HPS2 High Performance Solar 2

ABSCHLUSSBERICHT DES VERBUNDVORHABENS
High Performance Solar 2

Demonstration einer solarthermischen Parabolrinnenanlage und Dampferzeugungssystem basierend auf Flüssigsalz als Wärmeträgermedium

01.07.2016 - 31.05.2022

Deutsches Zentrum für Luft- und Raumfahrt e.V.
Institut für Solarforschung (DLR)
TSK Flagsol GmbH (FLG)
Eltherm GmbH (ELT)
Yara GmbH & Co. KG (YAR, als assoziierter Partner)
Steinmüller Engineering GmbH (STE, als assoziierter Partner)
Universidade de Évora (Portugal) (UEV, als assoziierter Partner)
RioGlass Solar SCH, S.L. (RIO, als assoziierter Partner)
RWE Renewables GmbH – (RWE, als assoziierter Partner)

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

Projektträger Jülich
Forschungszentrum Jülich

Vorhabensbeschreibung	HPS2 **H**igh **P**erformance **S**olar **2** - Demonstration einer solarthermischen Parabolrinnenanlage und Dampferzeugungssystem basierend auf Flüssigsalz als Wärmeträgermedium
Zuwendungsempfänger	Deutsches Zentrum für Luft- und Raumfahrt e.V. Institut für Solarforschung (DLR) TSK Flagsol GmbH (FLG) Eltherm GmbH (ELT)
Assoziierte Partner	Yara GmbH & Co. KG (YAR) Steinmüller Engineering GmbH (STE) Universidade de Évora, Portugal (UEV) RioGlass Solar SCH, S.L., Spanien (RIO) RWE Renewables GmbH (RWE)
Förderkennzeichen	0324097
Laufzeit des Vorhabens	01.07.2016 - 31.05.2022
Projektträger	Projektträger Jülich (PTJ) Forschungszentrum Jülich GmbH 52425 Jülich Ansprechpartner: Dr. Tarik Schwarzer
Projektleitung	Dr. Michael Wittmann DLR Institut für Solarforschung, Pfaffenwaldring 38-40, 70569 Stuttgart Telefon +49 711 6862 730, Email michael.wittmann@dlr.de
Autoren des Berichts	Michael Wittmann[1], Mirko Meyer-Grünfeldt[1], Niklas Dicke[1], Mark Schmitz[2], Raphael Detzler[2], Hans Gielen[2], Peter Schmidt[3], Mehrdad Torabzadegan[4], Jaime Paucar[5], Nils Gathmann[5], Pedro Horta[6], Paula Martins[6], Evaristo Esquinas[7], Augusto Maccari[7], Thorsten Miltkau[8] [1] DLR - Institut für Solarforschung (DLR) [2] TSK Flagsol GmbH (FLG) [3] Eltherm GmbH (ELT) [4] Yara GmbH & Co. KG (YAR) [5] Steinmüller Engineering GmbH (STE) [6] Universidade de Évora, Portugal (UEV) [7] RioGlass Solar SCH, S.L., Spanien (RIO) [8] RWE Renewables GmbH (RWE)
Status	29.11.2022

Table of Content

1. General

1.1 Interfaces to German national research objectives

The strategic goal of the project is to establish a German/international pool of experts in the field of parabolic trough power plants operated using molten salts as the heat transfer fluid that shall be able in the medium term to offer commercial power plants using this technology.

The greatest potential of improving the efficiency, and therefore the economy of solar thermal power plants, is in the increase of the process temperature and the storage of energy. The greatest potential is attributed here to using molten salts as the heat transfer fluid. Additionally, the salts facilitate direct storage. Electricity generation therefore meets the requirements of grid operators for demand-oriented feed-in.

The HPS2 industrial project is based on the HPS2 infrastructure project. The industrial consortium resumed with the work done so far and completed it collaboratively.

The project lays the foundations for the examination of the questions mentioned in Section 3.4.1 (Line-focussing systems) of the 6th energy research programme:

- Power plant concept with alternative heat transfer fluids, especially using salts as the heat transfer fluid with the goal of achieving higher power plant efficiencies,
- Measures and components for energy-efficiency improvement of the system,
- The development of concepts for operation, maintenance and monitoring.

Additionally, aspects enumerated in Section 3.4.3 Integrated storage, as well as overarching questions (Section 3.4.4) such as the adaptation of conventional components to the operating method of solar thermal power plants, are addressed.

Table 1 Project overview base plan

Project period	01.07.2016 - 31.05.2022
Project total budget	7.455.032 €
Funding of German Ministry of Economics Contribution from Industy partners Portuguese national funds of University of Évora	3.965.711 € 2.993.661 € 495.600 €
Project partners	7 Funded partners: DLR (DE), TSK Flagsol GmbH (DE), eltherm GmbH (DE) Associated partners: University of Évora (PT), Yara (NO), Rioglass (ES), RWE (formerly Innogy) (DE)
Project partners countries	3 (Germany, Portugal, Spain)

1.1 Introduction

Following the ground-breaking work Kearney et al [1] the use of molten salts as heat transfer fluid in linear parabolic trough collectors has been pursued as decisive for lowering the levelized cost of electricity (LCoE). This is more important, as such systems can provide through an integrated solution energy storage as well as dispatchable electricity. This overcomes the intermittency of solar thermal electricity production caused mainly by the presence of clouds and long claimed as an obstacle to the implementation of renewable energies. In this context, and to prove the feasibility of such a plant as the one conceived by Kearney et al [1] the Évora Molten Salt Platform (EMSP) is erected on the grounds of the University of Évora located in Southern Portugal (Europe) about 100 km southeast to Lisbon (38°31'N, 8°00'W), please, see Fig.1. This region is characterized by a very suitable solar resource reaching approx. 2000 kWh/m2 of direct normal irradiation [2]. EMSP is part of a rural facility owned by the University away from the city of Évora and having low levels of soiling [3] and attaining only moderate winds; two crucial aspects allowing a reliable operation of a solar platform.

Figure 1 Location of Évora

The project HPS2 is based on the project HPS "High Performance Solarthermie". The HPS project ran between 2010 and 2012 by Siemens as leading partner, DLR, SeniorFlexonics, K+S and Steinmüller Engineering [4]. The intention of the project was very similar to the HPS2 project: demonstration of molten salt as storage and heat transfer media in a demo scale parabolic trough power plant. The plants component design was dominated by Siemens power plant standard and equipment. Comprising an out-of-one-hand solution for the full plant from solar field, power block, process control etc.

Until 2012 the plant's erection was about 60% completed, leaving mainly the solar field and electrical system open. By this time all of a sudden Siemens stepped out of EPC business for CSP and, as a consequence, the HPS project and the erection of the pilot plant came to an abrupt stop. Since October

2013 the plant is owned by the University of Évora. In autumn 2016 the HPS2 project was started under a cooperation agreement between the University of Évora and DLR. The project consortium comprises DLR (project coordinator), TSK Flagsol, eltherm, University of Évora, Yara, Rioglass, Steinmüller Engineering and RWE. The HPS2 project will upgrade the former solutions, like using the HelioTrough® collector, designing of an integrated solar field heating system, using low-melting Yara MOST salt and improved molten salt heat collecting elements (HCE).

1.1 Technical Obstacles for market introduction and success of the project

There are fundamental concerns related to commercial usage with respect to the technology. The demonstrator was constructed so that every single concern can be permanently dispelled. In the following the overview is given.

1.) Draining and Filling

Above all during cold start-up, all filling and emptying procedures have been tested and optimized using water filling. To upgrade all safety equipment and minimize the risk of the plant, the filling and emptying procedures have been in focus at the beginning of the hot start-up with salt. The filling and draining of the plant worked out with no severe problems.

2.) High energy input during night-time operation to prevent solidification

The plant shall be designed so that night-time operation can be run using the energy from the hot tank, the cold tank, or both tanks. Furthermore, the plant is equipped with electrical trace heating and impedance heating system for emergency reasons. The plant is therefore completely flexible. It was shown that during the plant's heat losses during night operation can be completely covered by (reserved) molten salt from the storage tanks.

3.) Frost hazards in various operating modes (for example, reliability of the trace heaters for pipelines and fittings)

Various systems have been used for heating: Impedance heating, MI trace heating and plug-in heaters. All heaters are divided into single subordinate circuits and each can be individually controlled and balanced. This design permits the reliability of each individual type of trace heater. During the operation times of more then 5.000 hours only one freezing event occurred, the reason of this event was not due to due to an avoidable, improper installation of an MI cable.

4.) Blackout scenarios

The behaviour of a blackout is critical for the plant that allows molten salt to circulate in a widely distributed receiver network at a high melting point. The plant is upgraded with an uninterruptible power supply (battery, immediate usage) and an emergency-power unit (diesel generator) to react to blackouts. The control equipment is pre-programmed so that all necessary consumers are provided with sufficient power at the right time, ensuring that the plant can be operated in safe condition, even in isolated operation. Blackout situations occurred during the operation without danger for environment or plant.

5.) *Material requirements due to temperature and corrosion*

Various corrosion tests that simulated the principle use of the selected materials were already run in the laboratory during the previous projects. During plant operation, it was demonstrated that the pre-tests can be confirmed – no unexpected, additional phenomena was observed. The complete design of the plant is configured for a temperature of around 565 °C.

6.) *Performance of the SCA*
The molten salt has a modified hydraulic in comparison to heat-transfer oils. The performance of the receiver can be tested and determined under the condition with the HelioTrough (increased concentration in comparison to the EuroTrough, for example). This allows theoretical simulation models to be validated and parameterized. Furthermore, the upgrading of the HelioTrough and the flexible connections for the significantly higher rate of heat expansions have been demonstrated.

7.) *Flexible connections: Demonstration of operational readiness and tightness*
The flexible connections are an Achilles heel in the system. The use of flexible tubes without rotating connections have been installed. The peculiarity of the tubes is that they are comprised of very thin-walled parts; due to slow but steady salt corrosion, this presents a great challenge. Also, they are fitted with a trace heating system and impedance heating syste that can compensate for their higher rates of heat loss – in comparison to the HCEs. Operational readiness and tightness was proven due to the operation hours of the demonstrator.

8.) *Stream generator system*
There was a pipe break in the steam generator after an incident in the SolarTwo plant. The knowledge gained from this incident was considered in the design of the once-through boiler; additionally, an emergency system was developed just in case an incident occurs. The operational reliability of the steam generator was demonstrated due damage of the conventional feed-water pump. The repair and demonstration is being done in a parallel project.

9.) *Maintenance and operation tasks; dealing with unexpected events*
The effort for O&M required became clear during operation of the plant. Critical subsections/components for further development was identified. Experience on maintenance and operation tasks and overhaul intervals has been created. Operation experience show an uncritical behaviour of the system. Adequate control schemes have been implemented for the solar field control that reacts smoothly on varying weather conditions.

10.) *Stability and salt mixtures*
The thermal stability of salts is an important and widely considered topic. The real plant experiences on stability of ternary salt (CaNaK-NO3) show good behaviour of the salt. No significant change has been detected with maximum operation temperatures of above 500 °C. The thermophysical parameters of the salt mixtures remained constant during the test range.

2. Salts and salt process engineering

2.1 Identification and qualification of the salt mixtures

Yara Molten Salt consists of 56% NitCal K, 38% potassium nitrate and 15% sodium nitrate. NitCal K as one of the components is calcium potassium nitrate double salt which consist of 76% calcium nitrate, 8% potassium nitrate and 16% crystal water. The final Yara Molten salt product is eutectic mix of these three-nitrate salt and comprising 42% calcium nitrate, 43% potassium nitrate and 15% sodium nitrate.

Prior to HPS2, Initial analyses of high temperature stability, carried out at DLR laboratories 1.000 hours at 500°C, then further heating up to 525°C, keep this temperature for another 1.000 hours followed by another raise up to 550°C. At this very high temperature some decomposition of the salt was observed and the experiment was stopped after 800 hours at 550°C.

2.2 Salt melting process

More than 100 tons of Yara Molten salt comprising of NitCal K, potassium and sodium nitrate delivered at EMSP early 2018. In addition, Yara also provided Pre-Melting Unit (PMU) to feed the salts and melt the salts and drain it to drainage tank. The PMU was connected using a flexible hose to the drainage tank (Figure 2). This flexible hose has heat tracing to heat up the hose while pumping molten salt to drainage tank.

Figure 2 (Left) Pre-Melting Unit (PMU) installation at EMSP (Right) flexible hose with heat tracing.

The optimization of the melting process was first done in lab-studies and verified during the melting process for the small-scale application (with a total of 1.500 kg ternary salt-mix).

Filling the drainage tank and melting process started in October 2022. Salts in form of 25 kg bags was fed to PMU using a salt crusher and a conveyer belt transporting the crushed salt to melting tank in order to heat up to temperature above melting point (131°C). Once the salt is completely melted inside PMU tank then pumped into drainage tank through flexible hose (Figure 2 Right). The salt melting was performed in batches. Every batch the weight ratio of each component was followed in order to maintain eutectic mixture of all three-nitrate salt accordingly.

Inside the drainage tank ternary salt heated further up to 300°C in order to all the water evaporate from the salt. Most of the water evaporated already at around 220°C however, in order to remove any inner bound hydrates molten salt heated up to 300°C. Due to higher viscosity of the ternary salt around melting temperature, water vapor molecules escaping from the mix might cause foaming on the molten salt surface. It is important to control this phenomenon by adjusting temperature for smooth buildup of such vapor and at the same time maintain surface to depth ratio of molten salt as high as possible inside the tank. Once bulk mix reaching temperature above 200°C then lower viscosity would also help vapor transition from molten salt to head space.

Figure 3 Steam generation during salt melting

2.3 Salt analysis

After salt melting salt completed salt samples have been regularly extracted to investigate salt quality and potential degradation. In addition to offline salt sampling, to monitor the salt quality a NOx/O2 sensor at the drainage tank and hot tank was installed.

2.4 Determination of salt corrosion properties

Prior to HPS2 several tests concerning the corrosion properties were done, showing no significant corrosion on stainless steel (316L or similar). Salt analyses for iron (Fe), chromium (Cr), nickel (Ni), molybdenum (Mo), cobalt (Co) performed and results have not shown at any time significant levels of those ions.

It was agreed to place a basket made of perforated metal plate into the both hot and cold tank in a way that it will be always overflowed by molten salt (Figure 3). This was evaluated as best location for the sample holder. The basket will then host several pieces of different material of interest, mainly different stainless-steel qualities and alloys. These two corrosion test baskets were ordered by Yara. Detailed engineering and manufacturing of corrosion test baskets was performed by DLR.

Figure 4 Corrosion basket and placement of steel materials inside.

Type of steel materials has been selected based on feedback from all the partners and Table 2 shows the list of steel materials selected accordingly for testing in the corrosion basket.

Table 2 Steel material selection for corrosion testing

Grade	304L	304H	321H	1.4541	1.4571	1.4571	P91	347H
Source type	sheet	tube	tube	sheet	sheet	tube	tube	sheet
Sample type	strip	ring seg-ment	ring seg-ment	strip	strip	ring seg-ment	ring seg-ment	strip
Sample di-mentions	50 X 20 mm	~70 X 20 mm	~70 X 20 mm	50 X 20 mm	50 X 20 mm	~70 X 20 mm	50 X ~20 mm	50 X 20 mm
Number of samples	20	3	12	20	20	12	3	4

The steel material was exposed to the salt from start of the test period (Nov 2021) until salt change (July 2022). During this period both corrosion baskets in hot and cold tank was containing steel materials listed in Table 2 exposed to molten salt with extreme conditions.

At the end of testing period all the steel material sample were taken out from the corrosion baskets and sent to Salzgitter Mannesmann Forschung GmbH for analyzing and inspection. At the time of writing this report the sample preparation and surface analytics by scanning electron microscopy (SEM) has been performed and there is no sign of corrosion in steel materials. The only exception is P91 sample that some corrosion products observed.

Further analysis including metallographic preparation of cross section, analysis of cross sections by SEM and scale thickness measurement to determine potential corrosion damage to be performed.

2.5 Configuration and procurement of the filter system

Based on open discussions with all project partners and the results from other small-scale applications a need of a particle-filter-system was not identified and only CO2 filters were planned for the salt cycle. The requirements for the CO2 Filters were collected and finalized by DLR.

The filters were planned to be installed at the following locations:

- At the steam generator for venting during drainage
- At the cross over pipe of the solar field for venting during drainage
- At the chimneys of the three salt tanks for breathing of the tanks

After all open questions concerning the CO2-Filters (type of connection, way of orientation, allowed pressure loss as well as the filling level of adsorbents) were clarified, the assembly was triggered. After manufacturing in Holland by Yara's subcontractor the CO2-filters were shipped to Évora together with the PMU. After arrival in Évora the filter assemblies had to be modified in a Workshop in Évora due to some conceptual errors. After a slight delay due to the modification the filters were installed at their foreseen locations.

2.6 Synthesis and delivery of the salts

Calculation of the demanded quantity of molten salt is completed and set to 105 tons (sum of all three components) which allows to "produce 46 m³ plus some contingency. Amount of salt to be filled into plant calculated and defined, including the additional amount due to high level switches in storage tanks.

3. Design and installation of the HelioTrough solar field

3.1 Specification documents

The Design Criteria Document (DCD) for collector was defined according to the HPS2 project's basis of design and a final version agreed upon with the collector designer, incorporating all relevant standards, codes and rules for load calculation .

The structural design document describing the structural engineering, was provided by the subcontractor, submitted by FLG and approved by local authorities (CME) within the building permit.

3.2 Engineering

Solar field layout: The limitations of the available land in Évora have led to a shortened loop layout with four solar collector assemblies (SCAs) of in total 36 solar collector elements (SCEs), each 19 m long. The solar field design was eventually changed from 4 SCAs with 9 SCEs to 2 SCAs with 10 SCEs plus 2 SCAs 8 SCEs in order to qualify commercial-scale collectors (i.e. with 10 SCEs), to simplify the impedance heating system and to avoid isolating flanges in the salt piping.

Foundations: The geotechnical survey resulted in a soil report enforcing the deployment of spread foundations, as an extensive granite rock layer underneath the topsoil prevented the deployment of pile foundations. As the topsoil had relatively low load-bearing capacity, the foundations became very large.

Grounding-zero: A new concept of the grounding system was developed and implemented within the foundation design.

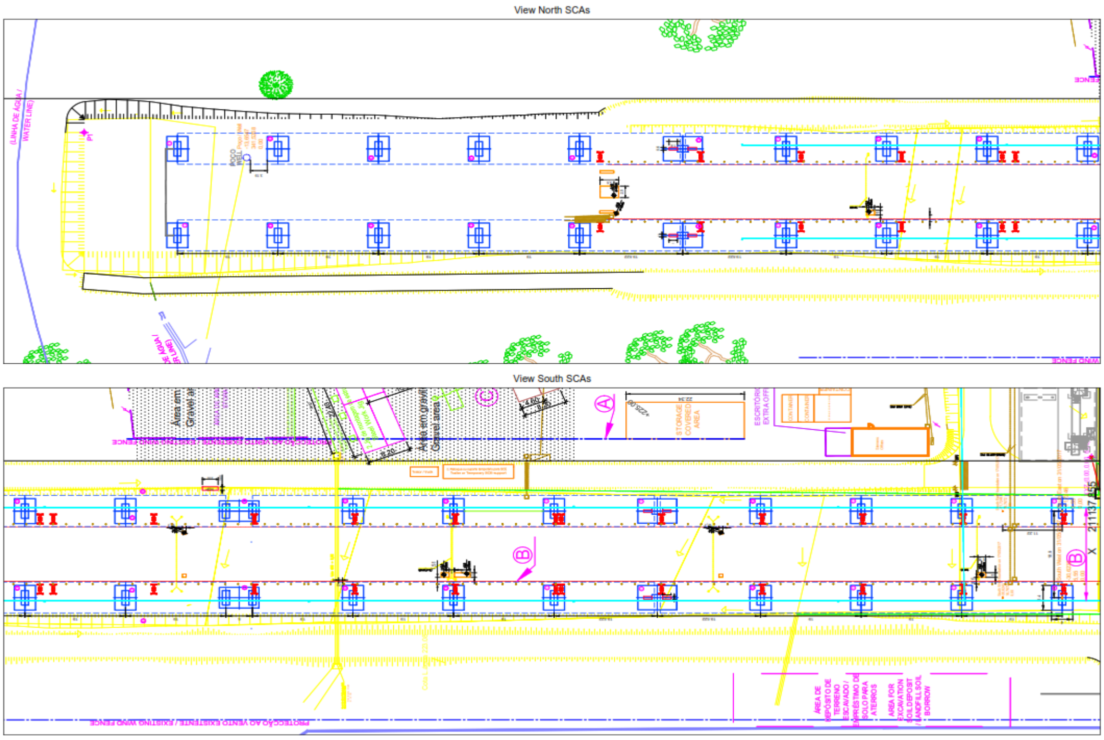


Figure 5 - Solar Field Layout with spread foundations (blue)

The layout shows the bigger footprint (Heliotrough foundations in blue) of the solar field.

Drainability: Because of the need of salt drainage, the layout had to be set up onto a virtually inclined plane, realized through increasing foundation top heights from south to north, with the nethermost foundation protruding about 50 cm from the ground. Local deflections in the collector structure, which lead to local minima in the HCE piping, have been calculated. A slope of collector of 0.15% was defined to reduce salt residues after drainage to uncritical levels, with a maximum fill level of 12mm in the middle HCEs of the SCEs at collector ends. The figure shows the total HCE bending-line as a result of combined site inclination, assumed tolerances of pylon-head heights and actual HCE-bending and TTU-bending.

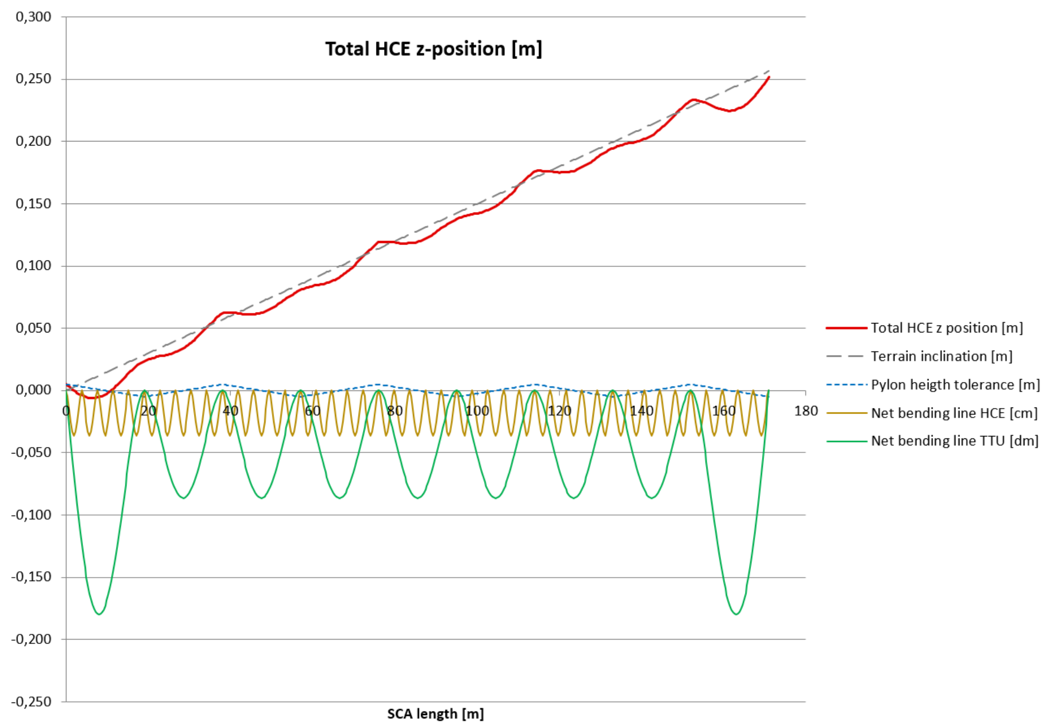


Figure 6 HCE bending-line = site inclination + pylon height tolerances + TTU-&HCE-bending

Impedance heating: after mutual evaluation, the ends and the very center of the collectors were used as sole connection points for the impedance heating. A design concept for electrical insulation of HCE posts (the steel arms holding the HCE) and HCE fixed-end-post pipe at the drive pylon was done (see drawing below). So, a new fixed-end-post head for the drive pylon was designed which has a hybrid function. It is used for mechanical connection with the fixed-end-post and provides thermal insulation for the impedance heating at the same time. The electrical insulation is realized further away from the high-flux zine at the foot of the fixed-end-post.

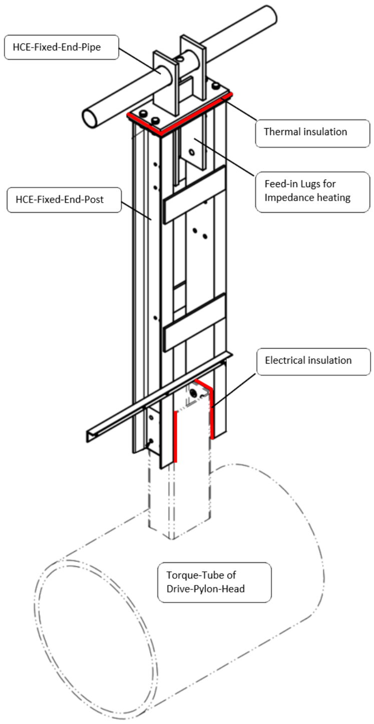


Figure 7 - Electric and thermal Insulation of Fixed-End-Post and HCE Fixed-End-Pipe at Drive Pylon

Assembly area: For the open-air assembly area, three large spread foundations and corresponding assembly jigs for steel structure assembly, mirror installation and balancing, have been designed to be erected in the east of the plant.

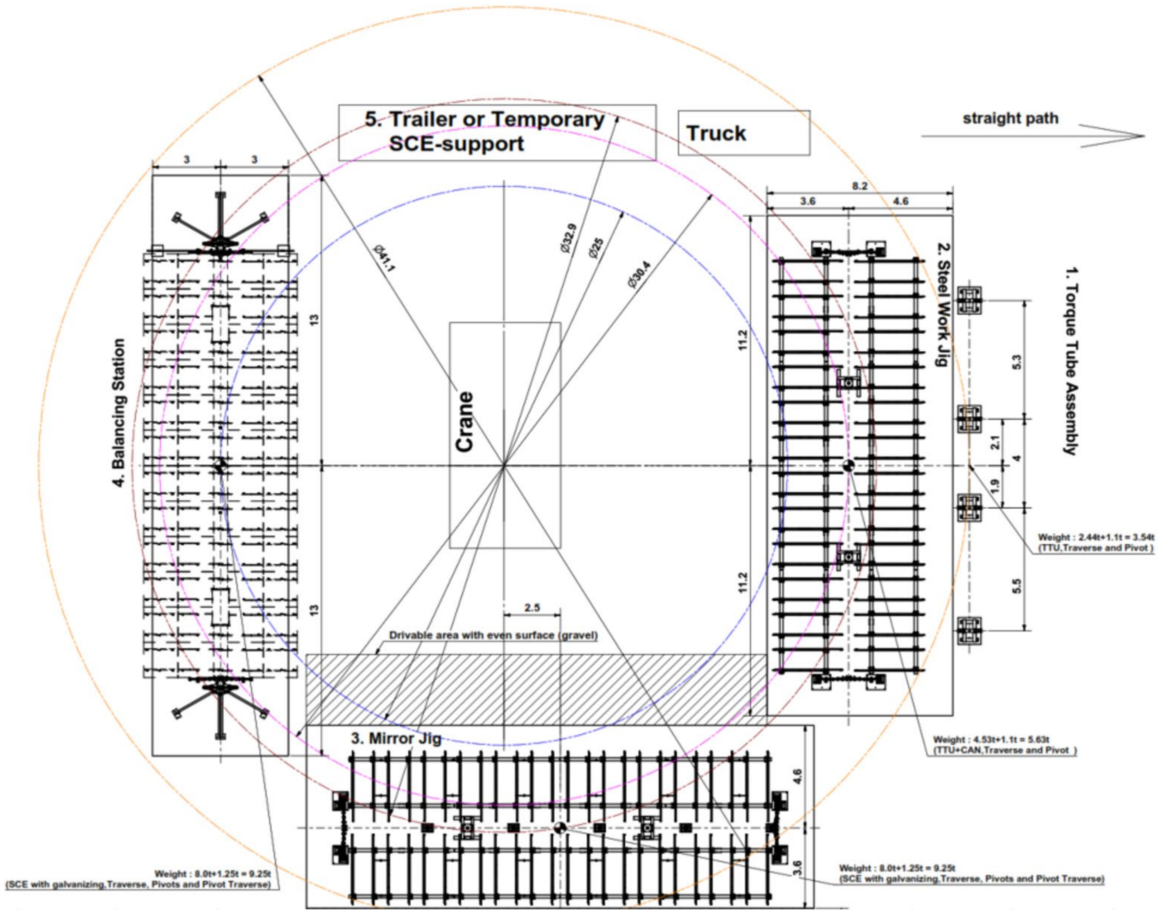


Figure 8 - Layout of the JIG-Area

Drives and controls: Hydraulic drive systems with accumulator for emergency back-track as well as local control unit (LOC) have been developed according to the project conditions. Furthermore, the specification for solar field instrumentation (temperature, pressure, level and position) was created.

Also, the interface between field supervisory control (FSC) and distributed control system (DCS) was defined and the cable specification for the sensors and communication cables was made. The programming of the FSC and the FSC operator manual was done and reviewed by DLR and UEV.

Design documents: component specifications for molten salt receivers, mirrors, drives, controls, foundations and metal support structures have been produced, as well as a complete set of manufacturing and installation drawings for jig area, foundations and collectors. Also, (bills of quantity (BOQs) as well as assembly and installation specifications have been created for jigs, foundations and collectors.

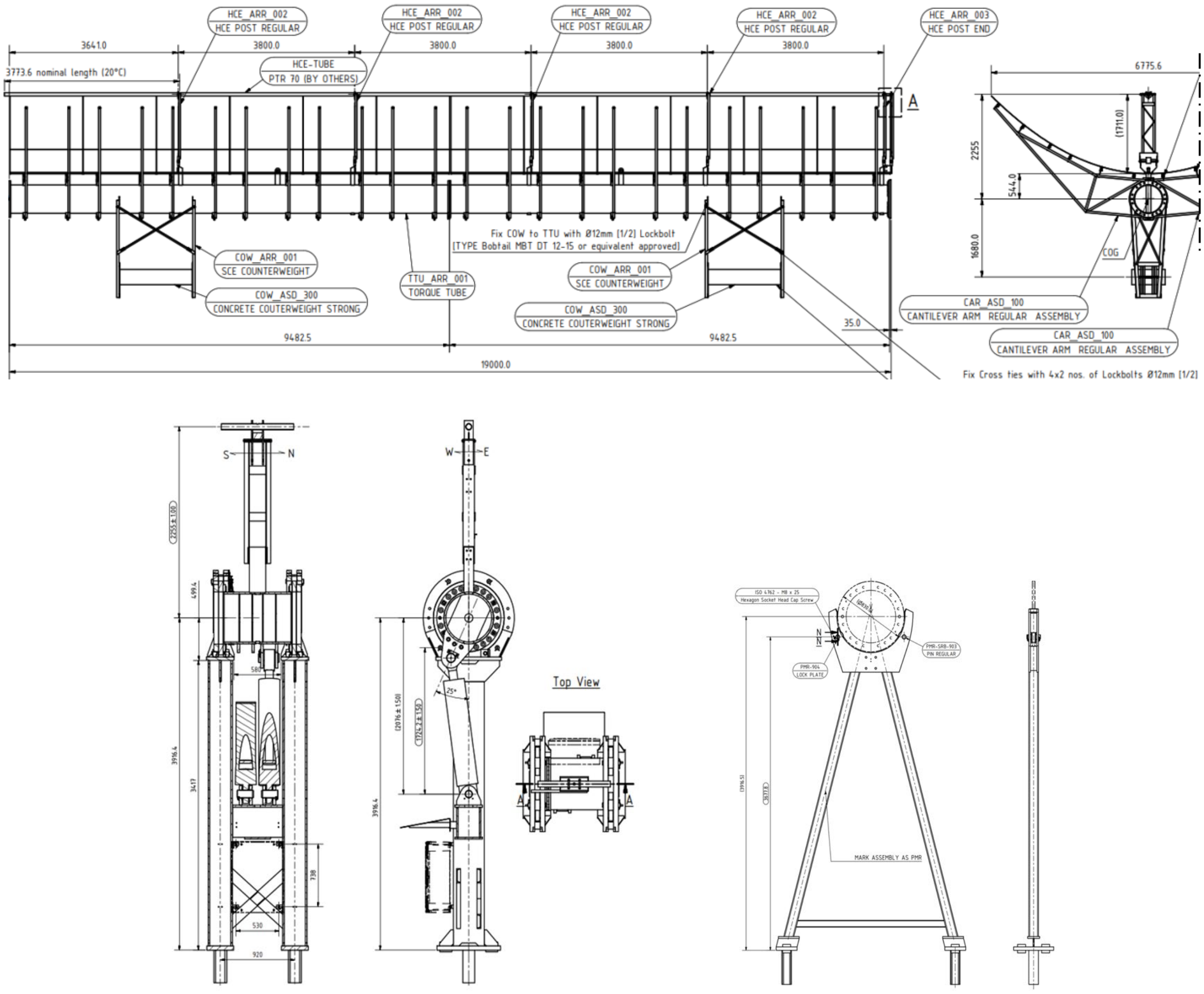


Figure 9 - Final design of Heliotrough® 2.0 © - SCE module, drive pylon and middle pylon

An erectability study for the solar field was done, including the order of the SCE installation and precise analysis of the movements of the 60-ton crane during the process in the confined area of the project site. Also, a cycle time study was done ensuring that one SCE can be assembled and installed in the field per day. The HAZOP study for the solar field has been developed over several revision stages. Also, a daily reporting scheme has been established to be followed by the supplier of metal support structure during the works on the EMSP. A running lessons-learned report, collecting points of possible design improvements based on construction experience, has also been maintained. For all systems in FLG scope, training documentations have been developed and an SCA O&M manual was created. For positioning the anchor bolts, which connect the collector pylons with the foundations, special anchor bolt templates have been designed. For the field alignment of collectors to each other after installation, a procedure has been developed and a set of special tools and hydraulic movers has been designed. Also, special HCE bellow shield insulations have been developed using prefabricated vacuum-formed calcium-silicate half-shells in order to improve the insulation at high temperatures and simplify their installation. The conceptual design, basic and detailed engineering of the cross-over pipe (COP) including compensator elements, emergency vent valve, salt spill tank and ladder to access the vent valve, as well as the connection of the REPA has been created.

All design documents have been agreed with the respective suppliers and supplier documentation as well as workshop drawings have been checked and approved. An additional specification for pulling tests of the mirror-pod glue connection (executed by the supplier) had been developed. The design documentation of the COP was provided to the other partners for the procurement of certain components. The documents with the coordinates of the collector foundations have been reviewed and a detailed list of x-, y-, z-position of each anchor bolt as well as the corresponding pedestal height was created for the subcontractor of the UEV. The design of the collector and jig foundations done by FLG's subcontractor had been submitted to UEV for procurement. The design of energy chain for the power supply cables for the impedance heating system was defined and the interfaces agreed with eltherm, including the relocation of the transformers for SOF heating. For the optical qualification of SCE modules in the balancing station, as well as for the complete collector loop after installation, flight routes have been developed and measurement data have been analyzed. The analysis of the single SCE modules was used to readjust assembly-jigs and -process. An analysis of the collector loop (in empty cold state) was done to generate a first optical qualification of the whole loop and to deduct improvements for the later measurements in filled/hot state in the follow-up project MSOpera. Eventually, check lists have been established for all procurement parts.

Control System Engineering: Functional descriptions for solar field supervisory control (FSC) system and the local controllers of each SCA (LOCs) have been created, interfaces FSC / LOC and FSC / DCS have been defined, active and passive safety features have been implemented. Flexible parametrization of salt types (e.g. density functions) was programmed. FSC programming was done on a Siemens PCS7 system, LOC programming on a Siemens S71200.

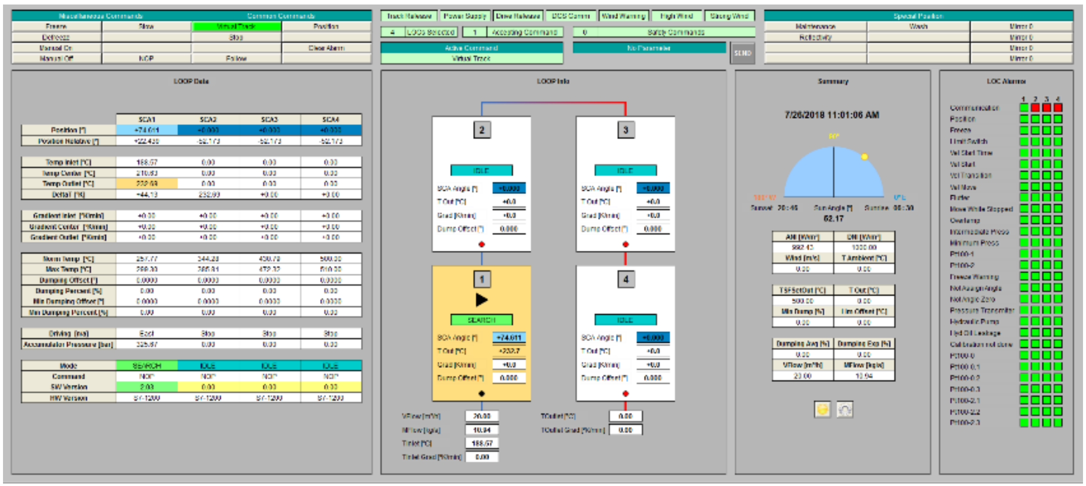


Figure 10 – Main screen of FSC user interface

Also, a human-interface-device (HID-Touchscreen) has been developed to set up the LOCs and run the collectors locally.

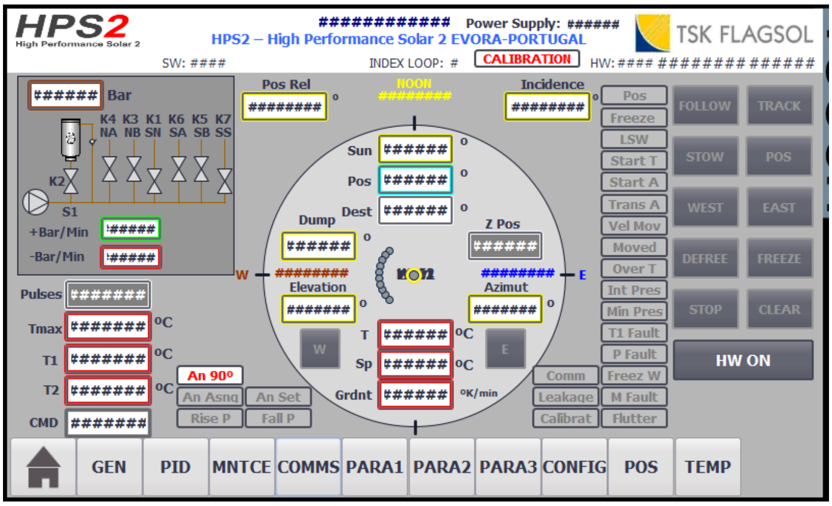


Figure 11 – Main screen of HMI for local control and configuration

The networking in solar field and the connection with DCS were specified, installed and tested. Sensor installation and calibration was done, data exchange and archival was tested, sun angle calculations and system wide time synchronization was verified.

3.3 Procurement of all collector parts and delivery to Évora

The tender to the construction of the solar field foundations was prepared. This tender already included the design of the foundations. University of Évora preformed the public tender while DLR was responsible for issue the purchase order. During the civil construction works, granite rocks were blasted to finish construction works. This construction phase also denominated as Phase 2 of works ended on July 2018.

For the main scope “Metal Support Structure” 3 offers had been received. As 2 of the suppliers drew back their offer, the order was assigned to the Spanish company Sencener of Spain for 1.3 M€. The works included manufacturing of collector and jig components in Spain, the delivery to Evora, erection of assembly jigs and assembly of SCE modules, as well as the field erection of the collectors (pylons and SCE modules). The works on site started in May 2018.

Offers for bearing flanges and supporting rollers for middle pylon and drive pylon were evaluated. The machined, induction hardened C45 components have been ordered. Requests for quotations have been sent and offers have been received for the following component: hydraulic drive system, mirror pods, bearing system drive and middle pylon, plastic parts, FSC, LOC, instrumentation (temperature, pressure, level, and position) and lifting device and control for mirror jig.

Request for Quotation (RfQ) campaigns and bid evaluations for most of the components have been completed. Purchase orders for the following components have been issued: Metal support structure, jigs, solar field assembly, anchor bolts, anchor bolt template, pylon bearing system, bolts, plastic parts, mirror pod samples, counterweights, hydraulic drives, lifting device, jig accessory, instrumentation (pressure, temperature, level), collector control system (LOC), solar field control system (FSC), drive pylon cabling, COP compensator, sealant guns. In total more than 20 individual purchase orders have been issued with a value of approx. 1.8 M€.

The following procurements activities have been completed in first half of 2018 (H1/2018): Stainless steel parts, hardened pins, cast and bent sheet mirror pods, energy chain, plastic parts, weld studs, spacer for hydraulic drive system, bearings for balancing station, motor balancing unit, pneumatic accessory, control system for motor balancing station, force sensor and amplifier for motor balancing, rollers for TTU station, special connectors, mirror bolts, sensor and communication cables, two-component glue for mirror gluing, alignment adapters for SCE installation, PPE equipment, tools, etc. More than 32 individual purchase orders have been issued.

Figure 12 - Parts for the collector assembly jigs area stored on jig foundations in May 2018

Offer comparison was done for three offers from mirror suppliers. The choice fell on Rioglass RP4 mirrors because of lowest mirror errors according to specification and lowest price.

Figure 13 - RioGlass RP4 mirrors being unloaded on site

HCEs were supplied by new project partner Rioglass. All necessary components to manufacture the receivers were supplied to RIO on time by their vendors. Main changes from the standard HCE are the new steel alloy for Molten Salt applications with increased wall thickness and new bellow components to withstand the higher temperatures, as well as a special selective coating featuring a lower emissivity at high temperatures. The prototypes dimensions have been adjusted to the Heliotrough 2 collector design with a length of 3.774 mm at ambient temperature. A mechanical, optical and physical model has been developed and validated by experiment. Manufacturing machinery and assembly process was adapted in order to assemble the special dimensions of the required HCE. Prototypes were produced and delivered to the EMSP in July 2018.

Flexible connections (REPA) were tendered, restricted to leakage-free systems due to safety reasons and requiring capability to be optionally operated with both, MI cable heating as well as impedance heating. After negotiations between DLR, FLG, ELT and the possible suppliers, the flexible connections (REPA) have been ordered, partially equipped with MI cable and all of them prepared for impedance heating from selected supplier Senior Flexonics in 12/2017 and were delivered to the EMSP in Q3/2018.

The following procurements activities have been completed in H2/2018:

MSS parts, collector small parts (pots, bolts and nuts, insulation material…), as well as erection tools and materials have been delivered to the site.

After the first batch of Middle- and Drive Pylon bearing flanges were destroyed during the hardening process by inadequate processing, the supplier delivered bearing flanges with a false corrosion protection: instead of electroplating the outer diameter area, only zinc spray was applied to the inner diameter area. A third-party supplier had to be involved to remove the existing zinc paint and to apply the electroplating corrosion protection. The specified surface hardness and roughness was then thoroughly tested after the arrival of the flanges on site .

Figure 14 - Testing of Rockwell hardness and surface roughness on bearing flanges

Components of the collector control system (encoder heads and magnetic bands for position measurement) have been procured as well as one additional LOC system in order to do torsional differential tests over one collector wing (see Chapter 6.5).

The drive pylons were delivered in a pre-assembled state after the installation and commissioning of hydraulic drives and LOC had already been executed in spring 2018 in Spanish Caceres.

Figure 15 – Two readily pre-assembled and commissioned drive pylons arriving on site

Tools for component repair and straightening benches, for steel parts deformed by welding without stress compensation, have been transported to the site.

Also, electrically isolating bushings, washers and plates were ordered, as well as more 2-components glue (due to necessary spilling volumes when changing the glue containers in the application gun).

The following procurements activities have been completed in H1/2019:

For the alignment of SCEs in the field, the previously designed set of tools (hydraulic lifting units, rotation blockers, supporting columns, etc.) have been procured with local supplier Sometambi. Further procurements: Tools for collector alignment (SCE lifting support, hydraulic jacks, PDR alignment sheet, blocker console, lifting-adapter, turning-adapter), pre-insulated pipe supports, metal support structure for COP and the HMI for manual collector movements.

Figure 16 – HMI connected to LOC for manual driving of collectors

The following procurements activities have been completed in H2/2019:

The bellow shields protect the sensitive metal-bellows of the HCE ends from concentrated radiation and at the same time insulate the HCE connection, whereas the secondary reflector reflects inclined sunrays that would otherwise hit the bellow shield, back onto the receiver. Bellow shields aluminum parts have been bought, as well as bending services to shape the latter into cans and discs before assembling them to the bellow shields with a secondary reflector out of laser-cut, PVD-coated aluminum (MIRO) with 95% reflectivity. Bellow shields insulation parts out of vacuum-shaped and baked/hardened calcium-silicate half-shells by Morgan-Advanced-Materials, have been delivered separately. The bellow shields protect the sensitive metal-bellows of the HCE ends from concentrated radiation and at the same time insulate the HCE connection, whereas the secondary reflector reflects inclined sunrays that would otherwise hit the bellow shield, back onto the receiver.

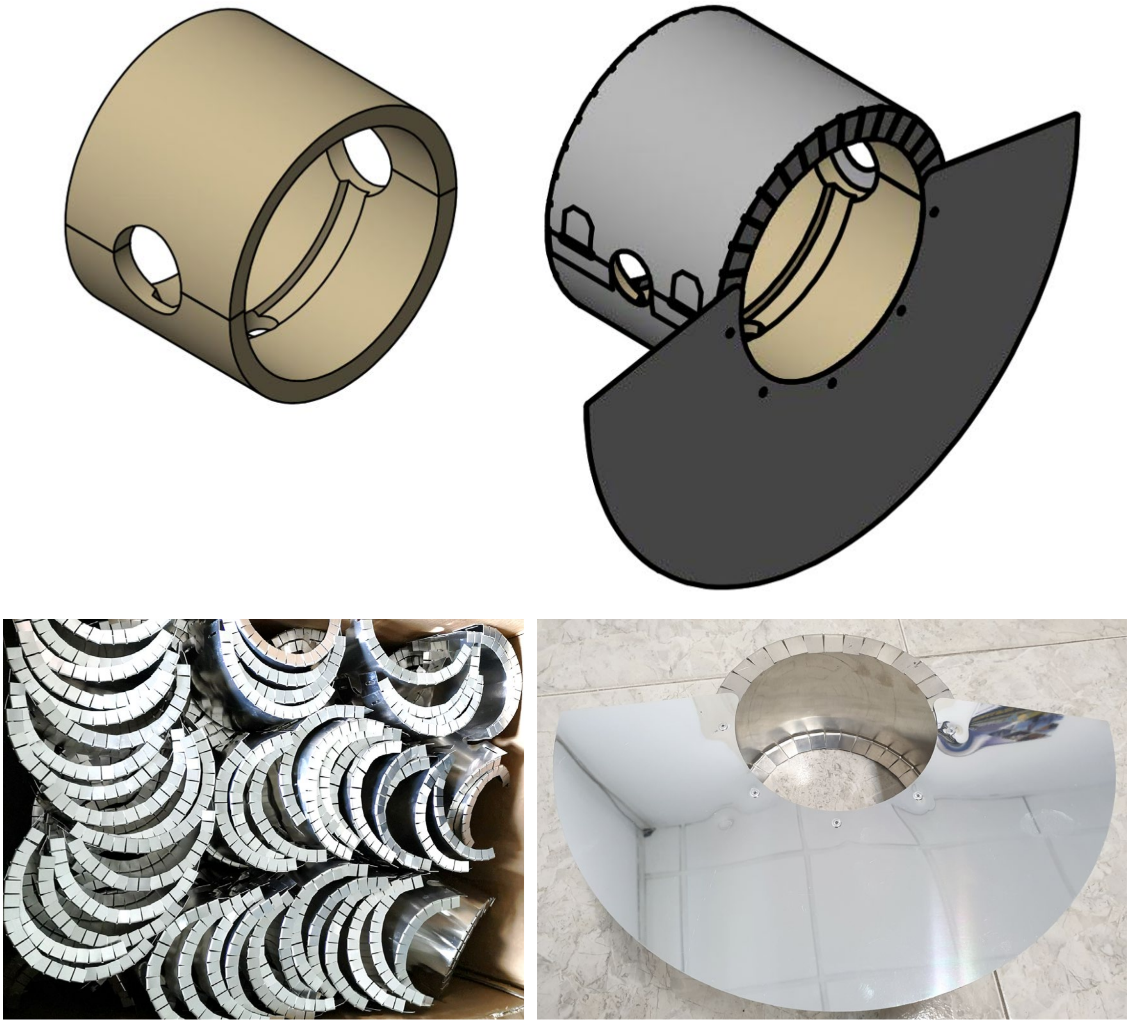


Figure 17 – Bellow shield: model, parts and finished aluminum body with secondary reflector

The following procurements activities have been completed in H1/2020:

The galvanized steel support structures of cross over pipe (COP), including access ladder and platform for access to the vent valve, as well as the CO_2 filter and the emergency tank have been requested and procured locally.

Furthermore, the energy chains for the impedance heating feeder cabling at the drive pylons and collector ends have been ordered from IGUS.

Although drainability was stated as essential in the procurement tender, additional REPA supports had to be designed, manufactured and mounted to improve solar field drainage in retrospect. First an additional support for the long thermal expansion compensating flexible hose was requested by DLR to be designed by the manufacturer Senior-Flexonics. The support was installed and tested and brought some improvements, but the two rotation-compensating flexible hoses were as well found to be sagging too much. Therefore, an additional support for one of these hoses was planned and installed, which again brought some improvements. The third and final hose however cannot be held by a fix support in the drainage position as this would be an obstacle for the rotation movement of the collector. A temporary support was designed for this hose, which is however not a really feasible solution for a commercial plant, because the installation is cumbersome. The aim of full drainability of the REPA systems could therefore not be reached.

3.4 Construction preparation

The first phase of construction works on the scope of UEV started with approval of the licensing by APA-Authorities for Water Affairs in Portugal. To the submission of the permit a certified civil engineer was contracted to compile and include all the modifications on the general layout of the facility. The set of documents together with responsibility terms was submitted to the city hall to issue the construction permit. Construction license was issued with validity until august 2020.

University of Évora was also responsible for all the adaptations on the general layout of the facility. The general layout drawing is a CAD document that presents the arrangement of the different equipment's of the plant. First change of the layout was regarding the transformation of HPS-1 in HPS2 layout. Construction phase started with the arrangement of the solar field and aligned with the needs of the construction phase. Some of the construction works done during this period was: solar field, inter-connecting piping (ICP, between collectors and salt tanks) and corss-over pipe (COP, closing the loop at the end of the collector rows) foundations, access road in the northeast and northwest, rainwater drainage system improved, construction of jig area. Also, old solar field ground screw foundations were removed and cable trays of the solar field modified.

A subcontractor responsible for the formal preparation translation of the permitting documents has been contracted (WASI, wasi Engenharia, Lda, Lisbon, Portugal) documents for the solar field permitting have been prepared and sent to the subcontractor in Portugal, the documents provided by the subcontractor have been sent to the Technical Services of the University.

The electrical project design of the DLR scope and the eltherm scope, was managed by DLR. The objective was to use of same responsible project author.

The HCE receiver manual with instructions for installation, operation and maintenance was supplied before handling and welding of receivers by Flagsol's sub-supplier IMEnergy.

Solutions for 2 foundations where rocks have been found and prevented a normal excavation have been discussed with the UEV, DLR and SBP to find an economic solution while still guaranteeing the structural integrity of the foundations.

3.5 Construction of the foundation

The tender to the construction of the solar field foundations was prepared. This tender already included the design of the foundations. University of Évora preformed the public tender while DLR was responsible for issue the purchase order. During the civil construction works, granite rocks were blasted to finish construction works. This construction phase also denominated as Phase 2 of works ended in July 2018.

Excavation and foundation work started in February 2018. In the north-west of the solar field, it became necessary to dynamite-blast surface-near granite rock volumes at some foundation positions.

FLG and SBP personnel was present during the casting of the first foundations in Évora in order to supervise the procedures. The coordinates of the anchor bolts measured by the topographers have been checked regularly.

Figure 18 – Casting of spread foundation base with reinforcements and anchor-bolt templates (red structure)

Figure 19 – Finishing of upper foundation pedestal with second formwork & casting

During the construction phase granite blocks were found where the foundations were to be built. To finish the foundation construction there was the need of blasting them.

The phase 2 of the civil construction works ended on July 2018. Quality assurance of the works was performed and accepted. A new tender to the construction of foundations of ICP and COP was prepared and submitted. A second tender to the erection of ICP piping was prepared. The tender included all the welding and erection works for: ICP, intra-connecting piping (IntraCP, connecting the two collectors in one row) and COP.

As a first step of metal support structure erection, the middle pylons were installed on the cast-in anchor-bolts according to 3D coordinates, incorporating the overall inclination of the plant of 0.15%.

Figure 20 - Installation of Middle Pylons

The supporting rollers including spherical plain bearings and pins had already been pre-installed in the middle-pylon heads before. As a second step the Drive Pylons have been erected and the fixed-end-pipes on the drive pylon head have been aligned with a special alignment jig.

Figure 21 – Installation of Drive Pylon

As a last step, the alignment of all pylons with targets and total station was completed along an inclination of 0.15%.

Figure 22 – Alignment of the Pylons

3.6 Assembly of solar collector elements (SCE)

The installation of the jigs for the SCE assembly was completed with a delay since the subcontractor did not adhere to the specifications and the required tools and measurement equipment was not on site to install the jigs accordingly. The fine alignment of the jigs was done and checked with a laser tracker and the final coordinates report has been checked by subcontractor SBP.

Figure 23 – Quality control of the Assembly Jigs with Laser Tracker

All mechanical systems for the assembly such as lifting columns or turning and balancing unit, have been commissioned and tested by Flagsol and SBP.

Figure 24 – Completed Jig area with central 60tons crane

The accuracy of the delivered MSS parts did largely not comply with the specified requirements. Most of the cantilever arms were considerably bent due to uncompensated welding stress, which did not allow to place them in the structure-jig. Also, deformations of such magnitude would lead to excessive stress in the mirrors when installed.

Figure 25 – Deformation of cantilever arms due to uncompensated welding stresses

Straightening tools and devices have been planned and installed on site in order to correct the parts.

Figure 26 - Straightening bench for cantilever rectification

The deformation of steel parts led to a very complex rectification campaign. 100% of all 1728 cantilever arms had to be checked, and the vast majority had to be bent manually into the specified shape. Also, 100% of the 72 counterweight supports had to be straightened.

About 60% of all torque tubes showed tolerance exceeding length deviations and their end flanges orientation were out of specification, so those torque tubes had to be transported back to Spain, disassembled, pickled (de-galvanized), re-welded and re-galvanized. After that, an extensive measurement campaign had to be done on site to firstly establish a known status and secondly find the right tube-halves for optimized torque tube combinations. As the tubes were lying in the plain sun and temperature differences around the tube circumference were up to 40°C, the measurements had to be done 4x (on the sides and on up- and downside), always combined with taking the respective temperature of tube surface and the temperature of the class 1 measuring tape at that point in time. In the later evaluation, all length measurements had to be corrected against tube- and tape-temperature and normalized for 20°C.

Figure 27 – Temperature-corrected measurements of tubes for optimized TTU combinations

In parallel to the straightening of steel components, the first SCEs were assembled.

In the following, a brief description of the assembly- and field installation process is given (only main steps):

(1) Lift the two halves of torque tubes (TTU) into a first precise alignment formwork (“jig”), orient them, connect them, attach bearing flange, attach positioning tools (“universal traverse”) at both ends.

Figure 28 – Torque Tube assembly and installation of Universal Traverse

(2) Lift the full TTU into the neighboring steel structure jig and adjust the front end flange using the universal traverses on the reference bearing points.

Figure 29 – TTU flange adjustment in the steel structure Jig

(3) Place all 48 cantilever arms (CAN), so that the tips of the mirror connection rods are in a defined position and tighten the bolts.

Figure 30 – Installation of the cantilever arms in the eSteelStructure Jig

(4) Connect glue pods to mirrors (6 each) and place 48 mirrors in the mirror jig

Figure 31 - Installation of glue-pods and placing the mirrors in the mirror jig

(5) Lift the steel structure out from the steel jig and move it over to the mirror jig. Lower the SCE steel structure down with the lifting system, dipping the rods into the pods (not touching).

Figure 32 – Moving the SCE to the Mirror Jig and lower it down with the lifting system

(6) Fill pods with glue. Because of sunshine-induced deformation of the steel parts of collector structure and jig, the gluing was done preferably at night, at cloudy sky, or with sun protection blankets draped to block the sun.

Figure 33 – Gluing of the rod-pod-connection of the mirrors at cloudy sky and at night

(7) Attach counterweight and their supports and HCE supports posts to steel structure

Figure 34 – Installation of counterweights (left) and HCE-posts (right)

(8) Lift SCE out of the mirror jig, move it over to the balancing station and use the 2-axis-adjustable counterweights to balance the SCEs.

Figure 35 – Move to the Balancing Station and balancing with Counterweights

(9) Prepare the balancing station and the SCE module with targets and execute Qfly optical qualification with drone camera

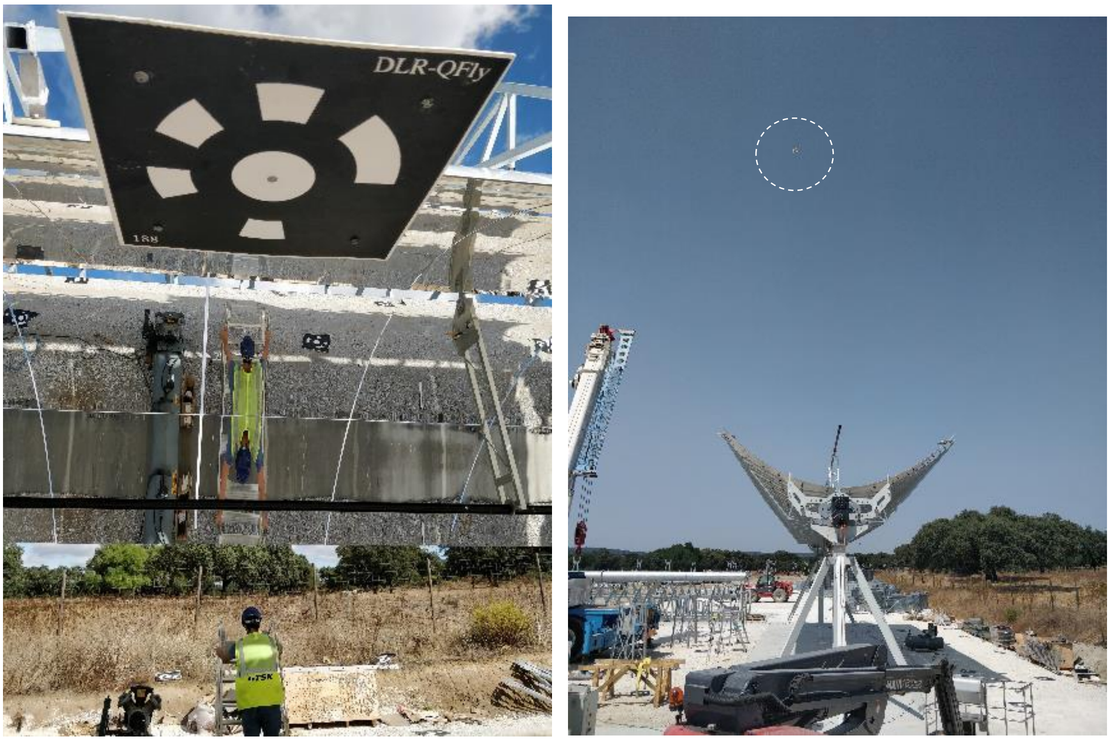


Figure 36 – Positioning of targets (left) and execution of Qflights with DLR's drone (right)

(10)Lift the readily balanced SCE module from the balancing station onto the trailer, and move it to its installation location in the field.

Figure 37 – Transport of the SCE modules in the field with crane and trailer

(11)Lift the SCE module into its target position and temporarily tighten the bolt connections.

Figure 38 – SCE modules placed and temporarily fixed in their position

(12)Use hydraulic jacks, alignment tools, leveling device and scale-rod in order to align the SCE modules with the drive pylon as well as with the adjacent SCE modules. As the mirrors are glued to the steel structure in a high-precision negative mold, the alignment of the SCE modules is done with the mirror-edge method, using a special alignment rod and levelling device.

Figure 39 – Collector alignment with mirror-edge method

The contracted steel structure supplier failed to deliver the required quality. Heavy deviations from design with both, the Assembly-Jig-Structures as well as with the pre-fabricated Collector Components, led to extensive modification, rectification and partly re-manufacturing, which then resulted in heavy delay of some months. This required a critical decision: as no field erection is possible in Evora during the winter months, because of the ground being too soft to support the 60tons crane that lifts the collectors into place, the procedure was accelerated in such a way that two collectors a day were assembled and installed.

All works that can be done with light equipment, especially the alignment of the collector elements to each other, were postponed. This decision was supposed to accelerate the completion of works and the deployment of heavy-duty equipment in the field, even though it was clear that it meant extra works for the post-construction alignment.

In November 2018 all 36 SCE were mounted, just in time before the rain season started.

In February 2019, the alignment of SCA2 was done exemplarily by Flagsol's team and special alignment tools, as well as an alignment procedure has been developed to be executed by a service provider later-on.

After completion of the structural assembly of the SCAs, the installation of secondary elements like HCE-Bellow-Shields, Energy Chains for the Impedance Heating Cables at Drive Pylons and Double-HCE-End-Posts, as well as Irradiation Shields at the HCE-End-Posts and HCE-Fix-Posts were completed.

At the Cross-Over-Pipe structure, an Emergency Tank was installed, as well as an Emergency Access (Ladder with fall-protection plus pedestal with handrails) to reach the drainage valve.

Finally, the installation of the temperature sensors throughout the solar field and pressure sensors were installed, isolated and connected. All in- and outlets of single SCAs were equipped with triple temperature sensors. Further to that, the Magnetic Positioning Sensors for the tracking control, the so-called Encoders and the related Magnetic Bands, had been installed with spring-supported sliding bracket holders, especially designed by Flagsol to compensate structural tolerances and the movements under operation.

Aside of the actual solar collector structure, a shelter for maintenance works close to the office building was erected, consisting of 2 distanced, parallel 20-foot-containers and a traversal roof construction, creating a covered work-area underneath.

The adapter tube-stumps for connecting the REPA to the SCA ends, were installed to the eight SCA ends.

The works on the SCA alignment started in H3/2018. It proved to be highly complex, due to the following reasons: Firstly, the alignment had to be postponed towards after the winter season and therewith separated from the crane installation. Thus, the alignment had to be done without a crane keeping the torque tube of the SCE straight and their end flanges parallel and vertical. As a consequence, massive bending of the SCE tubes and inclined end flanges made the alignment nearly impossible and provoked massive stresses in the upper bolt connections of the flanges during tightening. Also, the final bolt tightening changed the tediously reached alignment again that way. So, the alignment required additional tools to provide the functions otherwise provided by the crane, namely keeping the torque tube straight, the flanges parallel and the found alignment stable during bolt tightening. Therefore, new alignment tools such as hydraulic lifting columns, turning- and blocking adapters for the flanges were designed and manufactured and respective completions and modifications of the alignment procedure was introduced. After the northern half of SCA2 had been aligned on a trial basis by the Flagsol team in February 2019, the rest of the loop was then aligned by Flagsol's subcontractor. Rioglass carried out support on site during HCE's welding and installation of triples in the solar collectors.

Figure 40 – TIG-welding of the HCE triples with forming gas

Intensive communication with the HSE responsible the EMSP was required to solve all issues regarding permits and documentation for the people working on site.

In the further course of proceedings, several HCE posts have been observed getting loose. The root cause for the lack of friction grip in the HCE post/foot connection had been a change from hydraulically pre-stressed "Huck-Bolts" to mechanically pre-stressed "HV-Bolts" due to a Fixation of HCE

3.7 Completion of the salt system

The rotation and expansion performing assemblies (REPA) were tendered by DLR and subsequently the company Senior Flexonics was contracted for the manufacturing of 9 REPA systems consisting of three metal hoses each. Two metal hoses are performing the rotation movement and the third one the movement of the receiver tubes thermal expansion. During manufacturing 5 REPAs were equipped with MI heating cables by eltherm in the workshop of Senior Flexonics, while the remaining 4 were foreseen for impedance heating. Also, the MI cable heated REPAs were designed by Senior Flexonics to enable impedance heating as a second option in case MI cables would not perform as planned. After Manufacturing the REPA systems were delivered to site. The welding works for installation of REPA/HCE were as well tendered by DLR and the company IMEnergy was contracted for these works.

Due to the long storage time of the 6m long immersion salt pumps on site since the stop of the HPS project, the Salt pumps had to be refurbished at manufacturer's workshop Rheinhütte in Germany and were afterwards delivered back to the EMSP. Afterwards the five salt pumps were installed on their supports and leveled with the required precision.

The tender process to the erection of the interconnecting piping was restructured and the detailed engineering for ICP erection was made by the company Technoedif. The design was later reviewed and approved by Portuguese's notified body - ISQ. The documentation for the different tenders regarding the phase 3 of works was prepared and submitted by UEV.

First tender issued was regarding civil foundations which was awarded to local civil construction company Salvobra. Then a sequence of tenders was launched namely regarding welding, installation of heat tracing and insulation of ICP, Intra-CP and COP. The companies MASA, Eltherm Spain and Bilfinger Prefal were the companies/suppliers responsible for the execution of the mentioned works.

The HCEs were welded as triplets and installed in the collectors. The triplets were then welded together in the collectors. After installation nondestructive tests (NDTs) were performed by the notified body. The installation of the remaining REPA systems was overtaken by the University and executed by their subcontractor during the ICP welding works.

Also during this period took place the acquisition of some components such as preinsulated calcium silicate CaSi shapes and pipe supports (hanger and clamp supports). Inspection and test plan for control and shut off valves on salt side was performed.

3.8 Electrical installation, remaining tasks and pre-commissioning

The solar field electrical design was merged into the overall electrical design of the HPS2 plant. The grounding system of the solar field was designed according to the recommendations of DLR's subcontractor SIEMENS Portugal. The installation was executed by different subcontractors of the University and eltherm according to the SIEMENS design.

PVC pipes were installed as underground cable ducts for the solar field power cables. Unfortunately, these pipes were damaged during solar field erection by the autocrane and had to be repaired. After this repair the power and signal cables of the solar field as well as several sensor-supports were installed.

To ensure UPS power supply for the DCS workstations in the control room an additional UPS power cable and distribution cabinet was planned by DLR and contracted by FLG.

Regarding the installation of instrumentation: UEV has installed temperature, pressure sensors, ultrasonic flowmeter on salt side.

Electrical heat tracing on ICP, IntraCP and COP was installed and commissioned.

Modifications to the electrical cabinets was made in according to the specifications of the design responsible project author.

4. Design of the solar field heating system and assembly of the cable technology

4.1 Identification and implementation of trace heater method for the solar field

4.1.1 Identification

HCE heating

The HCEs and associated pipework of a parabolic trough solar power plant need to be preheated / maintained at a temperature above the freezing point of the solar salt prior to filling and also during the draining process. The typical design of the HCEs consisting of a coated inner tube arranged inside an evacuated glass envelope does prevent the use of traditional heat tracing via heating cables arranged on the surface of the fluid carrying tube.

Instead, voltage is applied directly to a suitable length of interconnected HCEs which heats the inner tubes via their electrical resistance due to Ohm's law (with $R = U / I$ and $P = U * I \Rightarrow P = U^2 / R$) [4].

The voltage required hence depends on the required power to compensate the heat loss of the tube and on the resistance of the tube (both at the desired maintain temperature) as well as on the resistance of the power cables from the impedance heating transformer to the feed points on the interconnected HCE tubes (at maximum ambient temperature).

At the same time, the required voltage needs to comply with voltage limits defined by local electrical codes.

As maintain temperature, tube resistance and tube heat loss are given features linked to the chosen salt and HCE types, heating circuit length and cross section of power cables can be used to influence the required voltage.

However, due to the modular grid of the mirror elements (19 m), the preferred heating circuit lengths had been 76 m and 95 m. The main task of the impedance heating design was to determine the voltage required for those circuit lengths and to verify compliance with the voltage limit in force. It was assumed that the highest voltage will be required in case of an empty pipe because this will have a higher resistance than a pipe filled with liquid salt. The voltage determination was then done based on the following application data:

Maintain temperature	290°C as per project specification
Maximum ambient temperature	40°C as per project specification
HCE specific heat loss at 300°C (p_{SCA})	120 W / m as per HCE data sheet
HCE wall cross section (A_{SCA})	468.6 mm²
HCE material	1.4404
Specific resistance of HCE material (r_{SCA})	0.75 Ohm mm² / m at 20°C; 0,95 Ohm mm² / m at 300°C as per 1.4404 data sheet
Specific resistance of copper (r_{Cu})	0.0182 Ohm mm² / m at 20°C; 0.0197 Ohm mm² / m at 40°C
Specific resistance of solar salt	16470 Ohm mm² / m at 300°C
Voltage limit	50 VAC as per Portuguese regulations

Heating circuit length (L_{SCA}) 95 m

Power cable length (L_P) 120 m

With $P_{SCA} = U^2_{SCA} / R_{SCA} = U^2_{SCA} / (L_{SCA} * r_{SCA} / A_{SCA}) = p_{SCA} * L_{SCA}$

$=> U_{SCA} = L_{SCA} * SQRT (p_{SCA} * r_{SCA} / A_{SCA})$ => $\underline{U_{SCA} = 46.86\ V}$

For the given geometry, the required voltage to be applied to the string of receiver tubes is 46.86 V, which is still below the voltage limit of 50 V. The power cable cross section A_{Cu} needs to be chosen in such way that the voltage drop is not exceeding 3.14 V:

With $I = U_{SCA} / R_{SCA} = U_{SCA} / (L_{SCA} * r_{SCA} / A_{SCA}) = U_P / R_{Cu} = U_P / (L_P * r_{Cu} / A_{Cu})$

$=> A_{Cu} = U_{SCA} * L_P * r_{Cu} / (U_P * L_{SCA} * r_{SCA} / A_{SCA})$ => $\underline{A_{Cu} = 183\ mm^2}$

The results are a little bit conservative (as heat loss and 1.4404 resistance are considered for 300°C instead of 290°C) and show that a heating circuit length of 95 m is just possible for the given application data.

In order to substantiate the calculated voltage results, a practical test on 4 interconnected HCEs has been made. The voltage actually applied to the ends of that HCE strip and the wall temperature inside the HCEs have been measured and the resistance calculated based on the measured temperature. For resistance calculation, resistance measurements documented in the "CINDAS Report No. 45" of September 1977 have been used [5]

.

Temperature test on string of 4 HCEs (M. Schumacher 11 Jan. 2017)									
measured values				results					
heated length (m)	voltage (V)	current (A)	HCE temperature (°C)	total power (W)	specific power (W/m)	HCE heat loss as per data sheet (W/m)	hot resistance calc. U/I (Ohm)	hot resistance Cindas (Ohm)	calculated voltage based on HCE data shet heat loss and Cindas resistance (V)
16,94	8,17	230,8	305	1885,6	111,3	125	0,0354	0,0349	8,53

Table 4.1: Results of Temperature Test

The test results showed that a stabilization temperature was reached with a voltage slightly lower than the calculated voltage, indicating that heating circuits could be designed based on the existing data.

As a precaution against overcurrents, the influence of the electrical resistance of molten salt needs to be considered. With the given cross sections of HCE wall and free inner area and with the nominal resistances of salt and pipe material at a temperature of 300°C, the electrical resistance of the salt in the HCE is approx. 10,000 times higher than the resistance of the HCE pipe wall and can hence be neglected in the design calculations.

REPA heating

In contrast to HCEs, REPAs are subject to bending and do not have a glass envelope for thermal insulation. The bending is however slow and the bending radiuses are moderate, which makes the REPAs eligible for traditional heat tracing with mineral insulated heating cable. However, following a suggestion by DLR, some of the REPAs were chosen for implementation of impedance heating systems so that pros and cons for two different solutions could be identified.

To the impedance heated REPAs the same design principles apply as to the impedance heated HCEs. As in case of the REPAs no exact heat loss figures were available and the fluid carrying tube consists of sections of different cross sections and designs (straight wall tubing, corrugated tubing with braid), the required voltage was more a result of assumptions than calculations:

a) REPA electrical resistance (total and sections) was taken from measurements at the REPA manufacturer’s facilities
b) REPA specific heat loss at 290°C was assumed to be 1.5 times that of a pipe of same dimensions insulated with mineral wool

A chance to verify heat losses by testing did not materialize prior to the REPA manufacturing. Due to the uncertainties involved, multiple taps were then chosen for the secondary side of the transformer in order to be able to choose from different voltages as appropriate.

In case of the REPAs with traditional trace heating, heat loss was assumed in the same way, but only one supply voltage per heated REPA segment was considered as the power is generated in the heating cable and differences in pipe wall cross sections do not affect power output in this case.

Cross over piping and instrumentation heating

Cross over piping and instrumentation are eligible for traditional heat tracing with mineral insulated heating cable. This was designed for a 230V power supply according to established industrial standards.

4.1.2 Implementation

HCE heating and temperature control

As the individual strings of receiver tubes would not be isolated from each other (e.g. by use of flange isolators), the heating circuits had to be operated in pairs back to back similar to “midpoint feed systems” described in IEEE 844 Section 8.3.4. This required each heating circuit in the pair to have identical length and resistance and to be fed with identical voltages and phases, hence leading to a symmetrical design of the solar field, where each SCA consists of two like sections (one on each side of the drive pylon).

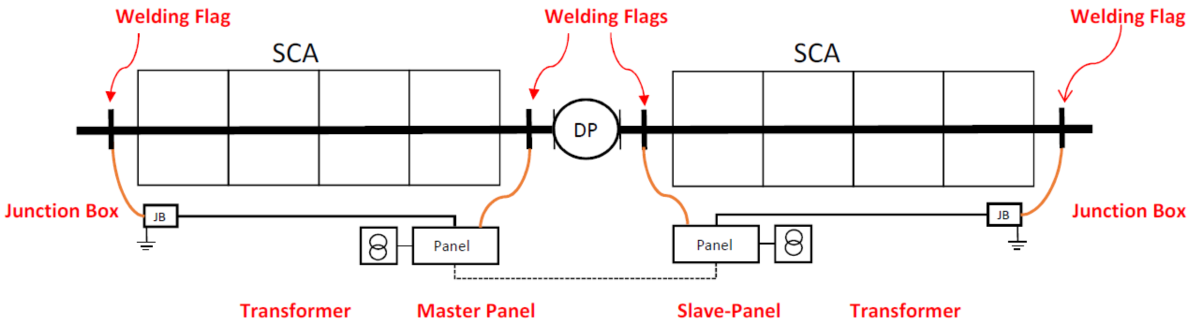


Figure 41 Impedance Heating Circuit Arrangement

Each heating circuit in the pair has its own transformer in order to keep the nominal current of the transformers low and also to avoid possible requirements regarding power cable cross sections being able to cope with high currents in case one of two strings of receiver tubes is disconnected from a common transformer. For the sake of interchangeability, the 95 m and the 76 m impedance heating circuits use the same type of transformers. In case of the 76 m circuits, choke coils are connected to the transformers to reduce the output voltage level.

In order to determine the involved currents, possible impact of the conductivity of molten salt needs to be considered. For the given HCE geometry and at 300°C, the electrical resistance of the salt in the HCE is approx. 10,000 times higher than the resistance of the HCE pipe wall and can hence be neglected in the design calculations.

In the same way the design of the HCEs prevents a placement of traditional heat tracing cable, it also prevents the placement of temperature sensors. The insertion of a length of sample pipe with standard thermal insulation with similar heat loss at 300°C as the glass envelope of the HCEs was also not possible due to interference with the modular grid of the HCEs and mirror elements. In consequence, the HCE temperature is being determined by calculation of the resistance of the string of HCEs (that form the impedance heating circuit) from the actual applied voltage and resulting current.

REPA heating and temperature control

Similar to the HCE impedance heating circuits, two REPAs of same length and resistance had to be operated back to back, so the REPAs next to each side of the center pylon was chosen. Due to the different tube wall cross sections in the rigid and flexible REPA sections, two Pt100 sensors are used for temperature control in each impedance heated REPA (one located in a rigid section and one in a flexible section).

In case of REPAs with traditional heat tracing there is still a low risk of heater failure due to REPA movement. For this reason, the heat tracing has been subdivided in 5 different circuits, so failure impact is limited and failure localization and detection is made easier.

Cross over piping heating and temperature control

The cross over piping connects the two rows of SCAs and consists of a plain pipe with conventional thermal insulation. Placement of traditional trace heating and temperature sensors is no problem here. Heating circuits are fed with 230V and controlled via standard temperature controllers.

4.2 Integration of the solar field control into the control equipment of the plant

All heating circuits are connected to a main field distribution panel (FDP) which hosts an industrial PLC system and associated I/O modules. On the PLC system the proprietary eltherm “TraceVision” software controls the heating circuit and provides data exchange via Profibus to the Siemens T-3000 DCS.

As the solar field heating control system operates autonomously, data exchange with the DCS is for visualization purposes. However, operating staff can access the TraceVision system via ethernet and can adjust settings and activate or deactivate individual heating circuits if desired.

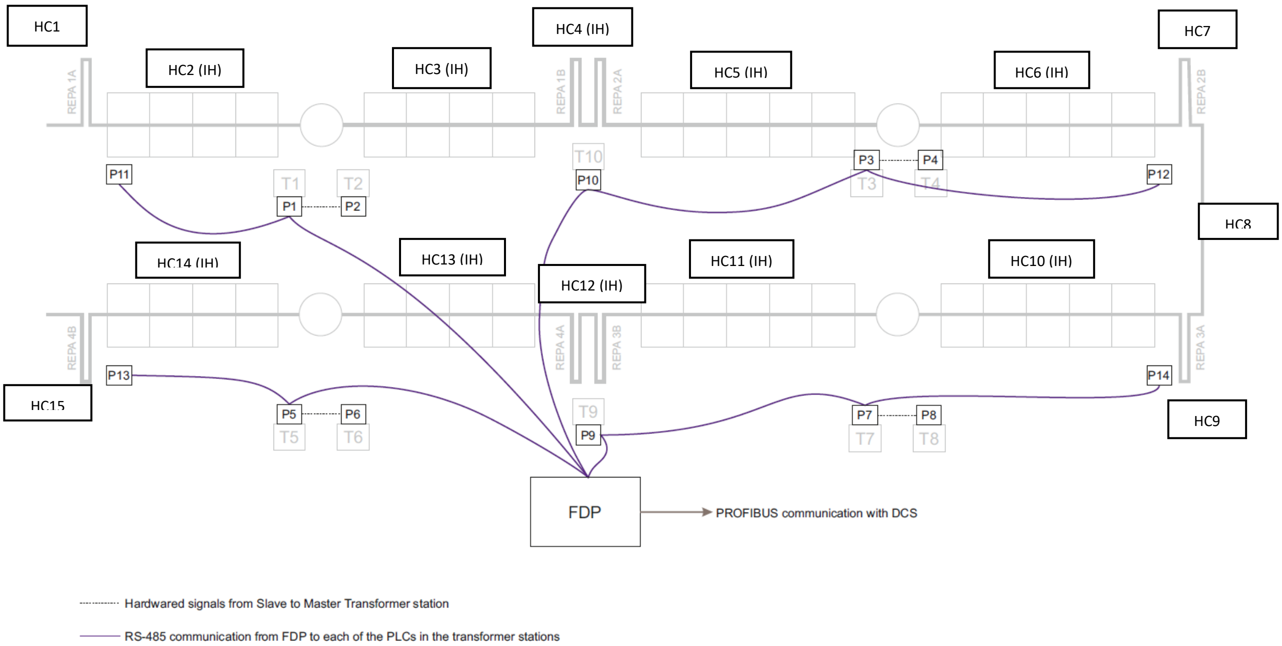


Figure 42 Solar Field Heating Network Topology

5. Completion of the steam generation system

5.1 Current state of the water/steam cycle

The complete SGS was designed and delivered to the site by Steinmüller Engineering GmbH already in the predecessor research project. The complete SGS was delivered pre-installed on two steel skids. One skid accommodates the vertically arranged heat exchangers (SG skid), the second skid the associated main equipment of the water/steam cycle e.g. for feedwater supply and steam condensation (condenser skid).

The heat exchangers on the SG skid form a 1.7 MWth once-through type steam generator system for molten salts. The special designed steam generator is optimized for highly dynamic operation and frequent load changes. The SG of the pilot plant consists of a combined economizer/evaporator, a separator and two superheaters (SH). The Eco/Eva as well as the SHs are conceived as counterflow heat exchangers with water/steam on the tube side and molten salt on the shell side. The economizer/evaporator comprises a helicoidally arranged heating surface inside a cylindrical vessel. Both, SH 1 and SH 2 are U-tube heat exchangers in a cylindrical vessel. All the three heat exchanger vessels are arranged vertically, placed in an upright position in a steel-frame structure. SH1-heat exchanger has a total height of ca. 5 m and the SH2-heat exchanger has a total height of ca. 8.2 m. The mechanical design bases on a salt inlet temperature of max. 600°C. In operation hot salt flows successively through the shell side of SH 2, SH 1 and economizer/evaporator until being cooled down to a temperature nearby to 290°C. The water in the tube side comes into the economizer/evaporator, evaporates and leaves the SH 2 as superheated steam. During start-up the separator ensures that no water comes into the SH stages.

The condenser skid is an arrangement of components which are destined to cool down the superheated steam (produced by the SG) and to condensate it in order to keep the water/steam side of the molten salt test loop working in a closed cycle. The condenser skid consists primarily of a feedwater tank, a feedwater pump, an electrical heater, a condensate tank, a condensate pump, an air-cooled condenser, a blowdown vessel, and a set of control valves and interconnecting piping placed in a steel supporting structure with a height of about 11 m.

The feedwater pump is a positive displacement pump (plunger pump) equipped with a frequency converter. The electrical heater is a process flow heater composed by a horizontal pressure vessel with an intern electrical heating bundle. The electrical heater is meant to heat the BFW flowing through it. The electrical heater makes sure that during the start-up the BFW reaches a temperature above 260 °C. This is a necessary measure to prevent problems because the molten salt inside the SG could crystallize, if colder water flows into the economizer/evaporator under operating conditions.

Figure 43 Installation of grating, ladders and platforms on pre-fabricated SGS skids

5.2 Assembly of the water/steam cycle

At the beginning of the HPS2 project the pre-fabricated SGS skids had been already mounted on the final location. However, several works were needed to achieve mechanical completion of the SGS.

To facilitate transport, not all equipment was installed prior to shipping. In a first step therefore lacking gratings, ladders and platforms had to be installed. For realizing the flow of molten salt and water/steam between the skids and the molten salt storage system, the interconnecting piping was installed. Thereafter sensible or protruding equipment was installed like safety valves and silencers.

5.3 Installing the measurement equipment

To avoid damaging sensible equipment during shipping and finalization of mechanical completion, the instrumentation was not pre-installed but assembled on the site. The installation includes for example level indicator on the feedwater tank and pressure & temperature sensors on both skids. Moreover, not only the sensors but also the associated I&C cabling including cable racks were provided and mounted.

Furthermore, the generation and distribution of instrument air and feedwater monitoring and conditioning was installed on site.

During the assembly it was recognized that due to a change of project partners not all components of the electrical heat tracing of the water/steam cycle were covered in the scope of deliveries so far. The SGS was already equipped with electrical heat tracing but the power supply and control system were lacking. Therefore design and supply of control cabinet for SGS heat tracing was organized by DLR.

5.4 Pre-commissioning

The SGS racks have been delivered some time before start of the HPS2 project. To ensure that the components were not damaged during stand-still and available for commission, critical components were inspected and where necessary refurbished.

After mechanical and electrical completion and successful completion of all related test for the pressure equipment, the cold commissioning plan, as elaborated by the partners was started.

Figure 44 Completed SGS skids.

One major aim of the pre-commissioning was, to check the W/S cycle as thoroughly as possible before filling in molten salt the first time. After checking all components in cold state, the preheating of the W/S cycle was initiated for testing. For preheating, water from the feedwater tank is pumped by the feedwater pump through the energized electrical heater, is heated up there and is then recirculated through the economizer/evaporator and separator back to the feedwater tank. In this mode, the water gradually heats up. Pressure also gradually increases once the feedwater temperature increases above 100°C. Target of the preheating is to reach a feedwater temperature well above the solidification temperature of the molten salt. For Solar Salt preheating up to 270°C is envisaged.

As the feedwater was heated up and pressure increased, it was found that leakage at the piston seals of the feedwater pump increased as well. Some leakage at the seals is required for piston lubrication. However, at elevated temperatures and pressures leakage increased drastically and it was found, that pistons and seals got damaged.

Figure 45 Damaged plunger of feedwater pump after leakage

After evaluation by the partners and consultation of the manufacturer, it was anticipated that this is a systematical weak point of the used plunger pump working with a liquid at its boiling point. A technical solution promising a sustainable repair of the existing pump could not be identified. Therefore, it was decided to cease the commissioning of the SGS system until a new feedwater pump is installed. This is expected to be realized in a follow-up project.

It has to be mentioned in this context, that this encountered problem is not representative for water/steam cycles in commercial applications. Feed water pumps in commercial power plants are not plunger pumps but centrifugal pumps. Centrifugal pumps have proven to provide reliable service in this application. However, the small size of the test plant and the therefore relatively low feedwater mass flow dictated the usage of a reciprocating pump in this specific application.

6. Process Engineering and cold start-up of the plant

6.1 Process engineering description of the overall plant

In this chapter the development of the process setup, the process description is described. The plant is designed to demonstrate and mimic the behavior of a full CSP plant with the exception of a turbine/generator. A turbine is not installed as this equipment is regarded as state-of-the-art and there is no need to demonstrate it. In the following paragraphs we split the description of the entire process into two parts: the salt side that comprises the solar field, thermal energy storage and steam generating system inlet; and the water-steam-side that comprises the steam generator and the condenser.

6.1.1 Salt Cycle

The salt side itself can be split due to the service of the thermal energy storage system: the solar field and the feeding of the steam generating system. The thermal energy storage system (TES), consisting of a Cold Tank and a Hot Tank, serves as interface. In the following table, the operation modes are described.

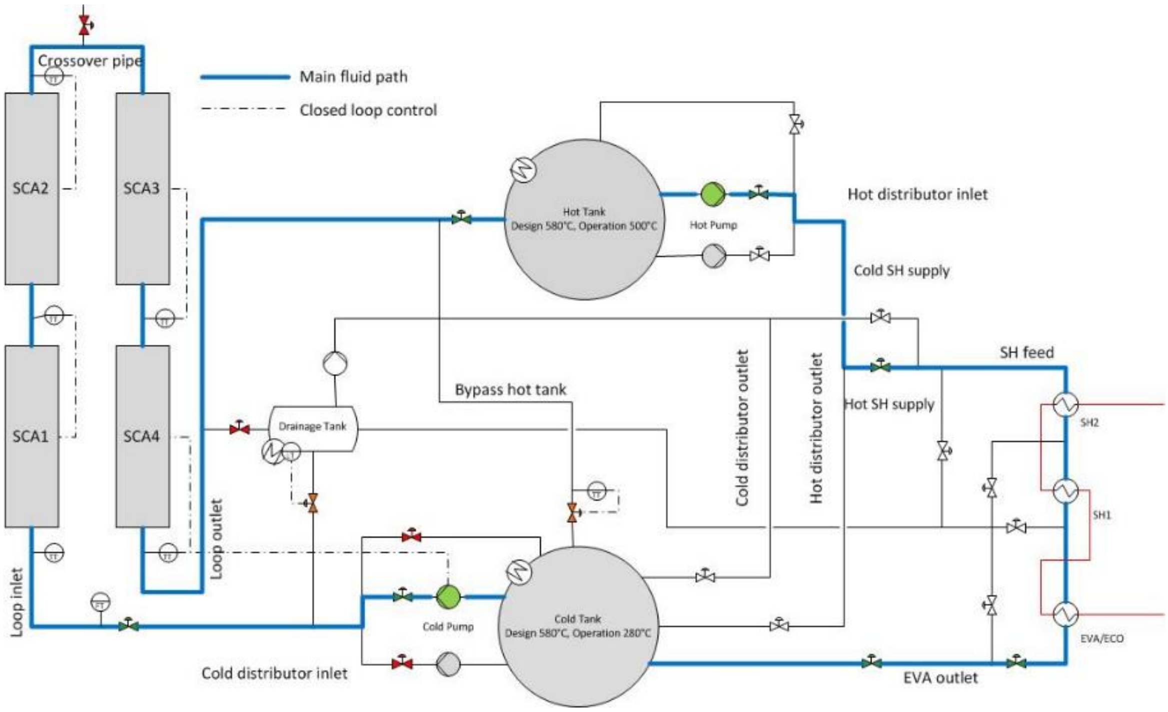


Figure 46 Process Overview Salt Cycle

Operation Mode - Solar Field Start-Up

Salt is circulated via the Cold Tank through the Solar Field. The Solar Field collectors are tracked. Neglecting density variations, the level of the Cold and Hot Tank remains constant.

The irradiated Solar Field will gradually increase the HCE temperatures and therewith the salt outlet temperature (inlet process temperature 290°C). The circulation will be maintained until a threshold temperature measured at outlet of the Solar Field is reached. With reaching the threshold temperature, the mode “Normal Operation” is entered.

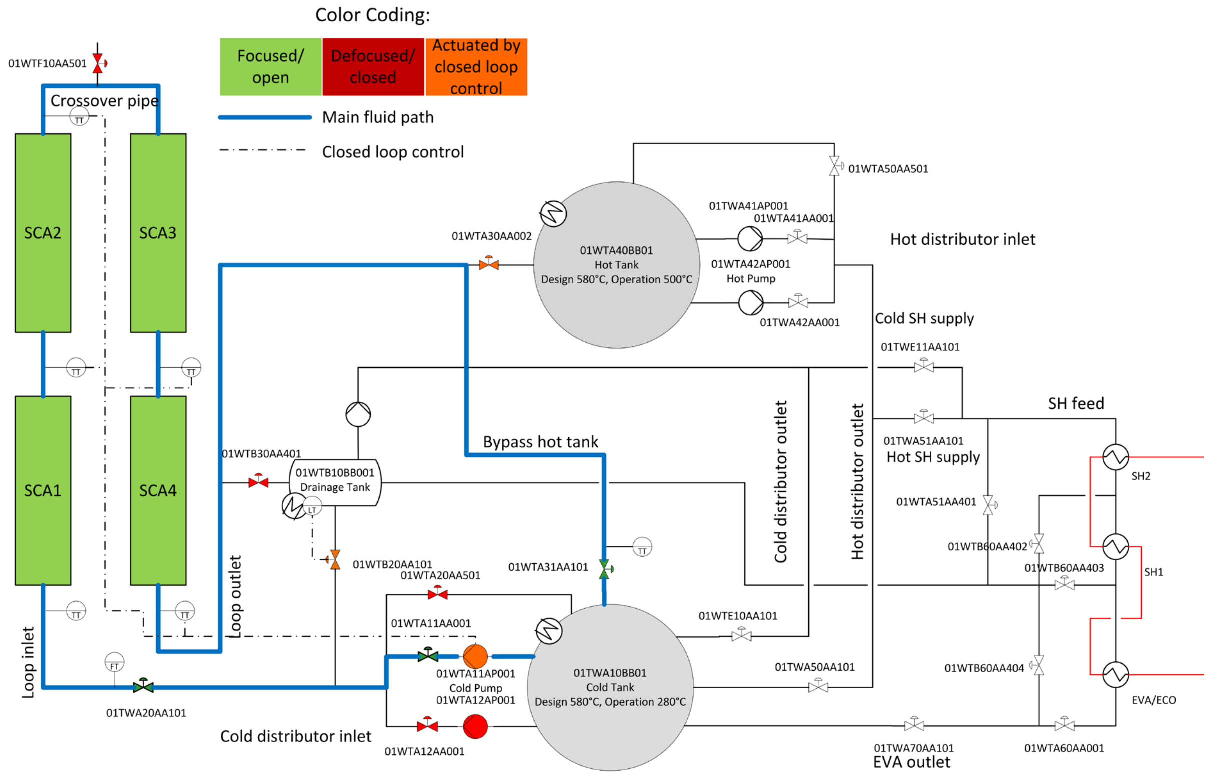


Figure 47 SF Start-Up Process

Operation Mode - Solar Field Normal Operation

The mass flow is directed from the Solar Field into the Hot Tank of the TES. Now salt mass is transported from the Cold Tank, heated up in the Solar Field and transported to the Hot Tank.

Temperature control is done in a combination of mass flow variations and partial defocusing. In case of a completely charged Hot Tank, the Solar Field will be defocused.

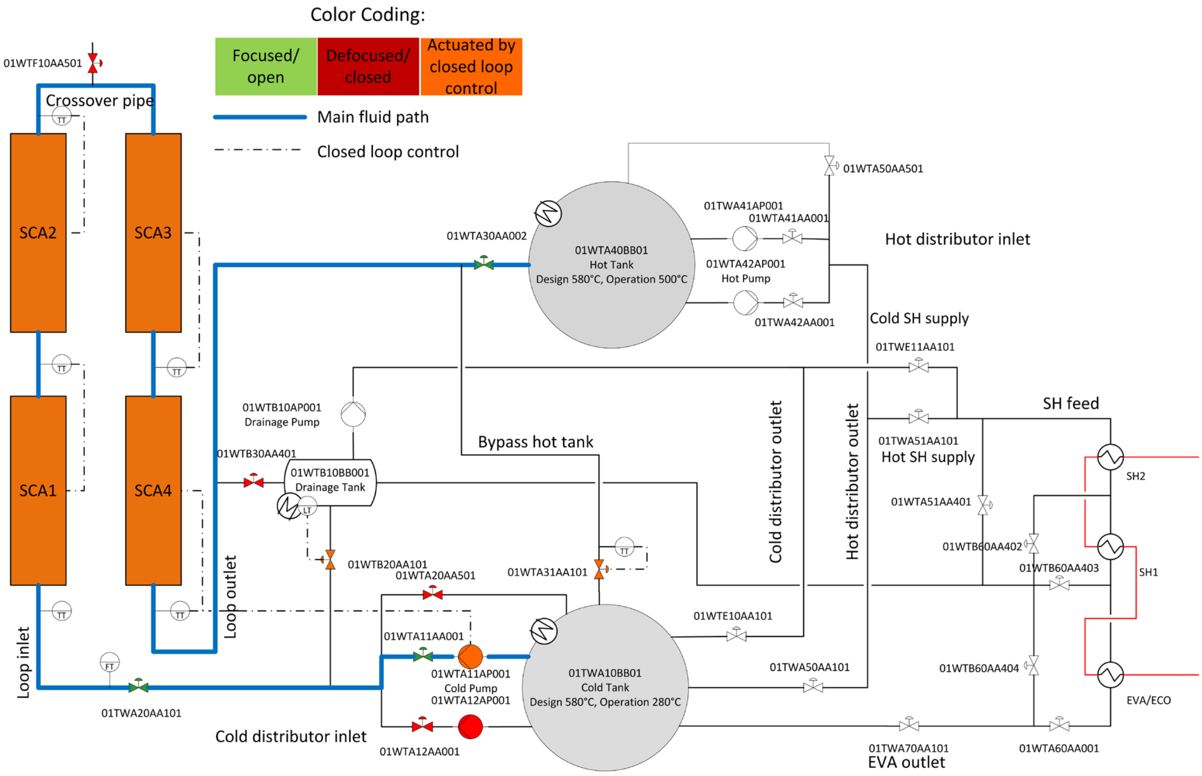


Figure 48 SF Normal Operation

Operation Mode - Solar Field Shut-down

After de-focusing the collectors, the mass flow is directed back to the Cold Tank. The temperature at the Solar Field outlet will drop gradually. The remaining heat stored in the steel mass of the Solar Field piping is transferred into the Cold Tank for night/anti-freeze operation.

The mass flow is controlled in such a way that the temperature drop in the Solar Field is limited to a safe level.

Hot and Cold Tank level remain again constant, in case that the SGS is not in operation.

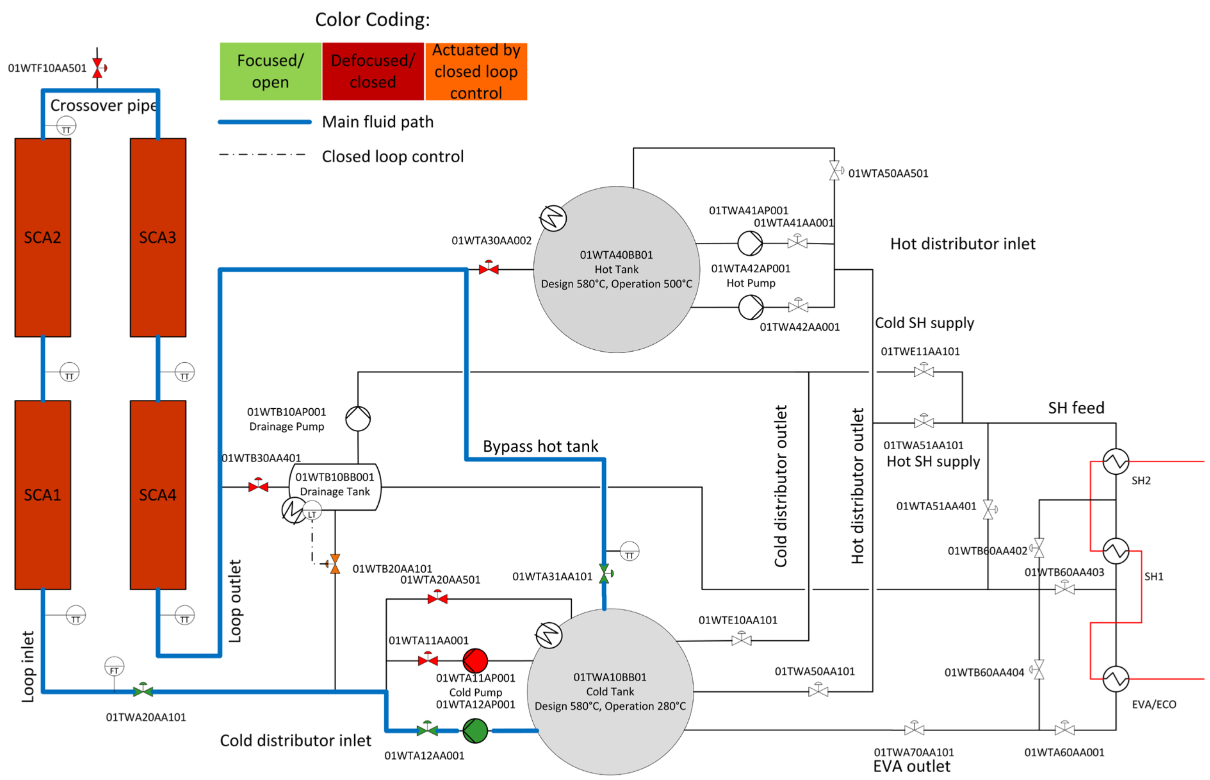


Figure 49 SF Shut-Down Operation

Operation Mode - Solar Field Night and Anti-Freeze Operation

The heat for maintaining the complete Solar Field in safe temperature ranges during the night is provided by the sun stored in the TES. Molten Salt from the Cold Tank (290°C) transports the heat into the Solar Field. After passing through the Solar Field the cooled down salt is redirected to the Cold Tank. Therefore, the Cold Tank cools gradually down.

The cooling of the tank can (a) be accepted as Yara MOST allows significantly lower temperatures, (b) be stabilized by the use of very small amounts of hot salt. During the operation of the SGS the cooling of the Cold Tank is significantly slowed down as the outlet flow of the steam generating system is feeding the Cold Tank continuously with heat at the nominal temperatures of the Cold Tank.

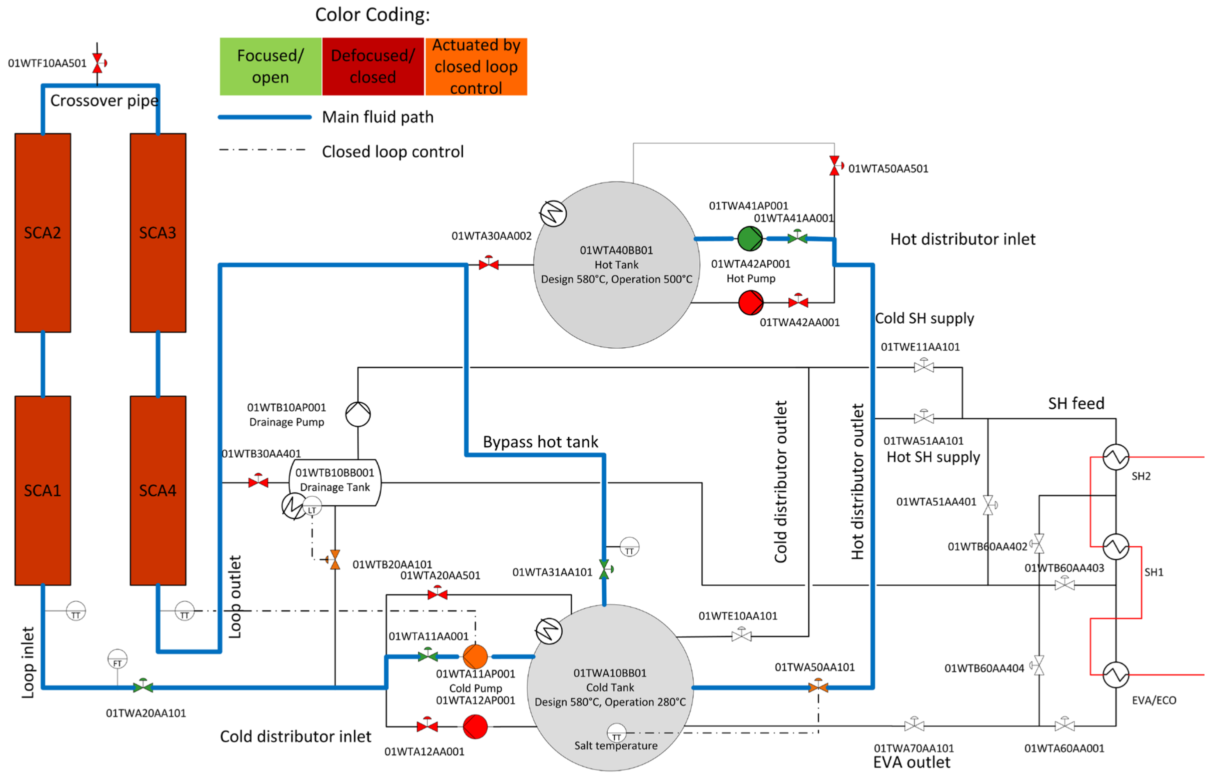


Figure 50 SF Night & Anti-Freeze operation

Operation Mode - Solar Field Drainage

The Solar Field can be drained independently from the Steam Generating System. The Drainage Tank is installed at the lowest point of the plant. All salt that is contained in the Solar Field pipes will be stored in the Drainage Tank.

The Drainage Tank is included in the process (see e.g. SGS Start-up). There are two reasons: the cold pump is overdesigned in terms of pressure head in order to allow for future Solar Field extensions. In order to maintain a safe process, the atmospheric Drainage Tank is used to decouple high pressure head from the Steam Generating System. Furthermore, the Drainage Tank is always heated, so that in case of emergency draining damages due to temperature shocks can be avoided.

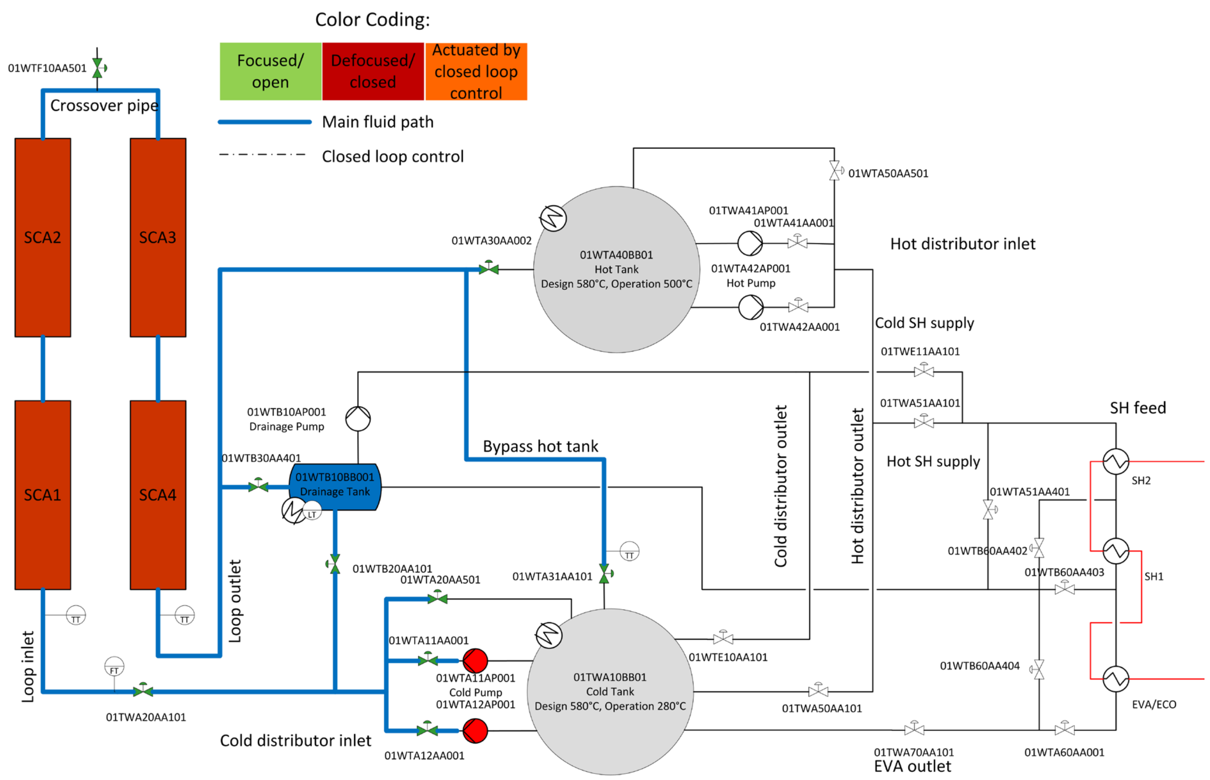


Figure 51 SF Drainage

Operation Mode - SGS Start-Up / SGS Shut-Down

The SGS start-up will be performed by gradually raising salt mass flow and temperature by mixing of mass flows from the Hot Tank and the Drainage Tank.

The SGS will start-up only if sufficient mass is contained in the Hot Tank. The Drainage Tank's salt mass is maintained constant by a controller that equilibrates the outlet mass flow with the inlet mass flow coming from the Cold Tank.

The SGS shut-down is basically done in the reverse path of the start-up: lowering temperatures to anti-freeze temperatures and lowering mass flow.

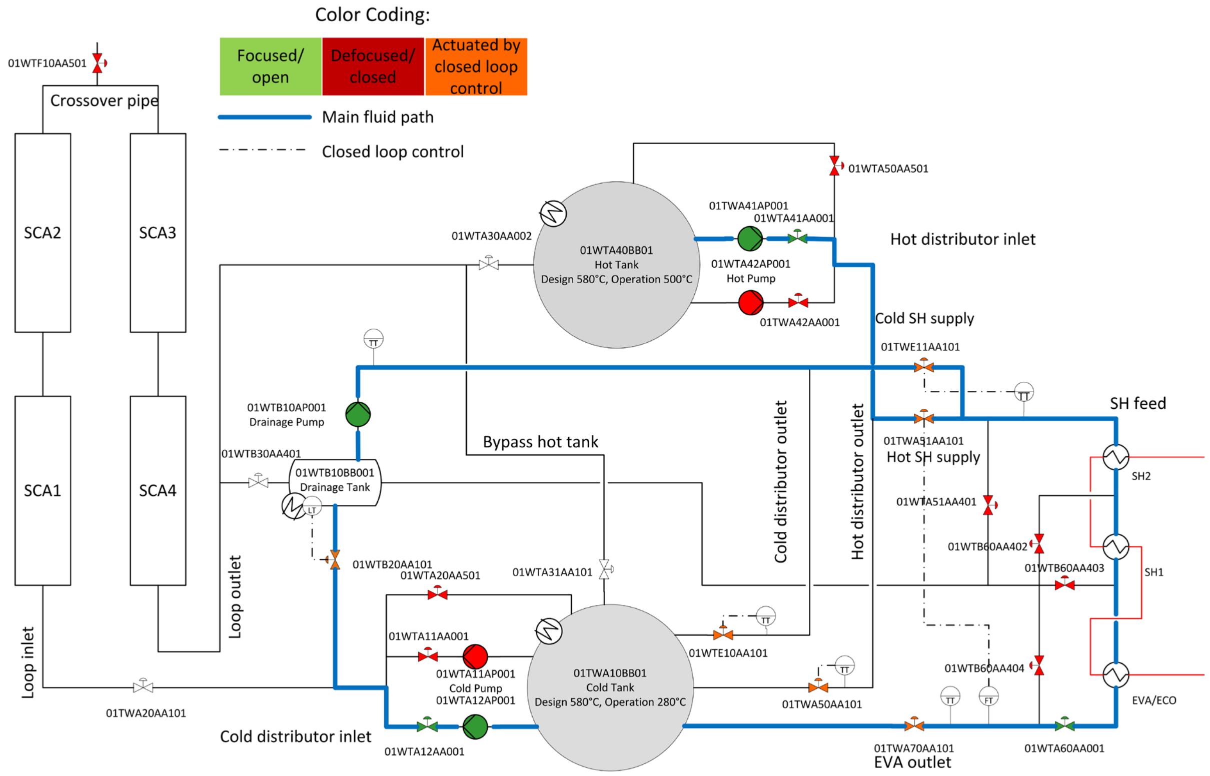


Figure 52 SGS Start-Up and Shut-Down Operation

Operation Mode - SGS Normal Operation

At normal operation the SGS will be driven at constant temperatures from the Hot Tank. Power variations will be done by varying the salt mass flow.

In normal operation the Hot Tank will be discharged via the SGS to the Cold Tank.

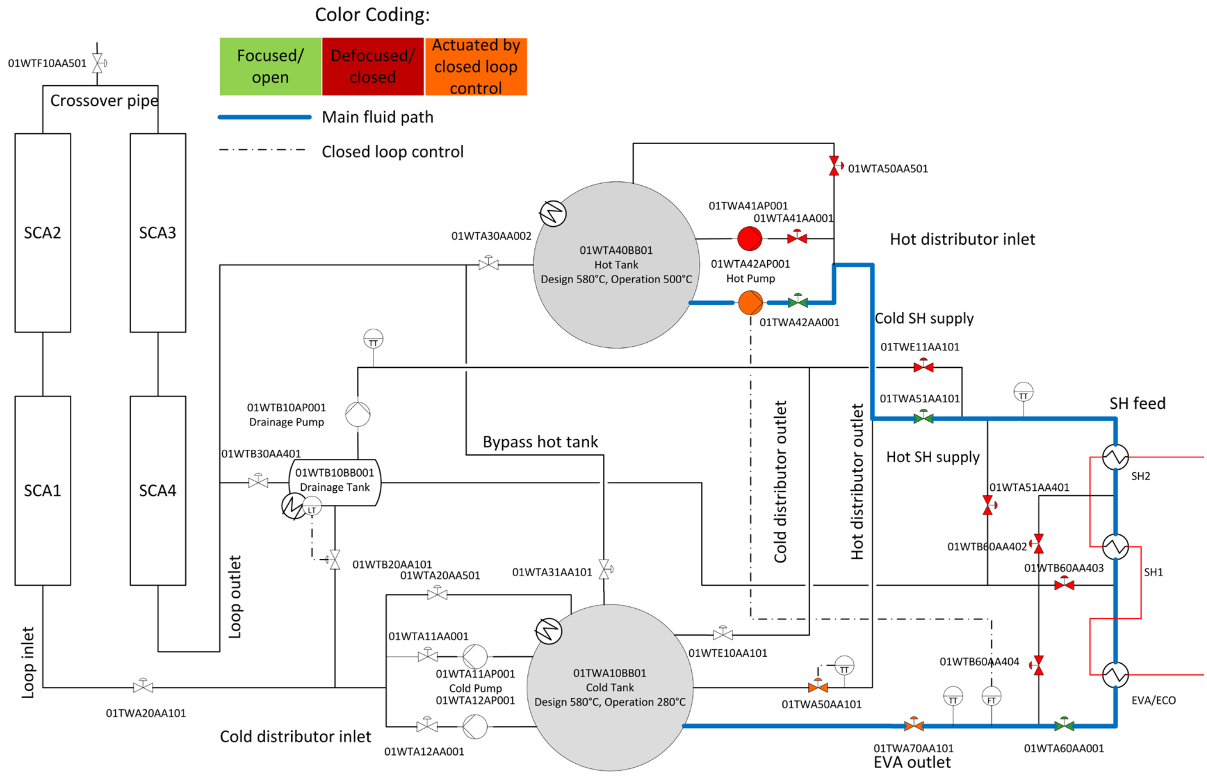


Figure 53 SGS Normal Operation

Operation Mode - SGS Night and Anti-Freeze Operation

After shut-down of the SGS, the feeding pipes and the shell of the SGS are charged with molten salt from the Drainage Tank.

The Drainage Tank level is controlled constant by mass flow from the Cold Tank. Hence, this operation is not limited in duration. In comparison to the Solar Field Anti-Freeze Operation (see above), here heat losses are significantly lower where the need of hot salt to stabilize the temperature in the Cold and Drainage Tank is used only exceptionally.

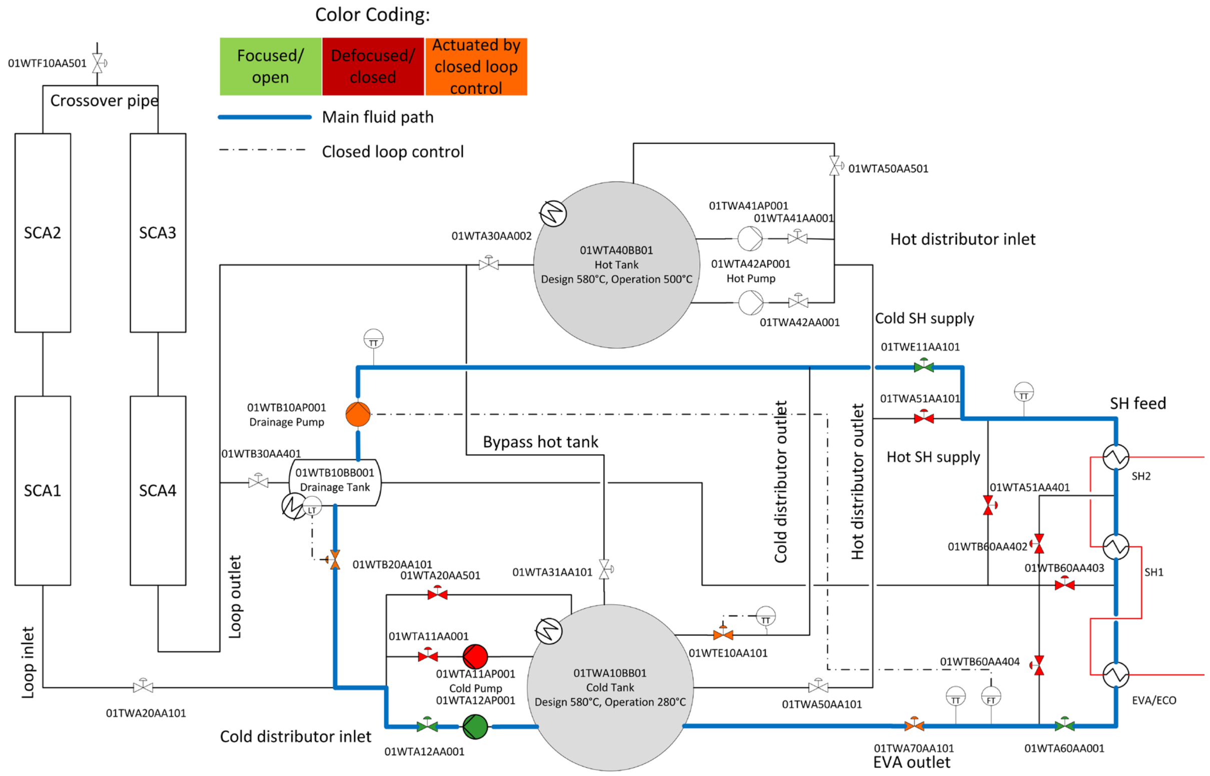


Figure 54 SGS Night & Anti-Freeze operation

Operation Mode - SGS Drainage

For longer outages, the Steam Generator System can be drained independently from the rest of the plant. The salt inlet valves are closed. The salt is directed to the Drainage Tank via the drainage valves.

If necessary the rest of the plant can be maintained salt-filled.

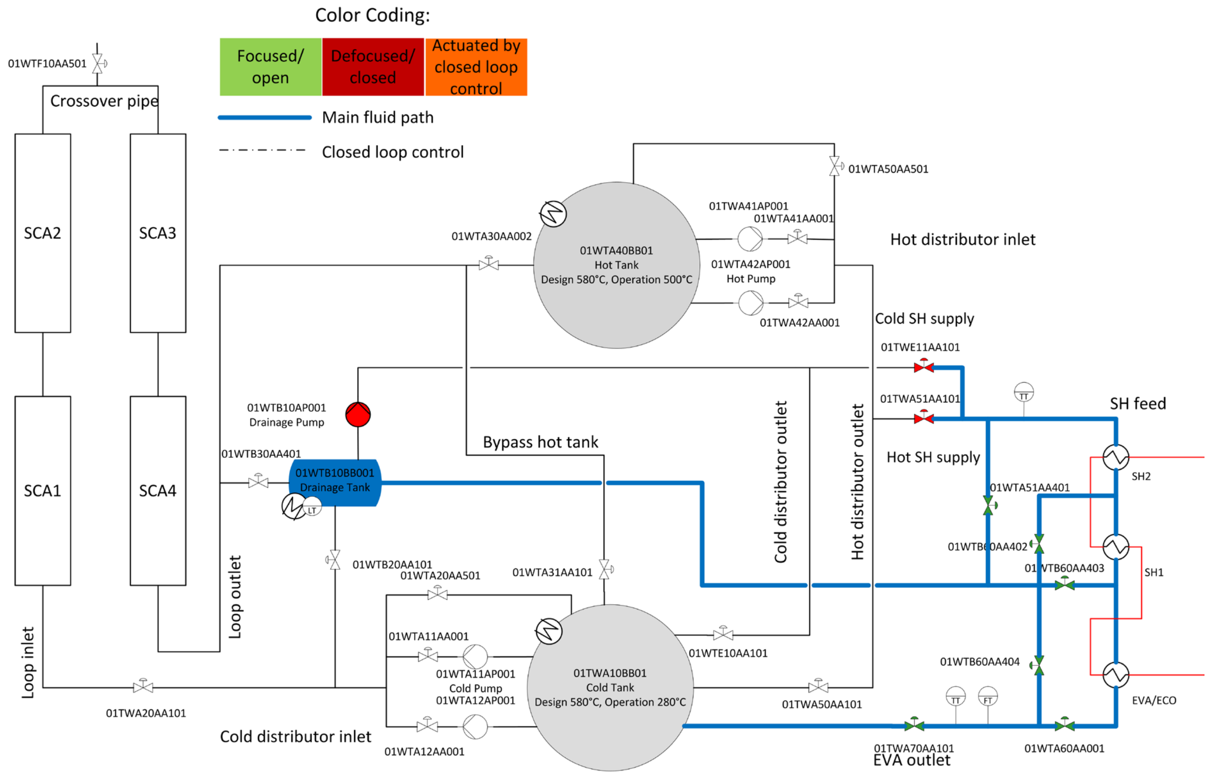


Figure 55 SGS Drainage

6.1.2 Water-Steam Cycle

Operation Mode – WSC Preheating

Before molten salt is filled into the heat exchangers, the water/steam cycle (WSC) is preheated. This is realized on the one hand by the electrical trace heating of the components and by the electrical flow heater in the WSC. For preheating the feedwater, water from the feedwater tank is pumped through the energized electrical flow heater to the Eco/Eva. Downstream the Eco/Eva the feedwater passes the water/steam separator and is recirculated back into the feedwater tank. By this recirculation and the continuous heating, the feedwater heats up to the requested temperature.

Operation Mode – WSC Normal operation

During normal WSC operation water from the feedwater tank is pumped to the Eco/Eva where steam is generated. The steam passes the separator and is superheated in the superheaters. Since the plant does not contain any turbine or similar to make use of the superheated steam, the steam is cooled down and depressurized in two stages in throttling valves. Steam from the intermediate pressure level is used to control the temperature in the feedwater tank. The depressurized steam is condensed in an air cooled condenser. The condensate is collected in the condensate tank. The level in the feedwater tank is controlled by feeding water from the condensate tank to the feedwater tank by means of the condensate pump.

6.1.3 Auxiliary Systems

Demin Plant

Demin water plant was already installed on-site by the predecessor research project. An evaluation regarding the production of demin water plant was done, but the osmosis process was not used to produce demin water as the process was regarded as expensive for the needs of the plant. The water coming from the pit and supplying offices is treated on this demin plant by the addition of hypochlorite. The demin water plant is connected to two tanks (volume of 3 and 30m^3) that were connected through a bypass to allow filling the SGS through one tank or another. First pipe routing layout of this tanks did not allow this option.

Building/Offices

Building offices are on-site by the time of predecessor research project. During 2019 UEV doubled the area of buildings by installing new containers. This building accommodates the control room of the facility, a meeting room, six rooms for engineering and technical staff and a kitchen.

Weather Station

Weather station existent on-site composed by 2 pyranometers, 1 pyrheliometer (installed on the roof of container building by UEV), 1 wind speed and direction sensor, 1 pressure sensor and 1 ambient temperature sensor.

Substation

The substation is equipped with a transformer with power of 800kVA and is electrically driven by RESP through a medium voltage line 15kV. The substation feeds the HPS-2 loop as well as the office buildings.

Emergency Diesel Generator

The emergency diesel generator (EDG) is used as a back-up source of emergency power, powering core systems to prevent salt solidification (mainly salt pump and heating systems) additional with other equipment necessary for maintaining the safe shutdown of plant to reach a drainage position. It has a power of 400 kVA (cos phi 0,8) and sufficient fuel to maintain a reliable and safe operation during black out situations.

6.2 Thermodynamic description of the overall plant

Basis of design for the thermodynamic calculations was solar salt and Yara MOST. Both salts have been chosen as the span a wide field of advantageous properties of nitrate salts for CSP applications. Solar Salt reaches highest possible temperatures austenitic steel can withstand. Yara MOST allows low solidification temperatures. The thermodynamic calculations have been performed with the commercial product Ebsilon Professional.

6.2.1 Normal Operation

Normal operation is defined with an DNI of 850 W/nm2 and ambient temperatures of 20 °C. The process parameters are continued from the predecessor project. Life steam parameters of 560 °C/140 bar result in solar field outlet temperatures of 580 °C.

The steam generating system generates approx. 1.6 MW of live steam with a mass flow of 0.7 kg/s. The solar field delivers 2.7 MW resulting in a charging power of the thermal storage system of approx. 1.1 MW.

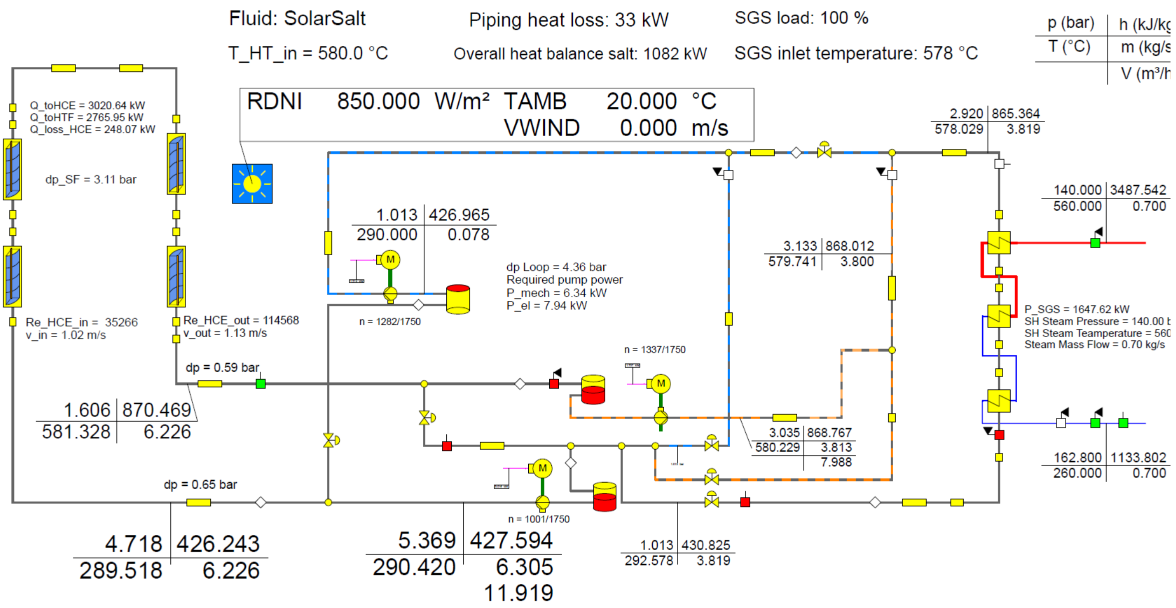


Figure 56 Design Point w/ Solar Salt

With the same ambient conditions (850 W/m2, 20 °C) the following figure shows the results with target temperatures for Yara MOST of 500 °C. Resulting in an off-design operation point (57 %) of the SGS with live steam parameters of 454 °C/93 bar.

The solar field net output is calculated with 2.8 MW thermal; SGS consumption with 830 kW. Resulting in a charging of the tanks of nearly 2.0 MW.

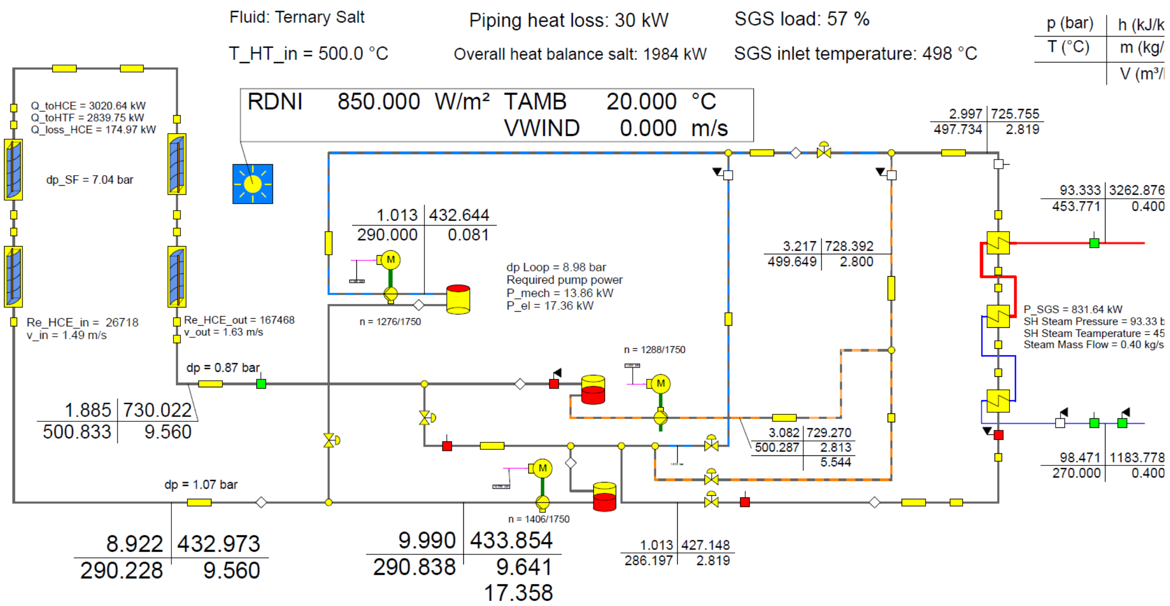


Figure 57 Operation with Ternary Salt @ 500 °C

The lowest solar field temperatures as set to 400 °C. This solar field outlet temperature result in the highest pump power of the cold pump as the solar field must be cooled significantly by running cold salt into the field, i.e. Hydraulic power of the cold pump 16.8 kW with a pressure drop of the solar field of nearly 18 bar and a volume flow of 34 m3/h.

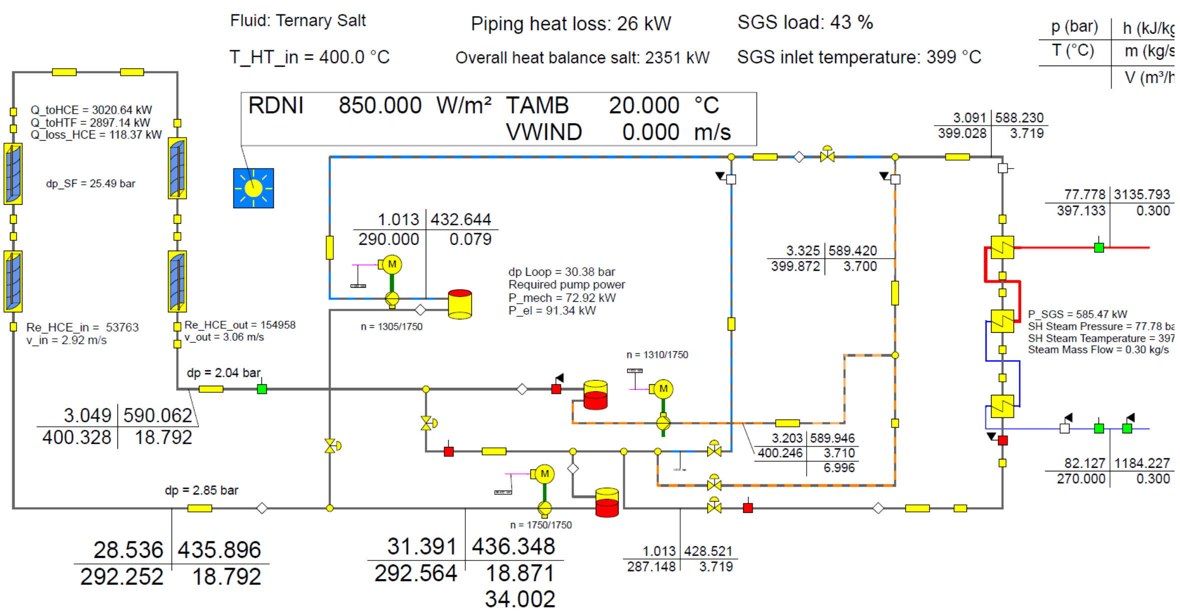


Figure 58 Operation at SF outlet temperatures of 400 °C

6.2.2 Anti-Freeze Operation

The heat losses during overcast or night situations are primarily covered by the thermal storage system. At 0 DNI and ambient temperatures of 0°C, we expect heat losses of the solar field 317 kW including HCE, piping, fittings and salt aggregates. The steam generating system counts for approx. 42 kW of heat losses including upstream and downstream pipes/equipment until the terminal points of the thermal storage system. Each tank is designed to have heat losses of 10 kW, resulting in 30 kW of the 3 tanks. In total the heat consumption during night and overcast situation is summing up to 389 kW (at 0 °C ambient temperature).

At 12 hours of night operation the total heat loss 4.7 MWh. Under normal operation this amount of heat is gathered within less than two hours in case when the SGS is not running. In case of a running SGS the amount needs to be gathered within 4 to 5 hours using Solar Salt and 2 to 3 hours using Yara MOST. A heating with electrical heaters is only necessary when the thermal energy storage is empty. Whereas with Yara MOST there is the potential to lower the salt temperatures by up to 100 °C resulting nearly halving the heat losses.

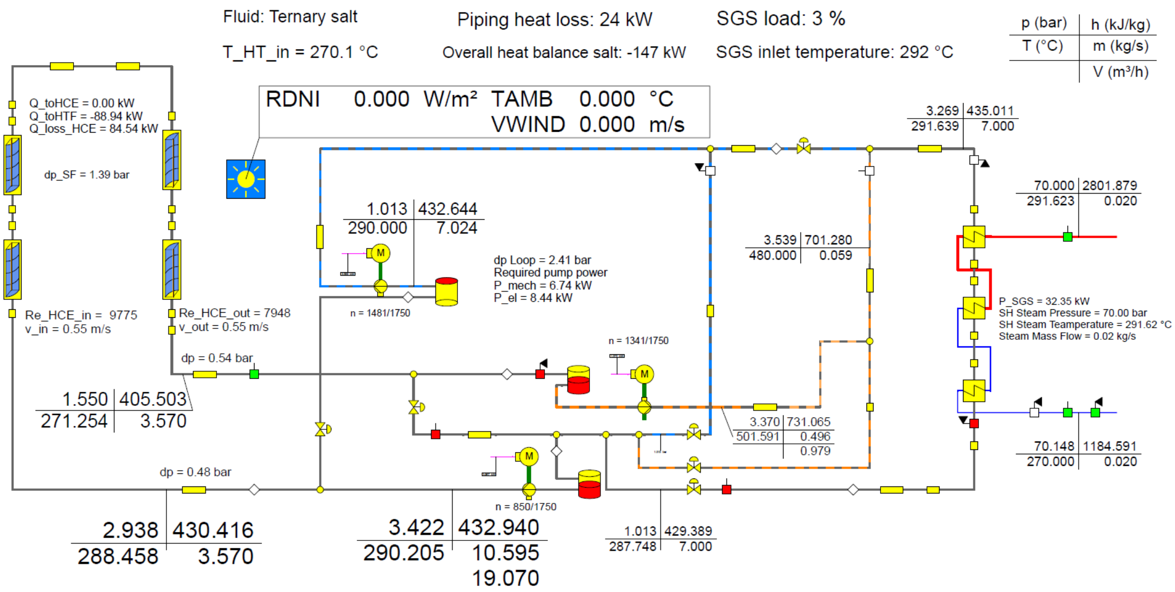


Figure 59 AF operation of SF and SGS @ 290 °C / ΔT=20 K and T_{amb}=0 °C

6.3 Piping and Instrumentation Diagram

A piping and instrumentation diagram (PID) is a detailed diagram in the process and energy industry which shows the piping and process equipment together with the instrumentation and control devices. Superordinate to the P&ID is the process flow diagram (PFD) which indicates the more general flow of plant processes and the relationship between major equipment of a plant facility.

Based on the process description and the process flow diagram the piping and instrumentation diagram (PID) was created. In the following figure the latest revision of the PID Salt Cycle is shown.

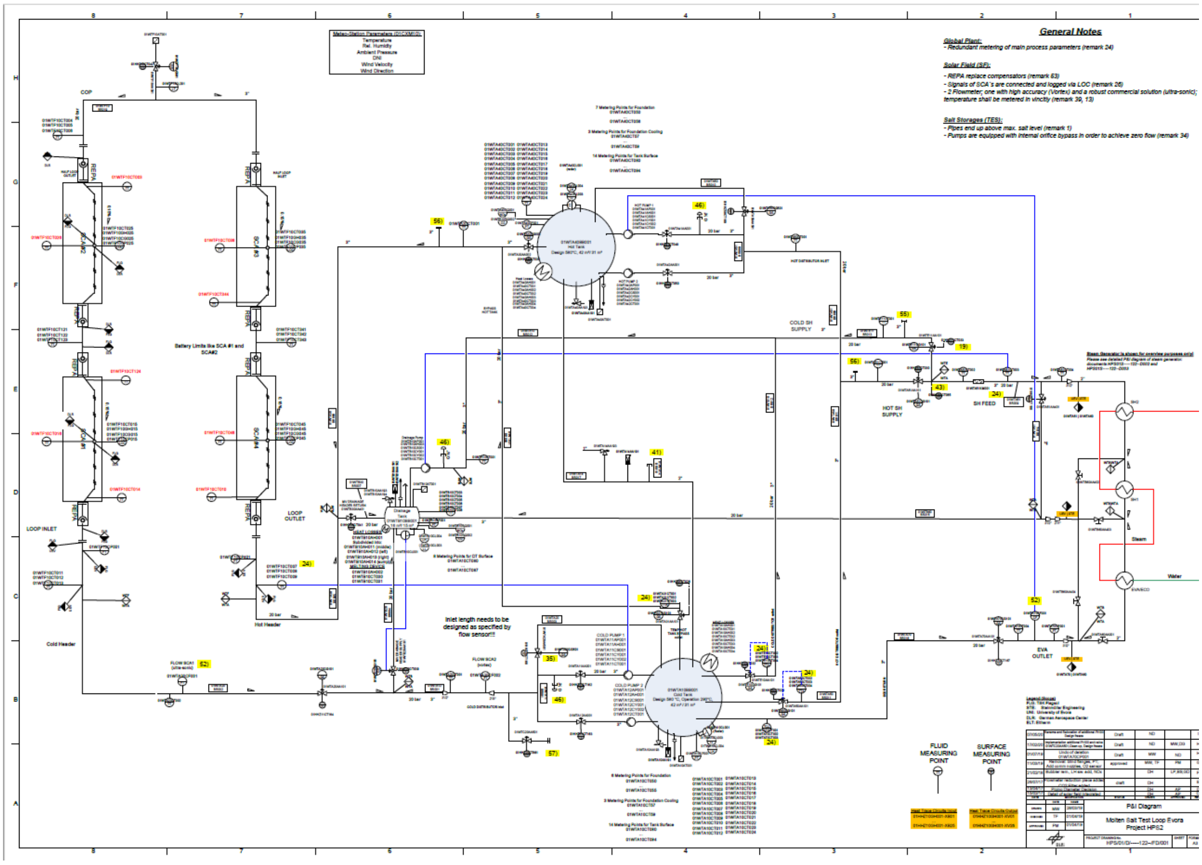


Figure 60 Piping and Instrumentation diagram

The PID of the steam generating system was already created within the predecessor project.

6.4 Hazard and operability study

A hazard and operability study (HAZOP) is a structured and systematic examination of a complex plan or operation in order to identify and evaluate problems that may represent risks to personnel or equipment. The intention of performing a HAZOP is to review the design to pick up design and engineering issues that may otherwise not have been found. The technique is based on breaking the overall complex design of the process into a number of simpler sections called 'nodes' which are then individually reviewed. It was carried out by a multi-disciplinary team during a series of meetings. The HAZOP technique is qualitative, and aims to stimulate the imagination of participants to identify potential hazards and operability problems. Structure and direction are given to the review process by applying standardized guide-word prompts to the review of each node.

During the project several HAZOP studies have been performed on salt cycle and steam generating system. All recommendations have been implemented.

6.5 Functional Description and DCS system

A distributed control system (DCS) is a computerised control system for a process or plant usually with many control loops, in which autonomous controllers are distributed throughout the system, but there is no central operator supervisory control. This is in contrast to systems that use centralized controllers; either discrete controllers located at a central control room or within a central computer. The DCS concept increases reliability and reduces installation costs by localising control functions near the process plant, with remote monitoring and supervision.

A DCS combines the following into a single automated system: human machine interface (HMI), logic solvers, historian, common database, alarm management, and a common engineering suite. The DCS controls the complete salt cycle and the steam generating system. The DSC is supported via different black-box systems for the solar field FSC and for the heating system.

The functional description document servers as interface between engineering team and the DCS programmer. It describes all logics, step sequences and controllers. In the following some examples of the functional descriptions are shown.

6.5.1 Cold Tank Pumps

For each aggregate criteria to start and stop are defined. Furthermore, interlocks are specified that allow the DCS to protect each aggregate.

Cold pump 1	**01WTA11AP001**	**KKS**			
Release Start	Speed Sensor for Frequency Converter	01WTA11CS002	0 rpm and no negative rotation		
All criteria to be met	Ball bearing temperature	01WTA11CT001.XH53	T < MAX 1	<105	°C
	Vibration measurement 1	01WTA11CY001.XM20	Channel Valid		
	Vibration measurement 2	01WTA11CY002.XM20	Channel Valid		
	Cold tank level	01WTA10CL001.XH01	Tank Level > MAX 1	>750	mm
	Valve	01WTA11AA001.XB02	Valve closed		
	Valve	01WTC20AA501.XB02	Valve closed		
	Valve Heating	01WTA11AH001.XB01	>MIN & <MAX		
	Pipe section heat tracing	acc. to table section vs heat tracing	>MIN & <MAX		
	Cold tank pressure	01WTA10CP001.XH04	Tank Pressure > MIN 1	>-10	mbar
Release Stop All criteria to be met	Other Pump in Operation	01WTA12AP001.XB01	MAIN PUMP CAN BE SWITCHED OFF MANUALLY ONLY WHEN THE OTHER PUMP IS IN OPERATION		
	Shut Off Valve 11 Closed	01WTA11AA001.XB02			
	Shut Off Valve 12 Open	01WTA12AA001.XB01			
		OR 01WTA10EE001 is ON ???			
Automatic Start	Automatic Change-Over	01WTA10EE001.XA01		Start Pump 1	
Automatic Stop	Automatic Change-Over	01WTA10EE001.XA02		Stop Pump 1	
Protection Start	Solar Field	01WTF10EZ002	Solar Field Low Flow	Trip	
Protection Stop	Cold Tank Level	01WTA10EZ002.XH56	Cold Tank Level Protection	< MIN 2	
	Ball bearing temperature	01WTA11CT001.XH05	> MAX 2	>120	°C
	Vibration measurement 1	01WTA11CY001.XH05	> MAX 2	8	mm/s
	Vibration measurement 2	01WTA11CY002.XH05	> MAX 2	8	mm/s
	Tank pressure	01WTA10CP001.XH56	<MIN 2	-15	mbar
	DT level	01WTB10EZ002.ZH05	> MAX 2	1000 mm	

6.5.2 Controller

The next example shows the controller concept of the HTF mass flow of the solar field in order to achieve an outlet setpoint temperature.

The controller is established as a feed-forward controller based on actual irradiance data, the inlet salt temperatures and setpoint outlet temperature. Parallel a PI-controller surveys the deviations and adopts the mass flow accordingly.

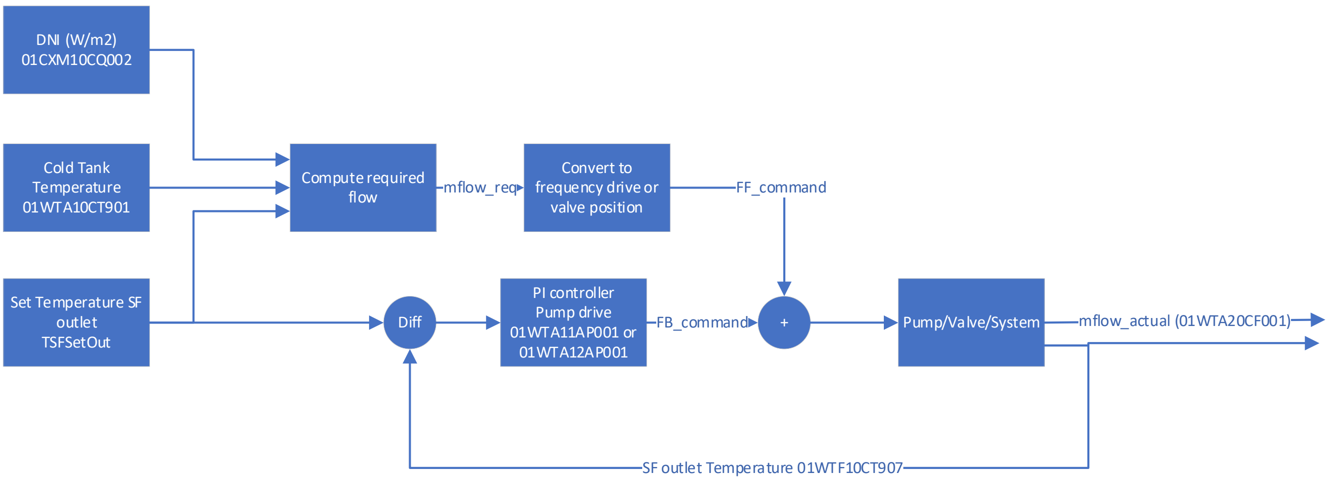


Figure 61 SF control

The mixing point upstream of the steam generating system is shown by the following control concept. Objective of the control loop is to set the mass flow and the salt inlet temperature of the SGS inflow. Two frequency converters manipulate the flow from the hot and the drainage tank, respectively. Both have impact on mass flow and mixing temperature. Two PID controllers are programmed. One serves to achieve the setpoint mass flow, the other the setpoint temperature.

The closed-loop controller is supported by a feed-forward controller that calculates the mass flow of the hot pump and the drainage pump based on the temperatures of the tanks, and the desired SGS inlet mass flow and inlet temperature.

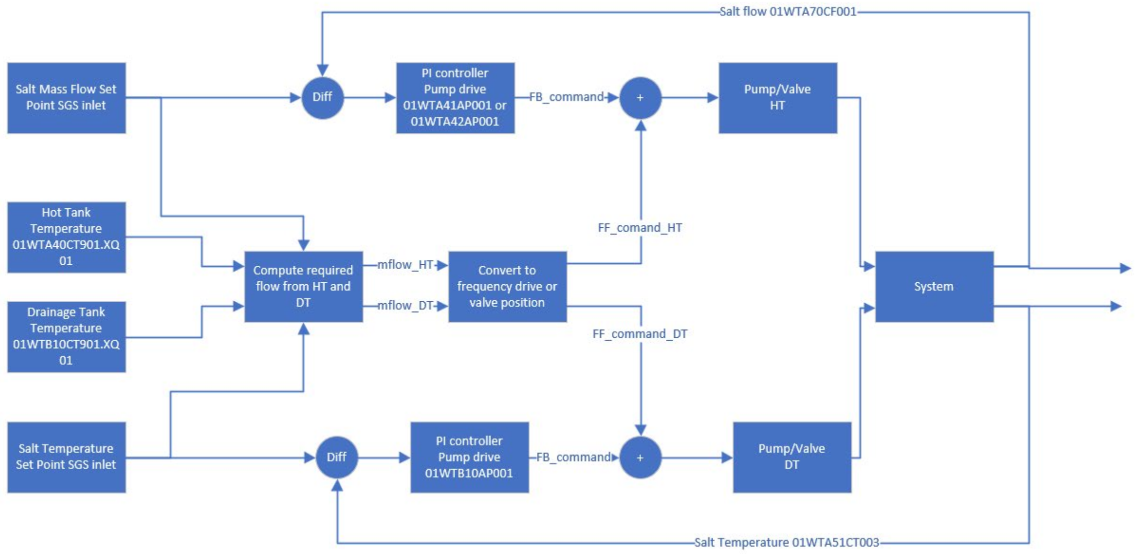


Figure 62 Mixing temperature

6.5.3 Step Sequence Filling

Step sequences are automated commands that are performed in sequences. The next step is entered when a defined condition is met. In the following the example of the 13 steps for solar field filling with molten salt is shown.

Step Sequence:

Solar Field Fast Shut-Down				
Step 1	KKS	KKS	Status	Command
	Cold Pumps	01WTA11AP001 And 01WTA12AP001		Stop Stop
	Cold Pumps	01WTA11AP001 And 01WTA12AP001	Stopped (RPM =0) Stopped (RPM =0)	
Objective: assure that cold pumps are stopped before opening venting/dearation valves				

Step 2	KKS	KKS	Status	Command
	Valve Solar Field Inlet	01WTA20AA101		Close (0%)
	Valve HT inlet	01WTA30AA002		Close (0%)
	Valve Bypass Hot Tank	01WTA31AA101		Open (100%)
	Valve Shut-Valve of Cold Pump 1	01WTA11AA001		Close (0%)
	Valve Shut-Valve of Cold Pump 2	01WTA12AA001		Close (0%)
	Valve Recirculation Cold Pumps	01WTA20AA501		Close (0%)
	Valve Drainage Line of 01WTA20	01WTB20AA101		Close (0%)
	Valve Drainage Line of 01WTA30	01WTB30AA401		Close (0%)

	Valve Solar Field Inlet	01WTA20AA101	Closed	
	Valve HT inlet	01WTA30AA002	Closed	
	Valve Bypass Hot Tank	01WTA31AA101	Opened	
	Valve Shut-Valve of Cold Pump 1	01WTA11AA001	Closed	
	Valve Shut-Valve of Cold Pump 2	01WTA12AA001	Closed	
	Valve Recirculation Cold Pumps	01WTA20AA501	Closed	
	Valve Drainage Line of 01WTA20	01WTB20AA101	Closed	
	Valve Drainage Line of 01WTA30	01WTB30AA401	Closed	
Objective: positioning of valves to prepare filling Remark: Normally the 01WTF10AA501 (Venting COP) would be opened 15% - but then condition Release Start of Cold Pump would not be achieved (see Chapter 9.1.5.1 and 9.1.5.2)				

Step 3	KKS	KKS	Status	Command
	Cold Pumps	01WTA11AP001 OR 01WTA12AP001		Start: 1000 rpm Start: 1000 rpm
	Cold Pumps	01WTA11AP001 OR 01WTA12AP001	Started Started	
Objective: Start one cold pump. Important Note: not both pumps shall be started (design 2x 100% w/ auto-switch-over)				

Step 4	KKS	KKS	Status	Command
	Valve Shut-Valve of Cold Pump 1	01WTA11AA001		Open (100%)
	Valve Shut-Valve of Cold Pump 2	01WTA12AA001		Open (100%)
	Valve Recirculation Cold Pumps	01WTA20AA501		Open (100%)
	Valve Vent COP	01WTF10AA501		Open (3%)
	Valve Shut-Valve of Cold Pump 1	01WTA11AA001	Opened	
	Valve Shut-Valve of Cold Pump 2	01WTA12AA001	Opened	
	Valve Recirculation Cold Pumps	01WTA20AA501	Opened	
	Valve Vent COP	01WTF10AA501	Opened (3%)	
Objective: Opening of valves nearby cold pump; and COP (see as well remark in step 2)				

Step 5	KKS	KKS	Status	Command
	Flow Controller	01WTA20DF101		SetPoint 4 m3/h = 2.2 kg/s; start controller
	Flow Controller	01WTA20DF101	active	
Objective: Start Flow Controller				

Step 6	KKS	KKS	Status	Command
	Pressure meter (SF inlet)	01WTF10CP001	> 750 mbar	
Objective: Wait until Detection of salt reaching high point of COP (=SCA1 and SCA2 are filled). Background: this pressure transmitter measures static pressure of salt column in SCA1, SCA2 to highest point in COP plus dynamic pressure drop. It gets constant when SCA1 and SCA2 is completely filled and flow rate is not changed.				

Step 7	KKS	KKS	Status	Command
	Pressure meter (SF inlet)	01WTF10CP401	> 350 mbar	

Objective: Wait until Detection of salt filled SCA3 and SCA4, too. Background: Salt will raise in the COP vent line (at valve 01WTF10AA501) once SCA3 and SC4 are completely filled.

Step 8	KKS	KKS	Status	Command
	Flow Controller	01WTA20DF101		SetPoint 0.25 m3/h = 0.13 kg/s; start controller
	Flow Controller	01WTA20DF101	Active	
Objective: Lower Set-Point of Flow Controller				

Step 9	KKS	KKS	Status	Command
	Level Venting line COP	01WTF10CL201	> 100 mm	
Objective: Wait until level reaches 100mm				

Step 10	KKS	KKS	Status	Command
	Valve Venting COP	01WTF10AA501		Close 0%
	Valve Venting COP	01WTF10AA501	Closed 0%	
Objective: closing of COP to avoid spillage Remark: If the level falls below 100 mm, the COP is to be opened (3%) again to remove the air transported by salt flow to COP venting line: hysteresis: Level >100 mm => Valve 0% (=closed); level <50mm => Valve 3%. hysteresis active until end of this step sequence				

Step 11	KKS	KKS	Status	Command
	Wait			Wait for 1 mins
Objective: closing of COP to avoid spillage				

Step 12	KKS	KKS	Status	Command
	Flow Controller	01WTA20DF101		SetPoint 10 m3/h = 5.4 kg/s; start controller
	Flow Controller	01WTA20DF101	Active	
Objective: Increase Set-Point of Flow Controller				

Step 13	KKS	KKS	Status	Command
	Valve Venting COP	01WTF10AA501		Close 0%
	Valve Venting COP	01WTF10AA501	Closed 0%	
Objective: closing of COP to avoid spillage Remark: If the level falls below 100 mm, the COP is to be opened again to remove the air transported by salt flow to COP venting line				

6.6 Commissioning of the DCS-System and electrical system

6.6.1 DCS Hardware and Commissioning

The main components of the DCS hardware from the HPS project were updated and upgraded to the current T3000 Siemens standards. The main DCS cabinets were modified according to the HPS2 detail engineering. The factory acceptance tests (FAT) of the DCS cabinets were afterwards performed by DLR's subcontractor SIEMENS, Portugal. After approval of the cabinets they were installed on site in the PCC/MCC container and cabling works of the instrumentation started. Once the instruments were connected to the DCS, the so-called loop checks started. The objective of the loop checks is to test the functionality and configuration of all sensors and actuators. The loop checks involved extensive work of the O&M team due to the brown field situation of the HPS plant from 2012 on. Numerous repair and calibration work had to be carried out on instrumentation and actuators before the loop check was concluded and water run could be started.

For the water run, the control room was set up with a total of two redundant operators' stations and one remote access station. The remote access to DCS was established to enable scientific team and Siemens support entering. In case of a Blackout all workstations are connected to the UPS to enable operator action all the time.

During the hot commissioning, the field instrumentation and communication with HMI was further tested and calibrated where needed. All instrumentation was checked and approved by an instrumentation technician contracted by DLR before the start of regular plant operation. The hot commissioning also involved a continuous check and adjustment of set-points, as well as the adaption of HMIs and controllers. Interlocks, component logics and step sequences related to the functional description were checked and tested.

After the implementation of the subsystem's interfaces by the programmers of the partners and DLR subcontractor Siemens, the communication with the black box systems was established. Therefore connection via Profibus (DP/DP coupler) were commissioned and data exchange was tested. It was tried to solve issues with the software and configuration of the interface to a large extent. Unfortunately, the interface to the eltherm system could not be finalized on the eltherm side within the project. As a workaround a notebook was setup in the control room from where the eltherm system can be visualized and operated with the manufacturers own software 'TraceVision'.

Trouble-Shooting to the DCS during commissioning of the plant was done with support of the subcontractor Siemens.

6.6.2 Electrical System Commissioning

To support the university in the preparation of the electrical operation permit, the scope project design was overtaken by DLR from the university and an electrical engineer was subcontracted as project author, responsible for the electrical design of the entire electrical system. The finalization of the electrical permit documentation on the official permit application forms, was performed by the project author after all documentation from the partners had been collected. The permit application was then handed in by the electrical engineer responsible for the operation of the electrical system, who was subcontracted by the university.

The factory acceptance test of the Power Control Center and Motor Control Center (PCC/MCC) was performed by DLR's subcontractor SIEMENS, Portugal. Subsequently the PCC/MCC was brought to site and installed inside an air-conditioned container. After finalization of the cable connections commissioning of the MCC/PCC was performed by SIEMENS.

Figure 63 Photo of the PCC (left) and the MCC (right)

A fiberoptic protection relay for fire protection was installed and tested by SIEMES.

When the MCC was confirmed to be operational, the motors were tested including AC phase checks. For the motor tests, the pumps were decoupled from the motors and their rotation direction and control was checked and confirmed.

To safely handle blackout situations, when the connection to the electricity grid is lost, an uninterrupted power supply (UPS) and an emergency diesel generator (EDG) were installed. The blackout concept of the functional description defines which consumer is connected to the UPS and which consumer has an additional connection to the EDG. To avoid overcurrents a sequence of restart in the case of a blackout is defined with a certain time delay between the individual consumers.

An additional UPS connection was installed to the operator stations in the control room, to ensure full control by the operators also during black out.

During commissioning of the EDG the start sequence of all consumers was tested as well as the power switch over from grid to EDG supply and vice versa.

6.7 Cold start-up of the overall plant

During the cold commissioning, the piping and control system were tested with cool demineralized water. During the so-called "water run" the salt piping system as well as the water steam cycle were flushed and later drained and dried.

The commissioning of the salt pumps was performed during the water run, pump switch over was tested and pressure measurements were performed at all salt pumps to confirm their performance. All speed drives of the motors except the one of the condensate pump were commissioned by DLR's subcontractor SIEMENS, the speed drive of the condensate pump was commissioned by the University and DLR.

Figure 64 Maintenance works of salt pump

The mechanical commissioning of the feedwater and condensate pump and the salt pumps was performed by a subcontractor of the University.

Pump commissioning went well, only at the condensate pump and issue was detected: The condensate pump tripped, due to too high current consumption of a fan motor. After measurement of currents, rotation tension, rotation vibration and motor temperatures the supplier allowed to change current values for motor protection device, which solved the problem.

During the water run differential pressure measurements were performed at the salt side of the steam generator and the blackout concept was tested successfully All instruments that could be tested with water as well as the tank heating, were commissioned and configured.

6.8 Collector torsion validation

With HelioTrough® 2.0, roller supports with spherical bearings are used for the first time in CSP history. The friction coefficients are not well known. They influence the torsion (twist) of the SCAs.

A complete torsion measurement campaign was performed for all 8 wings of the 4 SCAs, using a newly developed solution comprising a dedicated test software and 2 high precision inclinometers.

A single measurement was done by driving a SCA from east to west and then west to east and then to analyze the recorded position differences between inclinometer at drive pylon and SCA end.

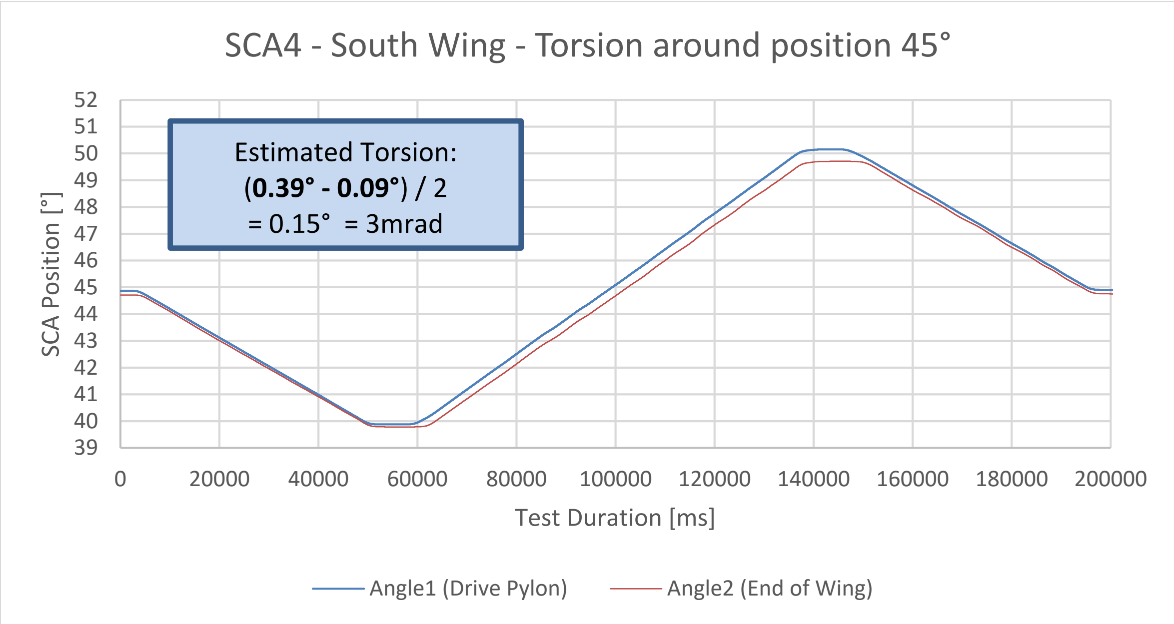


Figure 65 Measurement results from torsion measurement campaign, torsion can be calculated from the offset between the red and the blue line

Twenty measurements per SCA have been performed at different SCA positions, sample results for full-length SCA3:

SCA3 - Full Length with 10 SCEs					
N/S	Pos [°]	Test1 [°]	Test2 [°]	AVG [°]	AVG [mrad]
South	0	0,25	0,25	0,25	4,4
South	45	0,23	0,22	0,22	3,9
South	90	0,25	0,26	0,26	4,5
South	135	0,26	0,20	0,23	4,0
South	180	0,25	0,23	0,24	4,1
North	0	0,25	0,23	0,24	4,2
North	45	0,19	0,21	0,20	3,5
North	90	0,24	0,24	0,24	4,2
North	135	0,21	0,21	0,21	3,6

North	180	0,20	0,20	0,20	3,5
ALL	AVG	0,23	0,22	0,23	4,0

Figure 66 Results of torsion measurements campaign for SCA3

Results have been consistent and reproducible and confirmed that torsion stays within specification.

7. Operation of the plant, scientific support and monitoring

7.1 Coordination of the overall project

The character of the HPS2 project showed several challenges for the coordination of the works. Being a successor project of HPS, HPS2 foots on existing HPS buildings, equipment, components and is a brown-field project. Significant work was a classical EPC business that includes cutting edge technologies and prototypes. In contrast to EPC contracts, the joint project agreement of HPS2 has a cooperative instead of governing structure. The joint goal unites the partners.

Within the Kick-Off-Meeting all partners agreed to follow the following project lighthouses: cooperation, creativity, early information, one community and open communication. The partners followed these lighthouses throughout the project and provided an excellent basis for the project success. The project coordination worked as enabler of communications. Therefore, many meetings have been arranged on a whole bandwidth of topics: design review meetings, permit and licensing, workshops on commissioning, salt filling process O&M training and construction permits.

In the following tables all matters applied are shown in all areas of project management:

Table 3 Summary of all applied management areas with implemented matters

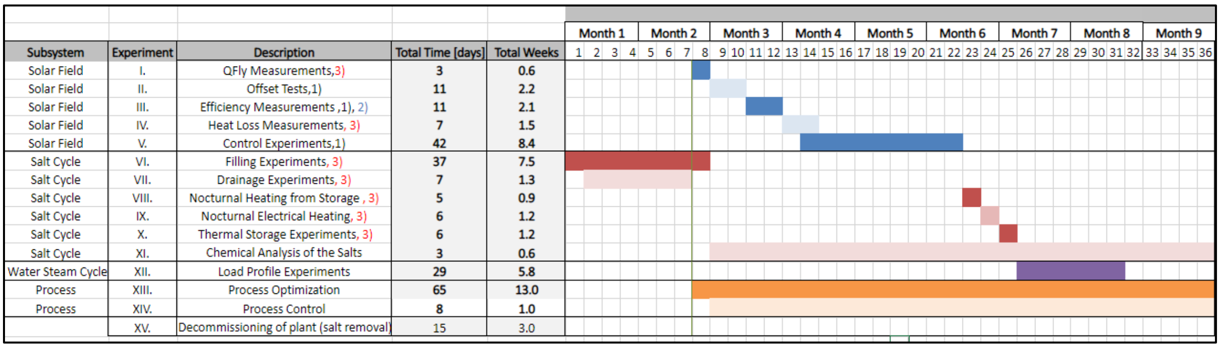
<u>Scope Management:</u> Kick-off meeting Division of Responsibilities Change Requests Lessons learned Project Lighthouses	**<u>Time Management:</u>** Kick-off meeting Time Schedule Activity Descriptions Note of Delay Change Requests Weekly Meetings Weekly Site Reports Lessons learned Project Lighthouses	**<u>Communication Management:</u>** Kick-off meeting Weekly Meetings (telephone) Design Review Meetings (in phase 1, each 2 months) Lessons Learned Project Lighthouses
<u>Risk Management</u> Risk Matrix Weekly Meetings Lessons learned Project Lighthouses	**<u>Quality Management (Project Execution)</u>** Kick-Off Meeting and Preparation Quality metrics (e.g. # NoD, # Urg Approval Enquiries, Delay in critical path) Design Review Meetings Open Communications	**<u>Quality Management (Product Quality)</u>** General Design Standards General Electric and I&C Design Standards Design Review Meetings Open Communications Project Lighthouses Lessons-learned Matrix

	Project Lighthouses Lessons-learned Matrix	
<u>Cost Management</u> According to JPA responsibility lies individually by each partner	**<u>Human Resources Management</u>** According to JPA responsibility lies individually by each partner	

7.2 Specifying the test program

The basic test program was first developed by DLR and later resumed by university of Évora. Several revisions and discussions regarding the tests plan took place throughout the project until the last version of the detailed test plan was issued by the end of September 2021. Also, it was defined a simplified test plan with the procedures of the intended tests.

A workshop regarding the detailed test plan took place during the commissioning phase in July 2021. Main conclusions of the workshop were integrated on the final document, and it was agreed to have flexibility on the sequence of test to deal with the meteorological conditions. The principal milestones to be achieved during the test campaign is successful drainage and filling of the solar field.



Subsystem	Experiment	Description	Total Time [days]	Total Weeks
Solar Field	I.	QFly Measurements,3)	3	0.6
Solar Field	II.	Offset Tests,1)	11	2.2
Solar Field	III.	Efficiency Measurements ,1), 2)	11	2.1
Solar Field	IV.	Heat Loss Measurements, 3)	7	1.5
Solar Field	V.	Control Experiments,1)	42	8.4
Salt Cycle	VI.	Filling Experiments, 3)	37	7.5
Salt Cycle	VII.	Drainage Experiments, 3)	7	1.3
Salt Cycle	VIII.	Nocturnal Heating from Storage , 3)	5	0.9
Salt Cycle	IX.	Nocturnal Electrical Heating, 3)	6	1.2
Salt Cycle	X.	Thermal Storage Experiments, 3)	6	1.2
Salt Cycle	XI.	Chemical Analysis of the Salts	3	0.6
Water Steam Cycle	XII.	Load Profile Experiments	29	5.8
Process	XIII.	Process Optimization	65	13.0
Process	XIV.	Process Control	8	1.0
	XV.	Decommissioning of plant (salt removal)	15	3.0

Figure 67 Initial agreed timeline of the test campaign

Offset Test Procedure
<u>Objective:</u> Quantify the tracking error of the parabolic trough collectors
<u>Conditions:</u> - A good weather with a minimum DNI is needed for each different test. - The closed-loop feedback device must be correctly designed, positioned and tuned. - Fluid must be circulated within the receivers during the tests.
<u>Data supervision:</u> - CT level (01WTA10CL001) - CT temperature (01WTA12CT001) - Solar field mass flow (01WTA20CF002) - Wind speed (01CXM10) and ambient temperature (01CXM10) - Reynolds number, calculated from mass flow (01WTA20CF002) and inlet temperature.
<u>Data acquisition:</u> - Tracking angle - Inclination angle (inclinometer) - Sun's position (calculated)
<u>Experimental procedure:</u> 1 Before night time, cold tank is filled with a minimum temperature of 290°C and it is maintained at this value. 2. When morning starts, the CP is started, for a mass flow of 8 $kg.s^{-1}$. 3. When a Reynolds number of 20000 is reached, the solar field starts to track the sun. 4. Hot pump (HP) is started in order to produce steam and carry away the heat. Cold salts return to the CT. 5. Conditions are maintained during the whole day 6. **Data acquisition:** tracking angle, inclination angle, sun's position (see **Erreur ! Source du renvoi introuvable.**).
<u>Post-treatment:</u> Comparison between tracking angles and inclinometer values

Figure 68: Procedure of a test to be preformed

7.3 Training the operation and maintenance team

For the O&M Team in total 9 operator + 2 site managers were hired until the training and commissioning. With this team, the plant was operated around the clock until the end of May 2022.

The project consortium agreed to carry out extensive theoretical and practical training for the operating team. For this purpose, a one-month training plan was agreed between the partners (Figure 59). This consists of 37 different presentations (90 minutes each) by all partners on the subsystems in their area of responsibility. The main focus of the training is on the basic understanding of the plant, safe operation and maintenance of the test facility.

		Non-DLR Partner Required		DLR/INO	DLR/INO	DLR/INO	UEV	UEV	DLR/INO	FLG
			Topic	Familiarization + Standard operation					Plant Visit + SF-Details	
			Phase	O&M Staff Training Phase						
			Day of Training	1	2	3	4	5	6	7
			Date	Mo, 05.04.	Di, 06.04.	Mi, 07.04.	Do, 08.04.	Fr, 09.04.	Mo, 12.04.	Di, 13.04.
Session 1	1.5h	08:30	10:00	A1	B3	C1	A2	D15	P1	
				Lecture	Lecture	Lecture	Lecture	Lecture	Plant Visit	
				Introduction and Organisation of Training	Daily Solar Field Operation	Anti-Freeze Measures & SF Drainage+Refill	Safety Instructions	Maintenance	Plant Visit	Transport from Andasol
Break										
Session 2	1.5h	10:15	11:45	X1	D5	C5	B3	D15	P1	
				Team	Lecture	Lecture	Simulator	Lecture	Plant Visit	
				Getting to know each other	Thermal Energy Storage (TES)	System Salt Drainage & Drainage Tank	Daily Solar Field Operation	Maintenance	Plant Visit	Transport from Andasol
Lunch Break										
Session 3	2h	12:45	14:45	B1	B4	B3	C1	X2	P1	D1
				Lecture	Simulator	Simulator	Simulator	Team	Plant Visit	HandsOn
				Theoretical plant overview	Introduction to Simulator	Daily Solar Field Operation	Anti-Freeze Measures & SF Drainage+Refill	Team challenge: ...	Plant Visit	Solar Field Control (FSC+LOC)
Break										
Session 4	2h	15:00	17:00	B2	B9	B3	C1	X2	P1	D1
				HandsOn	HandsOn	Simulator	HandsOn	Team	Plant Visit	HandsOn
				Plant walk-through at beginning of training	Detailed plant walk-through	Daily Solar Field Operation	Anti-Freeze Measures & SF Drainage+Refill	Team challenge: ...	Plant Visit	Solar Field Control (FSC+LOC)
Off-Schedule		Evening	Activities							

		Non-DLR Partner Required		FLG	FLG	FLG	RIO + STE	STE	STE + ELT	ELT
			Topic				Steam Skid + Electrical Heat Tracing			
			Phase							
			Day of Training	8	9	10	11	12	13	14
			Date	Mi, 14.04.	Do, 15.04.	Fr, 16.04.	Mo, 19.04.	Di, 20.04.	Mi, 21.04.	Do, 22.04.
Session 1	1.5h	08:30	10:00	D1	D1	D2	A5	B10	B10	D11
				Lecture	Lecture	Lecture	Written Test	Lecture	Lecture	Lecture
				Solar Field Control (FSC+LOC)	Solar Field Control (FSC+LOC)	Solar Field Operation & Maintenance	Midterm Exam	Steam Cycle	Steam Cycle	Impedance + Trace Heating System
Break										
Session 2	1.5h	10:15	11:45	D1	D1	D2	D14	B10	B10	D11
				Lecture	Lecture	Lecture	Lecture	Lecture	Lecture	Lecture
				Solar Field Control (FSC+LOC)	Solar Field Control (FSC+LOC)	Solar Field Operation & Maintenance	Receivers	Steam Cycle	Steam Cycle	Impedance + Trace Heating System
Lunch Break										
Session 3	2h	12:45	14:45	D1	D2	X5	B10	B10	D11	D11
				HandsOn	HandsOn	Team	HandsOn	HandsOn	HandsOn	HandsOn
				Solar Field Control (FSC+LOC)	Solar Field Operation & Maintenance	Team challenge: ...	Steam Cycle	Steam Cycle	Impedance + Trace Heating System	Impedance + Trace Heating System
Break										
Session 4	2h	15:00	17:00	D1	D2	X5	B10	B10	D11	D11
				HandsOn	HandsOn	Team	HandsOn	HandsOn	HandsOn	HandsOn
				Solar Field Control (FSC+LOC)	Solar Field Operation & Maintenance	Team challenge: ...	Steam Cycle	Steam Cycle	Impedance + Trace Heating System	Impedance + Trace Heating System
Off-Schedule		Evening	Activities							

		Non-DLR Partner Required		ELT	DLR/INO	Siemens	Siemens	DLR/INO	YAR	DLR/INO
			Topic		BoP + Emergency Situations+ DCS + Salt Properties					
			Phase							
			Day of Training	15	16	17	18	19	20	21
			Date	Fr, 23.04.	Mo, 26.04.	Di, 27.04.	Mi, 28.04.	Do, 29.04.	Fr, 30.04.	Mo, 03.05.
Session 1	1.5h	08:30	10:00	D11	C4	D7	D6	A4	D8	A3
				Lecture	Lecture	Lecture	Lecture	Lecture	Lecture	Written Test
				Impedance + Trace Heating System	Emergency Situations	Control System (DCS)	Power System	Organisation and Work Flows	Molten Salt Equipment and Properties	Final Examination
Break										
Session 2	1.5h	10:15	11:45	D11	C4	D7	D6	A4	D8	A3
				Lecture	Simulator	Lecture	Lecture	Lecture	Lecture	Oral Test
				Impedance + Trace Heating System	Experimental Operation / Simulator Buffer Session	Power System	Power System	Organisation and Work Flows	Molten Salt Equipment and Properties	Final Examination
Lunch Break										
Session 3	2h	12:45	14:45	X3	B8	D6	D6	A3	X4	A3
				Team	HandsOn	HandsOn	HandsOn	Exam	Team	Oral Test
				Team challenge: ...	Emergency Situations	Control System (DCS)	Power System	Self-study + Question / Answer Session	Team challenge: End Of Training Event	Final Examination
Break										
Session 4	2h	15:00	17:00	X3		D6	D6	A3	X4	A3
				Team		HandsOn	HandsOn	Exam	Team	Simulator Test
				Team challenge: ...	#NV	Power System	Power System	Self-study + Question / Answer Session	Team challenge: End Of Training Event	Final Examination
Off-Schedule		Evening	Activities							

Figure 69: Trainings plan for the O&M Team training within HPS2 project

Due to the Corona pandemic, the on-site training had to be postponed several times as travel was limited. For this reason, it was decided to use a hybrid format, so that all theoretical sessions were recorded by the partners. These are therefore also available to future new members of the O&M

team for familiarization. For the online training sessions, a Q&A area with engineering, scientific and O&M team was set up.

In addition to the theoretical sessions, 35 practical training sessions were held in person on the plant. The practical sessions were successfully completed in the summer of 2021 with the exception of the steam generator. This could not be put into operation as described in chapter 5 and therefore training was postponed.

Prior to the start of commissioning, all members of the O&M team received safety training to ensure safe operation and maintenance of the plant. One part of that safety training was a hands-on session on the construction machines in use on site and a first aid training.

One major part of the practical sessions was the training on the DCS, which was hold by DLR and it subcontractor SIEMENS (Figure 70):

- T3000 functionalities and logic training for important components and subsystems of the plant
- Step by step training for important operational modes, step sequences and controllers such as drainage, start-up, and shut-down
- Operation of controllers for automated plant control and safety
- Creation and handling of trends and reports
- Warning and alarm handling
- Blackout scenarios and countermeasures
- Remote control of DCS

Figure 70: DCS Training Session in the control room

Besides sessions regarding operation and maintenance in the solar field, a training on the LOC and FSC was conducted in several small groups. This allowed all operators to be specifically trained in the field operation and its software control software (FSC).

Another hands-on session was related to the heating systems of the salt cycle and the supplied control software "Trace Vision". The failure diagnostic on different heating elements and applications were trained to the O&M Team in the field.

In case of a blackout the facility is equipped with a 440 kVA emergency generator (EDG). All operators were trained in operation and maintenance of the aggregate by DLR subcontractor Siemens (Figure 71).

Figure 71: Operators training on EGD

When operating a test facility, documentation of the tests performed is important for tracking and evaluation. Therefore, a continues logbook was introduced, in which all essential interventions by the operators are recorded. Continues hands-on training of maintenance task was implemented.

The O&M team training was successfully completed with a final exam by all team members and a plant visit of Andasol 3 (Figure 72). The exam consisted of 60 multiple choice questions, which were prepared in advance by the partners.

Figure 72: O&M Team of HPS2 Project at Andasol 3 power plant technical tour

A training simulator was also developed on the basis of the DLR model “Virtual Solar Field (VSF)” and tested within the framework of HPS2 and reproduced the entire salt system (Figure 63). During the training, however, this was only used to a limited extent, as the T3000 DCS was already available and there were significant differences in its handling. In addition, there were some software updates between the development of the simulator and its use, which partly led to problems with the installation of the software.

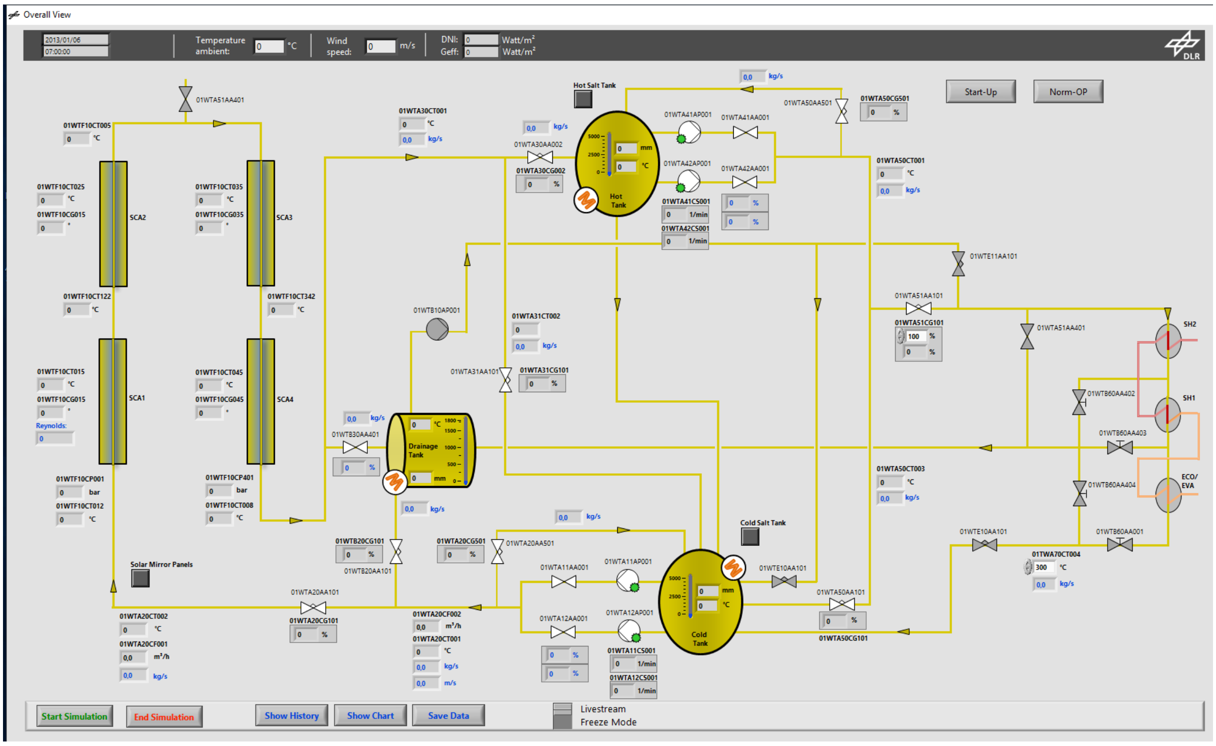


Figure 73: HPS2 full salt cycle simulator develop for O&M Training

Detailed manuals for all application in plant, divided by scopes of the partner, have been prepared. Together with the intensive training of the team the plant was operated over 5.500 h between October 2021 and May 2022.

7.4 Hot start-up of the overall plant

This commissioning step consisted of the initial salt melting, filling of the salt cycle and commissioning of the DCS in hot state.

7.4.1 Salt filling

For preparation of the first filling of the salt cycle the filling procedure was discussed and agreed on by all partners under coordination of DLR in close cooperation with TSK Flagsol.

During the pre-warming test, however the temperatures in the solar field were detected to be too low to prevent freezing of the salt during filling. The heating system was then enhanced by the use of an electric hot air blower.

To preheat the pipes for salt filling, the HPS2 loop is equipped with a trace heating and an impedance heating system that is designed and installed by the project partner eltherm. Trace heating systems use mineral insulated heating cables (MI cables), while the impedance heating system uses a high current flow through the pipe wall for heating. For safety reasons, the voltage level of the impedance heating system is limited to 50 V AC. All interconnecting piping system of the HPS2 plant is equipped with trace heating including the cross-over pipe and the rotating and expansion performing assemblies (REPAs) on the north and south-side of the solar field. The receiver tubes of the solar field and the REPAs in the center of the solar field are heated by the impedance heating system.

For temperature monitoring during operation, PT100 sensors with and without thermowell are installed in the solar field at the collectors' in- and outlets, and at the fixed pipe at the drive pylons. These PT100 measure the temperature of the fluid at the center of the pipes. The REPAs are equipped with surface temperature sensors for monitoring and control of the trace and impedance heating. Initially it was planned to derive the temperature of the impedance heated absorber tube from its electrical resistance. During commissioning however, it was observed that this approach is too unprecise due to leakage currents, which occur at various points of the impedance heating system. The estimated error of about 20% was considered too high to use this theoretically calculated temperature for control. Therefore, the concept was changed and the PT100 without thermowell, which feature a higher dynamic than the ones with thermowell, were used by eltherm for control of the absorber tube impedance heating.

During preheating and before filling with molten salt, the piping system is filled with air and only natural convection occurs inside the pipes. At this state, the PT100 installed in the center of the pipes do not reflect the temperatures present in the pipe walls since the losses due to heat conduction to the ambient are higher than the thermal transfer by natural convection to the measuring tip of the sensor. Therefore, temperatures measured in the solar field are much lower (by about 150 K) than the actual pipe wall temperatures. Only the surface temperature measurements of the REPAs with close contact to the wall indicated the actual preheating temperature. To overcome this problem, a hot air blower was used to apply forced convection to the temperature sensors inside the solar field and it could be observed that as soon as air is blown through the system, the measured temperatures increased significantly, reaching the expected values of up to 270 °C. Forcing convection in the pipes also helped to avoid potential cold spots and equalized the temperatures in the piping system before the first filling with molten salt. To improve temperature monitoring during preheating, surface temperatures sensors were installed in the follow-up project.

The following Figure 67 shows the effect of the air blower on the PT100 temperature measurements with (solid lines) and without (dotted line) thermowells at the drive pylons. In the morning the air blower was off and impedance heating was active in all collectors except solar collector assembly SCA1. Between 7:40 and 8:15, the hot air blower was tested to ensure air flow in the solar field and adjust temperature of heater to prevent overheating. At about 8:50, the blower was started leading to the steep increase in the temperature measurements. The temperature difference between the different sensors installations is around 20K. From sunrise until 13:00 the receivers were additionally exposed to unconcentrated sunlight. Afterwards, when the shade from the concentrators came onto the receivers, a slight decrease in temperature can be seen. In SCA1 it can be seen, that even without impedance heating, temperatures of more than 200 °C can be reached due to unconcentrated solar input. This temperature level would theoretically be sufficient to fill the collector with Yara Molten Salt without impedance heating.

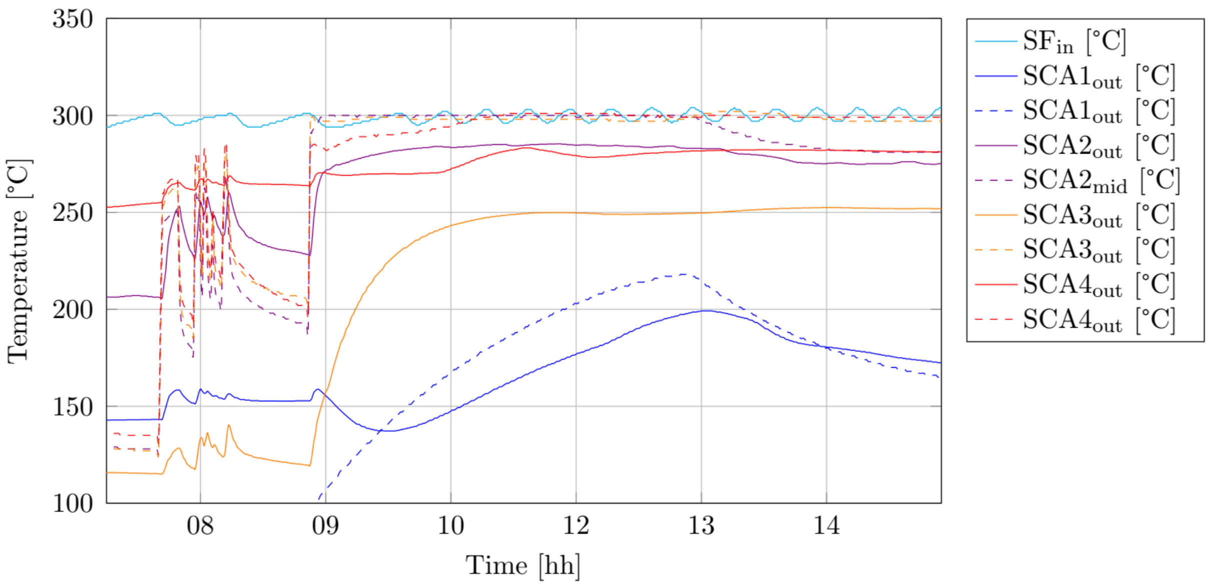


Figure 74: Pre-heating of the solar field (SF) with and without hot air forced convection.

One crucial aspect during the filling process is to avoid too large temperature gradients over the circumference of the receiver tubes, which could lead to bending and contact of the absorbers with the glass envelopes. In extreme cases, temperature gradients over the circumference can even lead to breakage of the glass tubes. One advantage of a molten salt system with trace and impedance heating is the fact that both the salt temperature and the temperature of the empty tube can be adjusted to the same temperature level before filling, eliminating the risk of problems due to temperature gradients.

On October 19th, 2021, the demo loop was filled with a mass flow of 10.8 kg/s (75% pump speed) within approx. 15 minutes without any technical issues. It was decided to use a relatively high mass flow during filling in order to avoid bending of the receivers due to temperature gradients over the circumference. During this first filling process it could also be demonstrated that venting at the cross over pipe valve is not necessary during filling as all air is pushed out of the piping system. Salt spillage from venting is therefore no issue and can be avoided. The receivers (Rioglass PTR 70) were monitored with cameras during filling, no deformations were detected.

7.4.2 Hot commissioning DCS

After filling of the solar field, controller tuning and troubleshooting on several devices were performed. Various restarts of the T3000 PLC and hence tests of total shut down and restart of the DCS occurred. Communication and interface check with the subsystems and subsystem control via DCS was tested. The step sequences were tested and validated by DLR together with the programmer from SIEMENS. Some step sequences, operation modes and controllers could only be tested with molten salt in the system as they were related to high temperatures and temperature differences, SCA focusing or activated heating systems. As most of the operation was initially manual, more operating experience is needed to complete testing of all modes. Also, operation of the SGS could not be tested completely as it could not be filled with molten salt due to the problems with the feedwater pump.

Behavior and safe operation of the plant were tested and adapted.

7.5 Running the scientific test program and operation of the plant

For detailed planning of the daily plant operation according to the scientific test program, the test protocols of the test plan were revised and the consortium decided under the lead-management of DLR and TSK Flagsol how the plant should be operated week by week in the weekly status meetings.

Initially, to ensure reliable and precise measurements, all sensors were verified, adjusted and calibrated where necessary by an instrumentation expert company before the beginning of the test program. To confirm the correct functioning of the control logic of the DCS software, operation mode tests were performed including: convective antifreeze, electrical antifreeze, filling, normal operation, shut down and drainage operation modes.

The first thermal tests performed with the solar field were the so-called ‘Offset Tests’. By changing the parameter “tracking offset” during these tests the collectors’ orientation towards the sun is changed. An analysis methodology has been developed to derive the ideal value of the tracking offset from performance changes, in order to achieve the maximum thermal power output of each collector.

Additionally, heat loss tests were performed. In these tests, the collector was left unfocused and salt was pumped at a high and low flow rates and at different salt temperatures through the absorber tubes. The resulting temperature drop in the salt was recorded so that temperature loss characteristics can be derived.

The drainage tests of the solar field confirmed that the collectors can be drained completely by gravity. For drainage the collectors are moved to the drain position, facing exactly east (0°), the valves to the drain tank are opened and the vent valve at the cross over pipe (COP) is opened. The salt is then draining into the drainage tank over the course of about one hour. Besides the level measurement of the drainage tank logged in the DCS this was also audio-recorded. In this first test some salt remained at one inlet of the drain tank due to a salt plug, which formed because of insufficient trace heating in a 30cm long pipe segment on the top of the drainage tank. The trace heating of this pipe segment was improved subsequently.

The performance measurements for evaluation of the solar field and collector performance contain different kind of tests and measurements. Before start of the tests all SCA´s were cleaned and reflectivity measurements were taken every 1-2 test days. The reflectivity was measured in 37 different positions over all mirror rows. In each measurement point an average of three close by measurements was calculated. These measurements were taken regularly on all SCA´s. Testing of the collector performance was executed under constant conditions of DNI, mass flow and inlet temperatures. For evaluation a period of 10-15 minutes of steady state outlet temperatures were needed. The performance test has been done with different inlet temperatures for all collectors and also for the whole field. Temperatures varied between 270°C and 450°C with salt mass flows between 6 kg/s and 9 kg/s. For the final evaluation Incidence Angle Measurement (IAM) have been performed. Therefore, different collectors had been tested between an incident angle of 20° and 0° with different inlet salt temperatures.

Beside the performance test the normal daily operation was tested, especially when ambient conditions did not allow performance tests. Main target was to reach highest possible salt temperatures in the system to gain experience with the Yara Molten Salt, the plant behaviour and collect energy to reduce electrical energy consumption. The detailed process description of the normal daily operation including process flow diagrams can be found in chapter 6.1.1. The daily operation begins with a startup sequence in the morning. Here, the mass flow in the solar field is increased, the collectors are sent to track mode, and salt is circulated into the cold salt tank until the target outlet temperature is reached. The switch over to the hot tank is done when the solar field outlet temperature approaches the hot tank setpoint by 20 K. This is followed by normal operation mode, where the collectors are focused and the nominal conditions are settled. If the maximum temperature at the solar field outlet is exceeded, it is possible to increase the mass flow or to apply a dumping factor to the collectors as in a commercial system. In the evening, the shut-down sequence transfers the plant into the convective anti-freeze mode. A salt mass flow of about 2 kg/s is pumped through the solar field to prevent freeze events. Salt is circulated into the cold tank and mixed with salt from the hot tank to compensate for the heat losses of the solar field.

7.6 Evaluating the test program

7.6.1 Evaluation of solar field heating

Evaluation of the solar field heating was possible to some degree in the time between the cold water cycling and the filling with ternary salt. Two operating conditions are of particular interest for the solar field heating:

1. the accuracy of the temperature measurements when the system is empty
2. the temperatures that can be reached by the heating system

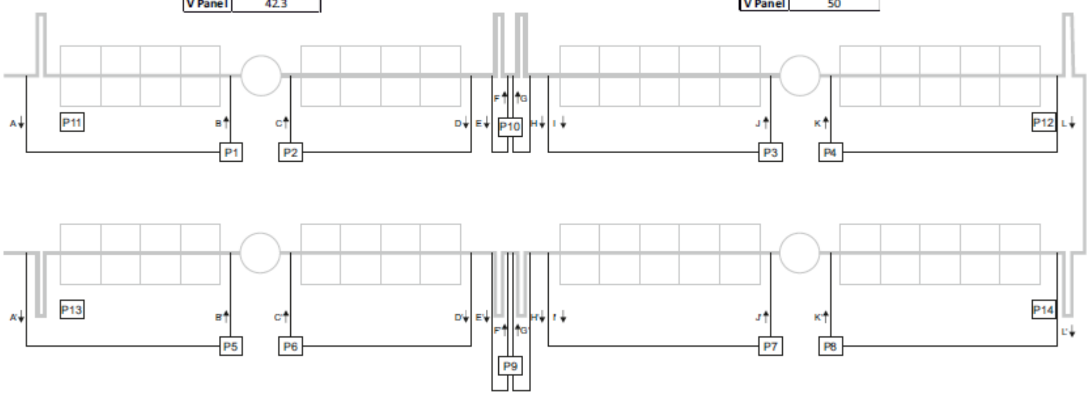
Performance of impedance heated HCEs

In case of impedance heating, the accuracy of the temperature measurements depends mainly on the accuracy of the measured current of the particular heating circuit. As it turned out, this is the weak point in the recent design with electrically interconnected heating circuits. The current measured in the panel of the impedance heating transformer is never matching the current actually flowing in the HCE string due to stray currents. The temperatures reached up to 270 °C in case of the impedance heating.

P1-P2	Current (ammeter)
A	236.7
B	274
C	293
D	161
E	105
F	0.3
G	0.95
H	13.35
I	14
I1 PLC	264.2
I2 PLC	287.2
V1 PLC	34.5
V2 PLC	34.2
V Traf	50.2
V Panel	42.3

P10	Current (ammeter)
D	95.6
E	153
F	260
G	245
H	156
I	94
I1 PLC	257
I2 PLC	246
V1 PLC	5.4
V2 PLC	5.4
V Traf	5.24
V Panel	5.24

P3-P4	Current (ammeter)
D	13.8
E	15.16
F	9.6
G	10.3
H	104
I	150
J	287
K	253
L	243
I1 PLC	287
I2 PLC	245
V1 PLC	39.6
V2 PLC	39
V Traf	50.3
V Panel	50



P5-P6	Current (ammeter)
A'	229
B'	268
C'	296
D'	154
E'	109
F'	1.51
G'	1
H'	16
I'	15
I1 PLC	267
I2 PLC	292
V1 PLC	33.4
V2 PLC	27.8
V Traf	50.4
V Panel	42.8

P9	Current (ammeter)
D'	86
E'	139
F'	214
G'	252
H'	94
I'	139
I1 PLC	251
I2 PLC	212
V1 PLC	5.4
V2 PLC	5.4
V Traf	5.26
V Panel	5.26

P7-P8	Current (ammeter)
D'	12
E'	12.8
F'	2.29
G'	2.5
H'	145
I'	105
J'	294
K'	248
L'	238
I1 PLC	285
I2 PLC	244
V1 PLC	39.5
V2 PLC	39.9
V Traf	49.9
V Panel	49.5

Figure 75 Measurements of currents of impedance heating circuits at ambient temperature

Figure above shows the currents measured on empty impedance heating circuits at ambient temperature. The heating circuits have been energized one by one for a duration of 10 – 20 seconds each in order to avoid influence from adjacent circuits and temperature rise. As an example, currents measured for panel P2 show that 293A are going out via path C, but only 161A are returning via path D. Another total 133A enter the circuitry connected to panel P10 via paths E, F, G, H and even to panel P3 via path I. This not only causes some parts of the current to go missing in the measurement performed in the panel of the particular heating circuit, but also fluctuations linked to the status of energization of adjacent heating circuits. A reliable current measurement that could be used for accurate resistance calculation and temperature determination is not possible without further examination under these circumstances.

Accordingly, the temperatures calculated prior to the first filling with salt showed some variation despite similarity of geometry of and voltage applied to the HCEs (see table below).

Table 4 temperatures calculated by TraceVision system in empty impedance heated HCEs Sept. 2021

heating circuit number	heating circuit location	temperature measured by immersion sensor (°C)	temperature sensor location	temperature determined by TraceVision control system (°C)
HC2	SCA 1.1	110	drive pylon SCA 2	245
HC3	SCA 1.2			225
HC4	REPA centre pylon west	n.a.	n.a.	128 (via surface-Pt100)
HC5	SCA 2.1	188	drive pylon SCA 2	300
HC6	SCA 2.2			251
HC10	SCA 3.2	283,6	drive pylon SCA 3	231
HC11	SCA 3.1			220
HC12	REPA centre pylon east	n.a.	n.a.	113 (via surface-Pt100)
HC13	SCA 4.2	200	drive pylon SCA 4	252
HC14	SCA 4.1			151

In order not to delay the ternary salt filling process, temperature readings obtained by immersion temperature sensors placed by DLR and Flagsol on the stationary tube sections on the pylons were used as guidance. In this case also the temperature readings are not accurately representing the HCE temperatures, as the sensors are placed outside the impedance heated circuit and heat transfer by thermal conductivity of the HCE tube material and by convection of the air inside the tubes is low. Therefore, a hot air blower had been connected to the tubing by the O&M team in order to reinforce the air convection and to provide additional power.

After that, temperature readings between 250°C and 280°C were achieved in the entire solar field with exception of SCA1, whose transformer had an electrical breakdown at the time of the test (see Figure 67).

After the successful filling with ternary salt, a better correlation between the temperatures measured by the DLR temperature sensors and the actual HCE temperatures became possible, as it can be assumed that the DLR temperature sensors are representative of the HCE temperature due to the heat transfer by the circulating salt. This allowed for the “calibration” of the resistance calculation method close to the point of operation.

Table 5 temperature calibration of TraceVision system (with salt flow)

heating circuit number	heating circuit location	temperature measured by immersion sensor (°C)	temperature sensor location	temperature determined by TraceVision control system (°C)
HC2	SCA 1.1	283,3	drive pylon SCA 1	283,3
HC3	SCA 1.2			283,3
HC5	SCA 2.1	282,7	drive pylon SCA 2	282,7
HC6	SCA 2.2			282,7
HC10	SCA 3.2	283,6	drive pylon SCA 3	283,6
HC11	SCA 3.1			283,6
HC13	SCA 4.2	282,7	drive pylon SCA 4	282,7
HC14	SCA 4.1			282,7

However, the temperatures determined by the TraceVision system after the calibration with circulating salt still require a verification in the empty state of the solar field. This could not be done before the expiration of the HPS2 project due to continuous salt filling. Performing that verification and the related determination of temperatures that can be reached by the impedance heating system could perhaps be part of a follow-on project.

Performance of impedance heated REPAs

Prior to the initial salt filling, temperatures achieved with a voltage of 5V were in part way below the desired value of 290°C. The main cause for this is the different tube wall thickness within the REPA (straight and corrugated tubing).

Table 6 temperature calibration of TraceVision system (with salt flow)

heating circuit number	heating circuit location	temperature measured by surface sensor (°C)	temperature sensor location
HC4	centre pylon West	199	southern half of REPA
		181	southern half of REPA
		189	northern half of REPA
		158	northern half of REPA
HC12	centre pylon East	270	southern half of REPA
		232	southern half of REPA
		242	northern half of REPA
		199	northern half of REPA

As a first consequence, the voltage level was raised to 7V, which in combination with the hot air blower described above lead to acceptable temperatures for the filling with ternary salt. Further testing and optimization were not possible due to the solar field being filled with molten salt for the remainder of the HPS2 project.

Performance of cross over piping and MI heated REPAs

By using a well-established trace heating technology for the COP, no surprises were to be seen here and the heating system performed as intended. In case of the REPA, the same technology was used, but somewhat off specification as the heaters are regularly being moved and bent. Temperatures between 250°C and 300°C have been achieved in all MI heated circuits. Due to the ambient conditions and regularly movement, moisture was able to enter into the connection points of two REPA heating circuits. This led to inadequate insulation and consequently to the opening of the RCD.

7.6.2 Evaluation of the solar field performance

The evaluation of the data from the performance tests in May 2022 – rather than yielding perfect performance results, it was designed to help deciding on test strategies. Another aspect was the limited testing time with the YARA ´Molten Salt` completed with the HPS2 project end, which did not allow repetition of many tests. The test campaign served this purpose well, because challenges in terms of test operation (e.g. tracking, parallel steady-state testing of two collectors), data acquisition and test conditions (cleaning and cleanliness measurement) became visible and could mostly be resolved.

Proper evaluation of this data is the next step and will be taken also in comparison with upcoming data with Solar Salt in the MSOpera project. Following the main challenges of the current data are listed:

- There is no good agreement of data obtained at different days (and very similar testing conditions) for the same collector and discrepancies cannot be solely explained by differences in collector cleanliness. The reason is yet to be found. However, the interval for taking reflectivity measurement was adapted to every or every second test day to get more detailed data.
- There is only a very limited number of test points for every collector due to the limitations in testing times.
- Due to the time of testing (May 2022) incidence angles up to 25° only were tested (minor issue)
- The Yara Molten Salt limited the maximum temperature to values lower than in the actual collector design (minor issue)
- Collectors exhibit different performance characteristics, but we do not know yet if these differences really are significant. They could also be due to the limitations in the data base or generally poor repeatability

7.6.3 Daily Operation

In the first months of 2022, the temperatures in the plant were successively increased from 350 °C to up to 500 °C hot tank (HT) temperature, depending on the weather as reaching the highest temperatures requires several hours of high DNI. An exemplary normal operation day is shown in **Figure 4**. The strong temperature fluctuation and oscillation is explained to the lack of a heat sink since the steam generator system is currently out of operation. With the convective anti-freeze mode, the solar field is kept warm during the night and with the increasing DNI, the start-up sequence is initiated. The temperatures rise and when it reaches the switch-over temperature of in this case 495 °C, the salt will no longer be circulated back to the cold tank, but fills the hot salt tank. The switch-over temperature is defined as the solar field outlet temperature -20 K. After the switch-over procedure the normal operation starts and the hot tank is heated up. As there is no heat sink available the cold tank temperature increases already during start-up and the hot tank is heated up until 9:30 consequently, the possible temperature increase in the solar field becomes smaller especially for the SCA1. As a result, minimum dumping of SCA1 was set to 100% and the remaining three collectors have to dump also up to 100% of the irradiation.

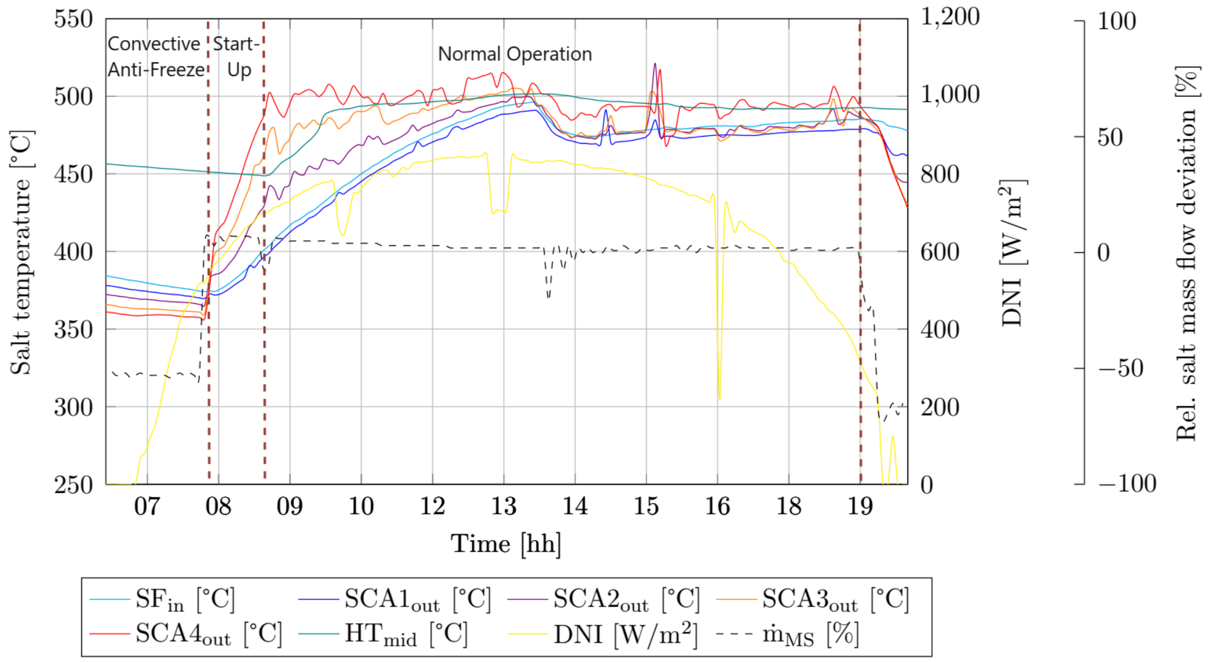


Figure 76: Measurements of DNI, relative salt mass flow, collector (SCA)- and hot tank temperatures with "Yara Molten Salt" on April 30th 2022 @ HPS2 test loop.

8. “Lessons learnt”

8.1 Identification of room for improvements – Lessons Learned

In the course of the project many technical challenges were solved and important insights for improvements were gained. These ‘Lessons Learnt’ will be presented in this chapter sorted by the different scopes of the plant.

8.1.1 Yara Ternary molten salt

It is important to note that Yara ternary molten salt contains crystal water and must be evaporated before molten salt is ready to use. Most of the water evaporated already at around 220°C however, in order to remove any inner bound hydrates molten salt heated up to 300°C. Due to higher viscosity of the ternary salt around melting temperature, water vapor molecules escaping from the mix might cause foaming on the molten salt surface. It is important to control this phenomenon by adjusting temperature for smooth buildup of such vapor and at the same time maintain surface to depth ratio of molten salt as high as possible inside the tank. Once bulk mix reaching temperature above 200°C then lower viscosity would also help vapor transition from molten salt to head space.

After heating the salt in the cold tank to 300°C, there was initially an increase in the formation of NOx emissions (Figure 77). These formed nitrite acid in the chimney of the plant through condensation of crystal water, which escaped from the expansion joint. The acid partially dissolved the aluminum cladding of the tank insulation (Figure 77). Therefore, it is important to establish a sufficient NOx measurement and personal protection for O&M personal.

It is important that during the melting process and during the operation process breath trough CO2 filters to avoid CO2 in contact with hot molten salt in order to avoid any calcium carbonate precipitation in the tanks.

Figure 77: NOx emissions after melting process (left), nitrite acid leakage on the compensator of the cold tanks chimney (right)

8.1.2 Salt cycle

In this section all lessons learned regarding the salt cycle are mentioned in different subsections.

Salt Pumps

Shortly after the hot start-up of the cold salt pump, a salt leakage was detected in the packing area between the shaft and the bearing (Figure 78). By readjusting the preload on the graphite packings, the leakage could be eliminated. It is therefore recommended to check salt pumps regularly during and shortly after hot commissioning.

Figure 78: Leakage of cold salt pump shortly after first start up.

Conductive level switches

During commissioning with molten salt, the high-level switches in the tank were closed even when they were not covered with salt. The measured resistance of the sensors is lower than specified, so the switch must be covered with a thin layer of salt, even when it is located above the actual level of the tank. This led to false alarms, which resulted in active interventions of DCS in the operation. The reason for this is probably the creeping ability of the molten salt and the diffuse salt mist which the pumps spray into the tank for bearing lubrication.

Solar Field Pressure Sensor

The pressure sensors in the solar field are specially optimized for use up to 600 °C in solar thermal power plants. The high operating temperatures are achieved by an additional cooling section in front of the stainless-steel diaphragm. When installing the insulation, care must be taken to ensure that the cooling fins are cooled convectively. The sensor at the solar field outlet was exposed to the highest temperatures of up to 520°C and was defective after the performance tests in May 2022. Silicone appeared on the connection line between the diaphragm and the pressure sensor (Figure 79). In addition, severe corrosion was observed on the membrane surface after about 5,500 hours of operation (Figure 79).

Figure 79: Leakage of silicone at the connecting line between diaphragm and pressure sensor

8.1.3 Heating systems

Electrical arc on REPA impedance heating system

High sensitivity of the REPAs to pipe alignment lead to the fact that the original drainage position support of the two rotation performing hoses was pinching into the insulation of the elbow between the hoses. Electrical potential from the impedance heating of the REPA induced here an electric arc, which eroded a hole into the piping and caused a small salt leakage (Figure 80).

Figure 80: Salt leakage on REPA elbow after electric arc

The photo shows the spraying leakage at the REPA elbow resulting from the electrical arc between piping and support structure caused by the impedance heating currents. The avoid this situation the original supports were modified, adjusted and electrically insulated (C).

Overheating of valve bonnet heating

On the salt control valves a design error from the manufacturer Flowserve lead to the problem, that the valve bonnet heating broke regularly by overheating of the heating elements. The reason for overheating is too much power, small angular distances, thermal contact to the bonnet housing and a big distance between temperature measurement and heating element.

The photos in Figure 81 show the problematic original valve bonnet heating, whose casing can simply be crumbled. The second photo shows a compressed bellows of the Flowserve molten salt valves with rest of solid salt. In this case this did not led to a leakage between the spindle and the housing, but frequently movement of the valve without sufficient bonnet heating will do and replacing the bellow is expensive.

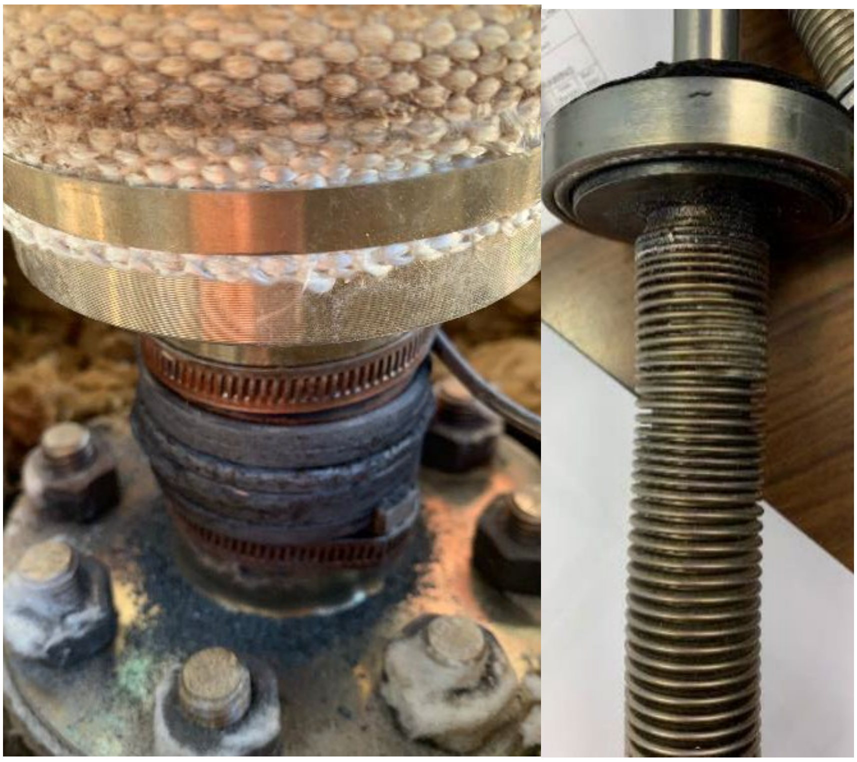


Figure 81: Original valve bonnet heating and damages due to solid salt in gaps of the valves bellow

Improvements to the solar field heating system

In summary, it was shown that the solar field impedance heating system works in principle and the filling with ternary salt was made possible. However, the accuracy of the calculated temperatures in the HCEs and also of the measured temperatures in the impedance heated HCEs remains unknown, and so does in consequence the temperature that can actually be reached by the heating system for empty HCEs. This had impact on desired testing of solar salt which has a higher melting temperature. The following improvements could be subject to further consideration.

Power increase in impedance heating circuits

In the current project the delta between the calculated required voltage for a 95 m impedance heating circuit and the maximum permitted voltage is only 3.14V or 6.7%. Thus, the margin for a power increase by the use of larger power cable (and a resulting reduction of voltage drop) is only small, and it comes at the price of a vast increase of cross section in the copper power cables. In contrast, a solution could be to increase the cross section of the wall of the HCE tubing. An increase of 0.5 mm would reduce the HCE resistance by almost 20%.

Power increase in MI heated circuits

Should MI heated REPAs be the preferred option, power can easily be increased by using a longer heater with a lower total resistance in the manufacturing process. The use of MI cables is somewhat off specification as the heaters are regularly being moved and bent, problems with the electrical isolation on the cold ends of the cables were detected at two REPA. This is due to the hygroscopic property of the insulator (MgO2), which binds water even though smallest openings such as micro cracks and thus becomes conductive. MI-heating might be recovered by cut the cold ends, dry and seal them again with resin. This procedure is not always successful, so that in some cases the entire MI-cables have to be replaced. If the affected heating circuit is installed in a REPA, the entire flexible hose assembly must be replaced with the current design.

Temperature measurement of SCA impedance heating circuits

Due to reasons explained in section 3.1, temperature control of the SCA impedance heating was based on calculated values of the resistance of the receiver tube material derived from measurements of current and voltage. Despite the separate earthing of each impedance heated SCA circuit, the lack of isolators that would separate the individual SCA impedance heating circuits has caused those measurements to be influenced by unintended current paths and by the operating status (on / off) of the adjacent circuits due to stray currents as shown in section 6.7. This finally resulted in hesitation on part of the O&M team to trust the indicated temperatures. Unknown or contradicting temperature information has been an important factor in delay of decisions (e.g. whether or not to start a filling process etc.). This situation could be improved by implementation of surface mounted temperature sensors in sections of the impedance heated receiver tubes that are not covered by the glass envelope, i.e. underneath the mounting brackets. This also requires a suitable spacer to accommodate the sensor without being squashed between tube and bracket as well as a thermal insulation on top of the bracket that has a heat loss similar to that of a receiver tube at approx. 300°C. Surface mounted sensors are the preferred option to immersion sensors since in the important heat up phase the pipe is empty and the still air temperature measured by the immersion sensors is not representative of the actual receiver tube temperature as shown in section 6.7. As an alternative, if a calculated resistance should still be used for temperature control, separation of the individual impedance heating circuits by isolated flanges would be recommended.

Temperature measurement of REPA impedance heating circuits

The temperature distribution in empty impedance heated REPAs is inhomogeneous due to the different wall thicknesses and structures of the flexible and rigid REPA sections. Therefore, a sufficient number of surface mounted temperature sensors is required to achieve a valid overview over the temperatures of those sections. This becomes even more relevant since there could be contact between the inner REPA piping and the outer cladding, leading to stray currents and hence local power loss and cold spots that would otherwise remain unnoticed. In the current impedance heated REPA designs, two temperature sensors were installed, but measured temperatures showed differences of up 150 °C. If a section is clearly identified as too cold and subsequent measurements of currents on the REPA show that this is not due to stray currents, a higher voltage can be chosen on the secondary side of the REPA impedance heating transformer (whilst observing the permissible currents for the power cabling). Even though other parts of the REPA might then heat up to temperatures well above 300°C, this is not critical considering a service temperature of approx. 560°C.

Length of impedance heating circuits

For future commercialization of a parabolic trough solar power plant, reduction of the cost of impedance heating is important. One of the main cost factors of the impedance heating system are the copper wires from the impedance heating transformers to the ends of each impedance heating circuit due to the required large cross sections. Those costs could be reduced by use of smaller cross sections. This would however require shorter heating circuits, which would have an enormous impact on the entire steel construction.

Instead, an increase of heating circuit length could be considered that would reduce the total number of power supply points (and hence the cost for junction boxes, power terminations, flexible power cables etc.). This has to be weighed against a possible cost increase caused by required larger power cable cross section. Also, raising the voltage limit or implementing HCE tubes with less electrical resistance is a prerequisite.

8.1.4 Steam generator system

Risk management for heat exchanger transport

During the cold commissioning of the SGS at the site in 2019 it was found that one of the heat exchanger tubes was leaking. The exact reason for the damage is unclear.

The tightness of the heat exchangers had been tested and confirmed by a pressure test in the manufacturing work-shop before the transport to the site. After arrival on the site the heat exchangers were not used several years due to delays in the project execution. Reasons for the damage could thus be excessive forces during transport or insufficient drying after the workshop pressure test and/or inadequate conservation measures during the long stand-still period.

In the end the heat exchanger could be repaired on-site successfully. However, learnings could be to thoroughly test equipment soon after shipment and to increase conservation ef-forts when longer stand-still periods are expected.

Suitability of feedwater pump

For pumping the feedwater to the heat exchangers a plunger pump was applied. The plungers are sealed from the ambient by graphite packings. During commissioning it was found that water/steam was leaking excessively through the plunger seals when temperature and pressure were increased, leading in the end to a pump breakdown. Since the pump was successfully tested in the manufacturing workshop at maximum pressure with cold water, it is assumed that not the pressure alone but the combination of temperature and pressure respectively the condition of the water (boiling water) led to the damage. Lessons learned could be to procure only equipment that has proven its suitability under comparable working conditions. If this is not possible, the associated risks should be managed properly (extended manufacturer guarantees, …). Furthermore, an adequate sealing of the plungers is paramount when these pumps are used for pumping boiling liquids. A membrane pump could be a suitable alternative, too.

8.1.5 Solar field

In general, the experience with the HelioTrough® collector has been very positive. Despite constituting a full EPC project, it could be handled at low costs with a team of R&D engineers. The innovative pendulum pylons have proved to work. No damages have been observed, neither at the foot nor at the roller bearings at the top of the pylons. The metal structure has been reliable.

The manual assembly of the collector in principle designed for high degrees of automation has worked well and efficiently with an output of up to two SCEs per day.

Some details have shown to be problematic:

- The steel parts were out of tolerance, many had to be re-fabricated. A closer monitoring of QA/QC procedures than is possible in an R&D project is definitely advisable for.
- The system to measure the collectors' tracking position had to be adapted on site, because its components did not fit well together. This component is still unreliable. It seems that the large-diameter torque tube does not work well with magnetic sensors in an outdoor environment. Solutions: smaller diameter of axis, or an inclination sensor of sufficient accuracy.
- The electrification of the absorber tubes has been successful in general, but some details have shown problems:
  - Energy chains: The electric power has to be conducted to the absorber tubes moving in a wide arch by means of thick cables and solid so-called "energy chains". There have been some damages to those chains and even some secondary damages (broken mirrors). After careful redesign this now seems to work
  - HCE post bushings: The arms holding the absorber tubes (a.k.a. HCEs in the focal line rotate a few degrees to allow thermal expansion of the HCEs. This joint was redesigned as a hinge in HPS2 to serve simultaneously as an electric insulation. Plastic bushings separate post foot from the post itself. These bushings are sensitive to correct installation. When pressed into their holes narrowed by zinc deposits, they broke and electric short-circuits appeared.
  - HCE fixed post: This post is insulated from its foot by means of various fiber-reinforced plastic parts and bushings. Due to wrong mounting, some bushings were not installed. A poka-yoke approach could mitigate this issue. An improvement would be to have all electrically insulating elements installed in such a way to be visually inspected.
- Due to an error in the tolerance management by the collector designer, some mirrors are too close to the so-called arch-beams at the top of the drive pylons. This has led to the destruction of two mirrors; others had to be removed to prevent damage. It is advised to analyses this spot in future designs by means of 3D CAD models which allow to implement manufacturing tolerances.
- It is common practice to first install all SCEs in the field and then align the SCEs to each other in a successive work step. As described in in Chapter 3.6, this proved to be a very cumbersome and time-consuming procedure. The main reason was that the flanges at the end of the torque

tube were not parallel due to the gravity-induced bending of the tubes, so that the flanges tended to lock. To mitigate this, a procedure has been developed, where the bending was equalized by jacking up the center of the torque tube. As a further development, the bending line was rearranged through a different pattern of pylons. This concept was engineered in detail, built and tested in the project MSOpera, co-funded by BMWK as well.

- The two counterweights, each fixed and adjusted with 8 bolts, allowed for too many degrees of freedom, some even counteracting each other. In the future a much simpler design is advisable. The lollipop design of HelioTrough 3.0 as developed in MSOpera is a result.

In total approx. 80 measures to improve the design regarding reliability, manufacturability and cost efficiency have been identified during the construction and testing of the HelioTrough® 2.0 collector.

8.1.6 Process control

Filling of the Solar Field

The filling of the solar field turned out to be uncritical, as both the salt and the pipes were heated to a similar temperature. A relatively high mass flow of about 10kg/s at 75% pump speed was chosen in order to avoid gradient over the circumference of the pipes. During filling no bending of the receiver tubes or other optical and acoustic abnormalities could be determined. It was not necessary to vent the solar field at the COP as all the air in the system is displaced by the salt. The fillings were completed in less than 10 minutes.

Drainage of the Solar Field

Drainage of the solar field is one of the most critical processes in a molten salt plant, because it is gravity driven and thus takes significantly more time than the filling – in the case of the HPS2 plant about 45 minutes. Even small cold spots can lead to salt agglomeration, which can block the entire pipe cross-section. During the first drainage of the test plant, a plug occurred at the connection point to the drainage tank, where due to an error at a scope interface about 400 mm of a pipe section were not trace-heated (A in *Figure 72*). Attentive construction supervision of trace heating systems is essential to avoid cold spots and special attention must be paid at scope boundaries.

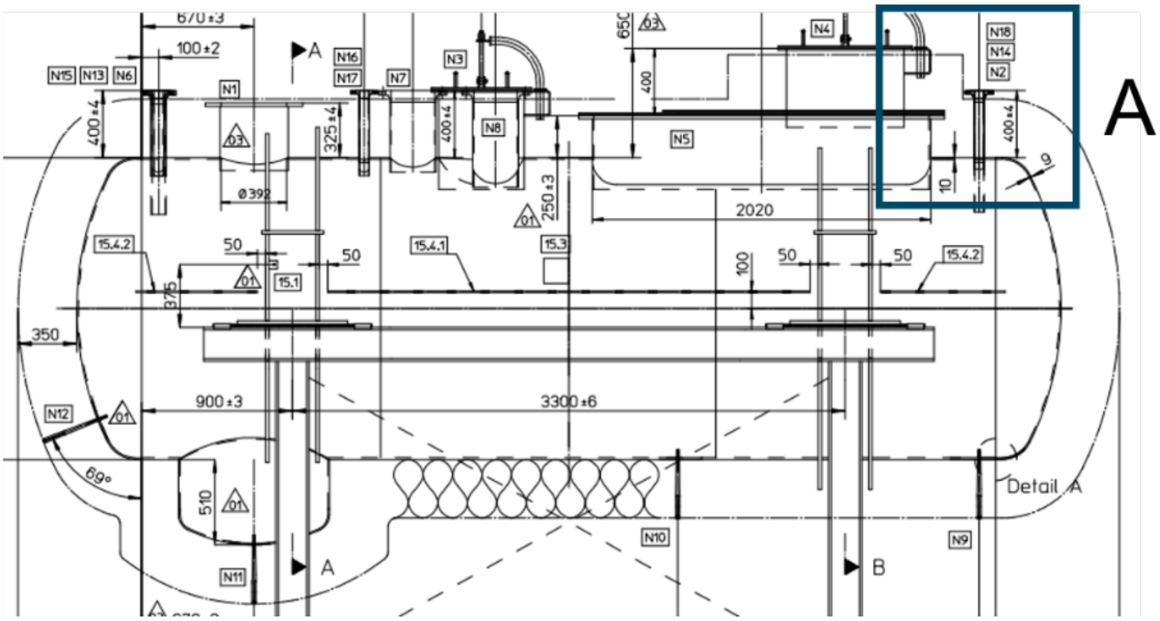


Figure 82: Drawing drainage tank with 400 mm unheated pipe section

This also applies to the installation of insulation for the extensive piping systems. In Figure 73a missing insulation at the COP of the solar field can be seen. Here the manufacturer of the insulation did not make the transition to the insulation sleeve and this could lead to a plug during drainage.

Using an IR camera at night makes hot/cold spots clearly visible and is useful for quality control of the insulation (Figure 73b). All weak spots should be eliminated before the first drainage, otherwise plugs can occur, which are difficult to find in an extensive piping network. There is currently no reliable method for plug detection, but the pipe temperatures are the best way to determine their position in an easy, but very rough manner. Drained pipes usually have lower temperatures than filled pipes (see 7.4.1 Salt filling).

Figure 84a: Lack of insulation at the COP of the solar field

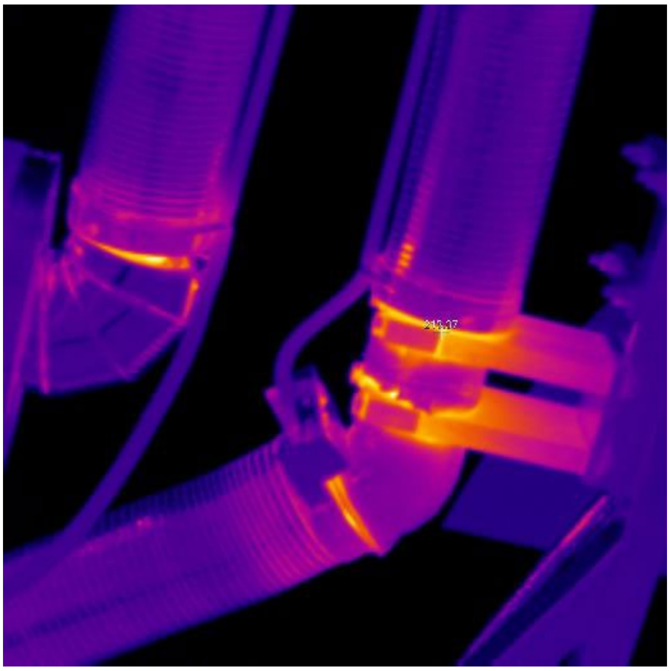


Figure 83b: Picture of REPA support structure with IR-camera

Besides cold spots the inclination of all piping is essential to enable complete drainage. The collectors of the HPS2 plant have a slight inclination of 0.15%, while the interconnecting piping was installed with an inclination of 2%.

Deviant from the tender specifications, the REPAs were found to be not fully drainable. This was due to sagging of the metal hoses, which was more pronounced than expected by the manufacturer. To improve drainability of the REPAs additional supports were installed. First an additional support was installed under the expansion performing metal hose (A), supporting it horizontally in the 0° drainage position. Subsequently another additional support was installed under one of the rotations performing metal hoses (B). The third hose of the REPA however could not be supported, as this would be an obstacle for the rotation movement. Full drainability of the REPAs could therefore not be achieved, but the additional supports brought significant improvements. The original support for the drainage position (C) had to be modified to a more round and better aligned shape, after an electric arc from the impedance heating system had damaged the pipe elbow (Figure 85).

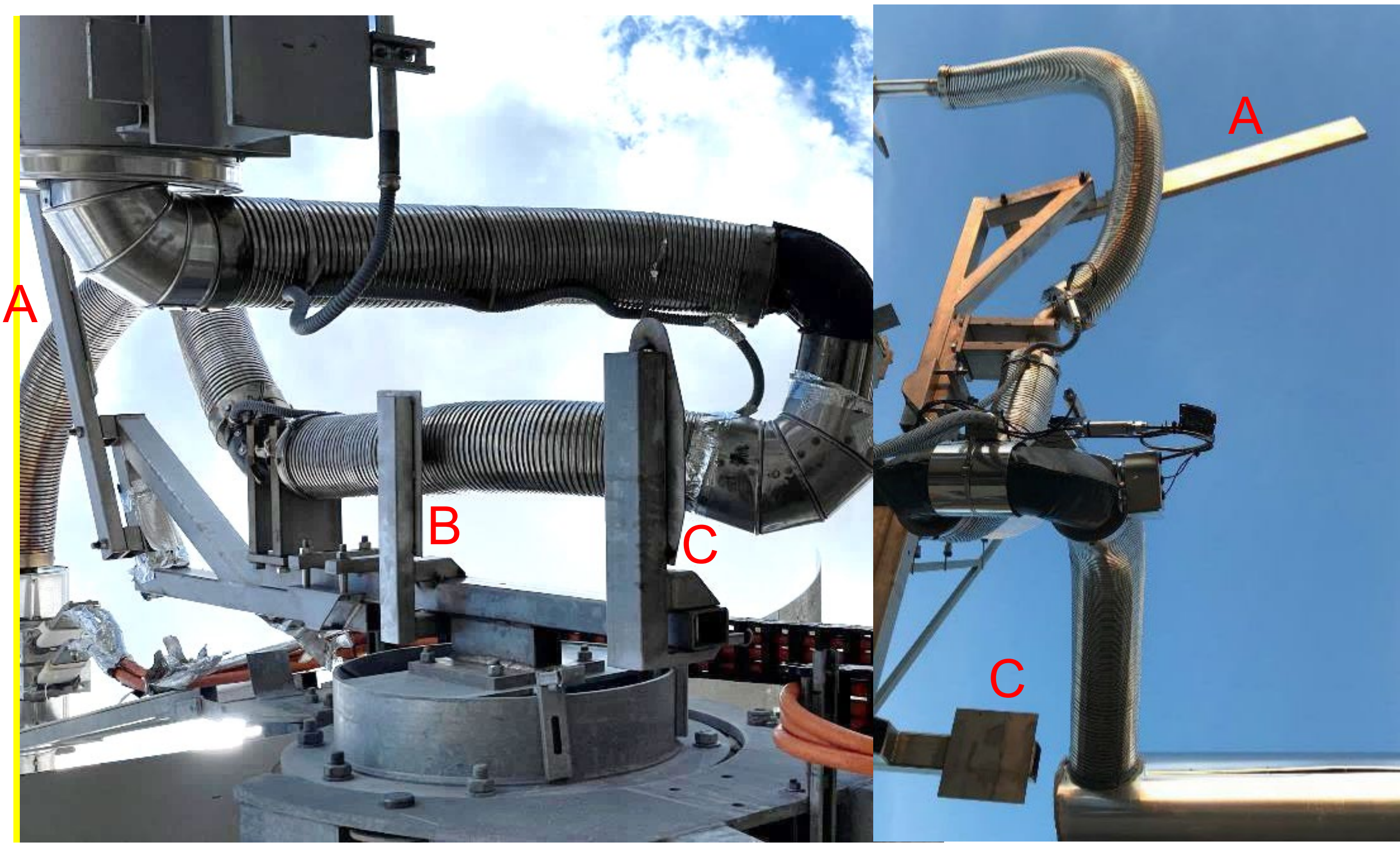


Figure 85 Photo of REPA and the support structure

DCS

The DCS is a T3000 from Siemens with two redundant servers to enable operation with highest expectations on operational safety and reliability. This is one advantage of the system, but this makes it very difficult to enter and modify the software for contractors outside of Siemens.

8.1.7 Others

The supply of spare parts by manufacturers the components is sometimes very expensive. The offers for spare parts and maintenance were partly by a factor of 10 higher than comparative offers from other suppliers, who are also active in the Spanish commercial solar thermal power plants. This is a good example of how O&M costs can be significantly reduced by having a larger pool of specialty contractors.

9. Bibliography

[1] D. Kearney, B. Kelly, U. Herrmann, R. Cable, J. Pacheco, R. Mahoney, H. Price, D. Blake, P. Nava, N. Potrovitza, Engineering aspects of a molten salt heat transfer fluid in a trough solar field, Energy 29(5–6), 861-870 (2004). DOI: 10.1016/S0360-5442(03)00191-9

[2] A. Cavaco, H. G. Silva, P. Canhoto, T. Osório, M. Collares-Pereira, Progresses in DNI Measurements in Southern Portugal, AIP Conference Proceedings, accepted (2018).

[3] . Ricardo Conceição, H.G. Silva, M. Collares-Pereira, CSP mirror soiling characterization and modelling, Solar Energy Materials and Solar Cells 185, 233–239 (2018). DOI: 10.1016/j.solmat.2018.05.035

[4] IEEE 844-2000(R2006) „Recommended Practice for Electrical Impedance, Induction, and Skin Effect Heating of Pipelines and Vessels“, ANSI 2006

[5] C. Y. Ho, T. K. Chu: "CINDAS Report 45", Center for Information and Numerical Data Analysis and Synthesis, Purdue University, Indiana, USA Sept. 1977