System/Component Modularization for SHIP Applications

IEA SHC Task 64 | IEA SolarPACES Task 4 | Solar Process Heat

Technology Collaboration Programme by iea

System/Component Modularization for SHIP Applications

This is a report from SHC Task 64 / SolarPACES Task IV: Solar Process Heat and work performed in Subtask B: Modularization

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Solar Heating and Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

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- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
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- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
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- ➢ *Solar Heat Worldwide*, annual statistics report
- ➢ SHC International Conference

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- Task I: Solar Thermal Electric Systems
- Task II: Solar Chemistry Research
- Task III: Solar Technology and Advanced Applications
- Task IV: Solar Heat Integration in Industrial Processes
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- Project in solar process heat in collaboration with the TCP on Solar Heating and Cooling (SHC TCP).

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Contents

1 Introduction

The main objective of Subtask B in Task 64/IV was the definition of modularized and “normalized” components/subsystems for SHIP (Solar Heat for Industrial Processes) applications (e.g., for the balance of plant, solar field, thermal energy storage and hydraulic circuit). The three activities planned to tackle this objective were:

Activity B1. Modular systems concepts for solar process heat applications
Activity B2. Standard components/packages for collectors and hydraulics (easy installation; easy dismantling)
Activity B3. Development of a modular and scalable BoP unit for solar process heat applications

The main objective of Activity B1 was the definition of modular concepts for the main components of usual solar process heat applications. For Activity B2, the main objective was the definition of “normalized” components and equipment used in solar fields and hydraulic circuits for SHIP applications to make their installation and dismantling easier and cheaper. Finally, the main objective of Activity B3 was the conceptual definition of a modular and easily scalable balance of plant (BoP) for SHIP applications. Here the term “BoP” considered was related not only to the mechanical/hydraulic interface (e.g., pipe, valve, etc.) but also to the instrumentation and signaling associated with the connection between the industrial process and the components included in the solar part (i.e., solar field and thermal storage mainly), as well as between the subsystems of the solar part.

The main results of Activity B1 were published in the first deliverable foreseen within Subtask B (D.B1: Integration schemes and BoPs more commonly used in commercial SHIP applications), which was published in October 2022 (https://task64.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task64-SubtaskB-DB1.pdf).

The present document gathers the most relevant results of the work carried out in Activities B2 and B3. Section 2 presents a proposal for a guideline for instrumentation and performance assessment of solar fields in SHIP plants with line-focus solar concentrators, while Section 3 presents the development of a modular and scalable BoP unit for solar process heat applications, which in good part summarizes the results obtained within the Modulus Project, coordinated by DLR and leader of Activity B3.

2 Guideline for instrumentation and performance assessment of solar fields in SHIP plants with line-focus solar concentrators

2.1 Purpose and field of application

The purpose of this guideline is to provide the procedures for on-site solar field performance testing in SHIP plants using liquid heat transfer fluid (HTF) and line-focus solar concentrators, thus allowing assessment of the solar field performance with the least uncertainty possible based on the best knowledge and engineering practices available in the solar thermal industry, using the ISO/IEC Guide 98-3 Guideline for its calculation. It must be made clear that this guideline is not aimed at solar field characterization over direct normal irradiance (DNI) and temperature values.

This guideline refers specifically to short tests under quasi-steady-state conditions as defined in Subsection 2.3.3.

This guideline describes the instrumentation and measurement techniques necessary for determining the following parameters which are required for finding the solar field performance:

- Useful/available radiant solar energy
- Net thermal energy delivered by the solar field

This guideline is applicable to solar fields in SHIP plants of any size using line-focus solar concentrating collectors in which the Sun is the main source of energy and all the elements and systems in the part tested are operative.

This guideline applies to acceptance testing of line-focus solar fields and any other scenario in which their performance must be determined. In this document, the parties involved are the Owner, Builder, Financer or any other entity interested in the solar field's performance.

Any other equipment or specifications not explicitly mentioned remain outside of the scope of this guideline.

2.2 Terms and definitions

The terms and definitions used in this guideline are as given in Guideline IEC 62862-1-1, complemented by the definitions for *the cleanliness factor* and the *response time* (t_r), defined in Point 11 of Subsection 2.3.1 and in Point 5 of Subsection 2.3.2, respectively.

2.3 General guidelines for testing

This section provides the test methodology for determining solar field performance and analyzing the general steps required for planning, preparing and performing these tests.

2.3.1 Test procedure

All details for preparing, testing performance, evaluation and reporting results must be included in a document called the ***Test Procedure***, which must be approved beforehand by the parties involved.

It is recommended that the Test Procedure includes at least the following points:

- Purpose of test, indicating planned duration.
- Guidelines to be applied.
- If the parties wish to verify the solar field's performance, it must state the assurance (or reference) value, uncertainty and comparison criterion.
- Test boundaries, identifying inlet and outlet flow rates and measurement points.
- Basic test plan.
- Description of test preparation activities to be performed, such as calibration and verification of measurement equipment, test staff training, equipment inspection and cleaning, and preliminary testing, if so agreed. The instrumentation to be used during the tests must comply with the specifications in Subsection 2.4. All the measurement equipment, both built-in field instruments and those to be used only temporarily for testing, must be checked, inspected and adjusted before starting.
- The procedure for determining the solar field response time shall be the one defined in Subsection 2.3.2.
- Description of activities to be performed during testing, such as testing start and end conditions, operating method, adjustments allowed before and during testing, and data recording. Test conditions may in no case exceed the equipment manufacturer's upper limits or normal solar field operating procedures.
- Reference to the solar field operating methods, including both main equipment and any auxiliary equipment that affects the test results.
- Definition of how the thermal energy loss in the solar field heat transfer fluid system piping is to be considered.
- A procedure for determining the solar field cleanliness factor, or predetermined value to be used during testing. The cleanliness factor is understood to be the quotient of measured reflectance and reference reflectance measured after employing the most effective technique. This reference reflectance will be agreed upon by the parties and defined in the *Test Procedure*.
- A procedure for including the cleanliness factor in the collector optical performance simulation model calculations.
- An exhaustive list of instruments and measurement equipment in the solar field, giving coding, calibration, location, number, type, uncertainty and main technical information.
- Calibration certificates for the instruments listed.
- Uncertainty analysis, setting the Type B uncertainty as per the ISO/IEC Guide 98-3 Guideline, "Guide to the Expression of Uncertainty in Measurement".
- A methodology for determining meteorological variables such as direct normal radiation, wind speed and direction, ambient temperature and relative humidity.
- Heat transfer fluid sample collection, preparation and analytical methods, explaining how and how often its parameters are to be measured or calculated.
- Identification of the laboratory that will analyze the heat transfer fluid.
- Heat transfer fluid thermophysical property tables as a function of temperature (at least density and specific heat for the entire operating range).
- Format in which data and results are to be provided.
- If the solar field has more than one sensor for a certain measure, the parties involved must agree on how to process the measurements of the parameter studied and the procedure to be followed should there be discrepancies in the data recorded for a single magnitude.
- Data distribution procedure. The measured data shall be stored in files available to the parties involved. Processing and calculations derived from these data shall not be done in the original measurement files, and a final report shall show explicit test results.

- Specific reference to the solar field simulation model and its description.

If the parties involved consider it advisable, they may omit some of the above *Test Procedure* points.

2.3.2 Before testing

The following must be done before starting the test:

1. Check that the instrumentation to be used in the test complies with the stipulations defined in Subsection 2.4.
2. Check beforehand that the pyrheliometers or solar irradiance sensors used are correctly focused and that their windows are not dirty.
3. Clean the collectors before testing and keep them as clean as possible so that their optical parameters (reflectance and transmittance) are as close to nominal as possible and do not reduce solar field performance and set the cleaning factor as stipulated in the *Test Procedure*.
4. Verify that the collector solar tracking system is working properly and that there are no errors impeding the collectors from being perfectly focused. Ensure that the solar collectors are not completely or partially defocused by the control system during testing, since that would vary the net solar field aperture area.
5. Determine the solar field *Response Time* (t_r), which is defined as the time required for the difference in temperature between inlet and outlet ($T_o - T_i$) to drop to 10% of its original value after completely defocusing the solar field, when the working fluid inlet temperature and flow rate are stable, and with a direct solar irradiance on its aperture, G_b, higher than or equal to 500 W/m^2. The *Response Time* may also be found as the time it takes for the temperature difference between solar field inlet and outlet ($T_o - T_i$) to rise to 90% of its final value with the solar field completely focused, direct solar irradiance on its aperture, G_b, greater than or equal to 500 W/m^2, and with the temperature and flow rate at the solar field inlet meeting the specifications in Section 2.3.3 for the preparation stage.
6. Before testing, Type B uncertainties in the various parameter measurements (specific heat at constant pressure, heat transfer fluid mass flow rate, solar field inlet/outlet temperatures and direct solar irradiance), must be determined.
7. The solar field inlet and outlet temperature sensors shall be located closest to the solar field inlet and outlet, respectively, preferably without any other instruments or equipment between them and the solar field, so measurements taken as faithfully as possible during the test are representative of solar field behavior.
8. Flow rate shall be measured at the solar field inlet, respecting the corresponding straight length of piping before and after the flow meter as per the manufacturer's specifications. In cases where the primary measurement of the flow meter is the volumetric flow rate, the reference temperature for calculating the fluid density and, thereby, the mass flow rate shall be measured as close as possible to the point where the flow meter is installed.
9. Reliable data on the thermophysical properties of the heat transfer fluid necessary for the energy balance in the solar field supplied by a recognized laboratory must be available. Constant values rather than temperature-dependent ones shall be avoided because they will induce errors.
10. The strongest wind gusts should not be over 5 m/s unless the parties involved explicitly agree to a higher speed.

2.3.3 Short tests under quasi-steady-state conditions

This guideline includes recommendations for determining solar field performance through short tests performed under *quasi-steady-state* conditions. The specific duration of the test shall be given in the *Test Procedure* agreed to by the parties.

The test shall be considered at quasi-steady-state conditions when the various parameters in the performance calculations are sufficiently stable. This ensures the accuracy and representativeness of the results. The main parameters which must remain stable are:

- Direct solar irradiance, G_b.
- Heat transfer fluid temperatures at the solar field inlet, T_i, and outlet, T_o.
- Mass flow rate of the heat transfer fluid circulating through the solar field, $\dot{m}$.
- The angle of incidence, θ, calculated with the precise solar field coordinates. This angle is the Sun´s longitudinal angle for Linear Fresnel collectors (see IEC 62862-5-2 for reference)

Therefore, to achieve quasi-steady-state conditions, the test must be performed under clear sky conditions at midday as close as possible to solar noon on clear days, when the above parameters are sufficiently stable for at least 30 minutes.

To ensure adequate stability of all the parameters involved, before starting the test a *preparation stage* is necessary before the test (see 2.3.3.2).

2.3.3.1 Adapting the test to the time of year and SHIP plant configuration

Depending on the time of year when the test is performed, whether or not the plant has an energy storage system, and oversizing of its solar field, it may be necessary to perform the test using only a part of the solar field. Thus, the following general cases could arise:

1. In SHIP plants without energy storage systems
   a. If the estimated maximum thermal power the entire solar field is going to yield at solar noon does not exceed the maximum that the BoP can accept, the test shall be performed with all the collector loops tracking.
   b. Otherwise, only a part of the solar field shall be run to ensure that this limit is not exceeded. Additional tests shall be done afterward until the entire solar field has been tested on dates as close as possible to the first one. The inlet hand valves at the collectors' rows not included in the test must remain closed during the test of the rest of the solar field in order to avoid any HTF flow through them.
2. In SHIP plants with energy storage systems
   a. If the estimated maximum thermal power the entire solar field is going to yield at solar noon does not exceed the sum of the maximum that the BoP and the storage system together can accept, the test shall be performed with all the collector loops tracking.
   b. Otherwise, only a part of the solar field shall be operated to ensure that this limit is not exceeded. Additional tests shall be performed afterward until the whole solar field has been tested on dates as close as possible to the first one.

If additional testing should be necessary to cover the entire solar field, collector loops already tested shall not be kept in operation. In this case, the solar field performance shall be found as the weighted mean performance found in each of the tests, where the weighting coefficient for each test is the percentage of rows of the solar field that were operating during the test.

2.3.3.2 Test preparation stage

Once the fraction of the solar field that is to be put into operation for the test has been determined as indicated above, the solar field operation shall start in the morning with that number of loops. After the start-up, the solar field HTF outlet temperature set-point shall be equal to the nominal temperature, and the flow rate shall be varied manually as needed.

Thus, the solar field shall be in operation until the preparation stage starts. The time the preparation stage starts shall be such that, assuming a duration of twice the solar field response time, it can be completed soon enough before solar noon for the test itself, which shall last no less than three times the solar field response time, to be performed around solar noon.

During the preparation stage, the temperature shall be controlled by the solar field feed flow at a set-point 5 K lower than the nominal temperature, and the solar field feed flow rate will be adjusted (either by the control system or manually by the operator) to keep the fraction of the field operating completely focused and the outlet temperature stable at about 5 K below the nominal temperature.

As orientation, the percentage variation in the flow rate should be a little below (this difference may be higher in the months with wider incidence angles, and lower in the months with smaller incidence angles) the percentage variation in the product of $G_b \cdot \cos\theta$, where G_b is the direct solar irradiance and θ is the angle of incidence on the solar collectors in operation (θ is the Sun´s longitudinal angle for Linear Fresnel collectors, according to IEC 62862-5-2).

For a more precise estimate of the percentage variation necessary in the flow rate as a function of the percentage variation in the product of $G_b \cdot \cos\theta$, it is recommended this manual control be tested before the day of the test, but on a date close to it. The purpose of this operating strategy during the preparation stage is to start the test itself under sufficiently stable solar field conditions and without the danger of exceeding the nominal field outlet temperature.

2.3.3.3 Performing the test and test requirement

When the preparation stage is completed, the operator shall keep the solar field feed flow rate constant, at which point the test itself begins.

For the test to be considered valid, the following conditions ensuring quasi-steady-state must have been met:

- Useful direct solar irradiance on the collector aperture, $G_b \cdot \cos\theta$, shall not be below 500 W/m^2, and the difference between its maximum and minimum value during the test shall not exceed 25 W/m^2.
- Useful direct solar irradiance in the solar field, $G_b \cdot \cos\theta$, shall not vary more than 5% during the test. This condition is usually met on clear days almost all year long, for the two hours around solar noon, for collectors with North-South orientation.
- The temperature of the heat transfer fluid at the solar field inlet, T_i, must vary less than 3% from the mean thermal change (during testing) between the inlet and outlet, $T_i - T_o$.
- The difference in temperature of the heat transfer fluid between the solar field inlet and outlet, $T_o - T_i$ must not vary more than 5% from its mean during the test. The speed of wind gusts lasting from 3 to 10 seconds must be under 5 m·s^{-1}, except if the parties involved agree explicitly to a higher wind speed.

The table below shows the conditions that must be met in quasi-steady-state tests:

Table 1: Conditions for quasi-steady-state tests

Weather conditions	Limit	Units	Comments
Maximum angle of incidence	30	°	

Minimum useful direct solar irradiance on the aperture $G_b \cdot \cos\theta$	500	$W{\cdot}m^{-2}$	During the test
Maximum variation in $G_b \cdot \cos\theta$	5%		During the test
Maximum wind gust speed	5	$m{\cdot}s^{-1}$	During the test
Maximum difference between max. and min. ambient temperature	5	K	During the test
Minimum ambient temperature	278	K	To avoid snow, ice, condensation on solar radiation
Operating conditions			
Maximum difference between max. and min. heat transfer fluid temperatures in the solar field inlet, T_i	3%		Of the mean temperature difference between solar field inlet and outlet during the test
Maximum difference between max. and min. change in heat in the solar field	5%		Of the mean temperature difference between solar field inlet band outlet during the test
Maximum difference between consecutive A and B recorded where: A) Maximum flow rate variation expressed as % and B) Variation in useful direct solar irradiance expressed as %	5%		During the test
Operating mode in “tracking” (no defocusing)			During the entire test

2.3.3.4 Data recording and test duration

During the preparation stage and the test, data recorded shall be the means for consecutive time periods with unit duration not over 2 minutes. The criterion recommended for determining the time interval between consecutive data records is that it should be no less than four times the response time of the slowest sensor involved in the calculations. When line-focus solar field performance is evaluated, the slowest sensors are usually the PT100 thermistors, which have a characteristic response time on the order of 20-30 seconds. Therefore, since PT100 sensors must be used for temperature measurement, the time between consecutive data records should be no less than 2 minutes. Furthermore, the total duration of the test should be determined keeping two conditions in mind:

- At least 30 consecutive data records must have been acquired (ideally 50 or more data records), and
- The total duration of the test (excluding the preparation stage) should be no less than 30 minutes.

Considering the recommendations above, both the minimum time between data records and the minimum total test duration necessary to determine the solar field performance may be set in advance. Time interval for collecting instantaneous data should not be longer than 10 seconds.

2.3.4 Test boundary

In general, the **test boundary** identifies the energy flows that must be measured to determine solar field performance. All the inlet and outlet flows necessary for the calculations must be determined at the point at which they cross the boundary. For the purposes of this guideline, it is unnecessary to determine the flows inside the boundary. The solar field test boundary is set between the pump and the solar field on the cold side, and between the solar field and BoP on the hot side. All the energy flows that enter and exit the boundary are identified with a point: the available radiant solar energy ($E_{in,solar\_avail}$) or the net thermal energy of the solar field ($E_{field,fluid}$) (Figure 1).

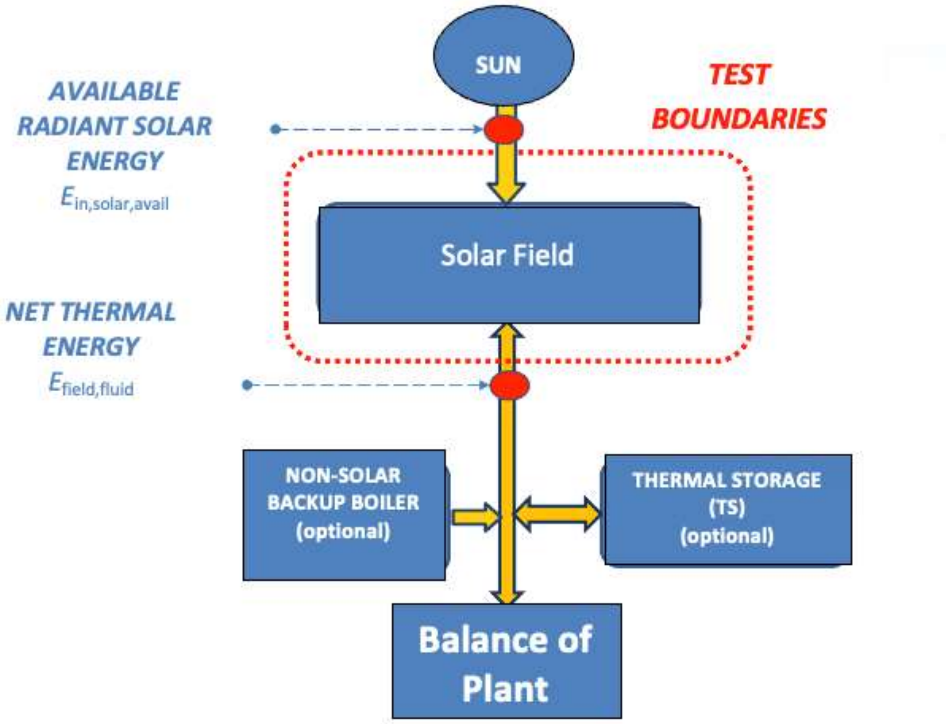

Figure 1: General diagram of the Solar Field Test Boundary

The heat transfer fluid inlet and outlet temperature measurement points and flow rate shall be those stipulated in Points 7 and 8 of Subsection 2.3.2, and in any case, the test boundary shall be defined in the *Test Procedure*.

Subsections 2.6 and 2.7 provide more detailed information on what measurements to perform and how to do so.

2.3.5 Definition of performance verification references

To compare the performance found in the tests with a reference, two elements are required:

1. A solar field simulation model that can generate the reference values when the inlet conditions measured during the test are entered.
2. To define the verification procedure. That is, how the measurement (+/- uncertainty) is compared to the reference (+/- uncertainty).

2.3.5.1 Solar field simulation model

The solar field simulation model (i.e., a mathematical model for simulating the solar field behavior for the purpose of calculating its characteristic variables over time) is a key element for verifying performance. The parties to this test shall agree on the model to be used for verification, and its validation shall be documented. It is recommended that at least the requirements in this section be complied with.

For the tests subject to this guideline, the minimum solar field simulation inputs and outputs shall be the following (see Figure 2):

- Inputs:
  - Power field location (geographic latitude and longitude)
  - Date and time the test starts and ends.
  - Records of date and time, direct solar irradiance and other weather conditions during the test (ambient temperature, wind speed, atmospheric pressure) at intervals of no longer than 10 minutes
  - Inclination and orientation of the collectors
  - Solar field availability during the test period
  - Solar field cleanliness factor
  - Solar field inlet/outlet temperatures
- Outputs:
  - Available radiant solar power/energy
  - Useful radiant solar power/energy
  - Solar field net thermal power/ energy

Figure 2: Minimum solar field simulation model inputs and outputs

The solar field model used for performance verification has to be validated. It is recommended that model validation include:

- Checking that the model actually reproduces the nominal outlet specifications when fed with reference conditions (Design point).
- Consistency in predicting other than reference conditions, showing that when input parameters vary, the output trends are congruent with those variations.

2.3.5.2 Verification procedure

The implicit purpose of verifying solar field performance is to compare the performance obtained from the tests with the guarantee or reference performance given by the model. Both test and reference data are subject to uncertainties, so treating uncertainties is very important in the verification procedure.

Both the standard (u) and expanded $(U = u \cdot k$, where k is the Coverage Factor) uncertainties of the solar field performance are characterized by a confidence level that shall be agreed upon by the parties for verifying the solar field. The verification procedure shall consist of comparing the reference value with the one from testing, taking the corresponding uncertainties into account. The criterion for comparison shall be defined in the *Test Procedure*.

As this point is considered critical, the *Test Procedure* shall clearly define the following concepts:

- *Standard uncertainty associated with the performance obtained in the test* (u_M).
- *Standard uncertainty associated with the reference value* (u_{VR}). The reference value shall be found preferentially from the simulation model and may be used as the guaranteed value of specifications. It should be indicated whether or not the uncertainty associated with the reference value is provided and if so, the procedure followed to calculate it should be explained.
- *Confidence level and Coverage Factor* (k) to be applied for determining the expanded uncertainty of the test value (U_M). If it is decided to include the expanded uncertainty of the reference value (U_{VR}), the associated confidence level and the coverage factor shall be indicated. It is recommended to use the ISO/EIC Guide 98-3 (ISO Guide to the expression of uncertainty in measurement, Table 1), as summarized in Table 2 below, for this.

Table 2: Confidence levels and associated coverage factors (Gaussian distribution)

Confidence level (%)	Coverage factor (k)
68.27	1
90	1.645
95	1.960
95.45	2
99	2.576
99.73	3

Although, as mentioned above, the criterion for comparison must be established in the *Test Procedure*, as an example, two possible cases for the comparison to be taken as satisfactory are shown below:

Case a): It is agreed that the whole measurement uncertainty band is higher than the reference value with its uncertainty band (Figure 4a):

$$(M - k_M \cdot u_M) > (VR + k_{VR} \cdot u_{VR})$$

Case b): It is agreed that the maximum of the measurement uncertainty band is higher than the minimum of the reference uncertainty band (Figure 4b):

$$(M - k_M \cdot u_M) > (VR - k_{VR} \cdot u_{VR})$$

Where:

- Coverage factor: k
- Measurement: M
- Reference value: VR
- Standard uncertainty: u
- Expanded uncertainty: $U = k \cdot u$

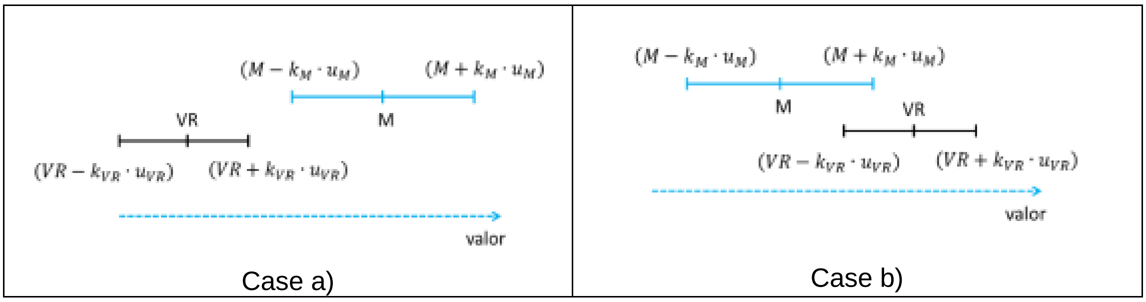

Figure 4: Examples of measurement (M) and reference value (VR) comparison criteria

2.4 Parameters, instrumentation and measurement methods

This section compiles the information necessary for measurement, which includes the type of measurements to be performed, how to measure and the specifications of the instrumentation used.

2.4.1 General requirements

To collect the data, the SHIP plant must have a data acquisition system able to record and store simultaneous measurements. The measurement channels of such a system must have at least a 12-bit digital resolution.

During testing, built-in solar field instrumentation, portable instruments or alternative sensors may be used, as long as they are considered adequate for the measurements and meet the specifications agreed by the parties.

In general, all the instruments used should have been either purchased or calibrated within one and a half years before the test. This calibration is a must for temperature sensors. The calibration certificates (laboratory, date, number) shall be recorded in the *Test Procedure*. Heat transfer fluid flow meters shall be verified and/or calibrated as the technology allows. The calibration requirements that flow meters must meet shall be defined in the *Test Procedure* when it cannot be done by authorized laboratories.

If the SHIP plant has more than one sensor for a certain magnitude, each must meet the stipulations defined in Section 2.2. The final magnitude measurement shall be found as the arithmetic mean of the several measurements, and their Type B uncertainty shall be obtained from the Type B uncertainty associated with each of the measurements, except for particular specifications contained in this guideline.

The use of multiple sensors to measure the same magnitude increases the reliability of the measurement since it enables any important problem associated with the measurement to be found quickly. This way, if one of the sensors breaks down or simply goes out of adjustment, it can be detected quickly by comparing the measurements taken by each sensor to each other. Since this is considered affordable, two temperature sensors at each temperature measurement point must be used because this decreases measurement uncertainty significantly.

When more than one sensor is used to measure the same magnitude, all the sensors are usually made by the same manufacturer and, therefore, calibrated using the same procedure and reference. In this case, the error of all the sensors would be correlated with the error of the reference used by the manufacturer, and the Type B standard uncertainty of the final measurement calculated as the arithmetic mean of the measurements provided by the various sensors used, would be equal to that of one sensor. When the various sensors used to measure the same magnitude come from different manufacturers and have been calibrated using different references, the Type B uncertainty of the final measurement calculated as the arithmetic mean is lower than that of one sensor because in this case the errors of the various sensors are not correlated and therefore, it is unnecessary to take the cross-sensitivities into account for calculating the Type B standard uncertainty.

2.4.2 Required measurements and instrumentation

The variables that must be obtained (by measuring or calculating) to determine a SHIP plant's solar field performance are:

- Direct solar irradiance, G_b, in [W·m^{-2}] (measured)
- Mass Flow rate of the heat transfer fluid circulating through the solar field, $\dot{m}$, e.g. in kg ·s^{-1} (measured, or calculated from measured volume flow rate and density at this temperature)
- Heat transfer fluid temperatures at the solar field inlet T_i and outlet T_o in [ºC] (measured)
- Ambient temperature, T_{amb}, in the solar field, in [ºC] (measured)
- Wind speed, v, in [m·s^{-1}] (measured)
- Angle of incidence of direct solar radiation, θ, in [º] (calculated from geographic coordinates and date/time))
- Heat capacity, c_p, or enthalpy, h, of the heat transfer fluid
- Density, ρ, of the heat transfer fluid, in case needed for mass flow rate.

- Reflectance or cleanliness factor (relative reflectance) of the solar field, as [%] (measured)

It will also be necessary to properly define in the *Test Procedure* the criteria to calculate the Net Collector Area of the solar field during testing.

Although wind speed and direction, along with ambient temperature, are not indispensable for calculating solar field performance, their measurement is necessary if one wants to compare the solar field performance calculated with the one from the simulation model, which does use these parameters.

The sections below provide the measurements to be taken during testing and the specifications that their sensors must meet, both to determine the parameters to be verified and the variables to be used in their evaluation.

2.4.2.1 Direct solar irradiance (G_b)

Among the various options existing for measuring direct solar irradiance, pyrheliometers mounted on their corresponding solar tracking systems are recommended because of their higher accuracy and reliability. The typical measurement range of the pyrheliometers, which must meet the following characteristics, is 0 to 1500 W·m^{-2}, with which their guideline Type B uncertainty of measurement is around ± 1.25%:

- Pyrheliometer field of view: maximum 6° of arc
- Have a thermoelectric transducer
- The spectrum of measurement of the transducer must include the 280-4000 nm range. The possible error associated with the tracking system may not be over $\pm$ 0.5°
- Have a solar tracking sensor attached to the tracker
- Pyrheliometers must be of “First class” quality as given in Table 1 of the ISO-9060 guideline
- For very large solar fields, the minimum number of pyrheliometers recommended is given by the quotient: total collecting surface/ 75000 m^2. In this case, pyrheliometers must be distributed in the solar field so that the measurements are representative of the direct solar irradiance in the entire solar field. When the solar fields are very large, although the day is clear, there could be different direct solar irradiance values within the borders due to the presence of aerosols and particles in suspension. It is recommended that the maximum distance from any collector to the nearest pyrheliometer is less than 500 m.

Although only one pyrheliometer would be sufficient in small solar fields, measurement reliability is increased if two pyrheliometers are used because errors can be detected easily if the measurements supplied by the two sensors deviate more than 2% from each other. Once the solar field commissioning is completed, the second pyrheliometer can be removed.

Special attention should be given to the place where the pyrheliometers are installed so their measurements are not affected by smoke or steam from nearby equipment (cooling tower, auxiliary heater, etc.). Before starting the preparation stage, the pyrheliometers must be cleaned and verified that they are properly aimed at the sun on the same day of the test.

When there is more than one pyrheliometer, in the days before the test, after cleaning and checking the correct aiming, it must be checked that the data acquisition system has no more than a 2% difference between accumulated daily measurements given by the various pyrheliometers in absence of clouds. If differences are over 2%, the instrument affected must be verified or calibrated and then checked again for differences before the test. The calibration certificate must bear a date within two years before solar field testing.

When there is more than one pyrheliometer in the solar field, they must all be installed the same way and must be checked before the test for absence of evidence of possible inconsistency among the measurements of the various pyrheliometers. This is done by measuring the usual range of direct solar radiation in the place the solar field is located, and checking that for any possible pair of pyrheliometers $|Z_{ij}| \leq 2$, where:

$$Z_{ij} = \frac{G_{bi} - G_{bj}}{\sqrt{[U_B(G_{bi})]^2 + [U_B(G_{bj})]^2}}$$

G_{bi} y G_{bj} are the data recorded by the data acquisition system in the same record based on the measurements provided by pyrheliometers i and j, respectively, and $U_B(G_{bi})$ and $U_B(G_{bj})$ are Type B expanded standard uncertainties corresponding to the measurements of pyrheliometers i and j, respectively.

The development of this criterion would be for cases when there are three pyrheliometers so that: $|Z_{12}| \leq 2$, $|Z_{13}| \leq 2$, and $|Z_{23}| \leq 2$.

This verification of pyrheliometers must be done in a clear day with very low atmospheric attenuation (i.e., visibility range of 20 km or more) to assure that possible discrepancies are not due to uneven distribution of aerosols at the site of the solar field.

If the various pyrheliometers used are the same model, are all installed the same way and have been calibrated using the same reference element, Guideline Type B uncertainty of the final measurement (found as the arithmetic mean of the data provided by all the pyrheliometers) may be assumed to be the same as for a single pyrheliometer.

2.4.2.2 Heat transfer fluid flow rate ($\dot{m}$)

There are different types of flow meters to measure the flow rate: differential pressure (orifice plate), vortex, ultrasonic, turbine and Coriolis flowmeters. The parties involved in the verification process shall agree on the type of flow meter to be used during the test. In any case, the equipment used must provide, within the range of the heat transfer fluid's working temperatures, a total Type B standard uncertainty in the mass flow rate measurement below 1.5%.

The requirements necessary to ensure proper equipment operation (respecting length of straight piping upstream and downstream of the flow meter, sensor position, etc.), defined by the equipment supplier must be respected.

The flow rate may be measured at the solar field inlet or the outlet, but it is recommended that it is measured at the solar field inlet.

When the flow meter measures volumetric flow, $\dot{V}$ (e.g. in $m^3 \cdot s^{-1}$), the mass flow rate will have to be calculated by multiplying the volumetric flow by the heat transfer fluid density, which is a function of temperature. For this, a temperature sensor is installed close to the flow meter without impeding its proper operation according to the supplier's specifications. Total measurement uncertainty for fluid temperature shall be below 2 K.

When fluid density is used to calculate the mass flow rate based on the volumetric flow, Type B uncertainty associated with the density calculation from the fluid temperature must be considered.

2.4.2.3 Fluid temperatures at the solar field inlet (T_i) and outlet (T_o)

The temperature sensors used must be Class A PT-100, DIN 1/3 (DIN EN IEC 60751) or better quality, with a 4-wire connection.

For each temperature measurement of the heat transfer fluid needed for the commissioning, two sensors shall be used and placed at a distance of no more than one meter from each other, inside a thermowell with a penetration into the pipe according to the specifications provided by the sensor´s manufacturer or immersed (unless otherwise specified by the sensors manufacturer) The thermowells shall be installed such that the one located upstream does not disturb the flow of the one located downstream. Adequate means should be used to ensure good thermal contact between the sensor and the inner wall of the thermowell according to the sensor´s manufacturer.

The maximum Type B standard uncertainty associated with the heat transfer fluid temperature given by each sensor as recorded by the data acquisition system shall not be over ± 1K.

For long connection lengths, it is recommended that an analog-to-digital conversion protocol is used for the transmission of the measurement value.

Two PT100 sensors corresponding to the same temperature must be installed the same way, and the absence of any sign of possible inconsistency between the two PT100 sensor measurements of the same temperature must be checked before the test. For this, temperatures within the usual range of temperatures in question (solar field inlet or outlet) must be measured with the two PT100s and then checked that:

$$|Z| < 2$$

$$Z = \frac{T_1 - T_2}{\sqrt{[U_B(T_1)]^2 + [U_B(T_2)]^2}}$$

T_1 and T_2 are PT100 1 and 2 measurements, respectively, recorded by the data acquisition system in the same record, and $U_B(T_1)$ and $U_B(T_2)$ are the Type B expanded standard uncertainties corresponding to PT-100 1 and 2 measurements, respectively.

If the two PT100 sensors corresponding to the same temperature are the same model, installed the same way and calibrated using the same reference element, the Type B standard uncertainty of the final measurement (found as the arithmetic mean of the data provided by the two sensors) may be assumed to be the same as for a single sensor.

2.4.2.4 Ambient Temperature (T_{amb})

Ambient temperature shall be measured in a position representative of the entire solar field, using a temperature sensor protected from nearby sources of heat or direct solar radiation. It shall be checked that the measurement is not affected by hot air drafts caused by gas or steam from nearby equipment. If there should be several ambient temperature measurements distributed around the plant, each one of them must meet the stipulations of this section and the final ambient temperature measurement shall be found as the arithmetic mean of the several measurements, and the Type B uncertainty shall be found from the Type B uncertainties associated with each of the measurements.

The Type B standard uncertainty associated with the data recorded by the data acquisition system shall be no more than ±1 K for ambient temperatures.

2.4.2.5 Mean wind speed on the solar field (v)

Horizontal wind speed shall be measured with anemometers located not more than 100 m from the collector field, at a height of not less than 5 m above the ground and 3 m above the highest point of the collector field, with a Type B standard uncertainty of recorded data below or equal to ±1 $m \cdot s^{-1}$.

If several wind sensors are used during testing, the maximum recorded (average) value by the various sensors shall be taken as valid for each record.

The speed in each data record for each anemometer shall be the mean of the instantaneous values measured every second during the recording period.

2.4.2.6 Angle of incidence of the direct solar radiation (θ)

A mathematical algorithm providing this angle as a function of the geographic coordinates of the site, the date and the time, shall be used to determine the angle of incidence, θ. For parabolic trough collectors, θ is the angle between the Sun´s vector and the vector normal to the aperture plane of the collector, while for Linear Fresnel collectors longitudinal, θ_L, and transversal, θ_T , incidence angles are required. Algorithms/formulas from SOLPOS or DIN should be used.

The angle of incidence considered for each of the periods the test time is divided into shall correspond to the middle instant of the period since variation in the angle of incidence is very slow around solar noon.

2.4.2.7 Heat transfer fluid enthalpy

The data supplied by a laboratory recognized by the parties shall be used to calculate its density (ρ) and increase in specific enthalpy (Δh) undergone by the heat transfer fluid or, in its defect, the specific heat at constant pressure of the fluid (c_p). Enthalpy difference should be used if accurate enthalpy data are available, instead of calculation by means of the specific heat integral, because the use of the specific heat introduces additional uncertainty and sources of calculation errors.

When an nth-degree polynomial of the enthalpy or specific heat is obtained from tabulated values versus the fluid temperature, the uncertainty associated with each of the coefficients of the polynomial must be taken into account when calculating the overall type B uncertainty of the enthalpy increase.

When accurate enthalpy values are not available, the increase in specific enthalpy of the usual working fluids in the solar field can be determined using the specific heat at constant pressure, c_p, of the heat transfer fluid and the temperatures of the fluid at the solar field inlet, T_i, and outlet, T_o:

$$\Delta h = h_o - h_i = \int_{T_i}^{T_o} c_p \cdot dT \qquad \text{(Eq. 1)}$$

If the specific heat of the heat transfer fluid at constant pressure, c_p, is expressed as a function of the fluid temperature using an nth-degree polynomial, $c_p = a_0 + a_1 \cdot T + a_2 \cdot T^2 + \cdots + a_n \cdot T^n$ the previous equation becomes:

$$\Delta h = a_0 \cdot (T_o - T_i) + \frac{a_1}{2}(T_o^2 - T_i^2) + \frac{a_2}{3} \cdot (T_o^3 - T_i^3) + \cdots + \frac{a_n}{n+1}(T_o^{n+1} - T_i^{n+1}) \qquad \text{(Eq. 2)}$$

For the usual temperature range in the solar fields of SHIP plants using thermal oil as heat transfer fluid, both the specific heat and the density of the fluid may be expressed accurately as a function of the fluid temperature using a 2nd-degree polynomial, which simplifies the previous expression yielding:

$$\Delta h = a_0 \cdot (T_o - T_i) + \frac{a_1}{2}(T_o^2 - T_i^2) + \frac{a_2}{3} \cdot (T_o^3 - T_i^3) \quad \text{(Eq. 3)}$$

When, due to the nature of the heat transfer fluid, its specific heat cannot be expressed as a polynomial, direct use of the enthalpies of this fluid at working conditions at the solar field inlet and outlet is recommended.

The test report shall indicate the origin of the calculation of the heat transfer fluid's thermophysical properties.

2.4.2.8 Reflectance or Cleanliness Factor

The use of the Reflectance Measurement Guideline issued by SolarPACES shall be applied whenever possible. Otherwise, the Test Procedure shall define the instrumentation and the procedure for determining reflectance in the solar field.

https://www.solarpaces.org/csp-research-tasks/task-annexes-iea/task-iii-solar-technology-and-advanced-applications/reflectance-measurement-guidelines/

2.5 Calculating solar field performance

This subsection gives the guidelines for calculating solar field performance and the parameters that serve as a basis for its calculation:

- Useful and available radiant solar power/energy
- Solar field net thermal power/energy
- Solar field performance

2.5.1 Useful/available radiant solar power and energy

The *useful radiant solar power* in the solar field, $P_{in,solar,useful}$, is expressed in units of power, typically kW or MW, and is calculated from the direct solar irradiance using the following expression:

$$P_{in,solar,useful} = N_{col} \cdot A_{net} \cdot G_b \cdot \cos\theta \quad \text{(Eq. 4)}$$

where N_{col} is the number of parabolic trough or linear Fresnel collectors in operation in the solar field, A_{net} is the net aperture area of one collector, G_b is the direct solar irradiance in the solar field and θ is the angle of incidence of the direct solar radiation. If there should be several types of collectors, or several angles of incidence in the solar field, the useful radiant solar power for the entire solar field shall be the result of adding up the values obtained by applying (Eq. 4) to each of the areas of the solar field where the various parameters in it are constant.

The net aperture area, A_{net}, is defined as the surface of the perpendicular projections on the aperture plane of the reflector/refractor panels forming the collector, plus the part of the orthogonal projection of the metal receiver tube on the aperture plane not overlapping it. According to this definition, neither longitudinal nor transversal separations in the reflector panels that comprise the collector concentrators are computed as aperture area (IEC TS 62862-1-1 Terminology).

Similarly, the *useful radiant solar energy* in the solar field during testing, $E_{in,solar,useful}$ is calculated by integrating the *useful radiant solar power*, calculated following (Eq. 4) over test time, resulting in the following expression:

$$E_{in,solar,useful} = \sum_{i=1}^{n} N_{col,i} \cdot A_{net} \cdot (G_{b,i} \cdot \cos\theta_i \cdot \Delta t_i) \quad \text{(Eq. 5)}$$

where $G_{b,i}$, $N_{col,i}$ and $\cos\theta_i$ are, respectively, the mean direct solar irradiance, the number of solar collectors and the cosine of the angle of incidence corresponding to time Δt_i, where Δt_i, is each of the "n" consecutive periods into which the test time is divided. Δt_i must coincide with the recording periods of the parameters measured during the test.

$E_{in,solar,useful}$ is typically expressed in kWh or MWh. As the tests included in this guideline are short and under quasi-steady-state conditions, N_{col} must remain constant throughout the test, otherwise the test will not be valid for the purpose of calculating the solar field performance.

The expressions of *available radiant solar power, $P_{in,solar,avail}$*, and *available radiant solar energy*, $E_{in,solar,avail}$, correspond to Eq. 6 and 7 respectively. In Eq. 7, the stipulations of Section 2.3.3 are taken into consideration and N_{col} and A_{net} remain constant throughout the test.

$$P_{in,solar,avail} = N_{col} \cdot A_{net} \cdot G_b \quad \text{(Eq. 6)}$$

$$E_{in,solar,avail} = \sum_{i=1}^{n} N_{col,i} \cdot A_{net} \cdot \left(G_{b,i} \cdot \Delta t_i\right) = N_{col} \cdot A_{net} \cdot \sum_{i=1}^{n}(G_{b,i} \cdot \Delta t_i) \quad \text{(Eq. 7)}$$

2.5.2 Solar field net thermal power and energy

The net thermal power transferred by the solar field to the heat transfer fluid, $P_{field\to fluid}$, is given by the following expression:

$$P_{field\to fluid} = \dot{m} \cdot (h_o - h_i) = \dot{m} \cdot \Delta h \quad \text{(Eq. 8)}$$

where $\dot{m}$ is the mass flow of the heat transfer fluid circulating through the solar field (under quasi-steady-state conditions, the mass flow is the same at the solar field inlet and outlet), and Δh is the difference between the specific enthalpy of the fluid at the solar field inlet, h_i, and outlet, h_o, Δh is calculated as indicated in Subsection 2.4.2.7.

The net thermal energy transferred by the solar field to the heat transfer fluid during testing, $E_{field\to fluid}$ is calculated by the following equation:

$$E_{field\to fluid} = \sum_{i=1}^{n}(\dot{m}_i \cdot \Delta h_i) \cdot \Delta t_i \quad \text{(Eq. 9)}$$

where $\dot{m}_i$ and Δh_i are the mean flow rate and the mean difference between the specific fluid enthalpy at the solar field inlet, h_i , and the outlet, h_o, for time Δt_i, where Δt_i is each of "n" consecutive time periods the test time is divided into. Δt_i must coincide with the recording times of the parameters measured or calculated during the test.

2.5.3 Solar field performance

The IEC TS 62862-1-1 Guideline defines solar field performance (efficiency) during a period of time, η, as the ratio of the solar radiant power absorbed by the solar field (solar field net thermal power) to the available radiant solar power, both integrated over a given period of time. According to this definition, the expression of solar field performance is given by (Eq. 10):

$$\eta_{DNI} = E_{field\to fluid}/E_{in,solar,avail} \quad \text{(Eq. 10)}$$

But when tests are short, as defined in this guideline, it is usually advisable to consider the angle of incidence, θ , and in this case for calculating performance, useful radiant solar energy must be used instead of available radiant solar energy, thus obtaining the expression for solar field performance given by (Eq. 11):

$$\eta = E_{field \to fluid} / E_{in,solar,useful} \qquad \text{(Eq. 11)}$$

When during the period considered, Δt_i, conditions are steady-state or quasi-steady-state, the solar field performance may be calculated as the quotient between solar field net thermal power and radiant solar power (available or useful, depending on what the parties agree to and show in the *Test Procedure*). Both powers shall be calculated from the means of the variables used for calculating them in (Eq. 4), (Eq. 6) and (Eq. 8) for the period considered. Thus, the expression of solar field performance is given by (Eq. 12) or (Eq. 13), where the subscript "DNI" is used to show that performance refers to available solar radiation:

$$\eta = \frac{P_{field \to fluid}}{P_{in,solar,useful}} = \frac{\dot{m} \cdot \Delta h}{N_{col} \cdot A_{net} \cdot G_b \cdot \cos\theta} \qquad \text{(Eq. 12)}$$

$$\eta_{DNI} = \frac{P_{field \to fluid}}{P_{in,solar,avail}} = \frac{\dot{m} \cdot \Delta h}{N_{col} \cdot A_{net} \cdot G_b} \qquad \text{(Eq. 13)}$$

At the same direct solar irradiance, the solar field performance depends basically on the ambient temperature, wind speed and angle of incidence. The ambient temperature, wind speed and angle of incidence corresponding to the calculated solar field performance must be referred to.

In view of the above, the solar field performance resulting from a test under quasi-steady-state conditions shall be the mean of the performance values found for the various data records which compose the test, calculating the performance corresponding to each record according to (Eq. 12) or Eq. 13), depending on whether the influence of the angle of incidence is considered or not. As mentioned above, (Eq. 12) is usually used for short tests to consider the effect of the angle of incidence.

Both the powers and energies in (Eq. 10), (Eq. 11), (Eq. 12) and (Eq. 13) are determined as shown in Subsections 2.5.1 and 2.5.2.

2.5.4 Recording, data processing and presentation of results

The first choice to be considered for recording data is an automatic data acquisition system (DAS). DAS reading intervals must not be over 20 seconds, recording the mean for intervals of not over 2 minutes.

The data acquisition system shall be synchronized with the solar field control system's clock, and the time base to be used shall be defined previously (preferably Coordinated Universal Time, UTC) to reconcile any data from external storage systems, such as meteorological data.

Data acquired shall be considered valid as long as the measurement instruments comply with the conditions demanded in Section 2.4 and with the specific stipulations in the *Test Procedure* or with the implemented quality assurance for measurements.

Data files shall be generated by the automatic acquisition system which can be duplicated and then exported to conventional formats for their later processing. Original data files shall never be worked on and backup copies of them shall always be available.

The test results must appear in numerical form (and graphical if applicable), containing the numerical value resulting from the applicable calculations in each case and their associated uncertainty. The measurements necessary for calculating the operating parameters are described in Subsection 2.4 of this guideline, and the calculating procedure is described in Subsection 2.5.

Presentation of results is proposed in Table 3:

Table 3: Example of presentation for the results

Parameters of Specifications					
Concept	**Symbol**	**Unit**	**Value**	**Uncertainty**	**Confidence level**
Useful radiant solar power/energy	$P_{in,solar,useful}$ $E_{in,solar,useful}$	MW/MWh			
Available radiant solar power/energy	$P_{in,solar,avail}$ $E_{in,solar,avail}$	MW/MWh			
Solar field net power/energy	$P_{field \rightarrow fluid}$ $E_{field \rightarrow fluid}$	MW/MWh			
Net solar field performance	η	%			

2.6 Report of results

A report of test results shall be written and made available to all the parties involved. The report of results should include the following sections:

- Executive summary
- Introduction
- Instrumentation
- Measurements
- Calculations and results
- Conclusions
- Annexes

The outline presented here is only a recommendation of format, and other formats are also acceptable as long as the information contained is at least the same as described below.

2.6.1 Executive summary

The Executive Summary must be brief and contain the following basic information:

- Type of SHIP plant and general information on it
- Description of the solar field

- Date and times of tests done
- Summary of test results, including uncertainties and confidence levels
- Verification procedure and its result
- Any agreement between the parties which has been made after the signature of the *Test Procedure* and is a significant deviation from it

2.6.2 Introduction

The points to be included in this section are:

- Test purpose, scope and methodology. Any general information on the power plant, the solar field and the test which is not included in the Executive Summary, such as a diagram of the test boundary
- List of representatives of the parties and their function in the tests
- Reference of the Test Procedure applicable to the test (Revision and date)
- Any agreement reached by the parties not mentioned in the Executive Summary

2.6.3 Instrumentation

The information on instrumentation to be presented is the following:

- List of instruments used in the test, including, type, description, characteristics and series number
- Summary of calibration certificates, verification procedures, or manufacturer standards

2.6.4 Measurements

This section should describe the following:

- Test period (date, time)
- Measurements
- Procedure for taking test data
- Measurements uncertainties

2.6.5 Calculations and results

This chapter should include in detail:

- Calculation methodology
- Table of recorded data used to calculate the results
- Detailed calculation of solar field parameters (net power and performance including the relevant test conditions (DNI, T_i, T_o, T_{amb}, …)
- Thermophysical properties of the heat transfer fluid, as well as storage fluid and fuel if applicable
- Calculation of uncertainties
- Comparison to contractual data or other reference specifications

2.6.6 Conclusions

This chapter shall only be included if there is a reason for explaining the test results with more details than in the Executive Summary.

2.6.7 Annexes

The report’s annexes consist of:

- Copy of the original data sheets and/or printouts from the data acquisition systems (electronic format is allowed)
- Copy of the operators’ records or other records made by the parties representatives during the test
- Report on laboratory tests made on heat transfer fluid and fuel if applicable
- Instrument calibration certificates, results of verification tests, or manufacturer standards

3 Development of a modular and scalable BoP unit for solar process heat applications

3.1 Introduction

Varying industry and site-specific conditions are major obstacles to integrating solar heat into industrial process heating systems. Customized solutions are often necessary, and the resulting technical planning and customization contribute disproportionately to costs and risks of error. To drive the adoption of solar process heat, the development of a standardized and modular BoP as an interface between the solar field and the industrial process heat system is essential. To this end, Subtask B3 focused on the development of a modular and scalable BoP unit for solar process heat applications. While subtask B3.1 addressed the identification and analysis of BoPs, subtask B3.2 focused on the design of such an interface. The results from the German national-funded Modulus project, which also envisages the modularization and standardization of such a BoP, form the basis for the information included within this section.

As part of the Modulus project, a consortium of three collector manufacturers (Protarget, Solarlite and Industrial Solar), one equipment manufacturer (Aura) and two research institutes (Fraunhofer ISE and DLR, who is the coordinator) was formed. During the Modulus project, which is planned to run from 2021 to 2025, three test demonstration units will be developed and installed. These test units will each cover different practice-relevant output sizes, temperature levels and customer-side heat transfer media, with the focus on concentrating collector technologies and medium temperature levels.

For successful standardization, the first step is to specify all relevant interfaces of a BoP in a solar heat installation. This concerns in particular the hydraulics, power supply, statics and signals/data protocols as well as the space requirements. Likewise, the basic functionalities, such as the control of primary and secondary circuits, must be defined. Another requirement for the BoP is possible scalability so that the standardization concept remains applicable for different capacities. Figure 3 shows the functional modules and interfaces of such a BoP schematically. For the primary circuit, scalable modules with thermal oil as a heat transfer medium are to be realized according to the power class. Depending on the requirements of the industrial process, the secondary circuit is operated either with hot air, saturated steam or thermal oil. The other components and subsystems of the BoP, in particular control technology and safety equipment, usually can be standardized and remain unchanged.

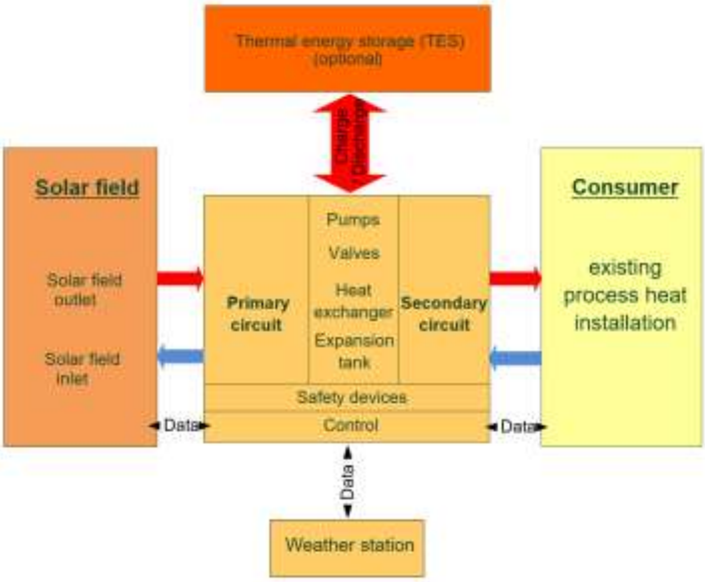

Figure 3: BoP function modules and interfaces

For successful standardization, the first step is to specify all relevant interfaces of a BoP in a solar heat installation. This concerns in particular the hydraulics, power supply, statics and signals/data protocols as well as the space requirements. Likewise, the basic functionalities, such as the control of primary and secondary circuits, must be defined. Another requirement for the BoP is possible scalability so that the standardization concept remains applicable for different capacities. Figure 3 shows the functional modules and interfaces of such a BoP schematically. For the primary circuit, scalable modules with thermal oil as heat transfer medium are to be realized according to the power class. Depending on the requirements of the industrial process, the secondary circuit is operated either with hot air, saturated steam or thermal oil. The other components and subsystems of the BoP, in particular control technology and safety equipment, usually can be standardized and remain unchanged.

Taking the specifications into account, a standardized P&ID scheme was developed in the Modulus project. Based on this, a first test unit was planned and installed on site. In addition, a test and instrumentation plan were developed describing the test sequences for commissioning.

Direct steam generation has not been investigated in the Modulus project and is not included in this deliverable.

3.2 Activity B 3.1: Identification and analysis of BOP

As a first step, the state of affairs is analyzed. In addition to a database, two surveys conducted by Solrico in 2021 and 2022 will be evaluated for this purpose.

3.2.1 State of theArt

Evaluation of the database for solar heat applications in industrial processes

For the development of a general concept for BoP standardization and modularization, an analysis of the state of the art in BoP design was performed. For this purpose, the database for solar heat integration applications in industrial processes [1], which was created within the framework of IEA Task 49/IV, was systematically evaluated. Besides the locations of the plants, the industries, plant capacity, process temperatures and heat carriers used were investigated. Subsequently, a comparison was made of the extent to which the planned demonstration plants fit into the previously identified trends and patterns. It was found that the demo plants planned for the project, as well as the plants already realized by the project partners, show comparatively high process temperatures and plant sizes (Figure 4). A possible reason for this observation would be the plant type considered. While in the past mainly water, pressurized water and steam were used as media, the planned project plants mainly rely on thermal oil.

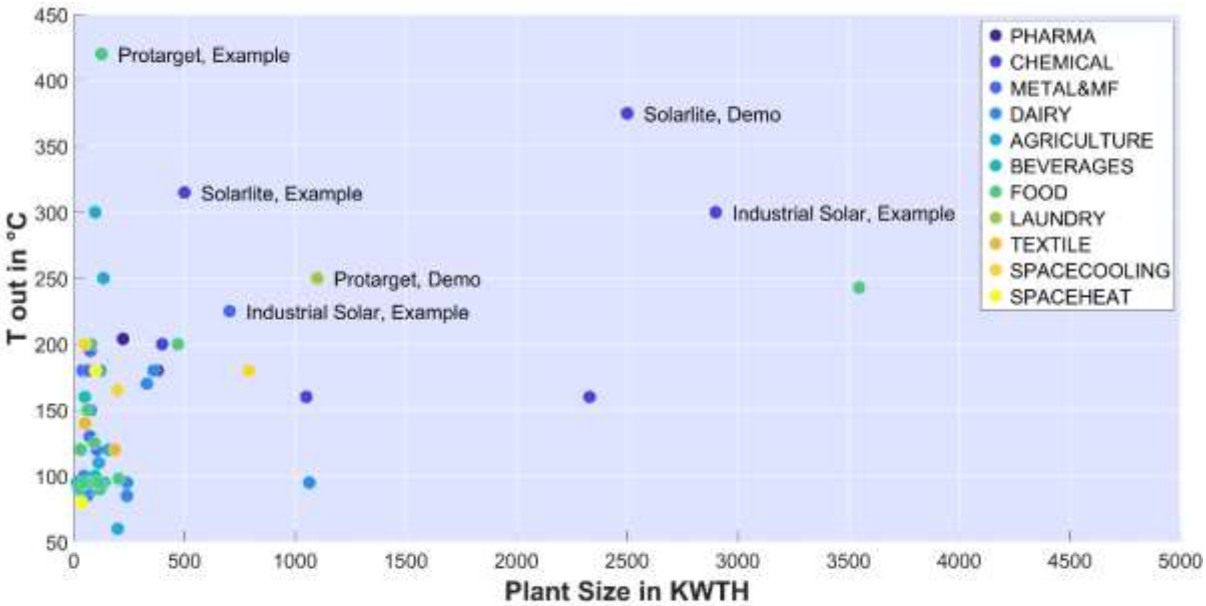

Figure 4: System power and process temperature of exemplarily selected process heating systems already installed (Example) by the project partners and planned in Modulus (Demo), in comparison to systems registered in ship-plants.info

Unfortunately, the database's evaluation could not identify any clear trends. However, it could be determined that around two-thirds of the plants operated with thermal oil are located in Europe. This reinforced the Modulus project's decision to focus on the European market and its standards and guidelines in standardization and approval procedures.

<u>Survey of solar process heat plants built in 2021, conducted in 2022 by Solrico</u>

Furthermore, a survey was conducted on solar process heating systems built in 2021 [2]. For this purpose, Solrico's annual survey of global SHIP (Solar Heat for Industrial Processes) manufacturers was supplemented with additional questions about BoP. Different trends between new and experienced companies could be observed. While new companies tend to involve an external specialist in the design and construction of BoPs, more experienced companies tend to take over the design and construction of BoPs themselves. Nevertheless, even experienced solar collector manufacturers, in some cases, prefer to outsource the design and construction of BoPs to companies that have competencies in process heat supply. Currently, however, outsourcing BoP manufacturing is still hampered by the lack of knowledge many utility companies have about solar field integration, as their knowledge is often limited to fossil fuel heat supply. As a result, 60% of stationary and tracked collector manufacturers believe that standardization of BoP could significantly reduce SHIP costs.

Market study to determine the status of solar thermal process heat for 2022, conducted 2023 by Solrico

Also, in 2023, Solrico, with support from the Modulus project, conducted a market survey to determine the status of solar thermal process heat in 2022 [3]. Of the 24 companies reporting new SHIP installations in 2022, 20 completed the BoP questions. The companies were mostly collector manufacturers and EPC (engineering, procurement and construction). Of these, 17 companies indicated that they had designed the BoP themselves. Only three companies did not plan the BoP in-house. Assuming that the 20 companies are representative of the market, this leads to the conclusion that BoPs are still planned and implemented by the vast majority of SHIP turnkey suppliers (85%). Due to a delayed commissioning of the large-scale plants, the SHIP plants in 2022 turned out to be rather small. Therefore, when a re-survey of the data will be conducted in 2024 using data from year 2023, when more large-scale plants are commissioned, this could lead to different results. Furthermore, 25 European companies were asked where they see the highest cost reduction potential. The results are shown in Figure 5. Ranked #1 is BoP, further reinforcing the importance of its standardizing.

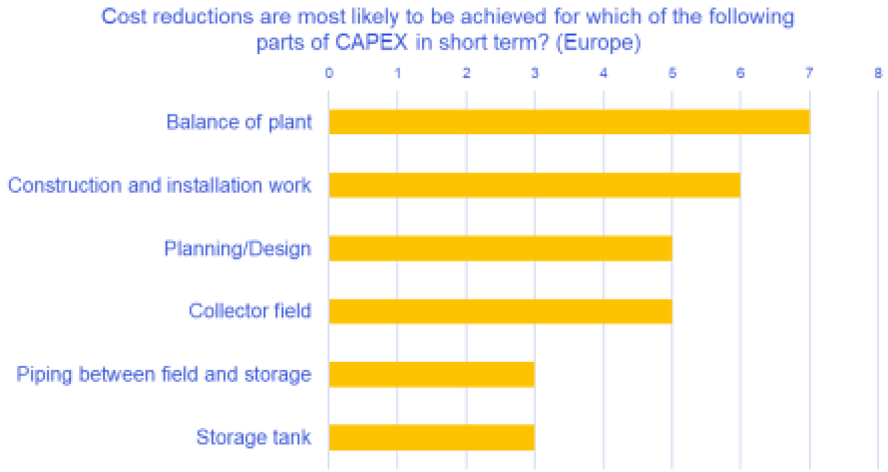

Figure 5: Share of concentrating collector technologies in the global SHIP market from 2020 to 2022, source Solrico [3]

Since Solrico began its annual surveys, the global market for concentrating solar thermal projects has grown significantly. At the end of 2017, an estimated 484,958 m² of concentrating collector area provided heat to C&I customers around the world. A large increase in 2019 was driven by the commissioning of a 180 MW solar steam unit in Oman. More SHIP project installations were commissioned in 2022 than in any other year since the surveys began in 2017, with project developers reporting a total of 114 installations with a capacity of 30 MW. However, the newly installed collector area is lower than in previous years at 43,390 m². This year, 12 systems with a combined total of as much as 171,274 m² have been scheduled to come online. Already, there are signs of a significant increase in solar process heat above 100°C. The expansion is being triggered by increased incentives.

The heat demand differs from customer to customer. While some require hot air for drying, others use hot water, steam or thermal oil. Different types of collectors are used depending on the heat requirement. Concentrating collectors are mainly used when high temperatures are required. Nevertheless, concentrating collectors accounted for only 16% of the global SHIP market in 2022. According to Table 4, this share is in the middle range of the last three years. Nine concentrating industrial heating systems with 4.9 MW were commissioned last year. A special feature of 2022 is three new linear Fresnel collector plants in Spain after no SHIP plant with this collector technology came online.

Table 4: Share of concentrating collector technologies in the global SHIP market from 2020 to 2022, source Solrico [3].

	2020	2021	2022
Total area, global SHIP world market (m^2)	132.316	50.819	43.390
SHIP world market with concentrating collector technologies (m^2)	10.038	8.936	6.931
Share of concentrating collectors	8 %	18 %	16 %

3.3 Activity B 3.2.: Basic design of a modular and scalable BOP

3.3.1 Standardization

Standardizing a BoP presents a number of challenges. One of these is the choice of heat transfer fluid, as its material properties affect important process parameters such as mass flow, evaporating pressure and expansion vessel size. For example, the required mass flow depends on the heat capacity of the heat transfer fluid. If silicone oil is used, a larger expansion tank will be required than with operation with water. Operating and maintenance costs depend not only on the market price of the heat transfer medium but also on its durability and the replacement conditions required. Another important factor is the danger due to freezing of the heat transfer medium.

Piping and instrumentation diagram (P&ID) of a standardized fluid/fluid BoP

Based on these considerations, a core P&ID of a standardized fluid/fluid BoP was created, which will now be described in more detail. First, the BoP was divided into different areas according to their functionality. These function modules include:

1) **Main fluid line:** In addition to the primary circuit from the solar field, it also includes the heat exchanger and the expansion tank as well as the corresponding valves, temperature sensors and pressure sensors.
2) **Compressed air system:** Contains all apparatus and pipes for generating and directing the process air as well as valves operated by them.
3) **Nitrogen blanketing system:** In addition to the nitrogen tanks, also contains all lines and valves from the nitrogen tank to the expansion tank.
4) **Overflow system:** Consists of the discharge tank and pipes with which the heat transfer medium can be safely discharged to the outside. Safety valves are also installed. The overflow tank is mainly used for thermal oils. Water can be piped directly to wastewater treatment if a discharge tank is not installed.
5) **Filling and emptying system:** This system includes piping, pumps and valves needed to fill and unload the solar field. Alternatively, it can be replaced by an external pump, which is used to fill the solar system with the heat transfer medium.
6) **Process side**

Initial results show that standardization is possible for a large part of the defined function blocks without much effort, so the integration of the function modules depends on only a few parameters and can, therefore, be standardized relatively easily, resulting in a good savings potential. Function modules that require little effort for standardization are: 2), 3), 4) and 5). The nitrogen blanketing and the compressed air system could be combined as one functional module, which remains the same for all sizes and temperatures. The design does not depend on the design and construction of the solar thermal system.

Only function modules 1) and 6) are more difficult to standardize and must be individually adapted. The main fluid line and the process side must be considered at the component level. In addition, planning must be carried out on a case-specific basis. Nevertheless, standardizations are possible for the individual components. These are described in the following subtopics. Standardization is particularly difficult for the heat exchanger and the process side since, in most cases, individual customer requirements and a large number of possibilities have to be considered. The heat exchanger, in particular, requires individual planning.

Figure 6 shows the piping and instrumentation diagram of a standardized BoP for the fluid/fluid case. All important components are already drawn in the P&ID and listed in Table 5. Also, important control variables are already drawn in. The standardization does not include heat storage, which can be added as needed. The primary circuit from the solar field passes through a heat exchanger (4), which transfers the heat to the customer's secondary circuit. Fluid temperature is measured at the inlet and outlet of each circuit (2, 10, 28, 29). Compressed-air operated valves are located in the primary circuit (19,1 and 21).

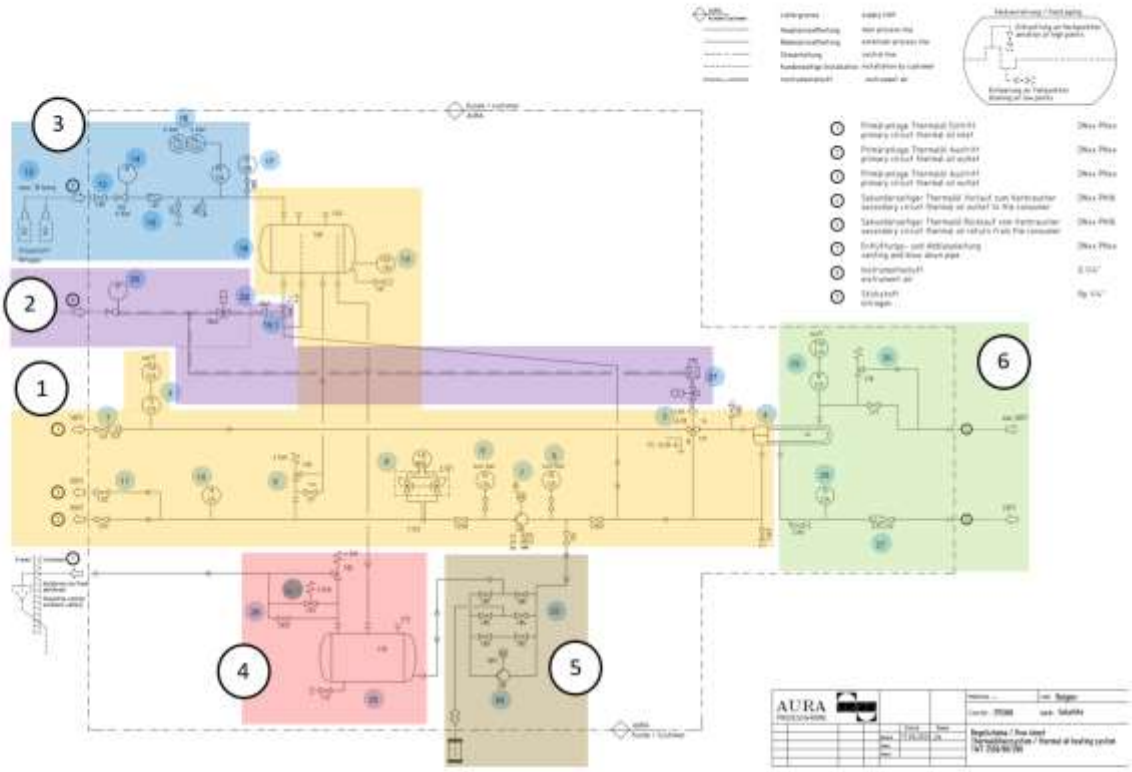

Figure 6: Piping and instrumentation diagram (P&ID) for the BoP of a standardized fluid/fluid installation

Table 5: Component list for a standardized BoP

Main Fluid Line		**Components**
Valves	1	Globe valve inlet
	11	Globe valve outlet
	3	3-way valve (bypass HX)
Filter	1,1	Filter
Temperature sensors	2	Temperature sensor inlet
	10	Temperature sensor outlet
Pressure measurement		
	5	Pressure indicator in front of the pump
	6	Pressure indicator after the pump
	7	Pump and motor
	8	Flow meter after the pump
	9	Safety valve Fluid line
	25	Overflow tank
	18	Expansion tank
	19,1 & 22	Pressure relief valve - Expansion tank
	26,1	Safety valve downstream of expansion vessel
	19	Level sensor and actuation for expansion vessel
		Piping
		Isolation
		Container
	4	Heat exchanger
Nitrogen overlay		
	12	Nitrogen tank
	13	Globe valve inlet
	14	Maximum pressure valve
	15	Dirt trap
	16	Max & Min Pressure Alarm
	17	Pressure indicator
	26	Shut-off valve
	26,1	Relief valve
Compressed air		
	20	Filter pressure reducer
	21	Pilot valve
		Compressor
Process side		
	27	Inlet valve
	28	Temperature sensor
	29	Temperature sensor
	30	Safety valve
		Exhaust valve

Control of the BoP

While it is obvious that the BoP supplier will provide the hardware such as piping, valves, pumps, heat exchangers, expansion tanks and electrical supply, there is a need to discuss who will control the actors.

The EPC (Engineering, Procurement and Construction) party is typically the solar field supplier that sells and possibly also operates the entire system, including the solar field and BoP. As the BoP connects the solar field with the customer and possibly a storage, placement of the interfaces, especially in the case of outsourcing, is a major challenge when designing a BoP. During the first discussions in the Modulus project, it seemed natural that the BoP supplier also supplies the control of the pumps and valves. But it is the EPC or, more precisely, the later operator who needs to control the supply of the heat to the customer and possibly the supply/release from a storage. The EPC needs to implement the logic for operation, which includes, e.g., pump speed and valve position.

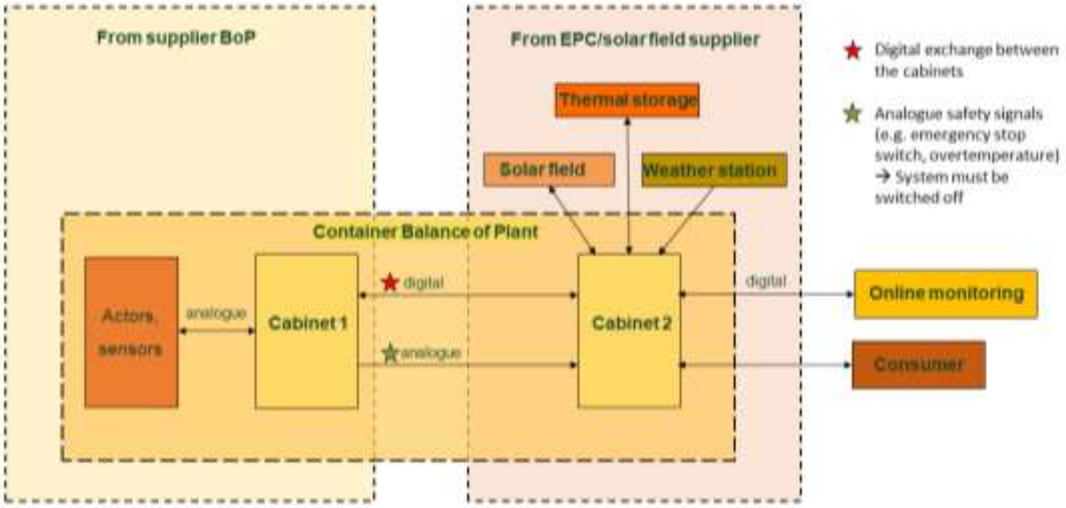

Figure 7: Monitoring and regulation of the BoP

The standardization concept provides for two separate control cabinets in the BoP container, one each from the EPC and the BoP supplier (see Figure 7). This leads to a clearly defined communication interface of process control and safety signals between the two parties. In addition to controlling the solar field, the meteorological station and, if available, the thermal storage, the EPC is also responsible for remote monitoring of the process heating system. Actuators and sensors in the BoP exchange analog signals to cabinet 1. The digital exchange between cabinets 1 and 2 includes actor and sensor data transfer from cabinets 1 to 2 and control signals from cabinets 2 to 1. Since digital signals are more susceptible to interference, analog signals from control cabinets 1 to 2 ensure that safety-relevant signals are forwarded from cabinets 1 to 2, as is foreseen in safety regulations. This ensures that in the event of a malfunction during operation, such as exceeding a maximum temperature or falling below a minimum flow rate, the system is defocused and the pump is switched off.

The customer must be able to shut down the heat supply, e.g., for maintenance periods. Therefore, it must be ensured that the EPC, being responsible to the customer, has access to the pump, valves and temperature controls. Consequently, the control of the entire system is taken over by the EPC and organized in control cabinet 2, since the safety system supplied with the BoP is limited to the safety functions.

Most installations are operated automatically and are monitored online via digital signals.

Modularization approaches

The arrangement of the components depends on various technical decisions for a variety of applications. These are the power class (size of the system) and the temperatures. The operating and/or storage temperatures affect the choice of the heat transfer fluid and the size of the solar field. The properties of the heat transfer fluid, in turn, affect the size of the expansion tank, piping diameters, pump sizing, and safety measures. This makes standardization difficult and is the reason why solar process heating systems and their BoP are usually custom designed. Additionally, the heat transfer medium on the secondary/customer side influences the design of the heat exchanger between the solar field and the customer. The connection of storage tanks opens up further possibilities.

There are three different approaches for modularizing a BoP:

1) One approach could be to design the BoP for a specific normalized power class. If larger powers have to be transmitted, identical BoPs are installed in parallel. For example, a BoP planned for a 1 MW field can be built four times for a 4 MW field, or the next class is used, which could be 5 MW. The first case would result in a higher number of components, while the second case would result in a slight oversizing of the BoP.
2) The second approach is to design a standardized BoP and then resize only the components. In this case, the number of components remains unchanged.
3) Another option that should also be considered is to standardize the BoP according to the operating temperature, which in turn affects the choice of the fluid. If the maximum temperatures do not exceed about 220°C, pressurized water could be an option, keeping the PN40 class. For higher temperatures, mineral oils, thermal oils or silicone oils with e.g. PN classes 16 or 40 can be adapted.

All three approaches build on the first step of standardization reflected by the integration of the functional modules described in the P&ID.

All approaches result in a lower design cost for new BoP plants. However, in comparison, the first approach is the least demanding. The standardized power classes favor a fast design but can lead to higher investment costs due to the increased number of components or oversizing. A positive effect of the first approach would be the increased redundancy. Nevertheless, the higher cost is a major drawback, and it must be weighed whether the higher capital cost is ultimately greater than the saved cost of BoP design and construction.

Following the second approach, a standardized P&ID should be created that specifies the arrangement of components and their specifics for integration into the solar loop. Likewise, the interfaces remain the same for each BoP designed with this standard. However, some residual planning will always be necessary, but the effort should be kept lower by these specifications. Since the characteristics of the heat transfer media have a major impact not only on the size of the components but also on the necessary components, modularization of the BoP should, therefore, also be considered for different heat transfer media.

The choice of the heat transfer medium itself often depends mainly on the desired operating temperature. This line of thought led to the third approach, which divides the BoP into different standardization classes depending on the temperature. The advantage of this approach is that many design decisions are related to the operating temperature. In addition to the heat transfer media, the pressure and, through the heat transfer media, the diameter of the tubes are also affected by the selected temperature. In summary, the first approach seems to be the least favorable. The third approach could be a good compromise between the higher planning and design effort of the second approach and the higher investment costs of the first approach. However, more practical data are needed to evaluate the best option. This is still under investigation in the Modulus project (status September 2023). Ultimately, a modularized BoP has the advantage of lower planning costs. These tend to be particularly high for smaller plants.

Basic design decisions

Pressure level

The pressure in the system helps to avoid evaporation of the heat transfer fluid. Cavitation must be avoided on the suction side of the pump, so the pressure must exceed the evaporating pressure during operation. Once this value is determined, the pressure side of the pump can be calculated. For the entire distance between the discharge and suction side of the pump, the pressure losses occurring in the circuit must be added to the upstream pressure.

Nevertheless, the choice of the fluid during design phase will tend to depend on the required operating temperatures. Depending on the selected pipe diameter, the flow velocity varies, which also influences the pressure losses that occur. The pipe diameter in the loop is connected to the diameter of the absorber pipes. The collector loop length, and thus the required flow velocity in the tubes, has a significant influence on the pressure loss within the loop for a given temperature difference. For a solar field, in addition to the length and number of loops, the arrangement of the loops in subfields must also be considered. Each subfield must be able to be supplied by a pipe. Optimizing the solar field layout can make a significant difference in the pressure drop of the header lines for larger systems. Accordingly, cooperation between the BoP and solar field manufacturer is important. Often the selected components and the associated costs have to be questioned and adjusted several times.

Choice of heat transfer medium

If process temperatures below 220°C are planned, the use of pressurized water should be examined. In addition to its good availability and low-cost factor, water also has a high specific heat capacity and density compared to thermal oils with comparatively low viscosity. In addition to its chemical stability, it is also unproblematic in the event of leakage, as it is not a hazardous substance. However, the relatively high vapor pressure of water makes thick-walled piping and vessels necessary. If a maximum pressure rating of PN40 is specified, pressurized water up to a maximum of 235°C can be used. If a safety margin of 15 K is considered, this results in an upper process temperature in the solar field of 220°C. A further disadvantage is the relatively high solidification temperature at 0°C. This makes it necessary to heat up the system and solar field in winter at days of frost. Thus, to prevent freezing, either heat must be supplied by pumping water or the system must be drained during cold winter days.

When selecting oils, other criteria, such as environmental compatibility, must be considered in addition to vapor pressure. Likewise, cost and degradation play a major role in the choice of thermal oil. The choice of the heat transfer medium significantly influences the choice of the other BoP components and their size as well as the pressure rating.

Storage capacity and choice of operating temperature

The maximum temperature is set at the outlet of the last collector in the loops and depends on the desired process temperature and temperature difference in the heat exchanger. The higher the temperature difference, the longer the loops can be planned, which in turn reduces the number of loops connected in parallel. Since (control) valves and other equipment are required for each loop, this can already result in considerable cost savings. This effect increases with the design temperature and pressure level. A slightly higher temperature at the collector outlet not only has a positive effect on the control margin in the case of cloud draught but also increases the storage capacity. To avoid costly large pipe diameters, a large ΔT in the range of 100 K is preferred in solar thermal applications for collectors that still have low thermal losses at high temperatures, such as those with vacuum receivers. To prevent cavitation, higher pressures are required with the higher temperatures that go along with a higher ΔT. As a rule of thumb, the cost of a BoP at 400°C/PN40 is about twice as high as at 300°C/PN16. This is due to the high costs of many components (e.g. valves and pumps) and the higher-pressure design of piping and flanges resulting from a larger diameter and a higher ΔT.

Standardization classes

The following components could be identified as function classes:

- **Piping and insulation:** Since the length of the piping in a bop depends only to a small extent on the solar field size, the piping in the BoP is usually of the same length. Thus, only the pipe diameter and the prevailing pressure, which is needed to determine the wall thickness, are relevant for the design. When choosing the pipe diameter, a compromise must be made between using relatively little material (reducing costs for steel and insulation) and keeping pressure losses as low as possible. The pressure losses increase quadratically with the flow velocity, which quickly leads to increasing costs in the operation of the pump. An economically optimized flow velocity v is usually 3 (+/-1) m/s. The flow rate $\dot{V}_{design}$ is already determined by the design point of the solar field. The nominal pipe diameter $d_{pipe,BoP}$ can thus be determined by the following formula:

$$d_{pipe,BoP} = \sqrt{\frac{4 \cdot \dot{V}_{design}}{\pi \cdot v}}$$

  As a rule, gradations are: DN50, DN65, DN80, DN100, DN125 for up to several MW thermal solar field power.
- **Valves:** The two globe valves and the three-way valve required in the main fluid line can be designed together as a functional module, whereby the standard pressure and the pipe diameter are important for the design. Finally, it must be clarified whether pneumatic or electric valves are used. This depends, in particular, on the requirements on the process side and will be explained in more detail later in the compressed air section.
- **Pump and motor:** The pumps are designed on the basis of required operation data, such as mass/volume flow and pressure. Since the design is very individual, the definition of delimited standardization classes is not recommended.
- **Filter:** Both standard pressure and pipe diameter are relevant for the design of the filter, resulting in a total of 10 standardization classes.

- **Safety valve main line:** The pressure rating, the design temperature, the expansion properties of the selected fluid and the plant capacity (or HTF volume) are relevant for the design of the safety relief valve. An individual design is necessary.
- **Temperature sensors:** Both necessary temperature sensors in the system can be combined as one function module. PT100 sensors can be used, which are selected according to the temperature range to be measured. For solar thermal systems, the temperature range of 50-400°C is considered relevant. Thus, the sensors can be divided into two temperature ranges. The first temperature range is defined at operating temperatures below 300°C, whereas the second is located at operating temperatures between 300 and 400°C.
- **Pressure measurement devices:** The two necessary pressure measurement devices, one upstream and one downstream of the pump, can be combined as one function module. It is assumed that the relevant range of solar thermal systems is covered with a pressure range of 0 to 40 bar. Thus, 2-4 standardization classes can be defined here:
  - For systems with a maximum pressure < 16 bar
  - For systems with a maximum pressure < 40 bar
  - If necessary, 2 intermediate classes can be added
- **Expansion tank:** Both the selected heat transfer medium and the maximum operating temperature, pressure and plant capacities influence the volume of the expansion tank. Therefore, the expansion tank must be designed individually.
- **Pressure relief valve expansion tank:** The pressure relief valve is selected on the basis of the pressure level.
- **Overflow tank:** The use of an overflow tank must be planned for all solar thermal systems. The size of the overflow tank depends on the amount of heat transfer fluid contained in the system and its expansion coefficient. As a rule, this is the fluid in all pipes of the collector loop, the BoP and possibly the storage. If it can be avoided that the BoP fluid content is heated, the expansion of the BoP content can be calculated individually for the maximum temperature expected. For being on the safe side also the temperature in the expansion tank can be assumed to be heated to the max temperature.
- **Safety valve overflow tank:** In addition to the pressure level, the medium, the system capacity and the resulting fluid flow are decisive here. Therefore, an individual design is required.
- **Heat exchanger:** The design of the heat exchanger depends, among other things, on the temperatures and pressures on the respective process side and on the heat transfer media used. The many boundary conditions make it difficult to define delimited standardization classes, which is why individual planning must be carried out here.
- **Flow meter and level sensor:** The flow meter behind the pump has to be adapted to the flow rate, while the level sensor has to be adapted to the tank height.
- **Control cabinet:** For most BoPs, the control technology remains unchanged, making it easy to standardize the control cabinet.

3.3.2 Case study: 2.5 MW process heat plant with Oil/Oil in Belgium

The next step is to transfer the designed standardization concept to the planned test plants. So far, the concept has been implemented at the test facility in Turnhout (Belgium) at a factory of Avery Dennison. The gained knowledge and results will be discussed in this subsection.

To provide the thermal power of the plant of 2.5 MW, 12 parabolic trough collectors with different lengths were installed. The different lengths result from the available space conditions, which will be shown later. The total aperture area is 5539 m². The generated heat is integrated into the heating circuit of the customer and is to be provided at a temperature of 280°C with an upper limit of 305°C. The solar collectors are installed in the heating circuit of the customer. From the parabolic trough field, heat can be supplied between 350 and 400°C with a return temperature of 280°C. As a heat transfer medium, mineral oil runs through a 240 m pipeline between the customer and the BoP, whereas silicone oil (Helisol 5A) is used on the solar field side. Since the solar field cannot cover 100% of the annual energy demand, the customer's existing fossil-fuel heating systems continue to operate. These serve as backup boilers and feed in additional energy if not enough power is provided via the BoP. In this test plant, the customer also requested the installation of a thermal storage tank, so this could be considered when creating the P&ID. Figure 8 shows the simplified piping and instrumentation diagram of the plant. In addition to the standardized P&ID already shown, the pipes for charging and discharging the thermal store are also drawn in here. Depending on the desired operating mode, the valves can be opened or closed.

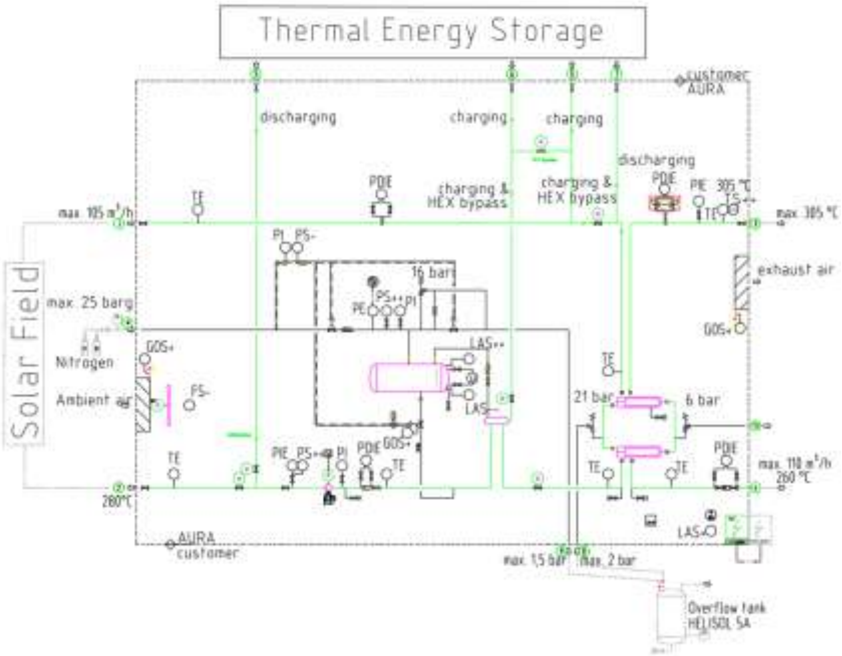

Figure 8: P&ID of an oil/oil plant

In normal operation, the silicone oil passes through the solar field in the first circuit and is heated. It then flows through the heat exchangers in the BoP, where it transfers heat to the secondary circuit. The silicone oil then leaves the BoP again, and the cycle starts again. A safety valve is installed between the heat exchangers, which is triggered when the pressure exceeds 21 bar. The silicone oil is transferred to an overflow tank when triggered. In the second circuit, the mineral oil first flows into the BoP at 260°C, where it is heated to a maximum of 305°C in the heat exchangers. It then delivers the process heat to the customer. A safety valve between the two heat exchangers limits the maximum permissible pressure to 6 bar by transferring the thermal oil to a drain tank if the pressure is exceeded. The thermal storage can be loaded or unloaded depending on the valve position. To load the heat accumulator, the valve upstream of the heat exchanger (charging & HEX bypass) is closed so that the silicone oil passes through the heat accumulator and then returns to the solar field via a small vessel. When discharging, the valve is opened again, and the silicone oil is diverted back into the thermal storage via a valve in front of the solar field. The expansion tank, located in the center of the figure, absorbs the expansion of the silicone oil by adding or draining nitrogen depending on the density of the silicone oil.

Figure 9: BoP of the company AURA for plant Turnhout still without container (photo: AURA)

Figure 10: Solar field layout for Turnhout, Belgium (right). Each cross indicates a collector module

The BoP was installed on site in November 2022 und fully commissioned in August/September 2023. Prior to that, it was completed on a rack at Aura's manufacturing facility (Figure 9). A large part of the space is taken up by the expansion vessel (outlined in yellow), since silicone oils expand greatly when the temperature is increased. This was already discussed during standardization and had to be considered here. To the right of this are the shell and tube heat exchangers (outlined in green). Behind the expansion tank, the two control cabinets were positioned, one of which is responsible for the electrical and safety equipment of the BoP. The other cabinet was supplied by the collector manufacturer and contains the control technology for the BoP and the solar field, a visualization of the system data and the digital connection to the outside. The rack was then pushed into a container and placed in Turnhout on the site shown in Figure 10. The solar field consists of SL5770 parabolic trough collectors (also called HYT6000) with an aperture width of 5.77 m and an aperture length of 12 m per module, arranged in several loops of different lengths to save space. Since the heat demand on the consumer side fluctuates and is mostly below 1.8 MW, the excess heat is transferred to a concrete storage tank with a heat capacity of 4.5 MWh. The storage integration explains the high solar field outlet temperature. Figure 11 shows the view from the roof. On the right side, the BoP and the thermal storage can be seen.

Figure 11: View of the solar field (photo: Left DLR, right Avery Dennison)

3.3.3 Functional test planning and performance evaluation

After the BoP has been manufactured, the BoP supplier tests the electronic functionality of all components, safety functions and pressure in his factory.

The introduction of a standardized BoP also requires a uniform evaluation of functionality and performance. This ensures that BoPs that follow the standard are comparable with each other. When planning the tests, a distinction must be made between the safety/function test and the meteorological performance evaluation. To save time, the former should be performed before delivery of the BoP. This avoids time-consuming and costly rectification of defects at the installation site and ensures safe commissioning of the plant. The tests to be carried out include the testing of the electrical safety of the plant in accordance with the relevant directives, the tests of the European Pressure Equipment Directive and a functional test of all sensors, actuators and the entire safety chain.

For more meaningful test procedures to evaluate the performance of a BoP, additional quality criteria must be considered besides the energy balance. The quality criteria for this result primarily from the specifications given by the customer and the process to be supported. An important quality criterion is the control quality, which comprises various aspects:

- Compliance with/stability of the required process parameters (+ analysis of the cause of occurring fluctuations and deviations)
- Plant behavior during the warm-up phase
- Plant behavior in critical situations (overtemperature, overpressure, falling below the minimum flow rate)
- Conformity of the preset control parameters with the real plant operation and possible improvement during commissioning

To plan corresponding test sequences, permissible deviations and fluctuations must also be defined in addition to the quality criteria. From these, requirements for the accuracy of the sensor technology to be used are derived. A compromise must be made between the most accurate possible evaluation and low costs. Therefore, for the systems planned in the Modulus project, the installation of higher-quality measurement technology was dispensed with. Only the sensors required for the operation were used.

Other technical aspects to be considered are:

- Temporal resolution of the measurement data
- Transmission of the measurement data
- Selection of the measurement quantities required for the planned evaluations
- Knowledge about accuracy and stability of the material properties of the HTF

Set up of test runs

The tests that follow are intended to provide a rough guide for setting up a test plan.

Before delivery

Table 6 lists the tests to be performed prior to delivery and their associated criteria and performing entity.

Table 6: List of tests that can be performed before delivery

Test	Test criterion	Performing entity
Testing in accordance with the Pressure Equipment Directive	According to classification according to PED 2014/68/EU	Accredited testing laboratory
Electrical safety check	DIN EN 60204-1 VDE 0113-1	BoP manufacturer
I-/O Check Sensors / Actuators	Signals arrive at interface with plausible value	BoP manufacturer

The tests according to the Pressure Equipment Directive are to be carried out for the components pipe, pressure vessel and heat exchanger. First of all, the quality of the weld seams must be checked. Three different methods can be used for this purpose: X-ray according to ISO 17636, ultrasound according to AD 2000 code, magnetic particle according to ISO 17638 and supplementary AD 2000 code. Following this, a pressure test must be carried out in accordance with PED. Here, a pressure vessel is filled with a liquid (water) at test pressure. The pressure vessel is selected depending on the classification according to the maximum temperature TS and the maximum pressure PS. After a holding time of 30 minutes, the pressure test is considered to have been passed, insofar as no pressure drop could be detected. After the test is completed, the water is first drained, and then the system is blown out with hot air. Residual water quantities are usually not a problem, they must be boiled out during start-up when heating up.

An electrical test must also be carried out for the control cabinets of the BoP. These are built on the basis of the requirements from DIN EN 61439-1 and -2. They must then be tested for electrical safety before delivery. This is done according to DIN EN 60204-1, which specifies the electrical testing for the electrical equipment of machines. In addition, functional tests are carried out on the motors with regard to their resistance and on the sensors with regard to their measuring range/switching point. The control cabinet supplied by the manufacturer of the collector array for controlling the entire system was already installed during the initial assembly of the BoP for reasons of accessibility but is not the subject of the test. It will only be connected at the final location. Since the voltage supply of the BoP control cabinet comes via the control cabinet of the collector array in the fully installed state, a provisional voltage supply is required for the tests. The subject of the safety test according to DIN EN 60204-1 is the testing of the protective conductor system, the insulation resistances and the emergency stop switches.

During the functional test and I/O check of all sensors and actuators of the BoP, all installed sensors and actuators are subjected to a functional test to enable trouble-free commissioning. Here, the signals are checked for plausibility.

On-site commissioning

Cold commissioning includes all functional tests that are carried out after the entire system has been set up but before the system is focused for the first time. It is particularly important to check all components that are located in the area of plant safety. The signals that are passed between the control cabinet of the BoP and the control cabinet of the collector manufacturer must also be checked. Here, the completeness of all transmitted signals and their correctness must be checked. In addition, the safety signals must be verified. A leak test of the collector field, as well as a pressure test of the entire system, must also be carried out. The leak test can be performed with nitrogen. The actuators are checked by starting them up in manual mode. The actuators to be checked include:

- Pumps (direction of rotation runs normally)
- Valves (controllable, open/close)
- Container ventilation (temperature controlled, on/off, flaps open/closed at setpoints)
- Fire extinguishing equipment (temperature, test on/off)

Furthermore, the data transmission must be tested. The test criterion is considered to be fulfilled if, in addition to the controllability, the Ethernet/VPN connection functions and all signals can be read out and assume plausible values.

Hot Commissioning

For the verification of the safety chain of the BoP and the solar field, compliance with the temperature limit, the minimum flow rate and the maximum allowable pressure must be checked. For checking the temperature limit, the temperature limit value is lowered to a lower temperature in order to perform the tests in non-hazardous areas. The temperature is then selectively brought into the limit range while at the same time recording the relevant measured variables and reactions of the actuators. The test is considered to have been passed if the actuators exhibit a previously defined behavior (defocusing, pump shutdown) when the limit value is reached. For the flow rate, an analogous procedure results, but here the limit value is set higher instead to perform the test in the non-hazardous range. It is tested whether defocusing occurs when the flow falls below the minimum flow rate. Since the pressure system is mechanical, the limit values cannot be lowered here. The pressure is increased until it reaches the limit value and then the behavior of the pressure switches is checked.

The start-up/shut-down process is checked by recording real start-up/shut-down processes on a sunny day for criteria such as reaching the position of the sun, pump switched on, focused mirrors, high temperature in the solar field and vice versa. Verification of coupling into the customer process is an iterative process. Here, the temperatures of the heat exchangers, as well as the flow on both sides and the position of the coupling valve, have to be observed over several days. The decisive factor is then how well the temperatures required by the process operator are maintained on the secondary side and whether the associated actuators work according to their design. For automatic operation, the temperature control must still be checked. For this purpose, the operation of the plant must be observed and compared with the planned control strategy. It may be necessary to adjust the control parameters again. This process could partly overlap with the coupling process, which makes an iterative approach necessary. It is then checked whether the control strategies are executed automatically as planned. Scenarios such as a possible storage tank filling, volume flow rate change and partial defocusing are considered. The loading and unloading of the storage tank must also be monitored. Here, for example, the storage tank discharge should stop when the specified maximum temperature at the heat exchanger is exceeded.

4 Conclusions

The global inventory of existing process heat plants showed that about two-thirds are located in Europe, have process temperatures below 200°C, and are designed for a power range below 0.5 MW. Since the focus of the project partners working with concentrating collectors is on higher temperatures and power classes, it was decided to concentrate on plant sizes between 0.5 and 10 MW. European standards and specifications were therefore used for standardization. The inventory was supplemented and updated by surveys of manufacturers of solar process heating systems who built a process heating system in 2021 or 2022. 60% of the collector manufacturers surveyed agree that standardization of BoP can significantly reduce project costs. Concepts were developed based on the inventory, the survey results and the experience of the participating industry partners. The potential for standardization of BoP components was evaluated, and finally, a conceptual P&ID was created. The systems use thermal oil or water on the solar field side to heat or generate thermal oil, air, or steam on the consumer side. Furthermore, the design of the required components and their influencing variables were explained in more detail. Later, these could be divided into standardization classes. The concept has already been successfully used to design and detail the BoP of one of the three plants in Europe. A BoP with a transmission capacity of 2.5 MW was completed as part of the Modulus project. Furthermore, test procedures have been designed for the functional test and the evaluation of the performance, which can serve as a starting point for the creation of an own test procedure. Subsection 2 of this deliverable includes a proposal of a guideline for on-site solar field performance testing in SHIP plants using liquid heat transfer fluid and line-focus solar concentrators.

5 References

[1] http://ship-plants.info/

[2] Solrico 2022, SHIP supplier survey 2021, Website solarthermalworld.org, https://solarthermalworld.org/news/encouraging-trends-in-the-solar-industrial-heat-market-2021/

[3] Solrico 2023, SHIP supplier survey 2022, Website solarthermalworld.org, https://solarthermalworld.org/news/high-level-of-dynamism-on-the-ship-world-market-in-2022/

6 Nomenclature

BoP	Balance of plant
CF	Cleaning factor
DNI	Direct Normal Irradiance
EPC	Engineering, Procurement and Construction
HEX	Heat Exchanger
HTF	Heat Transfer Fluid
I/O	Input / Output
P&ID	Process & Instrumentation Diagram
PED	Pressure Equipment Directive
SHIP	Solar Heat for Industrial Processes
VPN	Virtual Private Network