Dirk Krüger, Jakob Leicht, Sven Fahr, Bärbel Epp, Joachim Krüger, Stefan Bonleitner, Andreas Burger, Klaus-Jürgen Riffelmann, Jana Stengler(2024). Standardized Balance of Plant Engineering for Solar Process Heat. SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES Conference Proceedings, https://doi.org/10.52825/solarpaces.v1i.690

SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems

Solar Industrial Process Heat and Thermal Desalination

https://doi.org/10.52825/solarpaces.v1i.690

Published: 16 Jan. 2024

Standardized Balance of Plant Engineering for Solar Process Heat

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Abstract. The aim of the Modulus (Modular Heat Transfer Station) project is to achieve a cost reduction by standardizing the Balance of Plant (BoP) in the field of solar thermal process heat plants. A consortium of three parabolic trough collector manufacturers, one producer of conventional BoP plants, and two research institutes have joined forces to develop a conceptional approach: First, a worldwide research of existing process heat plants was carried out and the database "ship-plants.info" was evaluated. One partner analyzed in particular the plants that will be added in 2021. In the next step, the components of a BoP plant were listed in the power range from 0.5 to 10 MW, their potential for standardization was investigated and classified. Based on this, a standardized piping and instrumentation diagram (P&ID) was developed. This has already been used as a template for further detailing of the BoP for three process heat plants in Europe, which are presented in the third chapter. Finally, further standardization options for commissioning (functional and safety tests) and performance evaluation are discussed.

Keywords: Balance of Plant, BoP, Concentrating Solar, Solar Process Heat, Modulus

1. Introduction

In the field of solar thermal process heat, a large part of the costs is related to the engineering of the solar plants and in particular to the design of the solar field and the balance of plant (BoP). The latter includes pumps, tanks, heat exchangers etc. and forms the interface between the solar field and the consumer. Within the project “Modulus” the standardization of BoP is being investigated and first results are discussed in this paper.

The project consortium consists of three collector manufacturers, an experienced producer of fossil BoP and two research institutes. First, the experiences and approaches of the project partners involved with regard to BoP planning in previous projects were investigated. The planning and decision-making processes were considered and the most important parameters for this were identified. Technical variants of already realized plants were compared, such as the heat transfer fluid used, the dimensioning of various hydraulic components and the measurement and control technology, in order to identify promising starting points for standardization. The findings are summarized in the next section.

2. State of the art of BoP in existing plants

As part of the Modulus project, an analysis of the state of the art in BoP design was carried out in order to develop a general concept for the standardization and modularization of BoP. The goal is to thereby achieve a significant cost reduction, especially in the area of engineering. The database for applications of solar heat integration in industrial process [1], which has been created in the framework of the IEA Task 49/IV, was systematically evaluated. The distribution of existing plants with regard to industrial sectors, plant capacity, process temperatures and heat transfer fluids used as well as their local distribution was examined. The extent to which the demo plants planned in the project are reflected in existing trends and clusters was compared. It was noticed that both the demo plants planned in the project and the plants already realized by the project participants, which were evaluated in a questionnaire, show a large plant size as well as a comparatively high process temperature in a market comparison (Figure 1). This may be one of the reasons why mainly thermal oil plants are planned within the project, whereas in the past water, pressurized water and steam were the dominant media in the process heat market.

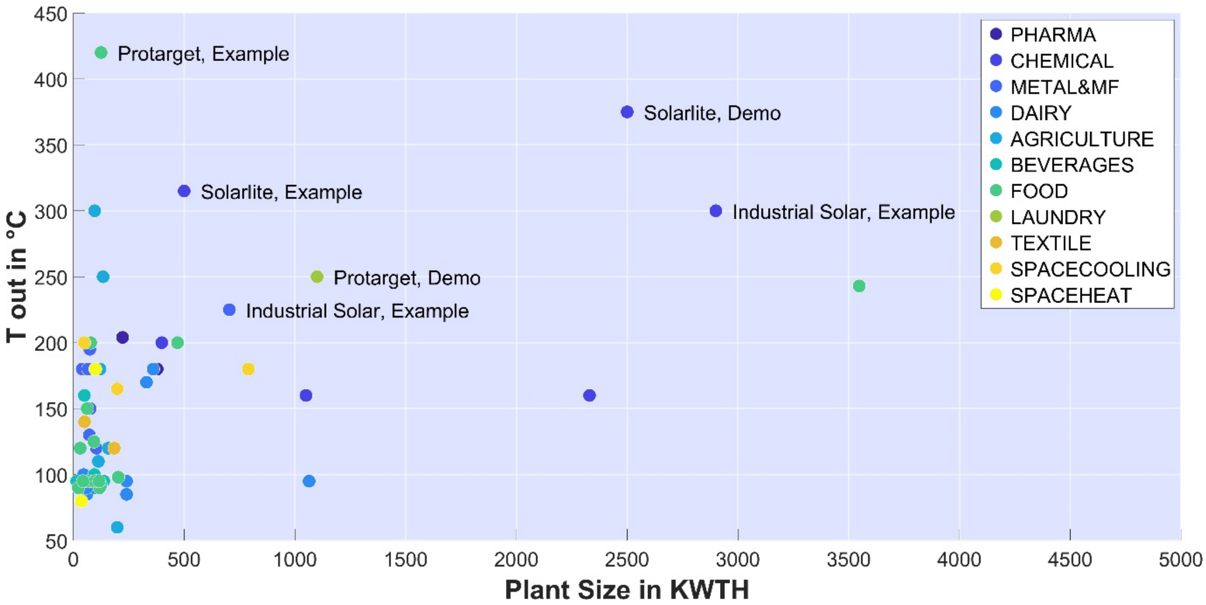

Figure 1. System power and process temperature of exemplarily selected process heating systems already installed (Example) by the project partners and planned in Modulus (Demo), in comparison to systems registered in ship-plants.info.

Overall, the evaluation of the database unfortunately revealed any hardly distinct trends. Only in the case of the local distribution of thermal oil-based process heating systems it was possible to identify a clear focus in Europe, where approx. 2/3 of them are located. When it comes to standardization, the consideration of approval procedures, and also the establishment of test procedures, it therefore makes sense to concentrate on the European market and European standards and directives.

Additionally, a survey on solar process heat systems built in 2021 was carried out. A group of questions on BoP was added to Solrico's annual survey of global SHIP manufacturers. Newcomers tend to integrate a third-party specialist into design and construction of BoP. Experienced companies mostly plan and build BoP themselves. But also experienced solar collector suppliers in some cases prefer to outsource the planning and building of BoP to companies which have knowledge in process heat energy supply. A constraint for outsourcing the BoP planning and construction is that most companies in energy supply have a good knowledge in fossil heat supply but hardly know how to integrate a solar field. 60 % of the companies producing stationary and tracking collectors agree that standardization of BoP could reduce SHIP costs significantly.

Generally, 2021 was again a tough year for SHIP suppliers with only 11,368 m² of concentrating collectors built, but 2022 will see significant growth. Mid-August 30 concentrating SHIP projects with 50,131 m² were under construction - a quadrupling of the previous year. And for 2023 the commissioning is planned for 12 plants with together even 171,274 m^2 (see figure 2).

Deployment is triggered by availability of incentives. Spain will see the largest number of new plants be put up in 2022 due to the subsidy scheme Thermal Energy Production and in California, USA, the three food and beverage plants to be commissioned this year received grants from the Food Production Investment Program.

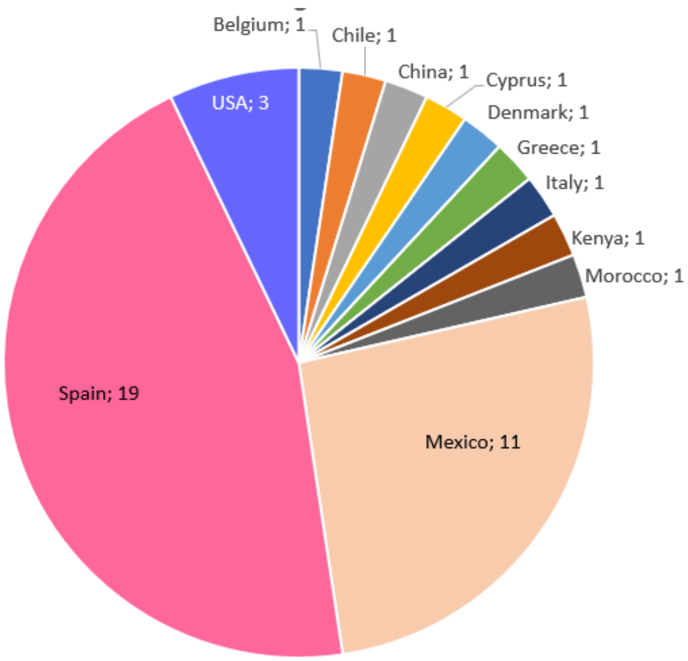

Figure 2. 42 concentrating solar heat projects either under construction in 2022 or contracted to be commissioned in 2023 by location of plant (status as of August 2022) [2] and [3]

The world market of concentrating solar heat projects has been growing significantly since Solrico started annual surveys. At the end of 2017 an estimated 484,958 m² of concentrating collector area supplied heat for C&I customers around the world. The big increase in 2019 was achieved by a 180 MW solar steam block commissioned in Oman. The world market will have been more than doubled in the six-year period between 2018 and 2023 reaching 1,036,120 m², when the already confirmed projects by August 2022 will be realized (Figure 3).

The world market is dominated by parabolic trough collectors. 95.5 % of the new additions between 2018 and 2023 according to Figure 3 are parabolic trough collectors. 2.5 % was added from concentrating Dish and 2 % from Linear Fresnel collectors.

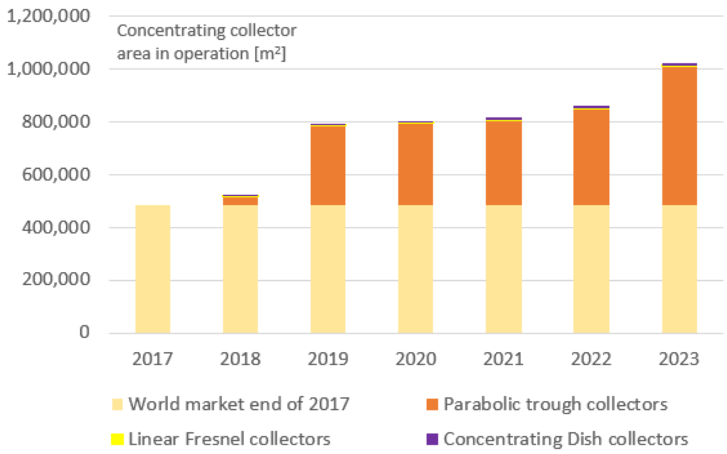

Figure 3. World market of concentrating solar heat projects in operation between 2017 and 2021 plus confirmed capacity additions for 2022 and 2023. Total aperture area of concentrating collectors in operation at the end of 2023 will be 1,036,120 m^2. (Status: August 2022)

3. Standardizing BoP

Based on this as-is analysis, the decisive challenges and starting points for a standardization process were identified. First of all, the choice of the heat transfer fluid plays a major role, it influences the mass flow (via heat capacity), evaporation pressure (thus pressure level), the expansion tank size (via expansion along temperature, which can be high especially for silicone oil), danger of freezing, as well as the operation and maintenance costs (including also durability of oil and required exchange terms). Essentially, the preliminary result is that some functional modules of a BoP depend only on a rather small number of parameters and can therefore be standardized relatively easily, but nevertheless offer good opportunities for simplifying the engineering process and thus potential savings. These include the instrumentation and control (I&C) and hydraulic interfaces, the nitrogen blanketing system and the compressed air system, as well as some components of the main fluid line on the primary (solar field) side. Focusing on a thermal power level from 0.5 to 10 MW_{th}, the nominal pressure will be either PN16 or PN40, and piping diameter will be from DN50 to DN125, according to European standard. Other functional modules, especially heat transfer to the secondary (consumer) side, are highly dependent on the process to be supported, and are therefore difficult to standardize.

A major issue, especially when outsourcing the BoP, is where to house the interfaces. From a hydraulic perspective, the BoP is delivered in a container that contains, for example, heat exchangers, expansion vessels, and safety equipment, to which the engineering, procurement, and construction (EPC) partner connects the solar field on one side and the customer piping on the other. The EPC is typically the solar field supplier that sells or operates the entire system, including the solar field and BoP. The BoP supplier manufactures and tests the BoP at its facility for electrical functionality of all components, safety functions, and pressure, if applicable. For the control of the system, it is important that the EPC has access to the pump and temperature controls, as they are the responsible party to the customer. The control system supplied with the BoP is therefore limited to safety functions and passes the signals from the EPC control to the actuators. The standardization concept is that there are two separate control cabinets in the BoP container, one from the EPC and one from the BoP supplier. This provides a clearly defined interface for communication of process control and safety signals between the parties involved. Solar field control and meteo station are connected to the EPC control. Process heat plants are now automatically operated with remote monitoring, which is also part of the EPC control.

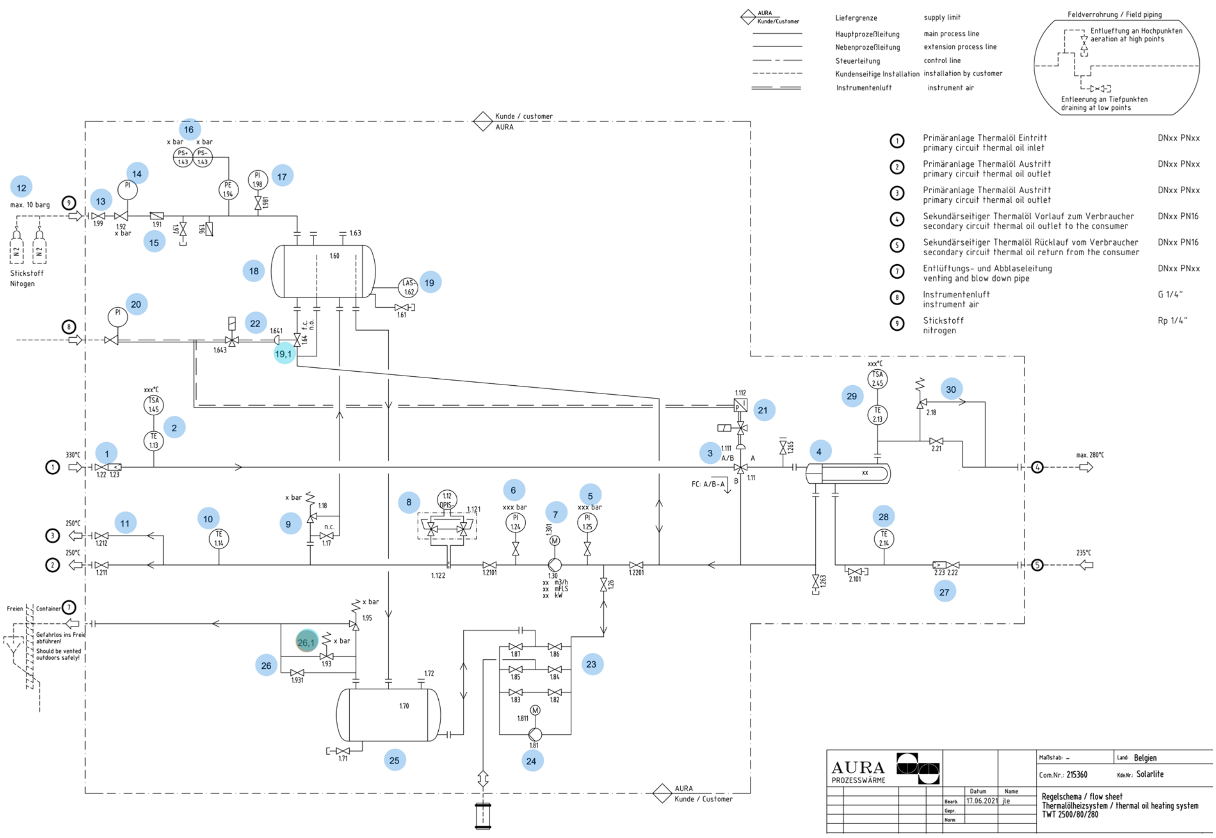

Figure 4. Piping and instrumentation diagram (P&ID) for the BoP of a standardized core oil/oil installation

To avoid costly large tube/head diameters, a large delta T e.g. in the range of 100 K is preferred in the solar field, at least for collectors with vacuum receivers, which still show low thermal losses even at high temperatures. On the other hand, 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 more complex design of many components (e.g. valves, pumps) and the higher pressure rating of piping and flanges. Furthermore, some additional components are required to meet the safety requirements.

4. Examples for BoP engineering based on standardization

4.1 2.5 MW process heat plant with silicon oil/mineral oil BoP in Belgium

For one of the three foreseen BoP in the Modulus project the configuration has already been detailed based upon the standardized layout. The plant will be located in Turnhout, Belgium. The BoP receives mineral oil from the customer through a 240 m long pipe (DN125, PN16) at 260 °C. The design outlet temperature at the tube bundle heat exchanger is 300 °C, transferring 2.5 MW heat at maximum load. A booster burner at the customer side allows for additional heating, if the design temperature is not reached. Figure 5 depicts the piping and instrumentation diagram (P&ID).

The solar field consists of parabolic trough collectors arranged in several loops with different length, due to land restrictions, and provides a heat capacity of 2.5 MW. In total, the aperture area is about 5,540 m² of parabolic trough collectors, heating up the heat transfer fluid from 280 to 380 °C. As the heat demand on the consumer side is fluctuating and most of the time below 1.8 MW, any surplus heat is passed to the concrete storage, featuring a heat capacity of 4.5 MWh. The storage integration explains the high solar field outlet temperature. The consumer operates with Therminol 66 while in the solar field Helisol5A is used, which allows operation up to 425 °C. Main advantage of Helisol5A is its low freezing point (- 30 °C) which supersedes any freeze protection measures. Commissioning is planned for October 2022.

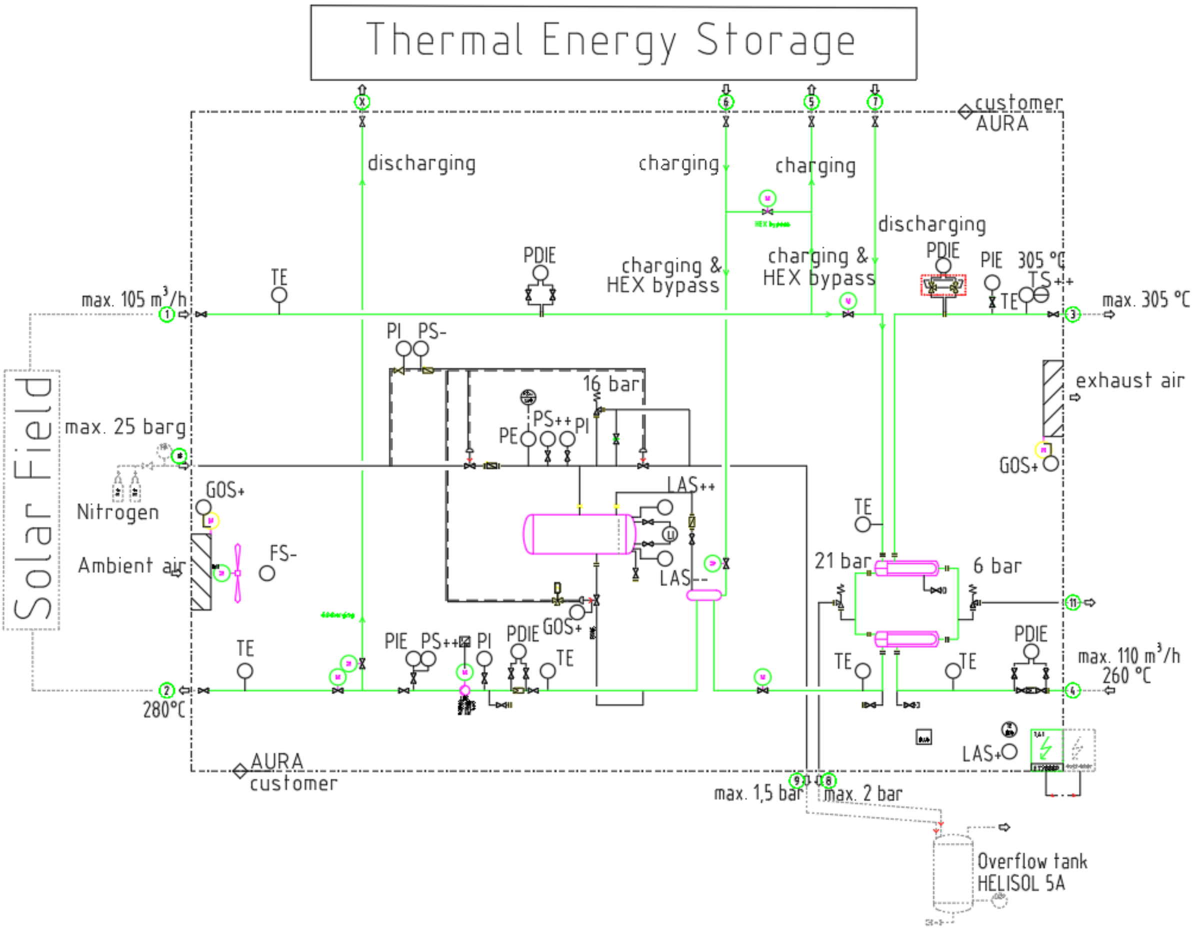

Figure 5. Simplified P&ID of the BoP with silicon oil/mineral oil installation.

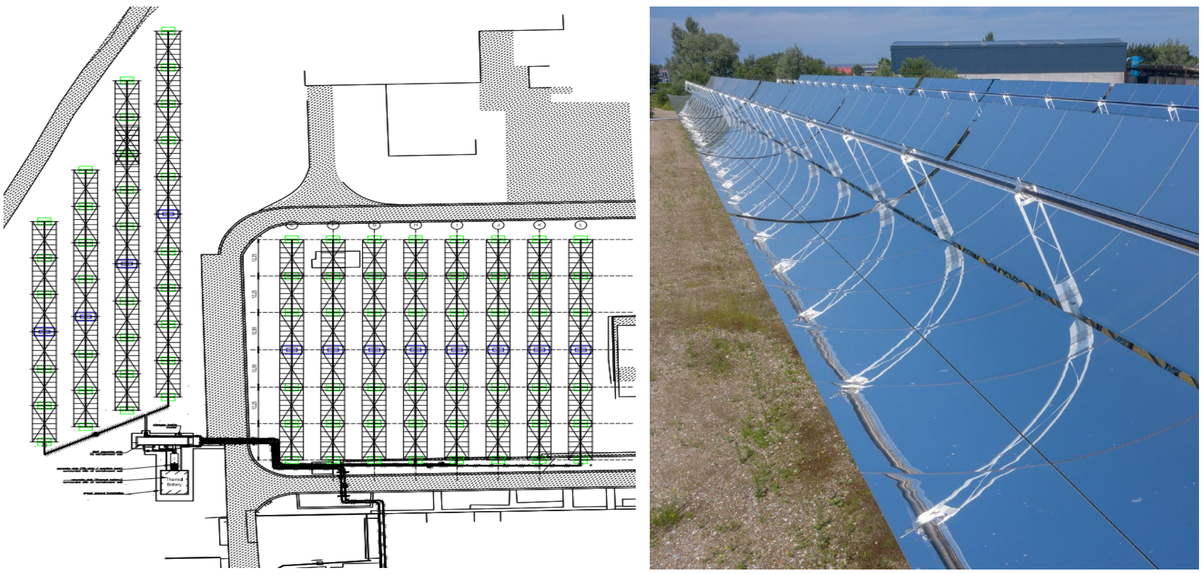

Figure 6. Solar field layout for Turnhout, Belgium (left) and representation of Solarlite's parabolic trough collector (right)

4.2 2.53 MW process heat plant with silicon oil/ steam BoP in Cyprus

Another industrial application within the Modulus project is a laundry in Cyprus with a production capacity of 50 tons of linen daily. Detailed engineering has still to be performed. Roughly 5 tons of steam are required every hour, in various stages of the laundry process which is currently produced with a conventional oil boiler running on Light Fuel Oil (LFO). The company´s thermal infrastructure distributes steam at 180°C and 9 bars, the condensate returns at 80°C and 1 bar.

As the laundry´s customers are mainly from the tourism sector, the need for steam is higher during the holiday season. This leads to the operating profile, shown in table 1 below which is an ideal match for the PTC system as the demand is higher in the summer months and lower in winter as is the solar irradiation. This in the end leads to a high solar share in the overall production process.

Table 1. Operation profile at laundry's customer showing a perfect match to the production of the solar system, enabling a high solar share.

LFO boiler capacity:	5	tons/hour
Process parameter:	Steam @ 180 °C,	9 bars
Condensate return:	Water @ 80 °C,	1 bar
Operating profile during main-season April - October:	12 7 100	hours/day days/week % capacity
Operating profile during off-season November - March:	8 5 30	hours/day days/week % capacity

The solar field comprises of 26 rows of Protarget's innovative PT950 collector modules, with each 12 metres in length. In order to utilise the available land as efficiently as possible, three different row lengths will be used. 9 of the rows with 8 modules, 11 rows with 6 modules and 6 rows with 4 modules, resulting in a total of 162 collector modules. This results in a total aperture area of 5,670 m² and a solar system capacity of 2.53 MW nominal, 3.2 MW peak.

To generate steam at the given temperature and pressure the solar field is designed to deliver heat at 250°C. The heat transfer fluid chosen is Helisol XLP from Wacker Chemie, a state-of-the-art, non-toxic silicon oil which returns at a temperature of 200°C. At these temperatures the system must be pressurised with about 4 bar g static pressure to overcome the vapour pressure of the HTF and also add a safety layer. The calculation of the dynamic pressure, including the pressure drop of the solar field and the BoP will be part of the detailed engineering.

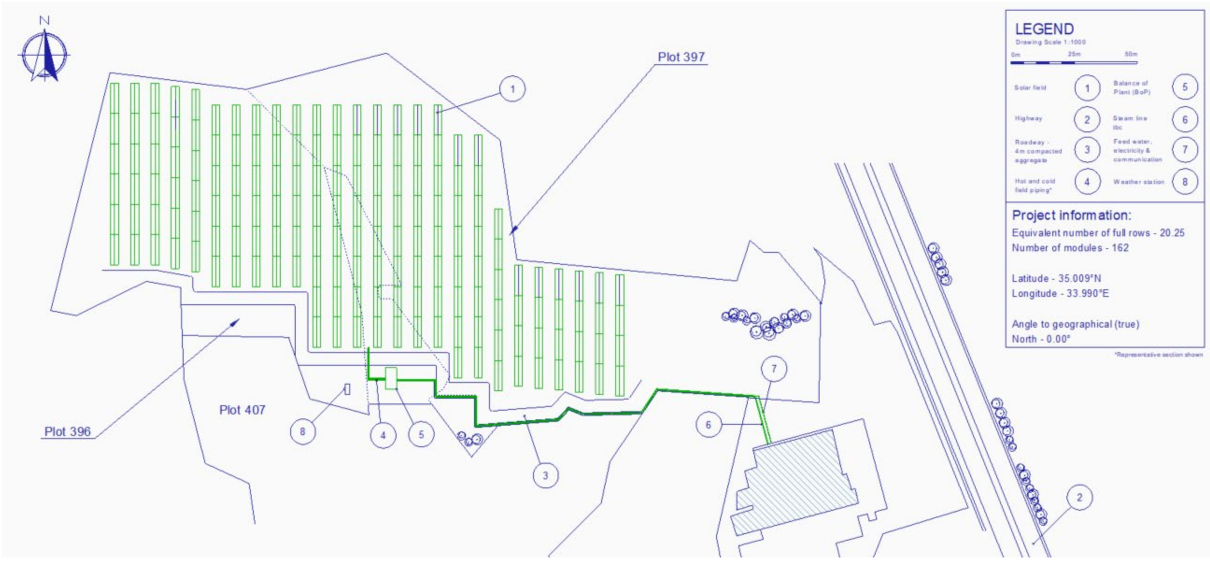

Figure 7. Solar field layout for steam generation in Cyprus.

As the solar system will be integrated in parallel with the existing LFO Boiler, the scope of supply foresees a separate boiler, so that the solar generated steam can directly be supplied into the existing infrastructure. About 4.6 t/h at peak (nominal 3.7 t/h) will be generated by the solar system, so that the conventional heater is only needed at peak load and during periods of bad weather. The laundry's operating profile (high steam demand in summer, low demand in winter) and the way it is integrated allow the PTC system to deliver a high solar fraction of well over 50% throughout the year without the need to integrate a heat storage tank. This in turn leads to lower capital expenses and therefor to a fast return of invest.

4.3 6.5 MW process heat plant with pressurized water/air BoP in Greece

With the aim of integrating a further BoP system developed in the Modulus project into a large-scale demonstration plant, Industrial Solar has prepared a design for a clay brick and roof tile plant in Greece. The processes require heat in the form of hot air to dehumidify clay material in several drying chambers and to pre-dry clay. Several suitable integration points at the process level were identified.

Thermal oil and pressurized hot water were considered as heat transfer media in the solar loop. For the specific application, pressurized water could provide better techno-economic results. Thermal oil would allow a higher operating temperature and could potentially reduce the dissipation of excess energy from the solar field. However, for the specific application, these advantages could not offset the higher thermal losses at higher operating temperatures and the higher capital and operating cost.

Related to the choice of water as heat carrier in the collector circuit, the safety limits were set at 230°C and 28 bar, the operating limit was set at 212°C. Based on the above operating parameters, the size of the solar field and the storage tank were optimized. The solar collector will provide 6.5 MW thermal power at reference conditions (160 °C/180 °C inlet/outlet temperature, 30 °C ambient temperature, DNI = 900 W/m², at solar noon). The stratified storage tank was sized at 110 m³.

Based on a hydraulic flow diagram and technical specifications, AURA performed a preliminary design of the BoP unit to prepare a budget proposal including a component list. In doing so, AURA was able to draw on expertise gained from the results of previous Modulus work packages.

5. BoP functional test planning and performance evaluation

Beside the design, safety checks and functional testing of the BoP is a further aspect for standardization. When planning tests and measurements, a distinction must be made between the aspects of safety and functionality testing and the meteorological evaluation of the performance. The former should and must, as far as possible, be carried out before delivery of the BoP in order to avoid time-consuming and expensive correction of deficiencies at the installation site and to ensure safe commissioning of the system. This includes first and foremost a check of the electrical safety of the plant in accordance with the relevant directives, the tests required to comply with the European Pressure Equipment Directive, and a functional test of all sensors, actuators and the entire safety chain.

Conclusive test procedures for evaluating the performance of a BoP include not only the energy balance assessment but also other quality criteria, which primarily result from the specifications provided by the customer and the process to be supported. One important quality criterion is certainly the control quality, which comprises various aspects:

- Compliance / stability of the required process parameters (+ analysis of the cause of occurring fluctuations and deviations)
- Plant behaviour during the warm-up phase
- Plant behaviour in critical situations (overtemperature, overpressure, undercutting of the minimum flow)
- How well do the preset control parameters match the real plant operation? Which improvements have to be made during commissioning and why?

In addition to the quality criteria, permissible deviations and fluctuations must also be defined in advance in order to plan appropriate test sequences. From these, in turn, requirements are derived for the accuracy of the sensor technology to be used. Here, the desire for the most precise evaluation conflicts with the project goal of minimizing costs. For the plants planned in the project, it was therefore decided to omit the installation of higher-quality measurement technology and to use only the sensors necessary for the operation of the plant.

Further technical aspects to be considered are:

- Time resolution of the measurement data
- Transfer of measurement data
- Selection of measurands required for the planned evaluations
- Knowledge on accuracy and stability of the material properties of the HTF

6. Conclusion

A consortium of three parabolic trough collector manufacturers, a balance-of-plant producer and two research institutes has set itself the goal of reducing the costs of engineering, manufacturing and commissioning the BoP by standardizing the components. The project partners first conducted a worldwide inventory of existing process heat plants. It turned out that about two thirds of the plants 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 use European standards and specifications for standardization and to focus on plant sizes between 0.5 and 10 MW. The inventory was supplemented and updated by a survey among manufacturers of solar process heat plants that have built a process heat plant in 2021 or will build one in 2022. While 2021 was a rather weak year with just under 11,400 m² added, 2022 is shaping up to be a fourfold increase. By far the majority of the plants added use parabolic trough technology. 60% of collector manufacturers surveyed agree that standardization of BoP can significantly reduce project costs. Based on the inventory, the survey results and the experience of the participating industry partners, concepts were developed. The potential for standardization of BoP components was evaluated and finally a conceptual P&ID was established. Even though the Modulus project is not yet completed, the work could already be used to design and detail the BoP of three plants in Europe. The plants use thermal oil on the solar field side to heat or generate thermal oil, air or steam on the consumer side. The next step is to assess cost reduction through standardization.

Data availability statement

The submission is not based on data.

Author contributions

D. Krüger contributed to the chapter on standardizing the BoP. K.-J.- Riffelmann had writing contributions to the section's examples of BoP engineering, abstract, and conclusion, and reviewed generally all sections. S. Fahr had writing contributions to the state of the art of BoP and the planning of test sequences sections. J. Stengler was writing, reviewing and editing, and supervised all. A. Burger had writing contribution to the section "Examples for BoP engineering" and reviewed. S. Bonleitner had writing contribution to section "Examples for BoP engineering " and reviewed, too. B. Epp had writing contribution to the section state of the art of BoP in existing plants.

The authors declare no competing interests.

Funding

The authors acknowledge the financial support by the German Federal Ministry for Economic Affairs and Climate Action under contract no. 03ETW021A. The sole responsibility for the contents lies with the authors.

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