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# Integration of Solar Thermal Process Heat

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**Abstract.** Varying conditions for heat integration still make individual designs and planning for the Balance of Plant (BoP) necessary and slow down the market integration of solar heat for industrial processes (SHIP). In addition to increased costs for planning, this also leads to higher technical and project management risks due to the lack of standardized engineering procedures. Therefore, the goal of the MODULUS project is to design a modular standardization concept, which is developed during the planning and engineering phase of three commercial SHIP projects. For testing the functionality, test plans have been drawn up which are intended to provide initial guidance for tests and their criteria to be carried out in each case prior to delivery, cold and hot commissioning. The BoP of the plant in Turnhout (Belgium) has already been installed and commissioned on site. Its example will be used to discuss the procedure for commissioning in the present work. Furthermore, a survey was sent to 80 companies to evaluate the trends of the SHIP world market. Several trends are discussed that will have a significant impact on market developments in the coming years.

**Keywords:** Balance of Plant, BoP, Concentrating Solar, Solar Process Heat, MODULUS

## 1. Introduction

In order to further advance the market introduction of solar process heat, the costs for solar process heat systems must be minimized. Besides the investment costs, the complex design and planning are important cost factors. Especially the planning of the BoP, the interface between the solar field and the customer circuit, often proves to be complicated, as it has to be designed individually. The aim of the MODULUS project is therefore to design a modular standardization concept. For this purpose, a standardized P&ID for a fluid/fluid system was designed at the beginning of the project, on the basis of which the three demonstration BoPs will be planned and built in the next step. A detailed description of the concept is given in [1] and [2]. In addition, several test plans for the functional testing of the BoP were created. These include, among other things, tests to be performed prior to delivery and tests to be performed during cold/hot commissioning. The standardization concept could already be implemented for the first of the three demonstration BoPs in Belgium. Here, a thermal power of 2.5 MW is provided to the customer from the solar field via the BoP. During the subsequent commissioning, the focus was particularly on the venting of the plant, which was carried out step by step. During the hot commissioning, heat was successfully supplied to the customer for several hours.

## 2. In-situ test plan

In order to be able to define a sufficient and target-oriented test plan for the standard qualification of BoPs, it was first necessary to clearly define the objectives. These are derived from the quality requirements placed on the product. In order to obtain an overview of the requirements that typically occur and the tests to be carried out, the participating solar system manufacturers were first asked about past projects. In the process, the requirements and tests were categorized according to various distinguishing features that have a significant influence on a testing process to be standardized. These characteristics were:

- Origin of the requirement: Product requirements can result from legal regulations, ordinances or technical guidelines, be based on customer requests or market requirements, or be based on quality criteria defined by the manufacturer itself. The origin of the requirement influences how strictly a specification is to be adhered to and how its fulfillment is to be documented.
- Scheduling of quality and commissioning tests: The timing of a test may be relevant both for technical reasons (e.g., testing may relate to individual components, parts, or the entire plant), but it also has a significant logistical impact. Some tests may require special infrastructure or equipment that may not be available everywhere or may be difficult to transport. At the same time, any problems that may arise during testing are usually easier, faster and cheaper to rectify if the test object is still at the production site and there are no expenses for the provision of spare parts or tools or travel costs for fitters.

Based on the compilation and categorization of the BoP requirements to be checked, a draft for a standardized test plan was created. This was then adapted in detail for the first plant realized in the project. The following tables show the tests to be carried out before delivery of the BoP and during cold and hot commissioning for the plant in Belgium. As delivery and cold commission have already been completed the listed tests have already been performed. Results and experiences from test performance are described in section 3.2.

***Table 1:*** *List of tests that can be performed before delivery*

| Test | Test criteria | Implementing body |
|---|---|---|
| **Test according to Pressure Equipment Directive** | Classification according to PED 2014/68/EU | Accredited test laboratory |
| **Electrical safety check** | According to DIN EN 60204-1 VDE 0113-1 | BoP manufacturer |
| **I-/O-Check Sensors / Actuators** | Signals received by interface with plausible value | BoP manufacturer |

***Table 2:*** *List of tests within the framework of cold commissioning*

| Test | Test criteria | Implementing body |
|---|---|---|
| **Electrical safety check according to local regulations** | According to AREI (Belgian requirement) | Accredited test laboratory |
| **Leakage/pressure test of entire system** | Leakage test at 1.7 bar followed by pneumatic pressure test at min. 1.1 x design pressure | Turnkey supplier |
| **I-/O-Check Sensors/Actuators** | Signals arrive at interface with plausible value | Turnkey supplier |

Since hot commissioning has not yet been completed completely, the following list should be regarded as provisional and not finalized in all details. It can nevertheless be regarded as a basis for a typical test sequence. The experience from the parts already executed is described in section 3.2.

***Table 3:*** *List of tests within the framework of hot commissioning*

| Test | Test criteria | Implementing body |
|---|---|---|
| **Safety chain test** | Verification of the function of safety switches for over/low pressure, over temperature, low flow protection. Verification of function of panic buttons, warning lights and UPS. | Turnkey supplier |
| **Pressure maintenance** | Correct maintenance of the nitrogen inlet pressure at different temperatures | Turnkey supplier |
| **Start-up procedure** | Proof if the procedure is initiated as defined (e.g. by mass flow, irradiation, etc.) | Turnkey supplier |
| **Shutdown procedure** | Proof if the procedure is initiated as defined (e.g. low irradiation, low mass flow rate, over temperature, ect.) | Turnkey supplier |
| **Integration into customer process** | Are the temperatures required by the process operator maintained on the secondary side and do the actuators function accordingly? | Turnkey supplier |
| **Temperature control, automatic operation** | Are the control strategies executed automatically as planned?<br>- Storage tank filling<br>- Volume flow regulation<br>- Partial defocusing | Turnkey supplier |

# 3. 2.5 MW demonstration plant for process heat with a silicone oil/mineral oil BoP

The previously developed standardization concept [1] is now to be tested and further developed on three demo BoPs. So far, the concept could be implemented at the demo BoP in Turnhout (Belgium) at a factory of Avery Dennison. The gained knowledge and results will be discussed in this section.

## 3.1 Setup of the demonstration plant

***Figure 1:*** *BoP of the company AURA for Turnhout plant still without container (photo: AURA)*

***Figure 2:*** *View of the solar field (photo: Left DLR, right Avery Dennison)*

For the description of the test plans and commissioning, the Turnhout plant will be briefly described in the following section. Further information about the plant including the P&ID can be found in our previous work [1] and [2]. The plant has a thermal power of 2.5 MW, which is provided by 12 parabolic trough collectors of different lengths with a total aperture area of 5539 m². The maximum operating temperature of the system lies at 390°C. The generated heat is supplied to the customer's thermal circuit at a temperature between 280°C and 305°C. Mineral oil is used as the heat transfer medium on the customer side of the BoP, while silicone oil is used on the solar field side.

The BoP was installed on site in November 2022 and hot commissioned started in August/September 2023. Prior to that, it was completed on a rack at Aura's manufacturing facility (Figure 1). A large part of the space is taken up by the expansion vessel, since silicone oils expand significantly when the temperature is increased. This was already discussed during standardization and had to be considered here. On the right side of the picture the shell and tube heat exchangers can be seen. Behind the expansion tank, the two control cabinets are 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 mounted into a container and installed in Turnhout on the site shown in Figure 2. The solar field consists of SL5770 parabolic trough collectors (also called HYT6000) with an aperture width of 5.77m and an aperture length of 12m 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 2 shows the view from the roof. On the left side, the BoP and the thermal storage can be seen.

## 3.2 Control of the BoP

For a standardized control of the BoP, it is important to determine in advance how the responsibilities are to be distributed between the EPC (engineering, procurement and construction) and the BoP supplier. The EPC is usually the solar field supplier who sells and, in some cases, also operates the entire system, including the solar field and BoP. Since the BoP connects the solar field to the customer and possibly a thermal storage system, the management of the interfaces, especially in the case of outsourcing, is a major challenge when designing a BoP. The heat supply is later controlled by the EPC or the operator of the system. In case a thermal energy storage unit is installed, the EPC must also consider the transfer of heat to and from the storage system when planning the control strategy. Therefore, the EPC must implement the logic for the operation, which includes e.g. pump speed and valve position.

The standardization concept provides for two separate control cabinets in the BoP container, one from the EPC and one from the BoP supplier (see Figure 3). This results in a clearly defined communication interface for process control and safety signals between the two suppliers. In addition, the EPC is responsible for the solar field control, the meteo station, an optional heat storage and the remote monitoring. Actuators and sensors in the BoP exchange analog signals between the two cabinets.

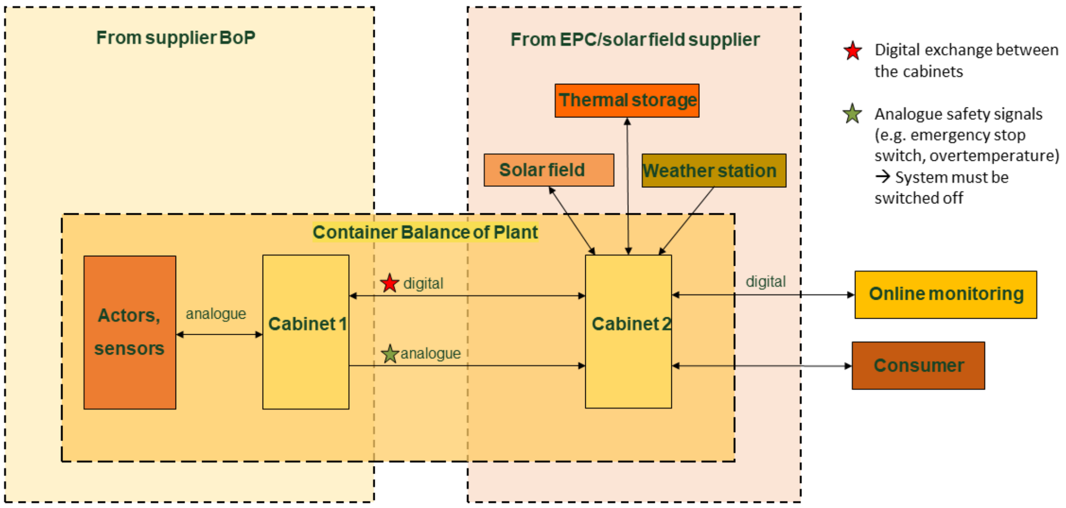


***Figure 3:*** *Monitoring and controlling the BoP*

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

The engineering of a BoP mainly follows the boundary conditions set by the process heat consumer. For example, the choice of heat transfer medium strongly influences the further design of the BoP, as its material properties affect important process parameters such as the mass flow, the evaporation pressure and the size of the expansion vessel. 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 its functionality. These functional modules include:

1. Main liquid 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 and pressure sensors
2. Compressed air system: Contains all devices and lines for generating and guiding the process air as well as the valves operated by them.
3. Nitrogen blanketing system: In addition to the nitrogen tanks, it also includes all pipes and valves from the nitrogen tank to the expansion vessel.
4. Overflow system: Consists of the expansion vessel and the 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. If water is used as the heat transfer medium, an expansion vessel is usually also required to reduce the temperature by cooling. At ambient pressure, the temperature drops to 100°C, so it should be checked whether the waste water pipes can withstand this temperature or if an additional cooling tank is required.
5. Filling and draining system: This system includes piping, pumps and valves required for filling and draining the solar field. Alternatively, it can be replaced by an external pump that is used to fill the solar system with the heat transfer medium.
6. Process side: Secondary circuit that supplies the solar heat to the customer's process. The heat transfer medium used in this cycle largely depends on the process on the customer side. Usually it is a heat transfer medium that is already integrated into the customer's process cycle.

Initial results show that standardization is possible for a large part of the defined function blocks without great effort. The integration of the function blocks therefore only depends on a few parameters, which leads to a significant potential to save costs and engineering hours. Function blocks that require little effort for standardization are: 2), 3), 4) and 5). The nitrogen superposition and the compressed air system could be combined as one functional module that remains the same for all variables and temperatures. The design is independent of the design and construction of the solar thermal system. Only the 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 component level.

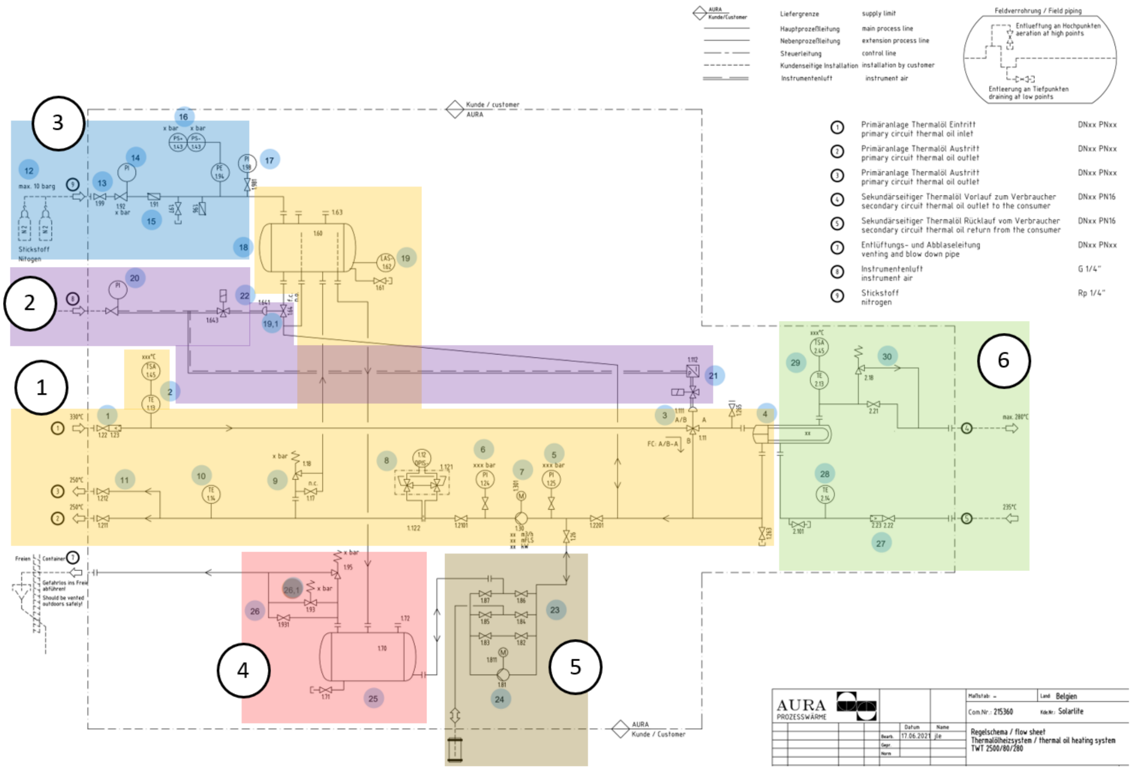


***Figure 4:*** *Piping and instrumentation diagram (P&ID) for the BoP of a standardized fluid/fluid installation*

## 3.4 Commissioning with a focus on venting

Before the start of the commissioning the control technology software was set up for visualizing and logging the data as well as for controlling the solar field and the BoP. The hardware had already been delivered to the BoP manufacturer as part of the control cabinet and installed there. The measured values were checked for plausibility. However, for some measured values it is only possible to determine whether they are plausible when the pump is in operation, e.g. the volume flow measurements, but also temperature measurements can't be verified properly without flow. Only when the heat transfer at the temperature sensors is increased by the oil flow past, the sensors indicate reasonably realistic temperatures. The heat dissipated to the outside via the sleeve and the sensor itself then has less influence. This effect increases with rising temperatures, as more heat is dissipated with a greater temperature gradient. The start of commissioning requires operation in manual mode instead of automatic mode, as initially only pumping with a low mass flow takes place, which must be changed during commissioning. In addition, initially lower temperatures between 80-90°C and the operation of individual collector fields are also not provided in automatic mode.

The solar field circuit was filled with *Helisol 5a* in February 2023. This includes most of the BoP with expansion tank and pipes, as well as the solar field. During filling, venting was already carried out at various high points. Since the BoP is lower than the pipelines in the collectors and also lower than a pipeline bridge, venting was initially carried out mainly outside the BoP. The pump was not yet operated.

In a next step, the expansion tank was pressurized with nitrogen so that the heat transfer medium would reach all areas of the system. The lines to the differential pressure measurements at the orifice plate measurements were also vented by slightly opening the screw connections. After filling the piping, the initial goal is to further check the signals during operation of the pump, especially the flow measurements. In the following days, oil leaks should be checked periodically, especially after pressure and temperature increases. During the startup of the pump, the pressure measurements must be readable to indicate the volume flow and the pressure on the pressure and suction side of the pump to the solar field. This also applies to the differential pressure measurement, which records the pressure upstream and downstream of the filter.

Before starting the pump, it is necessary to build up a sufficiently high pressure by adding nitrogen, as is usual in oil installations. In the Turnhout plant, this was about 5 $bar_a$. Furthermore, the valves were set in the right position for flow in the solar field.

The first test runs are done cold. Since the collectors may only be focused when there is flow, it must first be ensured that the flow is stable. During the first starts of the pump, pressure initially only built up irregularly, as can be seen from the measurement on the pressure side of the pump. A whooshing noise was heard, which gave the impression that air was still being pumped along. The start was aborted, after the pressure dropped too much so that the pump would not be damaged. This process was repeated several times. In each case, the pump ran for a period of about one minute. It is also possible to use an external pump for degassing during start-up so that the more expensive built-in pump is not damaged. After starting the pump several times and increasing the total pressure to 5 $bar_a$ by further filling with nitrogen, the pump then ran regularly and built up pressure.

The next step is venting the circuit, evaporate water and remove volatile oils. For this, a pipe was opened with the hand valve, which was installed for the sole purpose of directing part of the oil from the solar field into the expansion tank, so that gases can escape from the fluid. Typically, gases in the pipes are entrained with the oil if the flow is sufficiently fast and then exit in the expansion tank or in the small parallel tank (Figure 5, pos. 127) on the suction side of the pump, from which a branch leads to the expansion tank. The gases are led from the expansion tank via the valve 1.97 into the drain tank outside the container in which entrained liquid components are separated, which in turn has an outlet at the top where the gases are led to the outside.

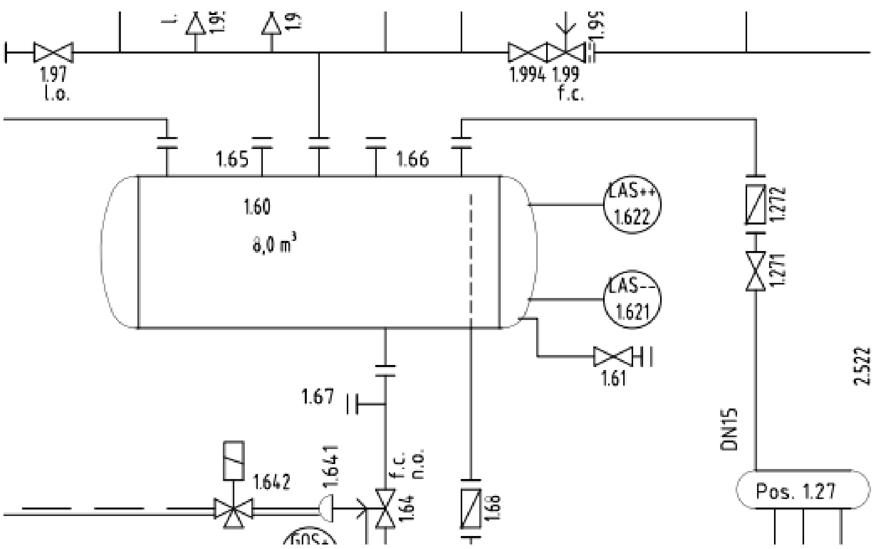


***Figure 5:*** *Expansion tank and connections*

First, the oil was vented at low temperatures between 30 and 70°C. To do this, the oil was pumped around for a few hours. Then the gas was released from the expansion tank and the pressure was increased again with nitrogen to the necessary starting pressure. This process was repeated several times.

To remove any residual water from the oil circuit, a temperature above 100°C or, more precisely, above the vapor pressure finally reached during the blow-off is required. For example, if blowing off to 1 bar overpressure, the evaporation temperature corresponds to about 120°C. The temperature of the oil should certainly be above this. Therefore, blow-off was performed several times at approx. 150°C. For this procedure it is necessary to know the temperature in the expansion tank. If no temperature measurement has been installed in the tank, temperatures of the flanges can be measured with infrared measurement as an alternative.

For the removal of volatile substances, the manufacturer of the heat transfer oil specifies the degassing procedure, in particular at which temperature levels degassing should take place. The temperatures were raised during the tests with heat provided from the solar field. The process is therefore only possible during sunny hours. The gas is blown into a 1 $m^3$ stainless steel tank, where it condenses on the walls. At the top there is an outlet where the gas can be vented. At high blow-off speeds, a considerable amount of oil is entrained. This was shown when blowing off at 150°C and 200°C. Most of the oil was collected in the drain tank. However, a considerable amount was entrained by the gas through the upper outlet of the drain tank. Therefore, the volume flow should not be too high. In addition, the pressure should not be released too far, as oil is then more easily entrained. To protect the environment and the operating personnel, a filter is useful in which the escaping gases and fluid particles are absorbed.

Venting has taken place via a short circuit, so that the heat exchanger has been bypassed. If a short circuit does not exist, the medium on the user side must be pumped at the same time so that there is a uniform temperature increase in the heat exchanger. A one-sided temperature increase must be avoided in order to prevent mechanical stress by high temperature gradients.

A first test of heat delivery to the heat consumer took place on 23 August 2023. The pumps were started in the solar field circuit and consumer circuit in cold condition. For a careful approach to the required temperature of ~270°C at the consumer, only a part of the collector field was focused. After reaching the target temperature, the consumer circuit was switched from short-circuit operation so that the heat flowed to the consumers. The temperature fluctuation could already be kept within an acceptable range for the customer at the beginning. The fluctuations at the outlet of the heat exchanger to the user circuit also result in fluctuations in the temperatures coming from the user circuit. In this test, a $\Delta T$ of approx. 25 K was observed between Heat Exchanger inlet (HEX in) and Outlet (HEX out) on the consumer side (Figure 6). The x-axis shows the time of the measurement in hours.

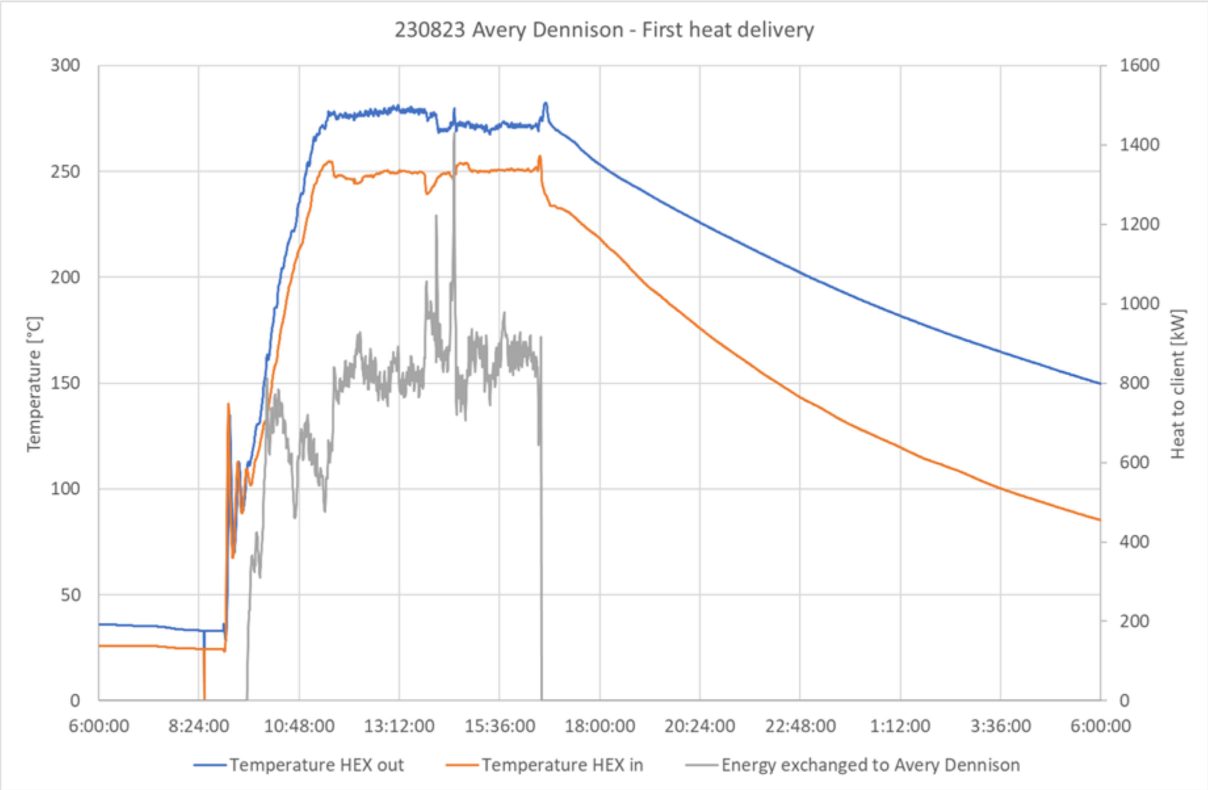


***Figure 6:*** *Temperature curves and heat flows during the first 8 hours of operation*

## 4. Statistical analysis of SHIP world market 2023

As part of the MODULUS project, a market survey was conducted which takes a look at the outlook for the global SHIP market without China. In summer 2023, more than 20 project developers from 13 countries shared planned SHIP projects with Solrico, resulting in the first Solar Industrial Heat Outlook 2023-2026 published in September 2023 [3]. According to the outlook, a clearly positive trend can be seen for the next few years. Currently, 62 plants with 331 MW are planned, half of them in Europe. In the next few years, the Middle East and Southern Europe will be the main target regions for solar process heat. Further developments are the increase of larger projects as well as the rising share of systems with temperatures above 100°C. A trend towards the business model "heat as a service" can also be observed.

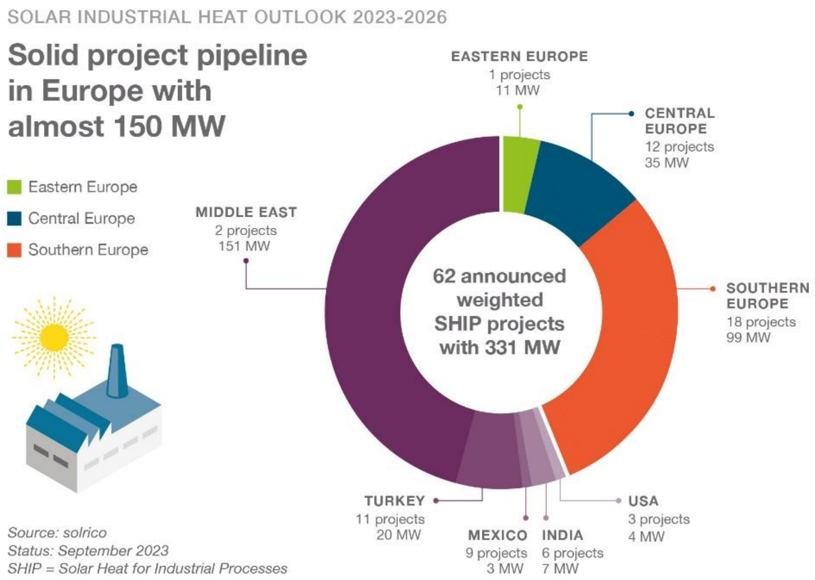


***Figure 7:*** *Solar Industrial Heat Outlook 2023-2026 [3]*

Important customers for solar energy supply can be found in the food, beverage, textile, chemical and automotive industries. In Europe alone, 31 projects of the total of 62 projects worldwide are planned. The food and beverage sector accounts for more than a third of the planned projects worldwide, with a total of 24 projects. For the automotive, mining, oil/gas, and wastewater treatment industries, only projects outside of Europe are planned.

Two fundamental trends are evident in the Solar Industrial Heat Outlook 2023-2026. The first trend shows the increase of larger SHIP plants with concentrating collectors. The share of concentrating collectors - especially parabolic troughs - will increase from currently 22% to 68% from 2023. In subsequent years, the share is expected to increase even further to 77%.

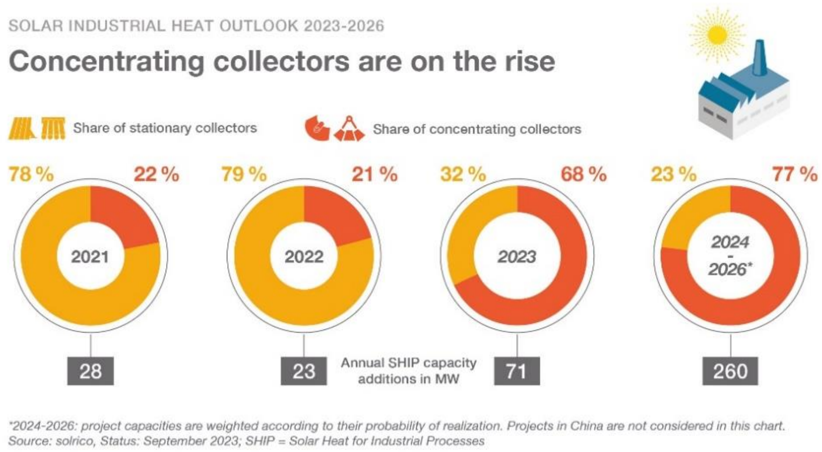


***Figure 8:*** *Solar Industrial Heat Outlook 2023-2026 Concentrating Collectors [3]*

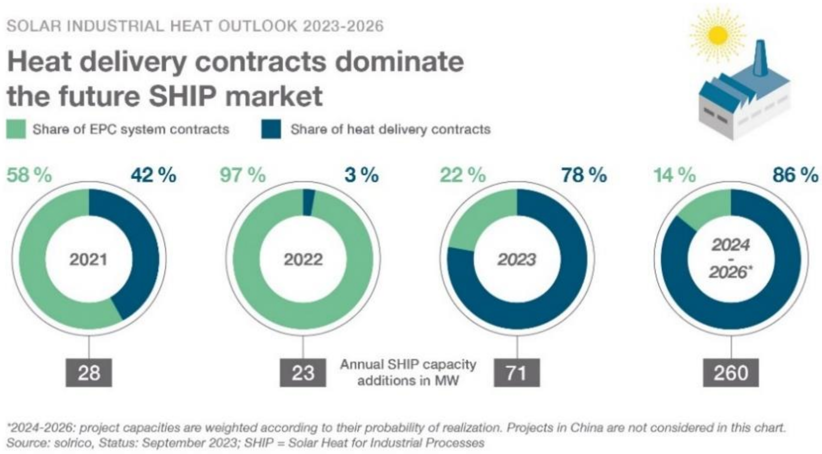


***Figure 9:*** *Solar Industrial Heat Outlook 2023-2026 Heat delivery contracts [3]*

A change in the business model could also be recorded as a further trend. Figure 9 shows the ratio of contracts between EPC and customers or heat suppliers (ESCO) and customers. While the share of contracts with heat suppliers was 42% in 2021, it is expected to increase to 78% by the end of 2023 and further increase to 86% in the period 2024-2026. According to the outlook, large ESCO projects will dominate the market in the future.

The chart below shows the growth of the global SHIP market (excluding China) from 2016 to 2022 with an outlook for 2023-2026. The announced SHIP project capacities are weighted according to their probability of realization. Depending on the planning stage, the outlook shows projects with 30%, 60% or 100% of their capacity. In 2022, the number of operating SHIP systems doubled from 500 to nearly 1000 compared to 2016, and the associated capacity increased even more from 300 MW to 700 MW, largely due to the large-scale Miraah project in Oman, which was commissioned in two phases in 2017 and 2019. During the pandemic, a decline in the annual increase in SHIP capacity was observed. However, a strong increase in the market is expected in 2023. According to the planning status in June 2023, 25 more systems totalling 71 MW are expected to have been commissioned by the end of 2023, which will result almost in a tripling of global capacity compared to 2016. Further projects with a weighted capacity of 260 MW have been announced for the period 2024-2026.

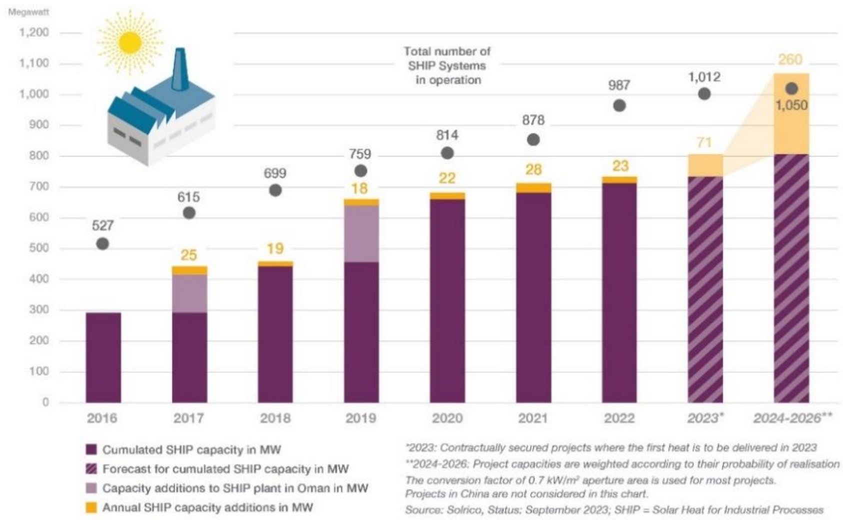


***Figure 10:*** *Solar Industrial Heat Outlook 2023-2026 Cumulated SHIP capacity in MW for different years [3]*

# 5. Conclusion

After the development of the standardization concept of a modular BoP [1], the commissioning of the first of the three planned demonstration plants was started in 2023. In order to achieve smooth commissioning, test plans were drawn up in advance which define the necessary tests and their test criteria as well as the bodies carrying them out. It should be noted that it is advisable to carry out initial tests before delivery of the BoP. This is especially important for tests that require a certain infrastructure or equipment in order to be able to act quickly in case of possible problems. Further tests were specified for both cold and hot commissioning. During the subsequent commissioning of the first demonstration BoP in Belgium, step-by-step venting had to be carried out at various points. Venting was started during the filling of the system with the heat transfer fluid. After initial venting, the surge tank was pressurized with nitrogen to ensure that the heat transfer fluid reached all points in the system. After filling the system, the measurement signals, especially those concerning pump operation, should be checked more closely. In addition, more attention should be paid to oil leaks in the coming days, especially after temperature and pressure increases. Initial test runs were then carried out cold to ensure safe operation of the system. This was followed by further venting of the circuit as well as evaporation of the water contained and removal of volatile gases. On August 23, 2023, heat was supplied to the customer for the first time during hot commissioning. Heat could be delivered to the customer for several hours at a required temperature of ~270°C with a temperature fluctuation in the acceptable range. In this first test run, a $\Delta T$ of about 25 K between heat exchanger inlet and outlet could be observed on the customer side. Besides the standardization activities performed within the MODULUS project, in a subcontract to Solrico, the worldwide SHIP market for the coming years was analysed. The results of the survey showed a positive outlook for the SHIP market in the next years, from 2016 to 2022 the capacity of the installed systems doubled and it is expected to triple by 2024-2026. Furthermore, two trends could be observed. The first trend showed the increase of concentrating technologies in the SHIP world market. While the share number of concentrating technologies in the newly installed SHIP capacity was still 22% in 2021, it is expected to increase to 68% at the end of 2023 and 77% in 2024-2026. A change in the business model could also be noted as a further trend. While the share of contracts with heat suppliers was still 42% in 2021, it is expected to reach 86% by the end of 2023, meaning that large ESCO projects will dominate the market in the future.

Binding figures for the outlook can be found on the solarthermalworld.org website from May 2024.

## Data availability statement

The data can be requested from the authors. A corresponding e-mail address is provided.

## Underlying and related material

There are no other associated materials.

## Author contributions

N. Konz contributed to the writing of the abstract, the introduction, section 3 “2.5 MW demonstration plant for process heat with a silicone oil/mineral oil BoP” and 4 “Statistical analysis of SHIP world market 2023” as well as the conclusion. T. Zippler and S. Mehnert both worked on section 2 on the in-situ test plans. Bärbel Epp contributed to the writing of Section 4 "Statistical analysis of SHIP world market 2023". D. Krüger wrote section 3.2 "Commissioning with a focus on venting". J. Stengler supervised the whole process of writing the paper. All authors participated in the review of the paper.

## Competing interests

The authors declare no competing interests.

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