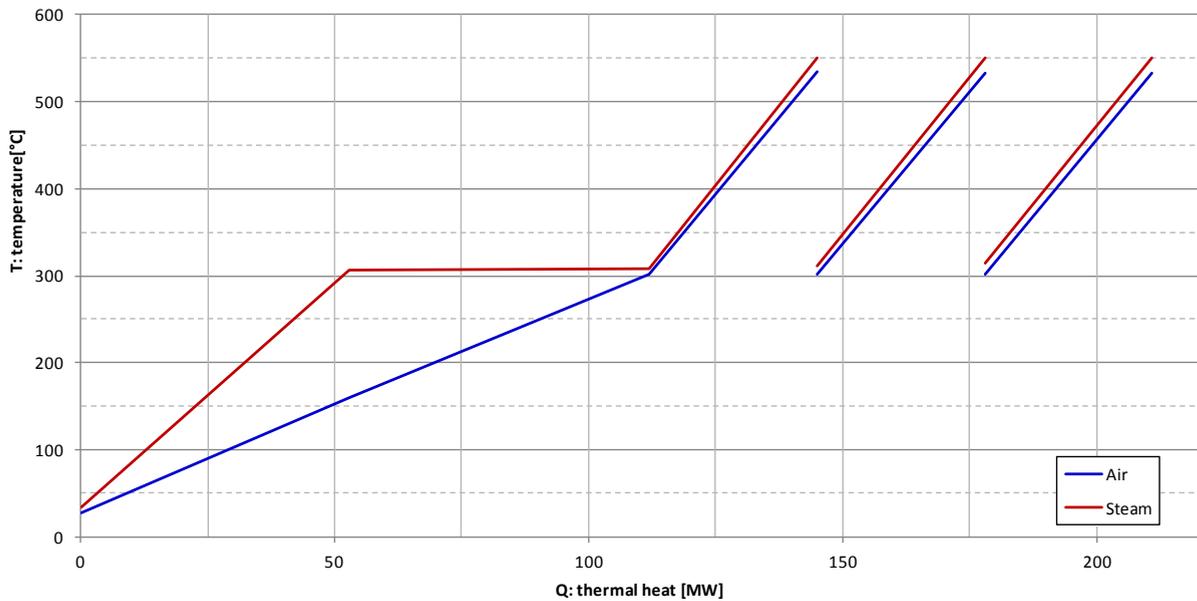


Figure 5: Example concept for application of the HTTES in a direct steam generation CSP-power plant (solar pure), q-T-diagram for charging

Without going more into technical details it can be stated that the enolcon-HTTES-system consists mainly of standard equipment such as air channels (ambient pressure range 1 – 1,15 bar), heat exchangers, fans etc. and only the storage containers are new designed equipment.

Diligent cost analysis have shown that such enolcon-HTTES-system (50 MW, 8 hours storage) is not only with regard to the O&M-costs at the same comparable level of molten salt- TES-systems but much lower in the investment costs with less than approx. 35 €/kWh_{th}. Furthermore, an increasing of the storage volume results in a much further drop of the specific because of the very cheap storage material.

The round trip efficiency depends on the design (temperatures, pinch points, but mainly the air-air-heat exchanger) and the temperature difference between the ambient air temperature and the temperature of the air leaving the system, which is driven by economics. Of course, the round trip efficiencies (solar heat to the storage (charging) converted into electricity during discharging, compared to the direct conversion during day-operation) is depending on many parameters (temperatures, pinch points, design of heat exchangers etc.). As an example calculations for direct steam generation with steam parameters of 500 °C and 100 bar (50 MWeI) show round trip efficiency figures for ‘solar pure’ of approx. 70 – 75 %. With supplementary firing during discharging operation the same electrical power capacity can be provided as it is the case during day operation.

2. Technology Development process and results

The technology development is proceeding in a structured manner and focussing on research with regard to dedicated questions and as well development with regard to enable an easy scale up for commercial application.

In the first pilot plant TESS001 enolcon has made a lot of measurements with regard to pressure loss through a bed with a length/thickness of 1,2 m and to learn more about the properties of solid bed material when being heated up and cooled down. This first pilot plant TESS001 formed as well the basis for the verification of developed calculation models. The theoretical models for the temperature behaviour and the pressure loss fit excellent with the practical measurements.

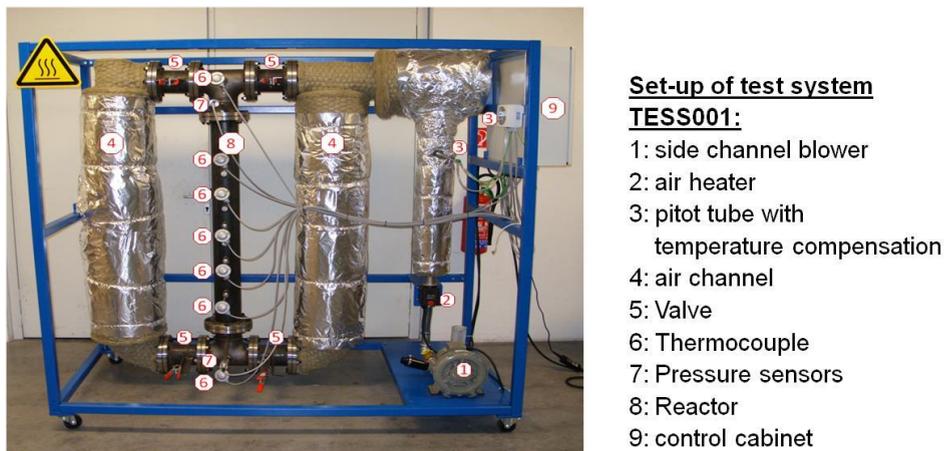


Figure 6: Development of enolcon-TES-technology, TESS001-pilot plant

In a next step a test plant has been build to verify CFD-calculations. In this test plant the air velocity in the air channel and at the surface of the bed material is already at the same level as it is planned for the large scale commercial TES-system.

With the TESS002-pilot plant enolcon has build a pilot plant which has already all features of the final storage containers:

- Operation at temperatures in the range of 500 – 600 °C
- Inner design about the arrangement of the solid bed
- Several inlet channels (two) and four storage material ‘walls’



Figure 7: TESS002, left with isolation, right without isolation for first functional tests

The TESS002 is meanwhile used for many tests and the air flow inlet channel has been further optimised and the heat flow is in verification with theoretical models. It is obvious, that an important task of the actual works is to create an inner design of the TESS-storage module that allows for a smooth air flow through the stones or solid bed. Furthermore a diligent planning of the isolation concept is supporting the efficiency of the storage system.

Already the first measurements have shown that there is no problem to reach a temperature of more than 500 °C in the storage material. Especially in light of the fact that the ratio between the surface (factor for heat losses) and the storage material is in such small plant worse compared to larger modules.

Until today no issues of the storage module and the used material has been observed due to the heating up and cooling down cycles.

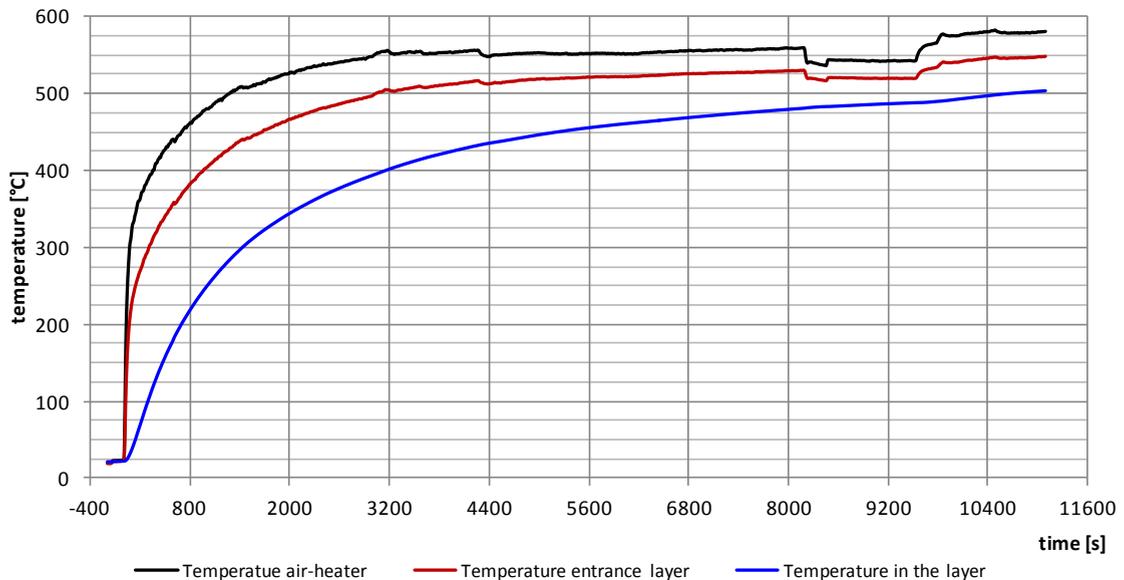


Figure 8: TESS002, first tests, temperature measurements of the air temperature at the air heater(black), the air channel before the layer (red) and inside storage bed (blue)

3. Outlook and next steps for the enolcon-HTTESS-technology

Enolcon has already started the engineering works for the pilot plant TESS003. The TESS003-demonstration plant will have all major parameters already in full scale 1:1 (air velocity, temperatures, stones/solid bed arrangement, inner design, length and thickness of solid bed, height, inner ‘storage material ‘walls’ and top- and end-‘walls’ etc.). Only the amount of storage ‘walls’ and the width will be smaller, meaning that there will be for the up scaling to commercial storage moduls only a ‘duplication’ but not a systematic change. The results from TESS002 and additional developed calculation tools form an excellent basis for the design of this new demonstration plant.

In addition and if necessary and applicable the TESS003-plant will already be equipped with heat exchangers and air valves to demonstrate the whole system in operation. It is planned to start operation of TESS003 in the first half of year 2014.

On the basis of the TESS003 enolcon and the EPC-partner STORASOL are then looking for opportunities to build full scale HTTES-system to demonstrate commercial viability. The sketch shown in figure 9 demonstrates how large scale moduls are expected to look like and how a demonstration TES-system layout could be arranged (in this case as CSP-superheater-TESS).

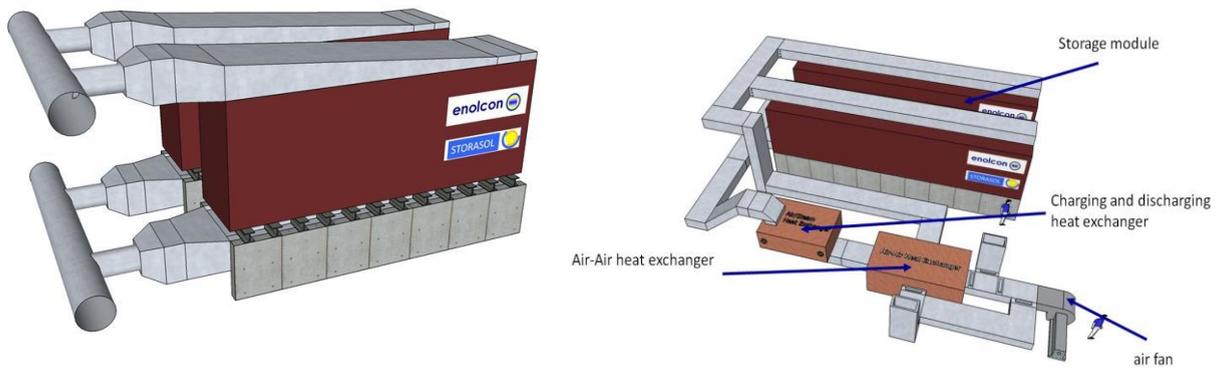


Figure 9: Design proposal for enolcon-TESS-modules (left) and a possible arrangement for a CSP-superheater-TESS demonstration (right)

4. Conclusions

During the last approx. 3 years the development of an alternative long term HTTES-system made good progress and meanwhile it can be stated that such system is technically and commercially feasible and will work and allow for convincing performance. With regard to efficiency there are and will be technically better TES-systems available, however the economics of such enolcon-HTTES-system are still by far superior to all molten salt systems available or even under development because of the high costs of molten salt.

It can be expected that this HTTES-system will allow for a step change in the LCOE of CSP-power plants, especially for applications with long term storages and in the light of development to solar tower technologies using air receiver technologies.

The technological risks have been determined down to the last issue of getting an even air flow through the solid bed to allow for optimized charging and discharging. The results of TESS002 are clearly indicating that such design can be worked out and will be demonstrated in TESS003.

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