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FROM LONG-TERM OPERATIONAL EXPERIENCE TO ROBUST SHIP DESIGN: PERFORMANCE GAPS AND TECHNO-ECONOMIC IMPLICATIONS FROM SWISS SOLAR PROCESS HEAT SYSTEMS

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Summary

This study combines long-term monitoring of seven Swiss solar heat for industrial processes (SHIP) installations (55–190 °C, with operating histories beyond twelve years) with a techno-economic assessment of hybrid solar thermal and high-temperature heat pump (HTHP) systems based on dynamic simulation models developed in *pytrnsys*. Although the analysed SHIP portfolio consists predominantly of pilot and demonstration plants and is not representative of mature commercial deployment, it provides transferable insights into long-term system performance. The results show that the annual useful energy yield depends not only on solar technology, but on availability, reliable operation, seamless process integration, maintainability and the long-term continuity of industrial heat demand over the solar system lifetime. Dynamic simulation models enabled the diagnosis of system performance issues and helped identify their underlying causes.

The simulated scenarios consider a 1 MW industrial heat peak load (3.60 GWh/a), supply process temperatures of 60–150 °C and hybrid solar systems deliberately sized to an ambitious annual solar fraction of approximately 50 %. Under the modelled current Swiss investment-support conditions, the hybrid solar–HTHP systems achieve the lowest levelized cost of heat (LCOH) at 60, 90 and 120 °C and remain close to gas at 150 °C. Solar integration reduces life-cycle greenhouse-gas (GHG) emissions by 57–78 % compared with gas boilers and, relative to standalone HTHPs, reduces electricity use by up to 49 % and GHG emissions by 29–40 %.

Keywords: solar process heat, SHIP, long-term monitoring, system integration, reliability, levelised cost of heat, dynamic simulation, TRNSYS / pytrnsys

Field of application for the findings: industrial process heat, large-scale solar thermal systems, hybrid renewable heat supply

Addressed audience: researchers, planners, plant owners and operators, system integrators, technology providers, policy makers

1. Introduction

The Swiss EvaSP programme (*Evaluation of Solar Process Heat Systems in Switzerland*) is a long-term research and evaluation programme funded by the Swiss Federal Office of Energy (SFOE) and dedicated to the assessment of solar heat for industrial processes under real operating conditions. Seven installations commissioned between 2011 and 2022 are considered in the present study (Fig. 1 and Table 1). They include parabolic-trough collectors (PTC), vacuum-tube collectors (VTC), vacuum flat-plate collectors (VFPC) and compound vacuum flat-plate collectors (C-VFPC), aperture areas of approximately 115–627 m^2, and process temperatures ranging from about 55 to 190 °C. Applications include dairy processing, industrial cleaning, process preheating, bitumen heating and hot-water production and sterilisation in a hospital.

The investigated systems largely consist of pilot and demonstration plants aimed at testing innovative SHIP concepts under real industrial conditions. They therefore provide particularly valuable evidence on long-term performance, integration and reliability, but differ from a set of mature, commercially standardised SHIP installations. Several systems accumulated more than a decade of industrial operation, allowing the present study to examine not only initial performance but also availability, ageing, maintainability and changes in the industrial heat demand over substantial parts of the expected plant lifetime. The study addresses three research questions: (1) Which mechanisms explain the gap between expected and useful heat delivery in long-term operation of the investigated SHIP systems? (2) How do process temperature, collector technology and investment support affect the technical and economic performance of solar–HTHP process-heat systems under current Swiss boundary conditions? (3) How strongly do monitoring-observed deviations from design conditions, particularly reduced process demand, affect useful solar yield and LCOH?

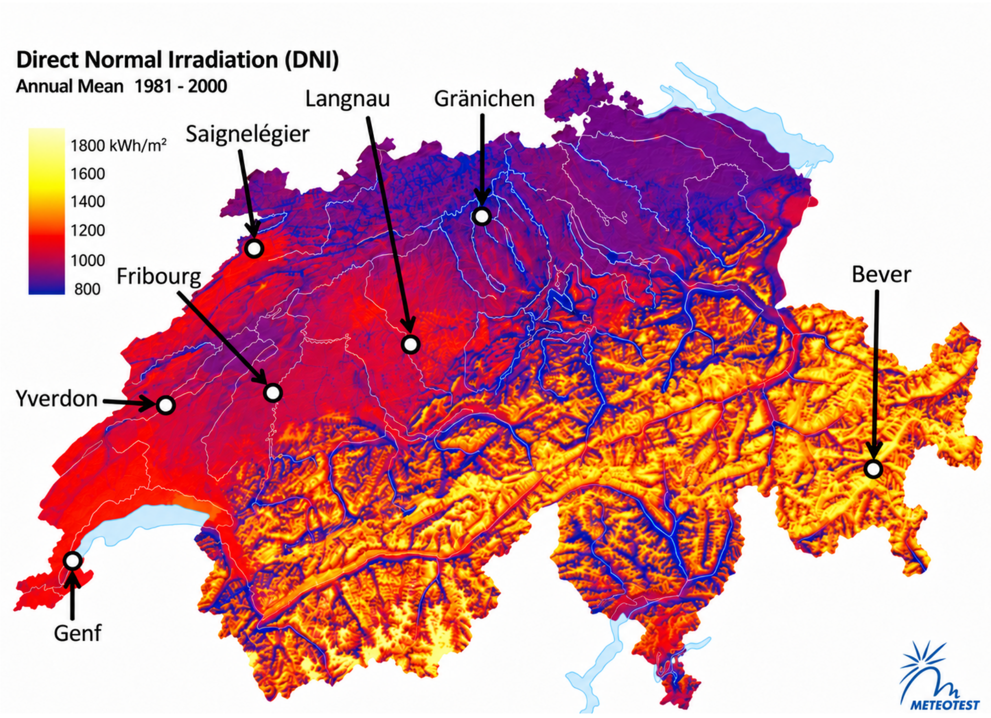


Fig. 1: Location of the seven solar thermal systems included in the long-term monitoring and assessment for EvaSP.

Tab. 1: Main characteristics of the SHIP systems included in the long-term monitoring assessment. Industrial partners and locations are deliberately anonymised.

ID	Application	Collector	HTF	T_{use} [°C]	A_{ap} [m^2]	Operation	Status
SHIP-01	Dairy / steam, cleaning	PTC	Thermal oil	190	115	2011–2018	Decommissioned
SHIP-02	Dairy / cleaning, production	PTC	Water–glycol	90	627	2012–2026	Operating
SHIP-03	HVAC manufacturer / Space heating, process preheating	VTC	Water	55 / 80	360	2012–2025	Site closed
SHIP-04	Dairy / cleaning, sterilisation	PTC	Water	120	581	2014–2019	Status unknown
SHIP-05	Road construction / hot water, bitumen heating	C-VFPC	Thermal oil	80 / 190	184	2014–2022	Decommissioned
SHIP-06	Hospital /hot water, sterilisation steam	VTC	Thermal oil	80 / 140	360	2018–2025	Operation paused
SHIP-07	Dairy / feedwater preheating, hot water	VFPC	Water–glycol	100	214	2022–2026	Operating

2. Methodology

2.1 Monitoring and performance assessment

The long-term assessment combines monitoring data from the successive EvaSP project phases with renewed site inspections and information from plant operators and technical staff.

The monitoring data included energy meters for assessing solar energy yield and, where available, process heat demand. The quantitative evaluation considered annual solar yield, collector-field and system efficiencies, and operating availability. Operating availability denotes the fraction of the annual monitoring period during which the solar system was operational. Planned seasonal shutdowns as well as maintenance- and fault-related outages are therefore reflected in this indicator. These indicators were complemented by component-level quantities where required to identify the causes of observed performance deviations. During the site inspections, both the solar field and the balance of plant were assessed, including hydraulic components, heat exchangers, storage, sensors and control systems.

Long-term changes in collector-field performance were assessed using quasi-stationary operating periods following the methodology established in EvaSP-II Rittmann-Frank and Caflisch (2020). This approach allows collector-field performance in different years to be compared under similar irradiation and operating conditions and thereby helps distinguish changes in collector performance from variations in weather or plant operation.

Where annual performance indicators alone were insufficient to identify the origin of a performance gap, digital twins based on dynamic simulation models were used as an additional diagnostic method. The models were implemented in TRNSYS using the open-source *pytrnsys*[1] framework and represent the collector field, piping, pumps, heat exchangers, thermal storage, controls, industrial heat demand and auxiliary heat supply. The monitored weather and process conditions were used as boundary conditions, allowing alternative hypotheses for deviations between expected and measured performance to be tested under the actual operating conditions experienced by the plant.

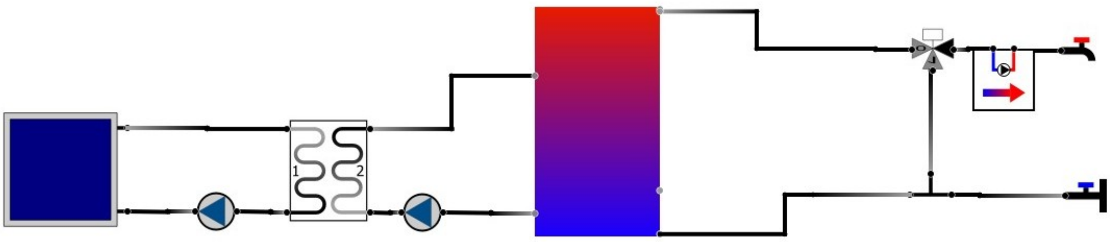


Fig. 2: Dynamic simulation model developed in *pytrnsys*, including the solar collector field, thermal storage, auxiliary heat source and process connection. This model was used for the techno-economic analysis, similar models were used to investigate the influence of process integration and operating conditions on the useful solar heat delivered to the processes

2.2 Techno-economic analysis

The complementary techno-economic assessment compares three heat-supply concepts: a natural-gas boiler, a standalone high-temperature heat pump (HTHP), and a hybrid solar thermal–HTHP system. All configurations supply the same hourly industrial heat-demand profile and are evaluated in terms of energy yield, levelised cost of heat (LCOH), and life-cycle greenhouse-gas (GHG) emissions.

The process operates five and a half days per week with an approximately two-week summer shutdown, resulting in an annual useful heat demand of 3.6 GWh_{th}/a and a peak thermal load of 1.0 MW_{th}. Process supply temperatures of 60, 90, 120, and 150 °C are investigated with a constant process temperature difference of 20 K.

Hourly weather data for 2025 from the MeteoSwiss Zurich/Fluntern station, representative of the Swiss Plateau north of the Alps, are used for the solar-thermal simulations. The same ambient-air temperature data are used as the source-side boundary condition for the simplified HTHP model. Industrial waste-heat sources, which could improve HTHP performance, are not considered.

The solar assessment includes flat-plate collectors (FPC) for industrial process supply temperatures of 60 and 90 °C, evacuated-tube collectors (VTC) for 90, 120, and 150 °C, and vacuum flat-plate collectors (VFPC) for industrial process supply temperatures of 90, 120, and 150 °C. Parabolic-trough collectors (PTC) and linear Fresnel collectors (LFC) were outside the scope of the present analysis, but could be considered in future work. Thermal-storage volume is scaled with collector aperture area using a fixed ratio of 0.10 m^3/m^2_{ap}, following the approximate modular sizing approach reported in the BillySolar project Rittmann-Frank et al. (2021).

All solar–HTHP configurations are iteratively sized to an annual solar fraction of approximately 50 %, defined

[1] `https://github.com/SPF-OST/pytrnsys` – `https://pytrnsys.readthedocs.io/en/latest/`

from the useful solar heat delivered to the industrial process. This deliberately ambitious design point provides a consistent basis for comparison and does not represent an economic optimum. The installed HTHP capacity remains 1.0 MW_{th}, allowing the HTHP to cover the full process load independently of solar availability.

HTHP performance is calculated hourly using a simplified Lorenz-cycle formulation with a relative Carnot efficiency of 0.45 and a pinch-point temperature difference of 7.5 K. In the hybrid configurations, useful solar heat is supplied preferentially and the HTHP covers the residual process demand. HTHP electricity consumption and auxiliary electricity for solar circulation pumps and the dry cooler are included in the annual energy balance.

The economic assessment is performed in constant 2026 CHF over a 20-year evaluation period. A real discount rate of 1.5 % is applied, representing a long-term, infrastructure-oriented financing perspective consistent with the study's focus on public investment support.

Investment, operation and maintenance (O&M), energy, and capacity costs are included. All recurring costs are assumed constant in real terms over the evaluation period, i.e. no real escalation of electricity or fuel prices is assumed. The principal economic and life-cycle GHG assumptions are summarised in Table 2.

Tab. 2: Principal economic and life-cycle GHG assumptions used in the techno-economic assessment.

Parameter	Base value	Unit / remark	Source
Economic assumptions			
Period of analysis	20	a	This study
Real discount rate	1.5	%	This study
Electricity price	0.19	CHF/kWh_e	Eisenring and Stocker (2026)
Natural-gas energy / capacity price	0.089 / 17	CHF/kWh_{gas} / CHF/kW_a	Energie 360° AG (2026)
FPC CAPEX, 1,000 / ≥5,000 m^2	546 / 471	CHF/m^2_{ap}	Augsten (2017); Beurskens et al. (2025); Rohani et al. (2025)
VTC CAPEX, 1,000 / ≥5,000 m^2	769 / 657	CHF/m^2_{ap}	Augsten (2017); Jesper et al. (2023); Rohani et al. (2025)
VFPC CAPEX, 1,000 / ≥5,000 m^2	868 / 769	CHF/m^2_{ap}	Engineering estimate; Abrecht et al. (2025); Epp (2021)
TES CAPEX, 60 / 90–150 °C	1,062 / 1,395	CHF/m^3	Rohani et al. (2025)
HTHP CAPEX, ≤125 / 150 °C	1,177 / 1,415	CHF/kW_{th}	Deutsche Energie-Agentur GmbH (dena) (2026)
Gas-boiler CAPEX	309	CHF/kW_{th}	Deutsche Energie-Agentur GmbH (dena) (2026)
Solar / HTHP / boiler O&M	1 / 2 / 2	% gross CAPEX/a	Beurskens et al. (2025); Jesper et al. (2023)
Solar investment support	2,400 + 1,000/kW_{TKN}	CHF	Bundesamt für Energie (BFE) (2025)
HTHP support proxy	0.18	CHF/kWh displaced fossil heat	Stiftung Klimaschutz und CO_2-Kompensation KliK (2026)
Life-cycle GHG assumptions			
Large-scale solar thermal	134	kg CO_2-eq/m^2_{ap}	Ramseier and Frischknecht (2022)
HTHP production and end-of-life	15.64	kg CO_2-eq/kg	Ramseier and Frischknecht (2022)
HTHP reference mass	11.4	t per 1 MW_{th}	ALTAL (2025)
Gas-boiler production and end-of-life	86	kg CO_2-eq/kW_{th}	Ramseier and Frischknecht (2022)
Steel sheet, uncoated	2.80	kg CO_2-eq/kg	KBOB and ecobau (2026)
TES steel mass, 60 / 90 / 120 / 150 °C	100 / 200 / 300 / 600	kg steel/m^3	Engineering estimates based on vessel data
Electricity consumption mix, EU 2024	0.288	kg CO_2-eq/kWh_e	Molina Sánchez et al. (2026)
Natural gas, life cycle	0.230	kg CO_2-eq/kWh_{fuel}; energy price incl. CO_2 levy	Ramseier and Frischknecht (2022)

The levelised cost of heat is calculated as

$$\mathrm{LCOH} = \frac{\mathrm{CAPEX}_{\mathrm{gross}} - S + \sum_{t=1}^{n} \frac{C_{\mathrm{O\&M},t} + C_{\mathrm{energy},t} + C_{\mathrm{capacity},t}}{(1+r_{\mathrm{real}})^t}}{\sum_{t=1}^{n} \frac{Q_{\mathrm{dem,use},t}}{(1+r_{\mathrm{real}})^t}}, \tag{1}$$

where S denotes subsidy or investment support, n the period of analysis, r_{real} the real discount rate, and $Q_{\mathrm{dem,use},t}$ the useful heat supplied to the industrial process. O&M costs are based on gross CAPEX, while annual O&M, energy, and capacity costs are assumed constant in real terms.

Investment support is evaluated in a separate supported scenario using the assumptions in Table 2. Solar-thermal support is represented by the modelled Swiss federal contribution, while HTHP support is represented by a proxy based on displaced historical fossil heat. These assumptions are used to assess the influence of current Swiss support conditions and do not imply project-specific eligibility or guaranteed funding.

Life-cycle GHG intensity includes annualised embodied emissions of the principal system components and operational emissions associated with electricity or natural-gas consumption, normalised by the useful process heat supplied over the same 20-year evaluation period.

Finally, two robustness analyses translate deviations observed during the long-term monitoring of the EvaSP solar thermal plants into economic consequences. First, usable industrial heat demand is reduced to 75 % and 50 % of the design demand while installed capacities and investment costs remain unchanged. Second, useful solar yield is reduced by 10–50 % while the installed system and associated investment costs remain fixed. Both sensitivities quantify the effect of reduced utilisation of the installed solar asset on LCOH.

3. Long-term operational experience: performance, reliability and integration

3.1 Solar collector performance, thermal energy yield and availability of monitored plants

Monitoring data reveal the performance and availability gaps observed across the seven SHIP systems, as summarised in Table 3. The measured solar-field yields span substantial ranges over the available monitoring periods, reflecting variations in weather, availability, operating conditions, and process integration. Importantly, low annual heat delivery was not generally associated with a persistent loss of collector efficiency. In several systems, the dominant limitations occurred outside the collector field, including prolonged outages, changes in process heat demand, and constraints in the solar energy integration into the process demand.

Tab. 3: Monitoring-based performance-gap overview of the investigated SHIP systems. Design and measured values refer to specific solar-field yield. Measured values are reported as ranges over the available monitoring periods and should therefore be interpreted together with the corresponding availability and dominant limitation.

Plant	Design yield [$kWh/(m^2a)$]	Measured yield [$kWh/(m^2a)$]	Availability [%]	Dominant limitation / observation
SHIP-01	521	40–356	25–100	Recurrent thermal-oil leakage and prolonged shutdowns.
SHIP-02	406	114–445	50–100	Despite leakages in the primary loop, the system has remained operational for more than twelve years with high availability; recent collector-field performance decline potentially caused by tracking deviation (under investigation).
SHIP-03	437	491–627	95–100	High availability and collector-field yield during 12 years; production site was relocated and solar system was shut down.
SHIP-04	300	171–380	83–100	No dominant long-term limitation could be conclusively identified from the available monitoring period; current plant status is unknown.
SHIP-05[1]	238	83–92	n.a.	Collector-field underperformance, hydraulic/control deficiencies and undersized heat exchangers; no spare parts.
SHIP-06	588	n.a.	unstable	Recurring thermal oil leakages and hydraulic/system-integration problems; operation paused since May 2025.
SHIP-07	748	171–413	33–83	Widespread integration challenges, including parallel energy-efficiency measures that reduced process heat demand and the division of responsibilities among integration stakeholders.

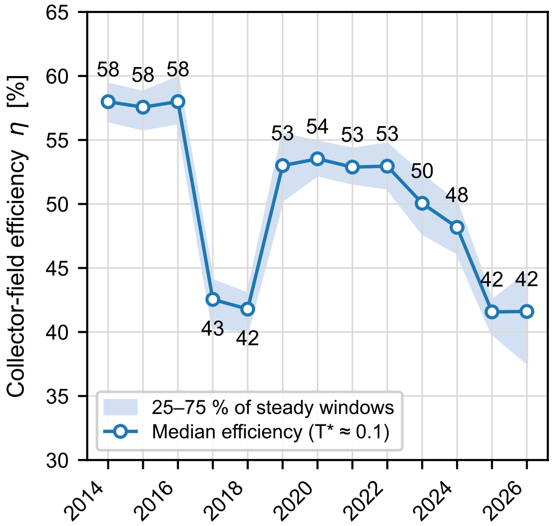
[1] Detailed monitoring and performance analysis of SHIP-05 were carried out by LESBAT/HEIG-VD within the dedicated P+D project; see Bunea et al. (2018).

The comparison illustrates that the performance gap cannot be described by collector efficiency alone. SHIP-01, SHIP-05 and SHIP-06 were strongly affected by leakage and resulting availability losses, whereas SHIP-07 was limited primarily by changes in the process boundary conditions and heat-transfer capability. SHIP-03 provides the opposite example: measured collector-field yield remained above the original design value during the monitoring period, while the long-term usefulness of the installation was ultimately constrained by industrial process relocation.

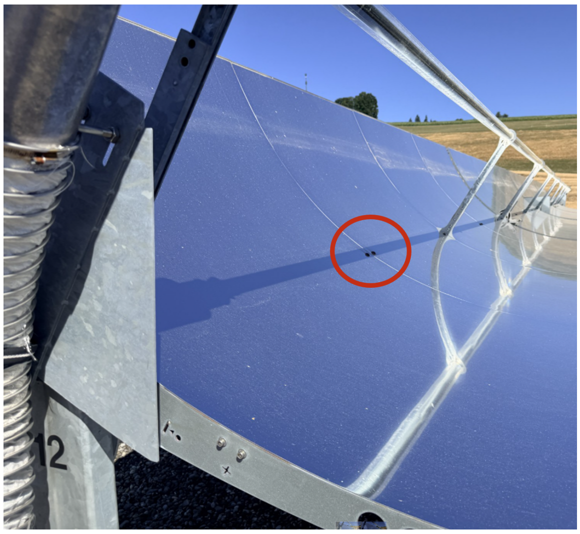
SHIP-02 demonstrates why long-term collector monitoring nevertheless remains necessary. Its quasi-stationary collector-field efficiency was approximately 58 % during the first monitoring years and recovered to approximately 53–54 % between 2019 and 2022 after a temporary reduction in 2017 and 2018 (Fig. 3a). The temporary reduction coincided with leakage-related outages of individual collector rows and therefore does not indicate continuous collector degradation. From 2023 onwards, however, the median quasi-stationary efficiency decreased from approximately 50 % to 42 % in 2025 and 2026.

The origin of this recent decline has not yet been conclusively identified. A tracking offset observed during field inspection (Fig. 3b) and mechanical deformation following a severe storm in 2023 are the most plausible contributors. The case therefore illustrates that genuine collector-field degradation may emerge after extended operation, but diagnosing it requires the combination of performance monitoring and digital twins with physical inspection.

Overall, the monitored systems indicate that long-term SHIP performance is predominantly a system-level outcome. Collector condition remains important, particularly after extended operation, but availability, process integration, maintainability, and the persistence of a suitable industrial heat demand were more frequently responsible for the observed gaps between design expectations and long-term heat delivery.



(a) Quasi-stationary collector-field efficiency by year.



(b) Observed tracking offset during field inspection.

Fig. 3: Long-term collector-field performance and observed tracking condition of SHIP-02. (a) Quasi-stationary collector-field efficiency at approximately $T^* = 0.1$. The temporary reduction in 2017–2018 coincided with leakage-related outages of individual collector rows and was followed by a recovery. A renewed decline is visible from 2023 onwards. The physical origin of the recent performance decline is still under investigation and may involve tracking deviations and mechanical deformation following a severe storm in 2023. Minor hail damage was observed but is currently not considered the dominant cause. (b) Observed tracking offset during field inspection. The mounting bolts mark approximately the centre of the mirror aperture; under correct tracking, the absorber-tube shadow should be centred on the mirror and pass approximately through this position.

3.2 Coordinated integration and design of the solar thermal system

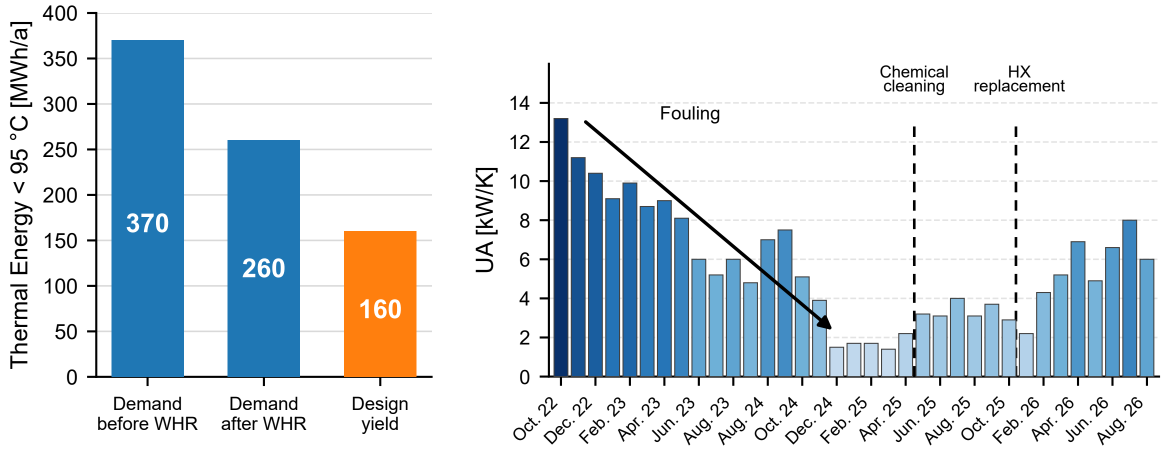
The long-term monitoring shows that SHIP performance depends strongly on coordinated design and integration between the solar system and the industrial process. Solar generation, storage, process integration, auxiliary heat supply, and control cannot be considered independently, particularly because industrial process conditions may change during the lifetime of a solar installation.

SHIP-07 provides the clearest example. The system was originally designed for a process return/supply temperatures of approximately 55 / 95 °C. After commissioning, additional waste-heat recovery was introduced in parallel with the solar system, increasing the return temperature to approximately 70 °C and reducing both the usable temperature difference and consequently the heat sink available to the solar installation (Fig. 4a). Although this improved the industrial heat-supply system as a whole, it strongly reduced the heat demand that could be supplied by solar thermal system from approximately 370 to 260 MWh_{th}/year.

As a consequence, the theoretical solar production potential estimated by the manufacturer, of approximately 160 MWh_{th}/year (Fig. 4a), becomes increasingly difficult to exploit as the process heat sink is reduced. The 25 m^3 storage tank, with an estimated usable capacity of about 435 kWh_{th} (approximately 3 h at peak collector output), provides limited buffering capacity. Consequently, periods of excess solar production occur in which the available heat cannot be accommodated by the process or storage and must be rejected through the air cooler. Thus the effective solar production is constrained by the reduced process demand and limited thermal storage.

A second limitation occurred in the heat-transfer chain. The effective conductance of the primary heat exchanger decreased substantially during operation, progressively restricting the transfer of solar heat to the process (Fig. 4b). The fouling was linked to an incorrect pH value of the heat-transfer fluid, which caused corrosion of the storage tank and the formation of rust deposits in the hydraulic circuit and heat exchanger. After replacement of the heat exchanger, the calculated UA value did not return to the initial level. However, the plant control strategy was modified at the same time, so the pre- and post-replacement UA values are not directly comparable.

These observations highlight the need for clearly defined system-level responsibility. Process-side modifications should trigger a reassessment of solar-system operation, control, and available heat demand. Coordinated design and continued responsibility across the process interface are therefore essential if the installed solar asset is to maintain its intended contribution over the plant lifetime.



(a) Thermal demand and design yield (<95 °C).

(b) Heat-exchanger conductance UA over time. Control strategy changed over time.

Fig. 4: Examples of system-level limitations observed in SHIP-07. (a) The available process heat demand for solar integration decreased after changes to the industrial heat-supply system, including the introduction of additional waste-heat recovery. (b) The effective heat-transfer conductance UA of the primary heat exchanger decreased substantially during operation, progressively restricting heat transfer between the solar circuit and the process. Both effects occurred outside the collector field and illustrate the need for coordinated design and responsibility across the complete heat-supply system.

3.3 Thermal-oil heat transfer fluid was associated with high maintenance requirements

The analysed systems indicate that heat-transfer-fluid selection can strongly affect long-term availability and maintenance costs.

SHIP-01 provides the clearest example. Although the PTC collector field performed close to expectations during available operating periods, recurrent leakage in the thermal-oil circuit led to prolonged shutdowns and ultimately limited operation. Similar leakage and hydraulic problems were observed in SHIP-06. By contrast, SHIP-02, which also uses PTC collectors but operates with a water–glycol circuit at a lower temperature level, experienced leakage-related interruptions but repeatedly returned to operation and remained in service for more than a decade.

The observations highlight that thermal-oil circuits require particular attention to long-term operation and maintenance. Leakage prevention, material compatibility, component accessibility, and suitable repair strategies should therefore be considered explicitly during design. Thermal oil remains a viable option for high-temperature SHIP applications, but the associated maintenance requirements must be anticipated.

3.4 Dynamic simulation models as digital twins support performance verification, diagnosis and enable more robust design

Annual energy balances are often insufficient to identify the physical origin of a performance gap. Digital twins based on dynamic simulation models provide an additional diagnostic layer by reproducing the interaction between collector field, storage, hydraulics, controls, and the industrial process under the operating conditions experienced by the plant.

In this study, *pytrnsys* models were used particularly for SHIP-06 and SHIP-07 to diagnose deviations between expected and measured performance. For SHIP-07, the simulations helped quantify the effects of changed process boundary conditions and reduced residual heat demand, while for SHIP-06 they were used to investigate restrictions in the collector field and balance of plant. Such analyses help link observed underperformance to specific physical mechanisms rather than relying only on annual yield indicators.

The same modelling approach can support design verification and commissioning by evaluating process integration, storage sizing, control strategies, and transient system behaviour before implementation. Updated with monitoring data, dynamic models can further enable performance verification, fault diagnosis, and operational optimisation throughout system operation. This approach is central to the EU-funded DIGISOLAR project, where system-level digital twins are combined with Fault Detection and Diagnosis (FDD) tool to enable early detection and diagnosis of operational deviations and support proactive maintenance DIGISOLAR (2026).

4. Techno-economic analysis and robustness

4.1 Cost competitiveness of hybrid solar thermal under current Swiss boundary conditions

Without investment support, the hybrid solar–HTHP configurations, sized to an annual solar fraction of approximately 50 %, are economically less competitive than the standalone HTHP at 60 and 90 °C, while the gas-boiler reference remains the least-cost option at 120 and 150 °C. With the modelled Swiss investment support, solar–HTHP systems achieve the lowest LCOH at 60, 90 and 120 °C and remain close to the gas-boiler reference at 150 °C (Fig. 5).

The evaluated configurations represent selected comparison points within a much larger design space. Solar fraction, collector area, storage capacity, process temperature, operating schedule, available industrial heat demand, energy prices, financing conditions and investment support can all influence the resulting LCOH. The results therefore describe the investigated Swiss boundary conditions and should not be interpreted as universal competitiveness thresholds.

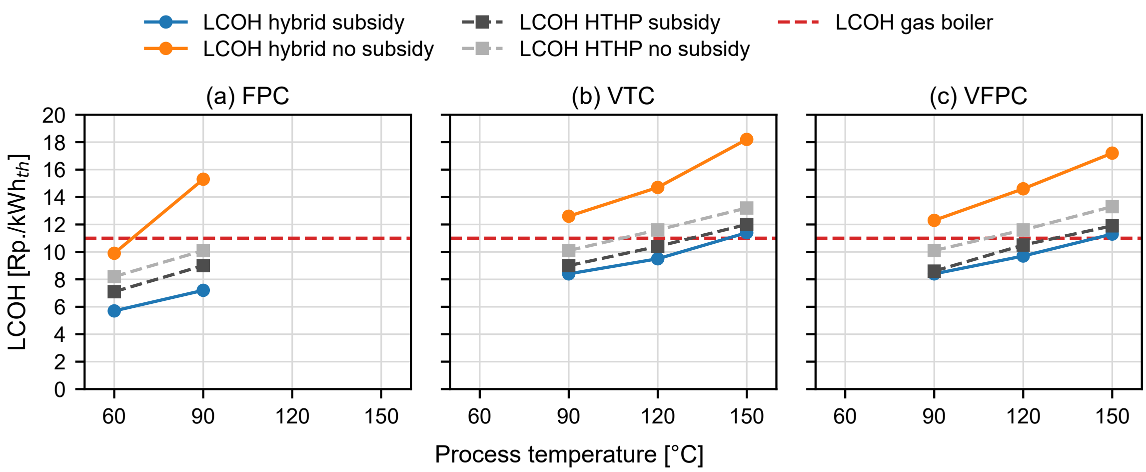


Fig. 5: Hybrid-system LCOH in [Rp/kWh$_{th}$] as a function of process temperature for FPC, VTC and VFPC configurations, shown with and without the modelled investment-support assumptions. The investigated temperature levels were selected according to the operating range and performance characteristics of each collector technology.

4.2 Sensitivity to reduced solar energy yield or demand

The economic performance of the solar–HTHP systems was further evaluated under conditions in which the installed solar asset delivers less useful heat than assumed in the design case. In a first sensitivity, useful solar heat delivery was reduced progressively while collector area, storage volume, HTHP capacity and investment costs remained unchanged. A 50 % reduction in useful solar yield increased the hybrid LCOH by approximately one third. The effect results from distributing largely unchanged investment costs over a smaller amount of useful solar heat. A second sensitivity considered a reduction in the industrial heat demand after system sizing. When the available process demand was reduced to 50 % of its design value, the specific useful solar yield decreased by approximately 26–33 %, depending on collector technology and temperature level, while hybrid LCOH increased by approximately 55–67 %. At the same time, the calculated annual solar fraction increased because the remaining demand was smaller. The same underlying mechanism was observed in SHIP-07, where additional waste-heat recovery reduced the available process heat sink and increased the design solar fraction without any change to the solar system itself.

These sensitivities show that the economic performance of the investigated systems is strongly affected by long-term utilisation of the installed collector field and storage. The results also provide a direct link to the monitoring observations, where reduced availability, process modifications and changing industrial heat demand were identified as important causes of deviations from design performance.

4.3 Electricity demand and life-cycle GHG emissions

Compared with the reference gas boiler, the investigated solar–HTHP hybrid systems with an annual solar fraction of approximately 50 % reduce life-cycle GHG emissions by about 57–78 %. Solar integration also substantially reduces the electricity demand of the HTHP. Across the investigated temperature levels, the approximately 50 % annual solar contribution reduces HTHP electricity consumption by about 46–49 % compared with the corresponding standalone HTHP reference. The absolute electricity savings increase with process temperature because the electricity demand of the standalone HTHP rises with the required temperature lift.

The life-cycle GHG assessment shows the same overall trend. Although the solar collector field and thermal storage add embodied emissions, these additional impacts are outweighed by the reduction in operational electricity consumption over the assumed 20-year evaluation period. All investigated solar–HTHP configurations therefore achieve lower life-cycle GHG emissions than the corresponding standalone HTHP system. The overall technical, economic and environmental results are summarised in Table 4.

Tab. 4: Summary of LCOH, specific solar process heat yield and life-cycle GHG emissions for the investigated heat-supply configurations. Light blue cells indicate the highest yield, the lowest LCOH and GHG intensity at each process-temperature level.

System	T [°C]	Specific solar heat yield [kWh/(m^{2}a)]	LCOH without support [Rp/kWh$_{th}$]	LCOH with support [Rp/kWh$_{th}$]	Life-cycle GHG [g CO_2-eq/kWh$_{th}$]	GHG reduction vs Gas boiler [%]	GHG reduction vs HTHP [%]
Gas boiler	60	–	11.0	11.0	257.2	–	–
HTHP	60	–	8.2	7.1	88.4	66	–
FPC + HTHP	60	477	9.9	5.6	57.5	78	35
Gas boiler	90	–	11.0	11.0	257.2	–	–
HTHP	90	–	10.2	9.0	117.6	54	–
FPC + HTHP	90	238	15.3	7.2	83.0	68	29
VTC + HTHP	90	480	12.6	8.4	72.8	72	38
VFPC + HTHP	90	578	12.3	8.4	70.8	72	40
Gas boiler	120	–	11.0	11.0	257.2	–	–
HTHP	120	–	11.6	10.4	139.4	46	–
VTC + HTHP	120	369	14.8	9.5	88.5	66	37
VFPC + HTHP	120	449	14.7	9.7	86.9	66	38
Gas boiler	150	–	11.0	11.0	257.2	–	–
HTHP	150	–	13.2	12.1	156.3	39	–
VTC + HTHP	150	273	18.3	11.5	110.0	57	30
VFPC + HTHP	150	355	17.2	11.3	103.5	60	34

5. Discussion: implications for robust SHIP deployment

5.1 Long-term performance requires deliberate and coordinated system-level design

The combined monitoring and techno-economic results show that long-term SHIP performance should be evaluated at the system level rather than from the performance of individual components alone. Collector efficiency remains an important design parameter, but the monitored installations demonstrate that annual useful heat delivery is strongly influenced by the reliability of the solar thermal system, its integration into the industrial process, component maintainability, and the continued availability of sufficient heat demand over the installation lifetime. Consequently, technically well-performing collectors do not necessarily translate into high annual system utilisation.

Achieving seamless integration of a solar thermal system into an industrial process does not occur automatically, but requires deliberate coordination throughout the design, implementation, and operation stages. This involves analysing process requirements, identifying suitable integration points, coordinating the solar system with existing equipment and controls, and addressing operational constraints in collaboration with the industrial partner. This is particularly relevant when process conditions change during operation. Process-side modifications can substantially alter the heat sink available to an existing solar installation, as illustrated by SHIP-07, where additional waste-heat recovery increased the return temperature and reduced the available solar heat demand.

5.2 Robust design requires defined responsibilities, maintainability and appropriate technology maturity

The system-level nature of SHIP performance has direct implications for robust deployment. Robust deployment requires clear system-level responsibility across the different stakeholders involved in process integration, together with adequate attention to maintainability. Process-side modifications should therefore trigger a reassessment of solar-system operation, control, and available heat demand, with the integration interface actively managed throughout the plant lifetime. Component accessibility, material compatibility, spare-part availability, and continuity of technical support can strongly influence whether failures lead to short interruptions or prolonged outages. Where reliable commercial heat supply is the primary objective, mature and field-proven components and system concepts should therefore be prioritised.

The experience with thermal-oil systems further highlights that technology choice should include maintenance and repair requirements in addition to CAPEX considerations. For high-temperature applications, specific risks such as leakage, accessibility, and repair strategies should be addressed explicitly during design. Ultimately, technology selection should be evaluated not only on the initial investment cost or thermal performance, but on the cost of the energy delivered over the entire installation lifetime, including maintenance, repair and performance degradation.

5.3 Implications for investment support and economic risk

Under the investigated Swiss boundary conditions, solar–HTHP systems with an annual solar fraction of approximately 50 % become cost-competitive with the modelled investment support at process temperatures up to 120 °C and remain close to the gas-boiler reference at 150 °C. Without support, the high initial investment of the solar system limits competitiveness despite its low operational energy demand.

The 90 °C results illustrate that the supported technology ranking also depends on the structure of the support scheme. The FPC configuration has the lowest specific solar yield and the highest unsupported LCOH, yet becomes the least-cost supported option. The modelled support reduces LCOH by 8.1 Rp/kWh$_{th}$ for FPC, compared with 4.2 and 3.9 Rp/kWh$_{th}$ for VTC and VFPC, respectively. Because the solar contribution scales with installed collector capacity rather than useful heat delivered, configurations requiring larger collector fields receive a higher absolute contribution.

The reported competitiveness also depends on the assumed financing and energy-price conditions. The real discount rate of 1.5 % represents a long-term financing perspective and favours capital-intensive technologies relative to options dominated by operating expenditure; higher industrial return requirements would therefore increase solar–HTHP LCOH more strongly. Likewise, real increases in electricity prices would tend to improve the competitiveness of solar–HTHP systems relative to standalone HTHPs.

A further limitation is the use of ambient air as the heat source for the HTHP. Industrial waste-heat sources may provide higher and more stable source temperatures, potentially improving HTHP efficiency and reducing electricity consumption and LCOH. The comparison may therefore underestimate HTHP performance at sites with favourable waste-heat availability.

Finally, investment support reduces the initial cost burden but does not ensure long-term utilisation of the installed solar asset. The monitoring results show that reduced availability, process changes and declining heat demand can substantially affect realised performance. Support schemes may therefore benefit from considering system quality, process-integrated design, commissioning and long-term performance verification in addition to installed collector capacity.

5.4 Building confidence through monitoring, verification and dynamic simulation

Long-term monitoring combined with dynamic simulation can reduce uncertainty about the origin of performance deviations and provide continuity between design and operation. While monitoring identifies when and where performance gaps occur, system models allow their physical causes and the consequences of changing process conditions to be investigated. Applying dynamic models already in the preliminary design stages can help identify and prevent potential performance limitations before implementation, while their subsequent use with monitoring data supports performance verification, fault diagnosis, and operational optimisation, thereby linking design improvement with long-term operation and increasing confidence in the realised performance of SHIP systems.

6. Conclusions

This study combined long-term monitoring of seven Swiss SHIP installations with dynamic simulation models and a techno-economic assessment of hybrid solar–HTHP systems. Although the monitored portfolio is largely composed of pilot-scale installations and the findings cannot be directly extrapolated to the large-scale deployment of SHIP technology in Switzerland, the results provide several transferable lessons for future deployment.

The monitoring assessment shows that solar energy yield, and consequently the cost-effectiveness and return on investment of SHIP systems, are strongly influenced by reliability and availability of the solar thermal system, which depend on holistic and well-coordinated integration with the industrial process. Component maintainability and the continued availability of sufficient industrial heat demand over the system lifetime are also critical. Across the seven monitored plants, these factors appeared to be more consequential for long-term system performance than potential degradation of individual solar-system components, such as collectors. These findings indicate that robust SHIP deployment requires systems to be planned, designed, and assessed at the level of the complete heat-supply chain, including coordinated design of solar generation, storage, auxiliary heat supply, and the industrial process, together with clearly defined system-level responsibility and adequate maintainability. Technology choices for components such as collectors and heat-transfer fluids (e.g., thermal oil) should account not only for thermal performance and CAPEX, but also for repairability and long-term maintenance requirements and associated OPEX. Ultimately, the relevant metric is the cost of the energy delivered over the system lifetime.

To extend the insights from the monitored pilot-scale installations, a complementary techno-economic analysis was performed to assess the cost-effectiveness and its limits for hybrid solar–HTHP systems under Swiss boundary conditions. Under the investigated conditions, solar–HTHP systems with an annual solar fraction of approximately 50 % become cost-competitive when the modelled investment support is included. Long-term utilisation remains critical: a 50 % reduction in useful solar yield increased hybrid LCOH by approximately one third, while reducing available process demand to 50 % of its design value increased hybrid LCOH by approximately 55–67 %. Solar integration also reduced HTHP electricity consumption by approximately 46–49 %, alleviating grid-demand, and lowered life-cycle GHG emissions compared with standalone HTHPs.

Finally, long-term monitoring combined with dynamic simulation provides a practical framework for performance verification, diagnosis, and operational optimisation. Beyond diagnosing operational deviations, the use of dynamic simulation models from the design and commissioning stages can help identify potential performance limitations before the final implementation and operation, enabling improved system integration, sizing, control strategies, and more robust and reliable design of future solar thermal plants.

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