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Techno-economic comparative analysis of solar thermal collectors and high-temperature heat pumps with PV for industrial steam generation

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Abstract

As industrial heat production is responsible for about 20% of total GHG emissions in Europe, shifting to sustainable sources is inevitable in achieving Paris Agreement goals. This paper focuses on two decarbonisation technologies for industrial process heat supply for multiple locations a) Electricity-driven high-temperature heat pumps powered with photovoltaic (HTHP+PV), as an advanced efficient technology in generating steam, and b) parabolic trough collectors (PTC), which produces heat economically with minimal carbon footprint. The aim of this paper is to evaluate the levelized cost of heat (LCOH) of these technologies to fulfil a comparative techno-economic analysis. A maximum PTC collector's solar fraction limit (SFlimit) is defined to indicate when the LCOH for these two technologies is equal. The evaluation is carried out through the annual energy yield using TRNSYS and MATLAB. The result shows that the design of a PTC system with optimal SF can reach cost parity with hybrid system of HTHP and PV for the locations with medium to high direct normal irradiation locations.

Keywords:
High-Temperature Heat Pump; Photovoltaic; Parabolic Trough Collector; Solar Fraction; Techno-Economic Analysis

1. Introduction

"Heat is half" of the global primary energy consumption [1]. The generation of heat from various fuel sources results in nearly 40% of the global CO2 emissions. Decarbonizing the heating supply is the "elephant in the room" and needs significant attention from policymakers to promote the right technological solution to facilitate the rapid replacement of gas, coal, and other fossil fuels.

Heat is consumed in buildings for space heating, domestic hot water, and industries to generate steam or hot water. The major focus regarding technical solutions for clean heating is often on electrification using electrical heaters or heat pumps (HPs). Residential heating demand can be decarbonized using commercial HPs, and their significance is further emphasized in Repower EU, which aims to deploy 60 million HPs by 2030, a projected 4-fold increase from current numbers [2].

It is important to note that industrial process heating demand constitutes 66 % of the EU's overall heating demand [3]. In addition, the concepts of positive energy district (PED) and climate-neutral city are promising nowadays, but they have not yet included industrial heating demand within their boundaries. With the ongoing challenges in gas supply, natural gas prices have increased exponentially in the past few years, thus creating an energy-tense situation in the EU [4]. This implies that a less price-volatile and reliable supply of fuels for industrial process heat should be prioritized. The process heat required in most industries is in the medium temperature range (i.e., 80 to 250 °C). Several technologies in the market can achieve this temperature with low carbon emissions, such as solar thermal (ST) collectors, high-temperature heat pumps (HTHP), and boilers utilizing green fuels such as waste biomass or biogas, or renewable electricity.

Industries typically use fossil fuel boilers to generate steam, which is used as a heat transfer fluid to carry out several processes. Retrofitting any new technology in an existing boiler system requires a detailed understanding of system boundary conditions. Economic feasibility is a crucial decisive criterion for industries to evaluate any technology. From market experience, it is realized that large multinationals can facilitate the capital expenditure (CAPEX) for an efficiency improvement process (such as the implementation of ST, HTHP) only if the payback is less than 5 years.

An indicative pre-feasibility assessment using economic key performance indicators (KPIs) can facilitate industries toward quick decision-making for a go/no-go decision concerning a detailed evaluation of any technology. Therefore, this paper is themed around doing a comparative techno-economic analysis for heat generation using typical boundary conditions encountered in industries. The focus is on two technologies to generate steam, i.e. (a) steam-generating HTHPs and (b) Parabolic trough collector (PTC), which is a type of concentrating ST collector. The sections provide a literature review and the current development status of using these technologies for industrial applications.

1.1. Hybridization of solar thermal with heat pumps

Terrestrial irradiation has daily and seasonal variations. For a typical solar PV system, the grid acts as a large battery that balances the production and demand with minimal waste of electricity. However, the solar heating systems are often retrofitted with individual/stand-alone boilers to continue the operation for non-sunny hours.

As most industries have constant heating demand throughout the day (and year). ST System design with a low SF allows the solar production to always be less than the user's heat demand, thus increasing the system's utilization. Therefore, SHIP systems are typically designed with low solar fraction and backup systems. However, if an ST is designed without thermal storage, the fraction of the overall heat demand met with solar collectors be limited.

To achieve high solar fraction, steam storage is often a limiting component restricting the cost feasibility of the system. Due to its very low density, steam storage is not economical. It is usually stored as sensible heat in solid media or liquid using oil or pressurized hot water. It is observed that for a given constant load profile, the economic feasibility of the solar thermal installation decreases after a threshold solar fraction due to the need for high thermal storage capacity. As the specific heat cost of a pressurized thermal storage is higher than that of a solar thermal collector, thus large tank volumes in the system result in a relatively high cost of heating. This situation puts a financial limit on the maximum solar fraction achievable.

As industries are looking for nearly 100% renewable heating systems, solar thermal has the opportunity to collaborate with other technological alternatives to compensate for the solar irradiation lack or fluctuation during the night and day to reach high renewable heating fractions using a concept involving several technologies, such as thermal storage and a heat pump driven by green electricity. The existing boiler use can be minimised if the system components are sized optimally.

Previous studies have shown that hybridizing the heat pump with solar thermal collector results in the lowest levelized cost of heating (LCOH) compared when these technologies are used individually [5]. Therefore, more research is needed to understand the techno-economic boundaries of solar thermal and HTHP in stand-alone and hybrid modes. This paper takes a step by looking into a comparative analysis of these two technologies. The current study is a base to investigate the combined hybrid systems in future applications.

2. Objectives

The central objective of this paper is a comparative analysis of both HTHP+PV and PTC systems for steam applications using industrial boundary conditions. Previous studies have performed a general feasibility analysis for solar thermal technologies or heat pumps. However, only a few have investigated comparing these technologies on with techno-economic boundaries. The most relevant work to the current paper is by Meyers et al. (2018), where the authors have developed a techno-economic comparison method using maximum turn-key solar investment as an indicator. This method can be used as a criterion to quickly compare and select between solar thermal and heat pumps based on boundary conditions. However, the study did not consider the effect of SF on LCOH. This variation is critical to consider while comparing technologies, especially with high-temperature solar thermal, due to the lack of steam storage technologies. The LCOH of the ST system increases exponentially after a threshold SF due to the diminishing added value of heat storage. Therefore, when comparing other technologies with ST, the SF is a critical criterion to define and is not considered in previous studies. Meanwhile, the LCOH of hybrid system of HTHP+PV would decrease in most cases while it is also dependant on many other factors such as: GHI, electricity prices and CAPEX. The current paper has overcome the limitations by using comprehensive variables as a comparison basis for both HTHP+PV and ST.

3. Method

This study aims to assess the energy and economic performances of Industrial PTC and HTHP+PV in four European climates. Figure 1 shows the flow chart of the method used for analysis. First, the evaluation is carried out through annual energy simulations performed with dynamic simulation software. After this, a systematic approach is followed to provide the reader with the information needed to understand the results. The analysis is carried out for two load profiles with constant peak demand to capture a broad range of industrial load conditions. However, the results obtained are parametrised to direct normal irradiation (DNI) and global horizontal irradiation (GHI) which can be used to assess the performance for any given location.

In Step 1, simulations for HTHP are conducted using TRNSYS for given load profiles to calculate the COP and thermal output [6]. The outputs are based on a performance map obtained from an HTHP supplier for a broad range of operating conditions. For PV part the annual yield have been simulated based on the results from renewable ninja while in calculating LCOH of hybrid HTHP+PV, the balance of PV yield and power consumption of HP has been considered. It is also assumed that all excess production over consumption been wasted.

In Step 2, dynamic simulations for PTC collectors are done. The product chosen for this study is restricted to a PTC manufactured by a Swedish company named Absolicon solar collector AB [7]. The product is designed for industrial applications and fits this study well. Simulation of the PTC system is done in two sub-steps. The component performance is analysed using TRNSED, and the system performance is simulated using the developed model in OCTAVE. Storage sizing optimization obtains each location's SF vs. LCOH curve. The LCOH calculations for ST and HTHP+PV are done using Excel spreadsheet.

Finally, in Step 3, based on the results obtained, the LCOH of both technologies is compared to provide boundary conditions to identify the strong economic hold of each technology. An indicator SFlimit is introduced to distinguish the economic advantage and to generalize the results.

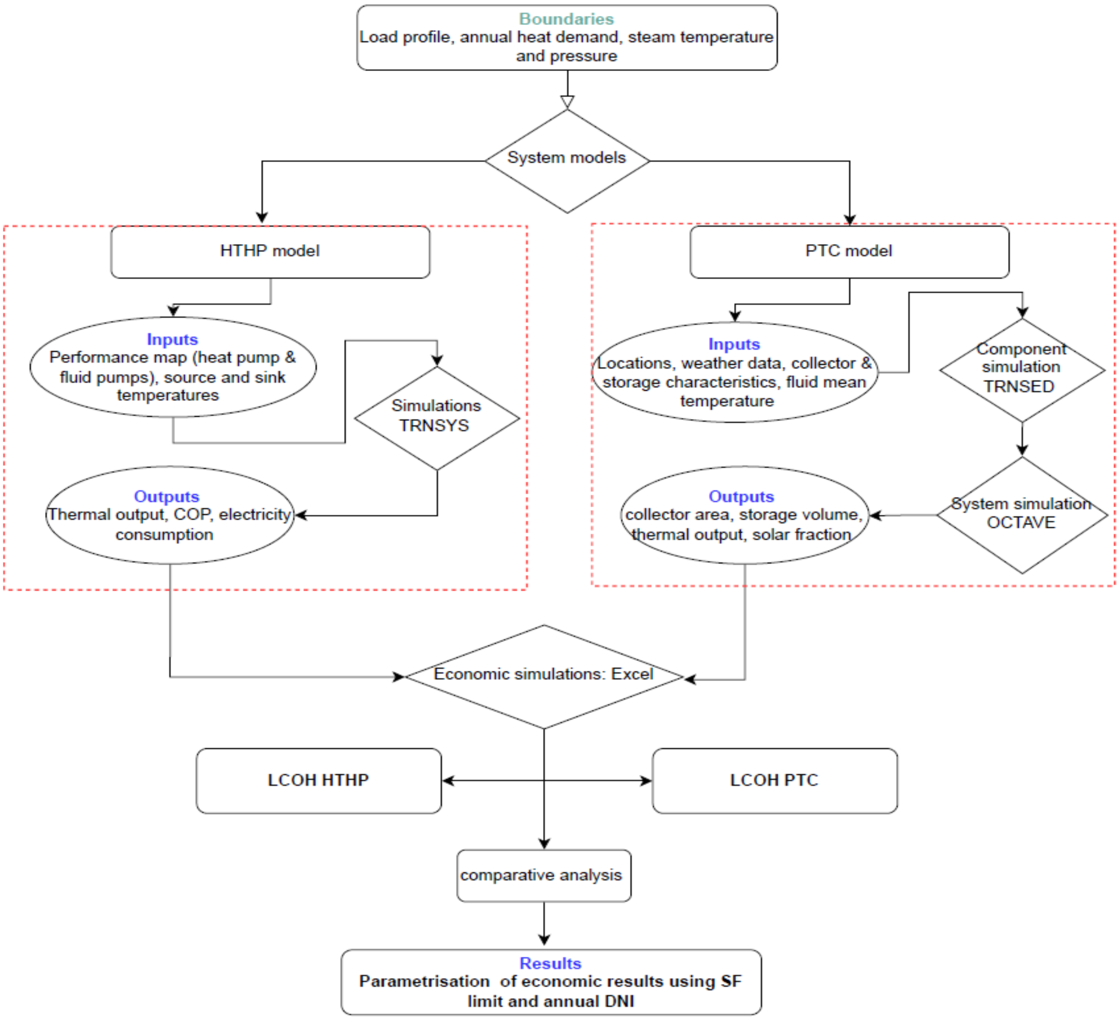


Figure 1 Flow chart for the method used for this study

4. System boundaries and Model

4.1. Load profiles and heating demand

The heat demand in the industries depends on the process characteristics and varies, which is difficult to capture by one study. However, the selection of load profiles to represent a significant share of industries is the focus of this paper. Two different load demand profiles are considered for the analysis. The peak heat demand is fixed at 500 kWth (steam flow of 0.8 tonnes per hour), typical of many process industries. As ST and HTHP are subjected to the same load constraints, the comparative results are not affected by the selection of peak load value. The steam demand is assumed at a constant temperature of 140 °C (saturation pressure 3.7 bara). The steam temperature range is commonly used in many food processing industries and fits well with temperature constraints for both medium-scale PTC and HTHP products. The two chosen load profiles are explained as follows:

- **Continuous demand**: Uniform demand throughout the year with 8760 annual operational hours, which results in annual heat demand of 4380 MWh/year. Such load profiles are prevalent in many large production factories, such as the pharmaceutical sector.
- **Daytime demand**: Uniform demand only during the day (10 hours per day starting 8:00 to 18:00 for whole week), resulting in an annual heat load of 1825 GWh/year. This load profile is typical for a small/medium production facility.

Weekly variation for considered load profiles is shown in Figure 2 . The presented week pattern is repeated for a whole year to obtain the annual heat demand.

Figure 2 Weekly variation of different load profiles considered for the analysis

4.2. HTHP integration

After industrial boundary conditions, the next step is to design an HTHP system and evaluate the techno-economic conditions. HTHP can be integrated at several points, for example, central steam generation for the whole plant or a specific process. This integration type will decide the inlet temperature of the fluid stream at the sink of HTHP to further convert into steam. Steam generated by the HTHP will be fed to the steam line. Therefore, the sink inlet fluid can be tapped feed-water or de-aerator of the existing boiler system. The feed-water pump used for the boiler can be utilized to obtain the required flow in the HTHP. If integrated with the boiler steam header, HTHP must generate steam at slight overpressure to ensure that steam from HTHP is preferred over boiler steam.

The HTHP is designed for peak heating capacity in this study. Therefore, it is considered the sole heat source for the energy system without any backup boiler. On the source side, the available wastewater stream is considered at the inlet, which transfers heat to the HP refrigerant and exits at a lower temperature depending on the temperature glide. On the sink side, the feed water stream enters the inlet and receives heat from HP to convert to steam, which is fed to the process line. A commercial HTHP (Kobelco model SGH 165) capable of generating steam at a maximum temperature of 165 °C is used to meet the steam requirement [8].

4.3. HTHP model

The HTHP used for this study can produce steam up to maximum temperature and pressure of 165 °C and 0.8 MPa-gauge, respectively. The applied refrigerant in this HP is a mixture of R134a and R245fa. The heat pump utilizes a semi-hermetic inverter twin screw compressor. The rated COP of the modelled HTHP is 2.5, specified at source and sink temperatures of 70 °C and 165 °C, respectively. A performance map based on data from the commercial HTHP [8] is used to calculate the electricity consumption. The performance map consists of the COP of the HTHP for various temperature lifts. The temperature lift represents the difference between the fluid temperature at the heat source inlet and the heat sink outlet. The heat pump has a variable speed capacity to operate at the part load conditions. The electrical consumption derived from the annual simulations is then used to calculate the LCOH.

The design temperatures for the HP model are shown in Figure 3. The source for the HP evaporator is considered a wastewater stream with a fixed temperature of 40 °C, available throughout the year. A temperature glide of 6 K is considered on the evaporator. The resulting temperature lift of the HTHP is 100 °C, corresponding to steam temperature of 140 °C. The feed-water temperature entering the HTHP arrives at 110 °C, resulting in a 30 K temperature difference on the heat sink side. The flow rate in the source and sink are varied to obtain the designed temperature glide and thermal capacity, respectively.

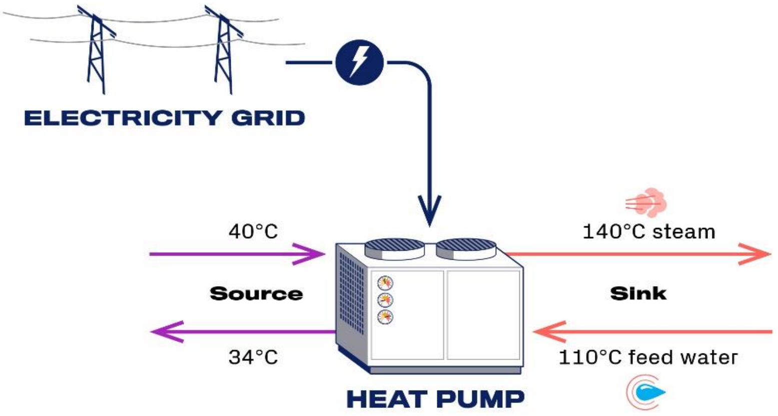


Figure 3 Various fluid stream temperatures of the HTHP system considered for this study

Other than the electricity consumption of the HTHP, there are water pumps on the source and sink side, which also consume electricity and is important in LCOH calculations. The pumps are sized to provide the desired flow rate in the network. Pressure drop calculations are done to estimate the total head in the network using Serghide's method [9]. The pump is designed for the total pressure drop of the network is 1 bar, assuming 20% safety factor while accounting for bends and joints, etc. Based on the flow and pressure drop, a commercial pump is selected from the manufacturer catalogue. The products are used to derive the pump curves (flow vs. head and efficiency vs. head) to simulate the working points of a given scenario and thus used for electricity consumption to calculate LCOH.

4.4. Economic inputs for HTHP

For the heat pump LCOH, it is necessary to include various costs. The analysis is done for three different capital expenditures (CAPEX) of 500, 1'000, and 1'500 Euro/kWth values derived from data based on implemented HTHP case studies [10]. The operational costs for HTHP consider the electricity to run the heat pump compressor and fluid pumps. The O&M costs for HTHP are usually higher than those for boilers and are set to 5% of the CAPEX value with the system degradation rate equal to 0.5%. The LCOH of both HTHP and PTC systems are compared for a time horizon of 15 years. The period is chosen to reflect the suitable timeline various multinational companies consider for energy-related investments. Three different electricity prices are chosen for analysis considering the range of industrial electricity tariffs in the EU.

For sensitivity analysis of LCOH, a total of 6 cases are analysed, accounting for three different cases with HP CAPEX and electricity prices for both load profiles (i.e., CAPEX, electricity price, and load profiles). The values of these variables are shown in

Table *1*.

Table 1 Different scenarios for the variables used in HTHP LCOH calculations

Description	Abbreviation	scenario 1	scenario 2	scenario 3
Load Profile [h/year]	LPR	8’760	8’760	8’760
HP CAPEX [Euro/kW$_{th}$]	CAP	500	1’000	1’500
Electricity Price [Euro/MWh]	ELP	70	100	150
Description	Abbreviation	scenario 4	scenario 5	scenario 6
Load Profile [h/year]	LPR	3’650	3’650	3’650
HP CAPEX [Euro/kW$_{th}$]	CAP	500	1’000	1’500
Electricity Price [Euro/MWh]	ELP	70	100	150

4.5. ST simulations-*PTC product description*

The ST product considered for analysis is a PTC collector manufactured by the Swedish company Absolicon solar AB. The product T160 is a concentrating parabolic trough collector that focuses direct solar irradiance onto an absorber tube that runs along the focal line of the concentrator and contains a working fluid that gets heated when solar radiation is concentrated on it. The collector works on single-axis tracking using the astronomical watch, which tracks the solar collectors, so they always face the sun. The product can generate steam and hot water from 60 °C to 160 °C, and is therefore suitable for many industrial sectors (e.g., dairy, brewery, chemical, etc.). The collector can be categorized as a small PTC type and is certified by solar Keymark. The optical efficiency of the collector is 76.6 % based on aperture area. The key technical specifications of the collector are shown in Table 2.

The main components of a collector consist of:

- Reflector, which reflects the incoming radiation onto the receiver.
- The receiver tube absorbs reflected radiation and converts it into heat; this heat is then dissipated by the agent fluid that is pumped through the receiver tube
- The protective glass avoids heat losses and protects the collector from dust, snow etc.

Table 2 Key technical specifications of T160 PTC collector

Item	*Description*
Collector type	Glass-covered PTC with one-axis tracking
Recommended heat transfer fluid	Water. Propylene Glycol (max 40%)
Volume of heat transfer fluid in receiver tube[Litre]	2.2
Operational temperature [°C]	60 to 160
Stagnation temperature [°C]	460
Maximum operating pressure[bar]	16
Receiver	Stainless steel, optically selective coating
Glass	4mm hardened glass, anti-reflective coating
Reflector	Polymer-embedded silver on steel sheet
Weight [kg]	148

4.6. Modelling PTC system

A dynamic simulation of the collector performance was carried out for a statistically normal year based on climate data from Meteonorm using time step of 15 minutes. Simulations are based on the Solar Keymark ISO 9806 collector parameters of the Absolicon T160.

The simulation approach for PTC is based on 2 steps. In the first step, the collector is modelled without interacting with the heating load. This can be considered as if the collector operates under infinite load, and thus all the heat generated by the collector is fully utilized. The simulations are done using TRNSED, which is an add-on to TRNSYS. The collector performance parameters based on the aperture area used in the TRNSED are shown in Table 3.

Table 3 Input Performance characteristics of T160 collector used for model [11]

Parameter	Value
Optical efficiency [%]	76.6
a_1 [W/m^{2}K]	0.368
a_2 [W/m^{2}K^2]	0.00322
K_d [-]	0.120
β, tilt [°]	Single-axis tracking E-W
$\boldsymbol{\gamma}$, azimuth [°]*	0

The output of the component analysis results in an hourly profile of collector output with other variables. The output is used in the system model for defined industrial boundaries. System simulations are done using the OCTAVE tool, on an hourly time-step basis for a year. The tool simulates the collector interaction with the load. Several iterations are performed to obtain the collector area and storage volume for a range of solar fractions for specific loss factors. The loss factor represents the maximum quantity of heat allowed to spill from the collector at any time step and is fixed at 20 % of the collector production. The loss factor is chosen based on previous experience. Based on the simulations, a curve representing the collector area and storage volume needed for a range of solar fractions is obtained. The range of SF is restricted from 1 % to 91 %. It is possible to run simulations for SF approaching 100 %. However, this is avoided so to reduce the computational effort.

Moreover, it is uncommon to design a solar thermal system for such high SF due to the excessive tank volume required, which negates the installation's economic gains. The power consumption of the PTC system due to tracking and fluid pumps is also derived from simulation results. The collector area and tank volumes required for various solar fractions are then used to calculate the LCOH of the system, as explained in the next section.

4.7. Economic boundaries & geographical inputs

The data for PTC economic analysis includes the capital and O&M cost. The economic input values are based on data collected from the PTC manufacturer as shown in Table 4.

Table 4 Assumptions regarded in PTC T160 simulations

Item	Symbol	Value	Unit	Remarks
Capital expenditure	CAPEX	350	Euro/m^2	Represents the installed cost
O&M cost	$EX_{O\&M}$	0.1	%	of CAPEX
Solar collector lifetime		25	Years	
LCOH evaluation period		15	Years	
System degradation rate	SD	0.1	%	

5. Key performance indicators

Levelized cost of heating: LCOH is a comparative indicator representing the cost of heating from any system considering capital, operation, and maintenance costs during the system's lifetime [12]. If the LCOH of a new solution is lower than the LCOH of the existing system, it implies that the new system implementation will have positive returns. It is a suitable performance indicator to compare various heat generation technologies. The LCOH is calculated based on Equation 1.

$$\mathrm{LCOH} = \frac{\mathrm{CAPEX} + \mathrm{Price_{el}} \cdot \sum_{n=1}^{N} \left(\frac{W_{\mathrm{Sys}}}{(1+\mathrm{DR})^{n}}\right) + \sum_{n=1}^{N} \left(\frac{\mathrm{EX_{O\&M}}}{(1+\mathrm{DR})^{n}}\right)}{\sum_{n=1}^{N} \left(\frac{Q_{\mathrm{Yield}}(1-\mathrm{SD})^{n}}{(1+\mathrm{DR})^{n}}\right)} \tag{1}$$

Where:
$CAPEX$ = Capital cost of technology used (including installation and commissioning) (€]
W_{Sys}= Annual power consumption of technologies (Electricity for fluid pumps, heat pump, and collector tracking system) (kWh)
$EX_{O\&M} =$ operation and maintenance cost per year (€/year]
$Price_{el} =$ Current unit price of grid electricity (€/MWh)
DR=Discount rate (%)

SD=degradation rate (%] of each technology
N= Project lifetime (years)
Q_{Yield} =Heat yield of the system (kWh/year)

SF_{limit}: To compare the cost of heating between HTHP+PV and ST based on location-specific characteristics such as annual DNI, a new comparative indicator SF_{limit} is defined for the analysis. The SF_{limit} refers to the point on the SF-LCOH curve of a PTC when the LCOH of HTHP for the analyzed condition becomes equal to the LCOH of ST. Therefore, if a PTC system is designed for an SF which exceeds the SF_{limit}, then the LCOH of PTC at the designed SF will be higher than HTHP. In other words, below the SF limit value, the LCOH of the ST system will always remain below the HTHP+PV LCOH. Therefore, a higher value of SF_{limit} would represent better cost feasibility and favorable conditions for PTC installation.

6. Results

6.1. HTHP simulation results

Table 5 shows the results for LCOH calculations for HTHP for 6 simulated scenarios representing load profiles, investment cost, and electricity price variation. For any specific load profile, the CAP1-ELP1 represents the LCOH of HTHP assuming CAPEX 1 (500 €/kWth), and Electricity prices 1 (70 €/MW), as shown previously in

Table *1*.

The results show that the LCOH of HTHP varies from 45-130 €/MWh for the simulated scenarios. The minimum LCOH (45 €/MWh) is obtained for the lowest CAPEX and ELP values in LPR1, when the HTHP is utilised throughout the year. For the same CAP and ELP combination, LCOH increases moving from LPR1 to LPR2 due to decreasing operational hours.

Table 5 HTHP LCOH [€/MWh] for simulated scenarios

Case	HP CAPEX EUR/kW	Electricity price EUR/MW	LCOH of HTHP (Euros/MWh)	
			Load profile 1 LPR.1 8'760 h/a	Load profile 2 LPR.2 3'650 h/a
CAP.1-ELP.1	500	70	45	58
CAP.2-ELP.2	1'000	100	66	89
CAP.3-ELP.3	1'500	150	98	130

6.2. PTC simulation results

The results from PTC simulations suggest that LCOH has a higher variation than HTHP. The reason can be attributed to a wide range of solar irradiation variations across simulated European locations. Furthermore, the LCOH also varies with solar fraction for any specific location.

The range of LCOH obtained from PTC varies is huge depending on the solar fraction. The minimum LCOH obtained is obtained for high DNI regions and at a lower solar fraction. A decreasing trend of LCOH with increasing DNI is due to high collector output. Furthermore, for the same DNI, the LCOH increases with an increase in solar fraction due to lower utilization of heat.

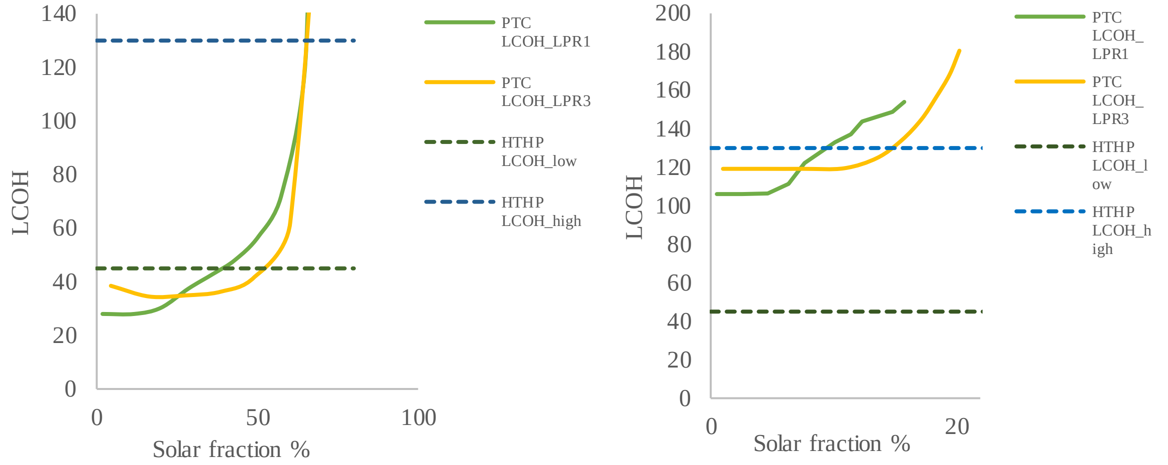
It is also important to consider that LCOH depends not only on the absolute annual DNI value but also on the temporal variation. The high temporal variation makes it difficult to achieve large SF due to the large tank volume needed, thus increasing the LCOH.

Then while comparing the LCOH of PTC or any ST product with other technologies, it is important to specify the SF at which the comparison is made.

The simulation results are used to generate SF-LCOH curve for a location, the LCOH will have a minimum constant value up to a certain SF, till all the collector heat is utilized by the system resulting in no excess heat and no storage tank. However, after a threshold solar fraction, the thermal production of the collector exceeds the load demand, bringing the need for thermal storage. The introduction of thermal storage adds additional cost to the system, increasing the LCOH. After this point on the curve, the LCOH increases exponentially as the thermal storage size required is very high with an increase in SF. Increasing collector areas/tank volumes would diminish the returns for utilized heat, increasing the LCOH. This curve is obtained for all the simulated locations and for two different load profiles. It is then compared with HTHP's LCOH to obtain the corresponding SF limit.

Figure 4[a] illustrates the LCOH comparison for both technologies for the Spain-Seville location. The curves shows the variation of PTC LCOH with SF for two different load profiles. For sake of comparison, the two horizontal lines in the graphs represent the minimum and maximum LCOH of HTHP for all simulated cases. Due to the high DNI in Spain, the minimum LCOH of PTC is always lower than HTHP for all simulated cases. It has been shown that for such a location for LPR 1, even with low CAPEX and OPEX of HTHP (bottom horizontal line), the SFlimit is at 37 %. SFlimit increases up to 65 % if the highest value of CAPEX and OPEX for HTHP are considered (top horizontal line).

The minimum LCOH of HTHP in LPR2 is higher than in LPR1. The reason is a lower number of operational hours while having the same CAPEX of HTHP, which results in high LCOH.



[a] [b]

Figure 4 LCOH comparison for HTHP (horizontal lines) and PTC (capex 350 €/m2) for Spain-Seville [a] (DNI: 1848 [kWh/(m2·year]) & Czech- Prague[b] (DNI: 708 [kWh/(m2·year)])

Comparative results are shown for a low DNI location (Czech-Prague) in Figure 4[b]. As can be seen, the PTC LCOH for Prague in LPR.1 are even higher than the worst case of HTHP LCOH (CAP3-ELP3). This implies that for such a case and under the analysed boundaries, HTHP would be more cost-effective option for heat generation than PTC. However, there would be a change by considering LPR.2, where PTC has lower LCOH up to SF of 15 % compared to CAP3-ELP3 scenarios. The SFlimit for this case is at 15.6 %.

6.3. Comparative analysis using SF_{limit}

Based on the analysis in PTC simulation results section, the values of SFlimit for simulated cases is shown in Table 6. The locations where no value of SFlimit is defined (such as in UK-London) indicate that LCOH of ST is always higher than LCOH of HTHP in all simulated cases. These countries often have very low annual DNI, resulting in lower economic feasibility for PTC.

Table 6 Summary of SF limit (%) of ABSOLICON PTC (T-160) and HTHP with and without PV for LPR.1 and LPR.2. Empty values indicate that LCOH of ST is higher than LCOH of HTHP or HTHP+PV

LPR.1

Location	Description	DNI^1/GHI^2	ABSOLICON LCOH	CAP1-ELP1	CAP2-ELP2	CAP3-ELP3
			HTHP LCOH without PV	45	63	98
Sweden-Borlange	PV-500 kW$_P$	1128^2	LCOH HTHP+PV	43	62	88
	SF without PV	1075^1	74.1			14
	SFWith PV	1075^1	74.1			11
UK-London	PV-400 kW$_P$	1399^2	LCOH HTHP+PV	42	60	85
	SF without PV	642^1	122.8			
	SF With PV	642^1	122.8			
France-Paris	PV-500 kW$_P$	1507^2	LCOH HTHP+PV	42	59	84
	SF without PV	790^1	86.9			
	SF With PV	790^1	86.9			
Spain-Seville	PV-500 kW$_P$	2124^2	LCOH HTHP+PV	39	55	79
	SF without PV	1848^1	28	39	55	64
	SF With PV	1848^1	28	30	49	59

LPR.2

Location	Description	DNI^1/GHI^2	ABSOLICON LCOH	CAP1-ELP1	CAP2-ELP2	CAP3-ELP3
			HTHP LCOH without PV	58	89	130
Sweden-Borlange	PV-500 kW$_P$	1027^2	LCOH HTHP+PV	57	82	111
	SF without PV	1075^1	74.1		17	29
	SF With PV	1075^1	74.1			26
UK-London	PV-400 kW$_P$	1356^2	LCOH HTHP+PV	53	75	102
	SF without PV	642^1	122.8			18
	SF With PV	642^1	122.8			
France-Paris	PV-500 kW$_P$	1468^2	LCOH HTHP+PV	52	74	100
	SF without PV	790^1	86.9			21
	SF With PV	790^1	86.9			
Spain-Seville	PV-500 kW$_P$	2103^2	LCOH HTHP+PV	45	64	85
	SF without PV	1848^1	28	60	62	70
	SF With PV	1848^1	28	57	60	63

7. Discussions

The cost aspects of any technology for low-carbon process heat assessment are extremely case-sensitive. The developed method serves as a valuable guide to quickly determine a preferred lower carbon heat solution just by looking at the annual DNI of any location and finding the optimal SF limit for that location. The analysis is comprehensive but restricted by the absolute values of the variables assumed. Several other aspects can change the techno-economic results in the near future. For example, the carbon tax can play a significant role in reducing the cost of heating. ST technologies consume significantly low electricity compared to HTHP technologies. If the CO2 emission cost is accounted for, the results will favour ST technologies and HTHP with PV. Also, as the electricity grid will have more renewable penetrations, the HTHP will keep getting attractive from a cost and emission perspective.

The land usage for HTHP is much smaller compared to solar thermal collectors. This is a big advantage for HTHP, especially if the industries have limited ground or roof space for solar collector installations. HTHP, on the other hand, needs more developments for low-GWP refrigerants.

A way forward could be to use both technologies in conjunction where ST is designed up to the SFlimit, and HTHP is used to meet the rest of the load. A hybrid system of optimized solar thermal collectors with a small tank volume and HTHP can produce process heat at lower LCOH compared to the technologies used individually. Technology combination is imperative to reach clean and economical industrial heat ambitions. Such a hybrid system could have significant potential to decrease the cost and emission and will be of focus for future studies and publications. For new energy system planning, a bivalent system where only PTC and HTHP are used together, there is a possibility to reach 100% renewable heating fraction if the electricity for HTHP is renewable. Such system can run without any need for boiler backups. In case of retrofitting with existing boiler system, ST can be used as a starting point to cover part heat demand. Then HTHP can be introduced in the system designed for peak heat load demand to phase off the boiler completely.

In addition, to accelerate the decarbonisation aims, the EU has set an ambition to build 100 positive energy districts and smart cities (climate-neutral cities) by the year 2025. However, the focus of current PEDs is mainly on residential and commercial buildings. The PED boundary unfortunately does not include industrial energy system at the moment. Nevertheless, there is a strong need to factuality the industrial decarbonisation and include industrial energy system in the PED development since it belongs to whole city energy infrastructure. If a city wants to achieve the climate-neutral goal, it must consider industrial segment. On the other hand, industry segment fits high synergies if it is considered in PED concept. For instance, the low temperature waste heat can be recovered from industries to meet space heating and DHW demand through 5th generation district heating network. In return, when PED produces extra energy, it can be exported to industries through above-addressed district heating via heat pumps to upgrade heat to the required temperature level. Therefore, to address the technologies for industrial heat is critical to fulfil the PED and climate-neutral city goals, such as HTHP and PTC, which can be the key technologies for a fully decarbonised urban energy system.

8. Conclusions

This paper compares the techno-economic aspects of HTHPs and PTC collectors for various industrial boundary conditions. The focus is on steam generation at 140 °C (3.6 bara), commonly used in many process heating industries. The characteristics of commercial HTHP and PTC products are used as input in the simulation model to obtain energetic results. For LCOH calculation, an excel spreadsheet is used. Finally, results are generalized using SFlimit as an indicator to distinguish the economic advantage of each technology.

The major conclusions of the study are as follows:

- The LCOH of HTHP for the analysed boundary conditions ranges from 45 to 130 €MWh. There is a clear trend of increasing LCOH with higher electricity prices and specific CAPEX costs. As the HTHP was sized for a peak load capacity of 500 kW, the total CAPEX is the same for both load profiles. However, the LCOH can be lowered by operating the HTHP for more hours. Therefore, the LCOH in scenario LPR1 is always lower than in LPR2 for the same cost of electricity prices.
- The least obtained LCOH comes from the PTC collector for high DNI regions and low solar fractions. If the meteorological conditions are suitable, PTC is a cheaper alternative to generate steam compared to HTHP. The LCOH range obtained from PTC simulations is 28 to 160 €/MWh up to 50% SF. Lower values of LCOH can be observed for high DNI regions and vice versa. High DNI regions are, for example, Spain, Portugal, and Southern Italy. Furthermore, LCOH has an increasing variation with SF. The SF-LCOH curve is not dependent on the absolute DNI but on the distribution of the DNI on a temporal basis, which decides the storage volume needed to increase the SF.
- As the LCOH increases with SF, a specific SF_{limit} exists when producing heat from ST gets more expensive compared to HTHP. This limit is higher for high DNI regions and lower for low DNI regions. The limit increases with higher ELP and CAP for the HP. In low CAPEX and electricity cost situations for an HTHP, a threshold DNI of 764 kWh/m^2 is needed for PTC to produce heat at a cheaper rate. In the high CAPEX scenario, this threshold DNI changes to 1'200 kWh/m^2, and the average SF limit varies from 25% to 55%. In high DNI locations (1'500 to 2'000 kWh/m^2), 15% to 30% for medium DNI (1'001 to 1'499 kWh/m^2), and 0% to 10% for low DNI locations (0 to 999 kWh/m^2).

- The decrease in PTC CAPEX results in lower LCOH for any given solar fraction, eventually leading to high SF_{limit}. When the CAPEX of PTC is lower and load profiles are favorable, a solar fraction limit of 32 % is obtained, even for the lowest DNI location. This situation indicates that cost decrease can result in PTC as the most economic heating source for low DNI locations.
- The industry segment fits high synergies if considered in the PED concept, while both HTHP and PTC can be the key technologies for a fully decarbonized urban energy system.

Author Statement

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Mohammad Ghasemi: Simulations, writing, reviewing, editing.
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Declaration of competing interest

The authors declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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