

Decarbonizing Industrial Heat – A Comparison of Embodied Carbon for PV and Enclosed Parabolic Trough Systems

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Abstract. Heat accounts for more than half the world's energy use. The largest user of heat is industry, and the pressure to decarbonize is high. Tendencies to “electrify everything” are seen everywhere, but electric energy is expensive for medium and high-temperature heat generation Compared to burning natural gas. Moreover, electric grids are on average still characterized by significant greenhouse gas emissions per kilowatt-hour. But how about PV behind-the-meter, being cost-efficient and well-established in generating electricity? Is PV also the solution for the provision of industrial process heat? To answer these questions our clients asked, we investigate the carbon footprint of manufacturing solar fields for heat production, comparing a PV system with Glasspoint's enclosed trough concentrated solar thermal system (CST). We exemplarily analyse the case of an industrial process heat consumer in a sunny region to show the difference in embodied carbon and land use. Our results show that this is not the case: Compared to enclosed parabolic trough collectors, PV is characterized by significantly higher embodied carbon values and needs about three times the land and corresponding structures to generate a given amount of heat. In a following paper, the analysis shall be expanded to full systems including storage and balance of plant.

Keywords: Embodied Carbon, CST, PV, Enclosed Trough

1. Introduction

According to the International Energy Agency (IEA), heat accounts for more than half the world's energy use, whereas electricity only accounts for less than 20 % [1]. The largest user of heat is industry, which alone accounts for about one quarter of the world's energy use. In other words: There is more energy consumption of heat and associated CO₂ emissions in the industrial sector than there is electricity consumed worldwide.

Industry is under increasing pressure to decarbonize. Pressure is coming from investors, regulators, governments, board members and ecosystem partners. Industry has responded by making net zero commitments. Despite the large heat demand, electricity, however, is talked about more [1].

It is clear that a path to net zero carbon requires the decarbonization of industrial process heat. The current mantra of “electrify everything” is misleading for two reasons:

1. The first problem is cost: using grid electricity for electrification is far too expensive. On average, industrial users pay \$0.12 per kWh for electricity. By contrast, burning gas for heat costs less than \$0.018 per kWh for large consumers in most of the US [2] or in Saudi Arabia. Very few industries are able to pay seven times more for their energy to decarbonize, even in Europe with exceptionally high gas prices it would be still three-fold.
2. The second problem is that electrification doesn't reduce emissions: Burning fuel to produce heat in a modern boiler is more than 93% efficient, which means it emits only about 200 grams of CO₂ per kWh. By contrast, most real-world grids have carbon intensities of over 400 grams per kWh. This means that electrifying heat production will double emissions. Even with relatively low greenhouse gas emissions for grids like California and Spain with averages of 261 g CO_{2eq}/kWh and 160 g CO_{2eq}/kWh, respectively [3], even partial electrification does not significantly reduce CO₂ emissions compared to burning gas on site.

Renewable systems need to be built to decarbonize process heat. In sunny regions, solar systems are an obvious option. Two technologies are available: PV and solar thermal. The paper analyses the equivalent specific greenhouse gas (CO_{2eq}) emissions for a kilowatt-hour of medium-temperature heat (345°C) provided by a PV system and an enclosed parabolic trough system, respectively.

Resources to achieve the required reduction of greenhouse emissions are limited in several ways, including money and land. Therefore, when investigating options to provide process heat, meaningful figures of merit to compare are 'cost per unit of heat provided' and 'land area required per unit of heat provided'. The latter is included in this paper.

Before presenting results of detailed calculations, some consideration based on first principles shall be shared: While, as of today, PV is characterized by lower electricity generation cost as compared to Concentrating Solar Power (CSP) plants, the situation is different when heat is the required output. Then, the efficiency of solar-thermal systems is about three times higher as compared to PV: While a PV module converts about 21 % of incoming solar radiation into useful energy at standard testing conditions, and not considering efficiency losses from inverter and electric heaters, a parabolic trough solar-thermal collector is characterized by roughly 65% design point solar efficiency, or even higher. This also applies to average annual efficiencies, and thus to land requirements: A PV system will require three times more land, i.e. three times more collector area has to be built, increasing material requirements and thus embodied carbon.

Despite the fact that PV is much further along the optimisation path than solar thermal due to its much larger installed capacity, the fundamental efficiency difference dominates the results.

2. Methodology

The approach mostly follows a standard Life Cycle Assessment based on ISO 14040.

Goal and system description. The goal is to estimate and compare equivalent greenhouse gas emissions related to industrial heat provision from two solar systems, the first using PV trackers and the second using enclosed parabolic troughs for the conversion of solar radiation into thermal energy, focusing on the solar field and the life-cycle stages A1-A3, cradle to gate, as those stages are considered as the main driver for the emissions.

Scenarios examined. Two scenarios are examined. In the first, PV plus electric heaters are used to cover heat demand, in the second solar thermal systems. For both, a typical industrial heat user in a sunny location is defined in terms of power and energy requirements. PV and

solar thermal systems are then designed to a) achieve the same solar share, defined as percentage of heat provided by the solar system, and b) occupy the same land area. For better comparability, the ground coverage ratio (GCR) of the PV solar field is also chosen to be the same as the densely packed GlassPoint's system.

Life cycle inventories. Inventories of material and energy inputs over the life cycle of both systems are obtained from literature, environmental product declarations (EPDs), proprietary bills of materials, experience of operating similar systems, and industry practices.

Results. Regarding performance, all systems are simulated using the publicly available software tool SAM [2]. 25 years technical life time are assumed. Results are presented as the sum of embodied carbon divided by heat as functional unit, provided over the technical lifetime.

Interpretation. Values of embodied carbon per heat in grams per kilowatt-hour are compared between both systems for both scenarios. In addition, they are compared against 'specific grid emissions' and natural gas.

2.1 Technology Overview

Parabolic trough designs use curved parabolic mirrors to focus the sun's rays onto an absorber tube. In standard designs, the mirrors and receivers are mounted on a torsionally stiff structure to minimize deflection for high optical quality and to withstand high wind forces in special stow positions.

GlassPoint (GP) has introduced an enclosed solar trough system designed for challenging environments to provide heat to industry customers. The parabolic trough collectors are enclosed within a modified agricultural "greenhouse", which protects the collectors from wind, sand and dust and reduces structural weight and non-tracking time due to wind forces. The design allows extremely lightweight collectors. It also leads to smaller row spacing considering that space around industry users is usually rare and relatively expensive. Obviously, to maximize heat generation on a given area of land, also conventional troughs and PV systems can be built more dense, i.e. with increased ground coverage ratios (GCR), defined as module or aperture area divided by ground area.

For PV, single-axis tracker systems with one row of modules in portrait orientation (1P) with bifacial modules are considered, since they now dominate the market.

Storage system are used to provide heat when the sun is not shining. In the case of solar-thermal systems, the most common option is to circulate synthetic oil through the absorber tubes to heat salt via a heat exchanger which is then stored in large tanks. In recent years, directly using liquid salt in combination with fixed absorber tubes is of increasing interest. These designs take advantage of the higher allowable temperature level of salt and the simpler and more efficient system design not requiring an oil/salt heat exchanger [4].

PV electricity is usually stored in batteries. However, if heat is required, the latter can be stored more economically in liquid salt. This option is used here for a fair and simpler comparison. Note that there are also other heat storage concepts for (PV) electricity input proposed or already on the market, e.g. using crushed rock as storage material [5].

Figure 3 shows typical plant layouts for heat generation systems based on PV and solar-thermal collectors. This study focuses on the solar field; storage and balance of plant are not considered. Note: The suitable storage size for a certain scenario can be assumed to be about the same for both technologies analysed.

2.2 Performance, reference data and life cycle inventories

For illustration, Figure 1 shows a comparison of the peak performance of an enclosed trough system and a PV system. Main losses of the trough system come from optical losses including shading, while for PV the main loss results from the conversion of solar irradiation into electricity. Peak values are shown because the PV industry always reports peak values instead of efficiency at a realistic design point or annual average efficiencies, which are more meaningful but also significantly lower.

Independently, for this study all performance calculations are done using SAM [6], considering realistic efficiencies separately evaluated for each hour of the year considering respective operating conditions.

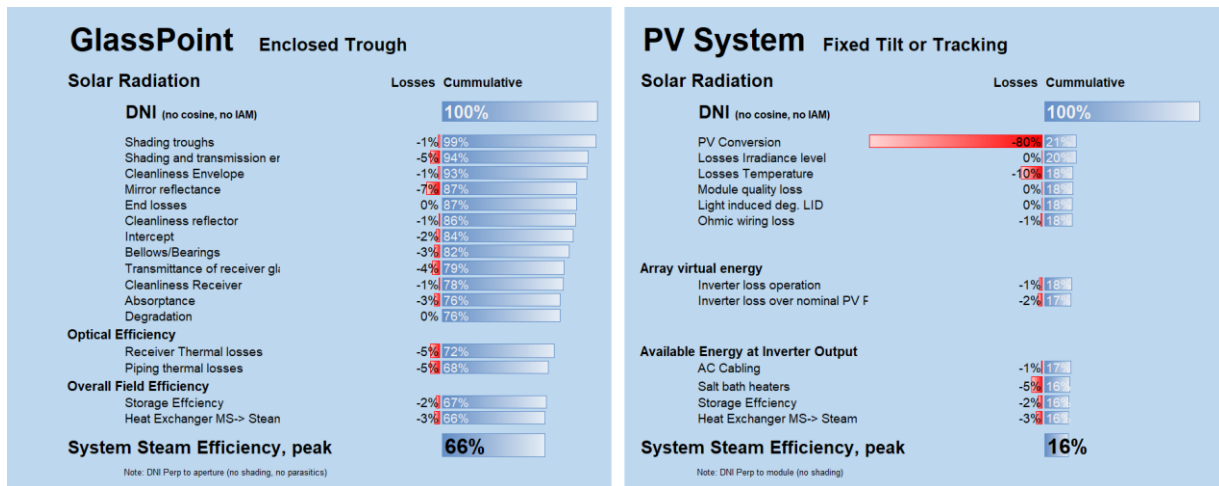


Figure 1. Peak efficiencies of enclosed Trough and PV for heat generation including storage losses

2.2.1 Embodied Carbon

Modules: In [7], Smith et al. provide equivalent CO₂ emissions (CO_{2eq}) for PV modules and trackers for the US. Since most modules are still imported, we use some representative values accordingly after comparing with other EPD reports from module suppliers and accounting for bifacial modules, resulting in a value of embodied carbon for modules of 650 kg/kW_p.

PV tracker: The inventory data for the single-axis tracker assuming post ramming rather than concrete foundations is approximately 19 kg/m² of module area resulting in 130 kg CO_{2eq}/kW_p [7]. We linearly adjusted the value to account for today's slightly more efficient bifacial modules assumed in our study. Aluminium makes up ~1 % of overall mass.

Enclosed Trough: Main materials of the enclosed GP solar field are aluminium (approx. 60 % of mass above foundations), carbon steel, stainless steel, ETFE and glass of the HCEs. The material quantities are based on our internal parts list, and the corresponding specific emission values for A1-A3 assuming manufacturing in the US can be found in the annex.

Specific mass of the GP System, i.e. mass per greenhouse ground area, is about 5 kg/m² for the concentrator and another 5 kg/m² for the film house enclosure. GCR is 0.73.

Note that no recycled materials, meaning a mixture of melted material scrap, were considered for the GP system. Using recycled materials would reduce embodied carbon especially for the aluminium parts. For the PV system [7] and in the module EPDs, the amount of recycled material in the raw material process is not clearly specified.

Table 1. Embodied carbon of materials used for the GlassPoint system

Material	Embodied Carbon [kg CO ₂ eq]	reference unit
Aluminium	8.40	kg
Steel	1.77	kg
Stainless steel	6.8	kg
Glass (for HCE)*	1.4	kg
ETFE film	20.9	kg
PE (Ground Cover)	0.37	square meter at t = 100 µm
Foundation concrete C25/30 incl. reinforcement	0.12	kg

Table 1 shows the embodied carbon values of the materials considered.

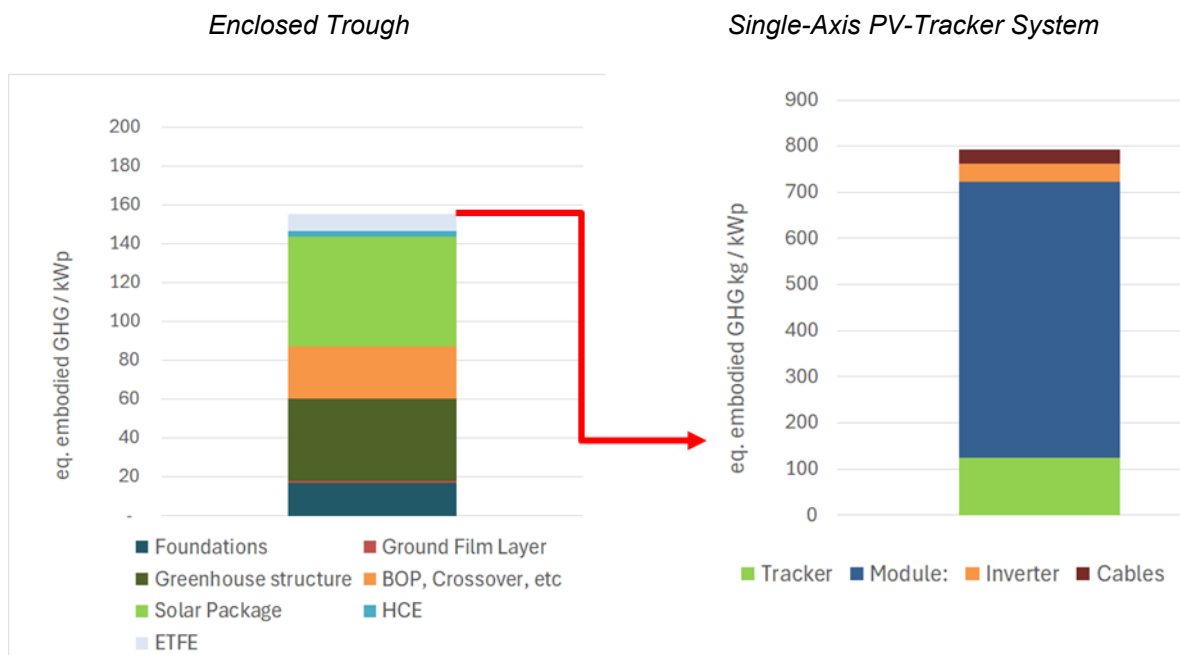
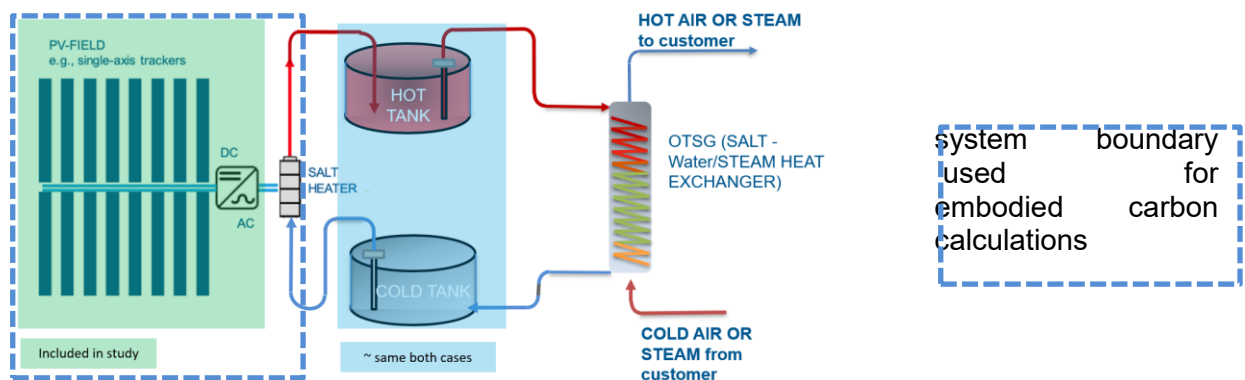


Figure 2. Embodied carbon for enclosed trough and PV tracker.

Figure 2 shows specific embodied carbon values, considered as input for the evaluation. We used typical reference units, which for the enclosed trough is the greenhouse area and for the PV system installed peak capacity.

2.3 System boundaries and analysed cases



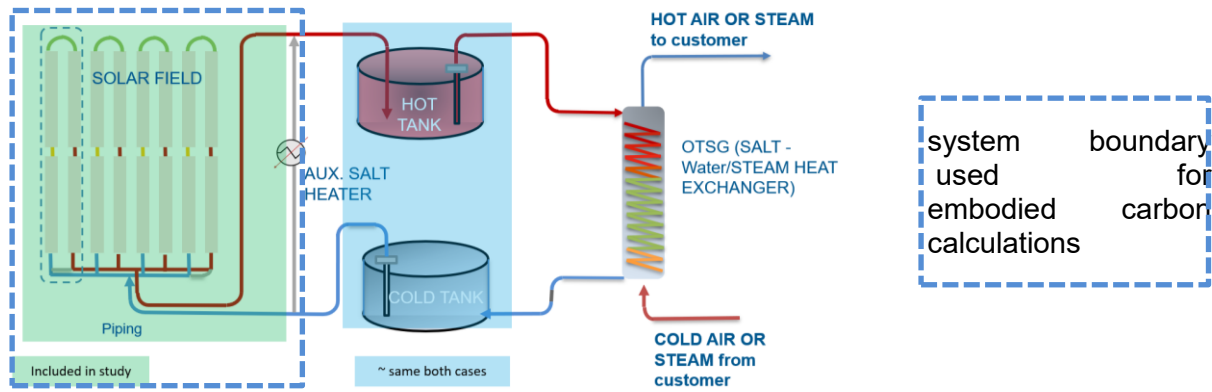


Figure 3. Plant layouts and limits (green) for study

The green background in Figure 3 indicates the limits for this study, where the focus is on the solar field, including the header piping of the trough field and inverters and cables for the PV system. Values for the latter are taken from [4]. Note that mass assumptions for the foundations of the enclosed trough collector are conservative. The storage size optimization target has been to minimize cost, not minimize CO₂ emissions.

A ‘typical user’ is defined as an industry customer with 137 MW_{th} demand 24/7 all year. Systems have been dimensioned to achieve about 67 % solar share. In SAM, insolation data for a sunny location in Southern California, USA, is used with an annual DNI sum of 2853 kWh/m² and GHI of 2190 kWh/m², respectively. Table 2 lists main design and performance parameters used.

The GCR for a dense PV system is selected as 0.6, which has been studied as a reasonable value for several locations before shading effects reduce the energy output more significantly; additionally we analyse a case with the same GCR as the enclosed trough, namely 0.73.

Table 2. Technical and performance parameters

Parameter	Value
Location	Southern California
annual DNI	2853 kWh/(m ² a)
Case a) : solar share	67 %
Demand 24/7, at heat exchanger	137 MWth
Orientation	North-South
Slope PV GP field	0 % 0.5 %
Aperture width GP enclosed trough	7.3 m
Row spacing GP enclosed trough	10 m
GCR PV: standard / dense / same as GlassPoint	0.3 / 0.6 / 0.73
Optical efficiency GP system: including shading, transmission losses, reflection, cleanliness	70.9%
GP total efficiency at design conditions	67.2%
GP field inlet / outlet temperature	225°C / 450°C
Storage size for both systems (information only)	~ 18 full load hours
Storage GHG footprint	excluded; same for both systems
DC/AC ratio PV	1.3
Electric salt heater for PV system	excluded
Technical lifetime	25 years
Bifacial module power at standard test conditions	665 Wp

3. Results

Results are presented in Table 3. Table 3 summarizes results for cases where the same solar share was the design criterion, Table 4 lists the results for a common given land area. Figure 4 puts the results into perspective by comparing them to other options.

The first column in Table 3 shows ground coverage ratio of the respective system. In column 2, resulting installation size is given in the respective reference unit – for the GlassPoint System the greenhouse size in square meters, for the PV system installed peak capacity. Column three contains specific embodied carbon for the reference unit for product stages A1-A3. This allows to calculate the total embodied carbon for the manufacturing of the solar field shown in the next column to the right. Based on a technical lifetime of 25 year and the corresponding energy production calculated with SAM, specific equivalent CO₂ emissions for the functional unit of 1 kWh of heat are shown in the column on the very right.

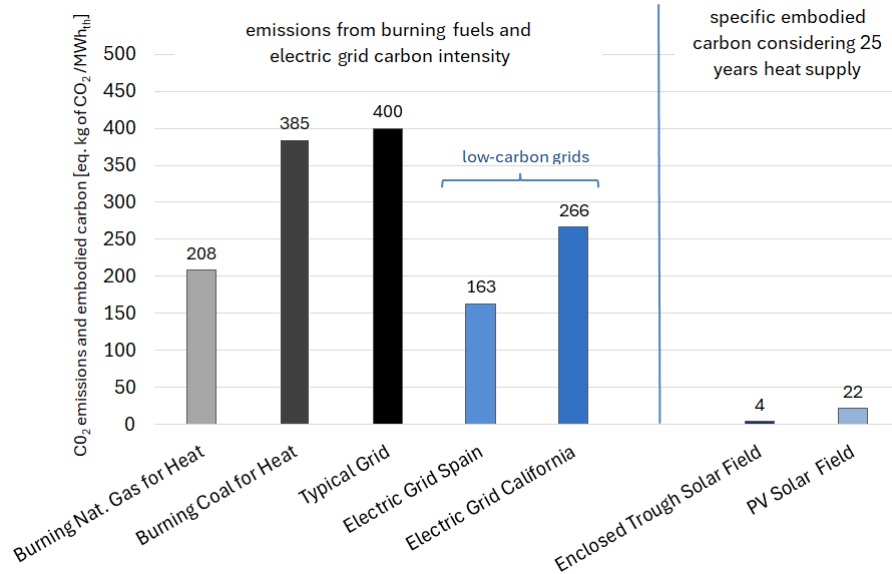


Figure 3. CO₂ emissions and embodied carbon for heat production (incl. 85% efficiency for gas and coal burners and 98% for electric heaters) [3,8]

The results show lower specific embodied carbon per heat supplied for the enclosed trough system compared to the PV single-axis tracker field plus heater by a factor of around 5.

Table 3. Results for a common solar share of 67 %, corresponding to 804 GWh/a

	land use [10 ⁶ m ²]*	Installation size	specific embodied carbon	Total embodied carbon [t]	CO _{2eq} [g/kWh]**
GP System GCR=0.73	1.4	1.2*10 ⁶ m ²	155 kg CO _{2eq} /kWp*** (75 kg CO _{2eq} /m ²)	88,522	4.4
PV typical GCR 0.35	7.9	575.4 MWp	762 kg CO _{2eq} /kWp	438,182	21.8
PV dense GCR 0.6	4.7	588.4 MWp	762 kg CO _{2eq} /kWp	448,129	22.3
PV very dense GCR 0.73	4.0	605.8 MWp	762 kg CO _{2eq} /kWp	461,371	23.0

* including 10% for streets, BOP, etc.

** calculated over 25 years without degradation

*** based on a design DNI of 1000 W/m² as used for PV

PV land requirements are higher by a factor of 6 to 3 for GCRs of 0.35 to 0.73. A GCR of about 0.6 for a PV tracker field can still be considered economically viable, taking into account increased shading losses and assuming that land around industrial heat consumers is relatively expensive.

Table 4. Results for a common gross land use of 1.346 million square meters

	Solar Share [%]	Energy at heat exchanger [GW _{th} /a]
GlassPoint System	67	804
PV typical GCR 0.35	11.4	137
PV more dense GCR 0.6	19.1	229
PV GCR = GP of 0.73	22.6	272

For reference, we also show the resulting solar share for a given land area in Table 4. When using PV trackers with their lower solar-to-heat efficiency, the same land area used results in a correspondingly lower solar share, which ultimately limits the overall emission savings achievable with a PV system for medium and high temperature heat.

4. Summary and Conclusion

For both cases, PV and enclosed trough, CO₂ savings as compared to burning natural gas or coal are significant (Figure 4), while using grid electricity for heat production will not help to reduce greenhouse gas emissions at today's grid emission levels.

In total, embodied carbon is about five times higher for a PV tracker field as compared to an enclosed trough collector system. This is a consequence of the large difference in solar-to-heat efficiency of about a factor of three. Thus, a PV system must be three times larger. In addition, there is higher material input in PV systems.

Logically, a comparison based on the same available land area shows that the energy yield is lower by a factor of three (assuming the same GCR), which limits the solar share and therefore the maximum possible greenhouse gas emission savings of a plant. To meet industrial user and climate protection targets, the decarbonization rate of installations should be maximized, clearly favouring solar-thermal systems like the enclosed trough analysed.

5. Outlook

Further studies are required to obtain more precise and optimized values of the two systems, including further details and optimization, extending the scope to storage system and balance of plant, and an analysis of construction, usage and end of life stages. In general terms, however, we do not expect the relative ranking and ratios to fundamentally change, because thermal storage and balance of plant will be very similar for both systems analysed.

Author contributions

Markus Balz: Conceptualization (lead); Methodology (support). **Verena Goecke:** Methodology (lead); Formal Analysis (lead); Writing (lead). **Gerhard Weinrebe:** Methodology (support); Formal Analysis (support); Writing – review & editing (lead).

Competing interests

The authors declare the following competing interests: GlassPoint owns enclosed trough technology for process heat applications, and PV is often considered a competitor. Nevertheless, GlassPoint is not committed to closed trough technology, but chooses technology on a project by project basis, seeking the techno-economic optimum for our clients. PV is considered in our systems wherever reasonable, typically when electricity is required.

Data availability statement

Wherever place allowed, data used is provided directly in the paper. Other data used like weather data and additional SAM input data can be made available upon reasonable request. Detailed mass data of GlassPoint systems will be kept confidential.

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