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

Puneet Saini [a,b,c], Mohammed Ghasemi[b], Cordin Arpagaus[d], Frédéric Bless[d], Stefan Bertsch[d], Xingxing Zhang[b].

[a] Absolicon solar collectors AB, Fiskaregatan 11, Härnösand, Sweden. 87133.
[b] Department of Energy and community buildings, Dalarna University, Sweden.
[c] Department of Engineering Sciences, Civil Engineering and Built environment, Uppsala University, Sweden.
[d] Eastern Switzerland University of Applied Sciences, Institute for Energy Systems, Werdenbergstrasse 4, 9471 Buchs, Switzerland
*Corresponding author. Email address: puneet@absolicon.com, pks@du.se. Phone: +46(0)700264251.

Abstract

Industrial heat production is responsible for around 20% of total greenhouse gas emissions in Europe. To achieve the climate change goals defined in the Paris Climate Agreement, the EU commission has shifted its focus on sustainable means to generate heating. Moreover, global dependencies are leading to a re-organization of natural gas supplies. Therefore, there is a need for less vulnerable and less price volatile solutions for heating. This paper focuses on two decarbonization technologies for industrial process heat supply: (a) electricity-driven steam-generating high-temperature heat pumps (HTHP), a technology that is more efficient than fossil fuel boilers in generating steam, and (b) solar parabolic trough collector (PTC), which can produce heat economically and at a minimal carbon footprint compared to other technologies. The main aim of this paper is to evaluate the levelized cost of heat (LCOH) of these technologies to fulfill a comparative techno-economic analysis. A maximum PTC collector's solar fraction limit is defined to indicate when the LCOH for these two technologies is equal. This limit allows distinguishing between the economic stronghold of each technology. The evaluation is carried out through the annual energy simulations using TRNSYS and Excel spreadsheets for HTHPs, while TRNSED and OCTAVE are used for the solar thermal part. Boundary conditions for European geographical constraints have been applied to establish use cases for the analysis. The result shows that the design of a PTC system with optimal SF can reach cost parity with HTHP for most of the analyzed locations. The developed methodology serves as a valuable guide to quickly determine a preferred lower carbon heat solution, thus easing the decision-making for industries.

Keywords: High-Temperature Heat Pump; Parabolic Trough Collector; Solar Fraction; Techno-economic analysis

1. Introduction

"Heat is half" of the global primary energy consumption, while the other half is due to energy use in transport and electricity sector [1]. The generation of heat from various fuel sources results in nearly 40% of the global CO2 emissions. Therefore, the decarbonization of 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

doi:10.18086/eurosun.2022.05.10 Available at http://proceedings.ises.org

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. Therefore, 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 attractive (typical expectation 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 specific technologies to generate steam, i.e., (a) electricity-driven steam-generating HTHPs and (b) solar-powered parabolic trough collectors (PTC), which is a type of concentrating ST collector.

2. Objectives

The central objective of this paper is a comparative analysis of both HTHP and PTC systems for steam applications using industrial boundary conditions. Previous studies have performed a general feasibility analysis for solar thermal technologies or HPs. However, only a few have investigated comparing these technologies on a large spatial scale with techno-economic boundaries. Moreover, there is a lack of studies comparing HTHP for the steam generation with PTC-based collectors.

Perez et. al compared the techno-economic performance of 3 types of ST collectors, and photovoltaic powered heat pumps [5]. The methodology used to compare ST and PV systems is based on the calculation of the levelized cost of energy and greenhouse gas emissions. However, only a residential heat pump with maximum temperature upto 60 ºC is considered without dynamic modelling, and the ramping up of temperature upto set point is done by resistance heater. Neyer et. al compared the techno-economic assessment by comparing an air/water heat pump with photovoltaic and solar thermal, to support for a small multifamily house located in Madrid [6]. However, the results are restricted to residential temperature range, and does not apply for industrial sectors. A similar study concluded that a hybrid system of solar thermal collector with Natural gas boiler is competitive to air source HP system, with boundary conditions applied to residential buildings in Europe [7]. There is a lack of studies dealing for decarbonising heating technologies for industries, specifically comparing HTHP for the steam generation with PTC-based collectors. The most relevant work to the current paper is by [8], where the authors have developed a techno-economic comparison methodology using maximum turn-key solar investment as an indicator. This methodology can be used as a criterion to quickly compare and select between solar thermal and heat pumps based on boundary conditions. However, even 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. The current paper has overcome the limitations by using comprehensive variables as a comparison basis for both HTHP and ST. The paper also considers updated analysis from a techno-economic perspective capturing the recent development in PTC and HTHP while considering the effects of improved efficiency and cost reductions. The next sections provide an overview of research methodology

3. Research methodology

This study aims to assess the energy and economic performances of industrial PTC and HTHP in the context of the European climates. Figure 1 shows the flow chart of the methodology 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 3 different load profiles with constant peak demand to capture a broad range of industrial load conditions. The geographical focus for simulations is limited to Europe. However, the results obtained are parametrized to direct normal irradiation (DNI) and 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. The outputs are based on a performance map obtained from an HTHP supplier (ref) for a broad range of operating conditions.

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 [9]. 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 are done using a developed model in Excel.

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 SF_{limit} is introduced to distinguish the economic advantage and to generalize the results.

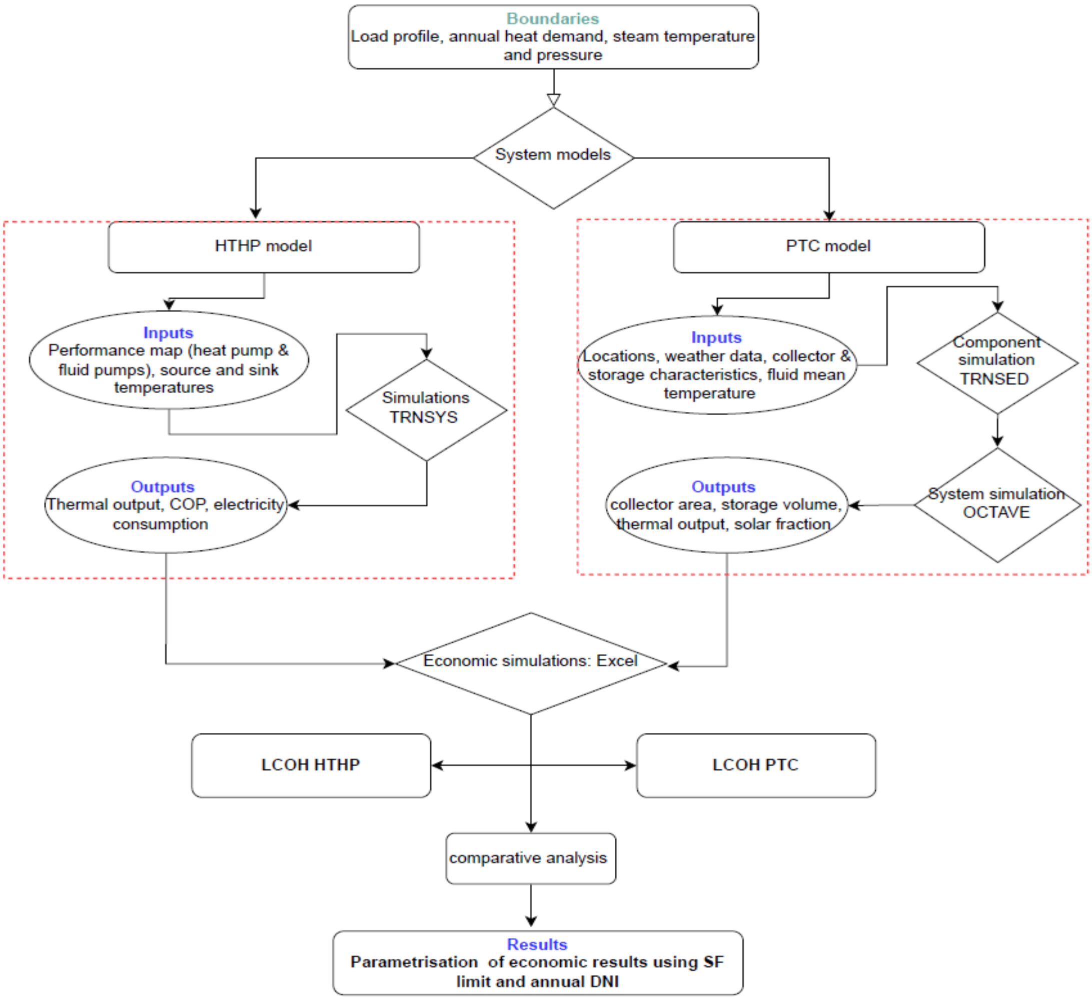

Figure 1 Flow chart for the methodology used for this study

4. Boundary conditions

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. Three different load demand profiles are considered for the analysis. The peak heat demand is fixed at 500 kW_{th} (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 bar_a). 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 3 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.
- **Weekday demand**: Uniform demand throughout the weekdays of the year (no operation during the weekend). The annual heat demand for this case is 3132 GWh/year, corresponding to real cases in industrial load. An example of this load variation can be found in the food and beverage 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.

A summary of the considered load profile cases for simulations is shown in Table 1.

Table 1 Summary of the load profiles considered for simulations

Load profile	**Nos of operational days per year**	**Operational days per week**	**Operational hours per day**	**Peak Power [kW]**	**Annual heating load [GWh]**	**Time**
1	365	7	24	500	4.38	24*7*365
2	261	5	24	500	3.13	24*5
3	365	7	10	500	1.82	8:00 to 18:00 each day

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

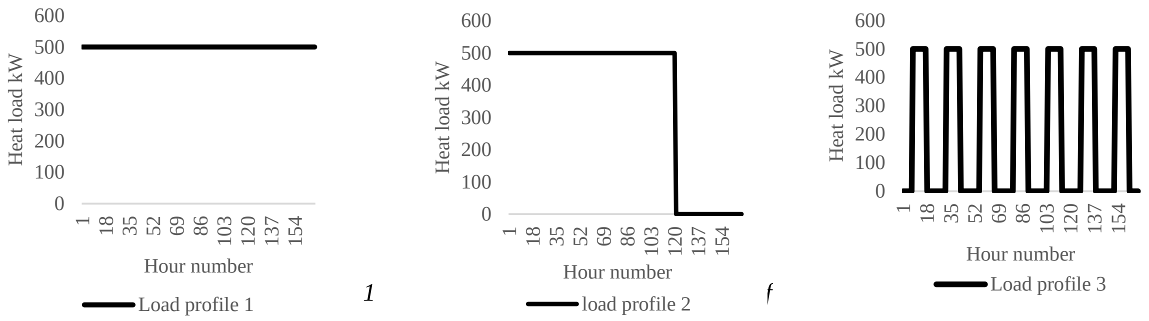

Figure 2 Weekly variation of different load profiles considered for the analysis.

4.2 HTHP boundaries

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 165) capable of generating steam at a maximum temperature of 165 °C is used to meet the steam requirement [10]. The HP 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 HP 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 is used to calculate the electricity consumption. The performance map consists of the COP of the HTHP for various temperature lifts, as shown in the Figure 3. The temperature lift represents the difference between the fluid temperature at the heat source inlet and the heat sink outlet. The HP 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.

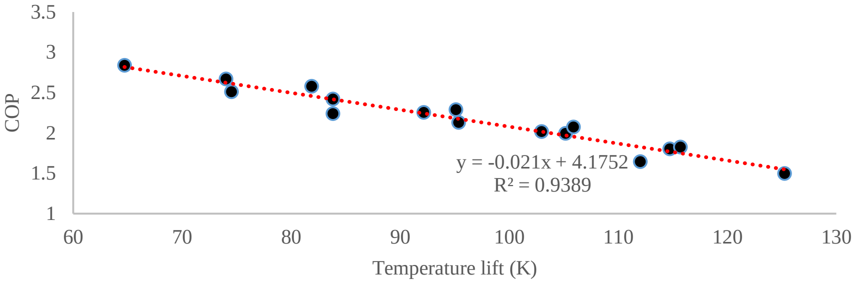

Figure 3 Variation of HP COP with temperature lift

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 °C is considered on the evaporator. The resulting temperature lift of the HTHP is 100 °C , corresponding to steam temperature of 140 °C. The feedwater temperature entering the HTHP arrives at 110 °C, resulting in a 30 °C 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. The HP is designed for peak heating demand of 500 kW; the specifications are shown in Table 2.

Table 2 *Specifications of HP considered in this study* [34].

Parameter	*Value*
Compressor	Semi-Hermetic Inverter Twin Screw
Refrigerant	Mixture of HFC134a & HFC245fa
Dimensions [mm]	W4400 H3180 L2810
Weight [kg]	7090
Heating capacity[t/h] @0.6MPaG, source 70°C	0.839 @20°C supply
Power [kW] @0.6MPaG, source 70°C	253.9
Heating COP@0.6MPaG, source 70°C	2.5

Economic inputs for HTHP

For the HP LCOH, it is necessary to include various costs. The analysis is done for 3 different capital expenditures (CAPEX) of 500, 1000, 1500 Euro/kW$_{th}$ values derived from data based on implemented HTHP case studies [11]. The operational costs for HTHP consider the electricity to run the HP compressor and fluid pumps. The operation and maintenance (O&M) costs for HTHP are usually higher than those for boilers and are set to 5% of CAPEX value. The relevant parameters for HTHP thermo-economic modelling are shown in the Table 3. The LCOH of both HTHP and PTC systems are compared for time horizon of 15 years. The period is chosen to reflect the suitable timeline considered by various multinational companies for energy related investments. Three different electricity prices are chosen for analysis considering the range of industrial electricity tariffs in EU.

Table 3 Assumptions regarded in HTHP simulations

Parameter	*Abbreviation*	*Value*	*Units*
System degradation rate	SD	0.5	%

Capital expenditure	CAPEX	500/1000/1500	Euro/kW$_{th}$	
O&M cost	EX$_{o\&M}$	5	%	of CAPEX
HP lifetime		15	Years	
LCOH analysis period		15	Years	

For sensitivity analysis of LCOH, a total of 27 cases are analyzed, accounting for 3 different values of three variables (i.e., CAPEX, electricity price, and load profiles). The values of these variables are shown in Table 4.

Table 4 Different scenarios for the variables used in HTHP LCOH calculations.

Description	*Abbreviation*	*Case 1*	*Case 2*	*Case 3*
HP CAPEX [Euro/kW$_{th}$]	CAP	500	1000	1500
Electricity Price [Euro/MWh]	ELP	70	100	150
Load Profile [h/year]	LPR	8760	6264	3650

4.3 Solar thermal collector simulations

3.3.1 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 5. 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 5 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[Liter]	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

3.3.2 Collector integration in the system

The overall system is divided into 2 circuits. The pressurized water stays in a closed loop called the solar loop, or primary loop. Pressurized water is warmed up by circulating in the solar collectors and is later cooled down through the heat exchanger, which has its secondary side connected with a steam separator. The steam separator is a vessel which contains a mixture of steam and hot water. When the required pressure is reached in the vessel, the steam will be sent to the customer's main steam line.

The generated steam is separated from the remaining saturated liquid in the steam separator, and it has priority over the boilers-generated steam due to small overpressure. Its primary use is maintained high by the small overheating. The saturated liquid separated from the steam in the steam separator is mixed with the incoming water from the deaerator and recirculated to the steam heat exchanger. The separation of steam and water (that occurs by gravity) creates inside the steam separator two regions (one of steam and one of liquid at nearly the same temperature), the volumes of which can fluctuate and absorb small power surges or reductions

The system arrangement considers PTC collector fields with a storage system to generate steam at 140 °C with feedwater temperature at 110 °C, same as considered for HTHP. Whenever solar production exceeds the demand, heat is diverted to thermal storage. The storage system is considered a pressurized tank using water as a storage media. When the storge is fully charged, the water Is heated to a maximum temperature of 160 °C. After discharging, the tank is cooled down, corresponding to the bottom temperature in the steam separator (approximately 140 °C). This results in an effective temperature difference of 20 °C In the thermal storage between charging and discharging.

3.3.3 Modelling of 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 6.

Table 6 Input Performance characteristics of T160 collector used for model [29]

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
γ, azimuth [°]*	0

3.3.5 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 7.

Table 7 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	%	

The simulation for PTC is done for various locations in Europe, as shown in 4. If the country's direct normal irradiance (DNI) is spatially uniform, then one city from each country is used for simulations. However, some of European countries (for e.g France, Italy and Germany), have a significant variation of DNI. Therefore, multiple cities within the same country are selected for better representation. The LCOH results of PTC for each country would be compared with the LCOH of HTHP to determine the solar fraction threshold below which ST is more economically attractive than HTHP.

Figure 4 Map representing the various locations used for PTC simulations

4. Results

4.1 HTHP simulation results

Table 8 shows the results for LCOH calculations for HTHP for 27 simulated scenarios representing variation in the load profiles, investment cost, and electricity price. For any specific load profile, the CAP1-ELP1 represents the LCOH of HTHP assuming capex 1 (500 €/kWth), and Electricity prices 1 (70 €/MWhe), as shown previously in Table 4. 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 while moving from LPR1 to LPR3 due to decreasing operational hours. Furthermore, for the same CAP value and any load profile, the LCOH increase with a higher electricity process (when moving from ELP 1 to ELP 3).

Case	HP CAPEX EUR/kW	Electricity price EUR/MWh	*LCOH of HTHP (Euros/MWh)*		
			Load profile 1 LPR.1 8'760 h/a	Load profile 2 LPR.2 6'264 h/a	Load profile 3 LPR.3 3'650 h/a
CAP.1-ELP.1	500	70	45	49	58
CAP.1-ELP.2	500	70	59	63	73
CAP.1-ELP.3	500	70	84	88	98
CAP.2-ELP.1	1'000	100	51	58	75
CAP.2-ELP.2	1'000	100	66	73	89
CAP.2-ELP.3	1'000	100	91	98	114
CAP.3-ELP.1	1'500	150	58	67	91
CAP.3-ELP.2	1'500	150	73	82	106
CAP.3-ELP.3	1'500	150	98	107	130

4.2 PTC simulation results

The results from PTC simulations suggest that LCOH has 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 from 28 to 160 €/MWh. The lowest LCOH is obtained for high DNI regions (for example, cities in Spain, Portugal and Southern Italy), and at a lower solar fraction. Figure 5 shows the variation of LCOH for PTC collectors at 3 different solar fractions (5%, 25%, and 50%) and for LPR1 (8'760 h/a) using all simulated locations. There is decreasing trend of LCOH with increasing DNI due to high collector output. Furthermore, for the same DNI, the LCOH increases with increase in solar fraction due to lower utilisation of heat.

It is also important to consider that LCOH not only depends 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 large tank volume needed, thus increasing the LCOH. This can be seen by comparing the 2 data points in 5 at 50 % SF (compared data points are marked black border). These 2 locations have nearly the same annual DNI value of around 1500 kWh/m^2. However, the LCOH for one location is much higher (147 €/MWh) compared to the other location (75 €/MWh).

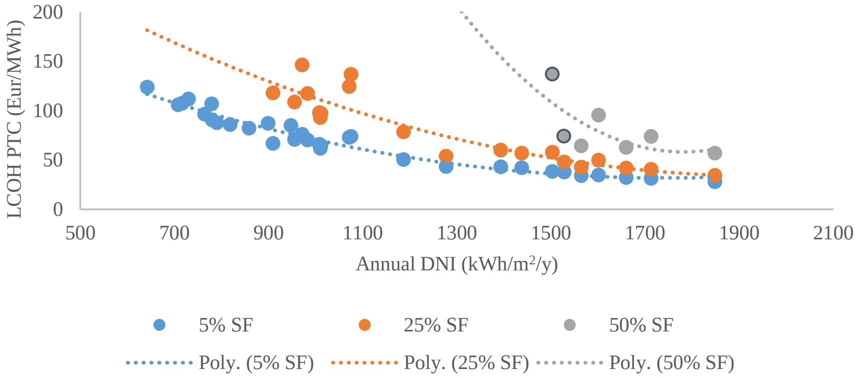

Figure 5 Variation of LCOH with SF for all locations at 3 different solar fractions and load profile 1 (8760 h/a)

The range of PTC LCOH for all 3 load profiles is shown in Figure 6. Results indicate that load profile 3 has the lowest LCOH at high solar fraction (50 %), due to high coincidence in solar irradiation and load demand. LPR2 has the highest LCOH at any SF. This is due to the lack of heating load during the weekend in LPR2, which results in high storage volume or heat spillage from the collectors.

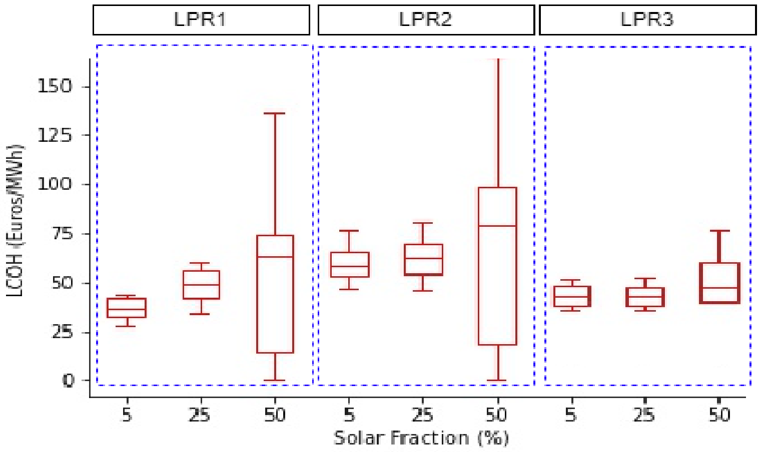

Figure 6 Range of PTC LCOH for 3 load profiles and 3 different solar fractions for all simulated locations

Based on the analysis in section above sections , the values of SF$_{\text{limit}}$ for all simulated cases is quantified, and normalised to DNI as shown in Figure 7.

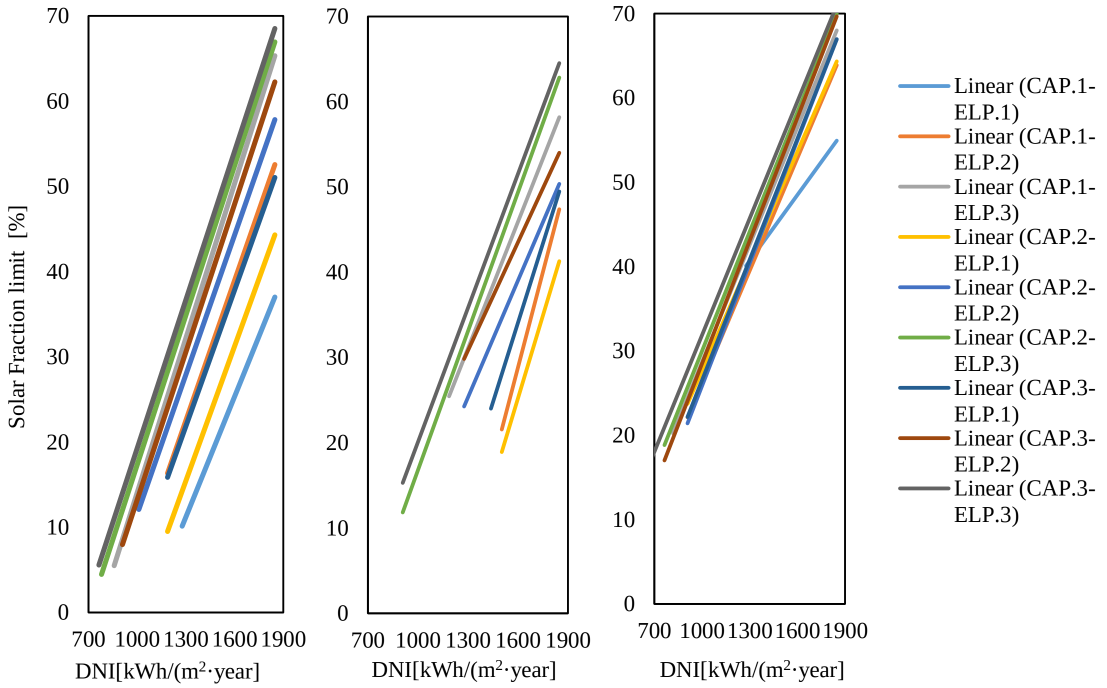

Figure 7 Variation of SF_{limit} with DNI for LPR.1 (left), LPR.2 (middle), and LPR.3 (right)

In high DNI regions (1'500 to 2'000 kWh/m^2), the average SF_{limit} varies from 25 % to 55 %, indicating that ST technologies are a cheaper way of reducing the emission by at least 1/4th. In such regions, the demand up to 55% can be met by solar thermal collectors at economical LCOH if the load profiles are favourable (LPR3). In medium DNI regions (1'001 to 1'499 kWh/m^2), SF_{limit} varies from 15 % to 30 %, lower than the high DNI regions. If the boundaries favor HTHP (low CAPEX, low electricity price, and high operational hours), the DNI at any location must be higher than 1200 kWh/m^2 for PTC to compete. In low DNI regions (500 to 999 kWh/m^2), the maximum SF_{limit} obtained is 10 %. In such regions, HTHP is cheaper than PTC for low and medium CAPEX/el price value. However, if the electricity and CAPEX are high, PTC can compete with HTHP at a minimum DNI of 764 kWh/m^2.

Comparing the results for different load profiles, there is an increasing trend of SF_{limit} with increasing DNI when moving from LPR.1 to LPR.3, indicating better economic results for PTC. When the consumption and production have high coincidence for example in LPR.3, there is a small need for storage, which would result in lower LCOH for PTC collector, and therefore higher value of SF limit can be seen. For all load profiles, Higher SF_{limit} can be obtained for high DNI locations, due to high thermal output of the collectors. In LPR 3, a SF_{limit} can be obtained even for low DNI (764 kWh/m^2) due to favourable match in DNI and load. Such figures can be used to do a quick cost feasibility analysis for both ST and HTHP, and can be very useful tool for designers.

5. **Conclusions**

This paper compares the techno-economic aspects of HTHPs and PTC collectors for various industrial boundary conditions for 3 load profiles. The focus is on steam generation at 140 °C (3.6 bar$_a$), 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 model is used. Finally, results are generalized using SF_{limit} 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 analyzed 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 all 3 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 and LPR3 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, an SF_{limit} exists when producing heat from ST gets 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).

- Industry segment has high synergies if it is considered in PED concept, while both HTHP and PTC can be the key technologies for a fully decarbonised urban energy system.

References

[1] "Heating – Analysis - IEA." [Online]. Available: https://www.iea.org/reports/heating. [Accessed: 14-Aug-2022].

[2] "Article - EHPA." [Online]. Available: https://www.ehpa.org/about/news/article/repowereu-heat-pump-strategy-required-to-help-sector-deliver/. [Accessed: 14-Aug-2022].

[3] "Heating and cooling." [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en. [Accessed: 14-Aug-2022].

[4] L. Cebotari, "EU-Russia energy relations: problems and perspectives," *Proc. Int. Conf. Bus. Excell.*, vol. 16, no. 1, pp. 1001–1014, Aug. 2022.

[5] E. Pérez-Aparicio, I. Lillo-Bravo, S. Moreno-Tejera, and M. Silva-Pérez, “Economical and environmental analysis of thermal and photovoltaic solar energy as source of heat for industrial processes,” AIP Conf. Proc., vol. 1850, no. 1, p. 180005, Jun. 2017.

[6] D. Neyer, M. Ostheimer, C. Dipasquale, and R. Köll, “Technical and economic assessment of solar heating and cooling – Methodology and examples of IEA SHC Task 53,” Sol. Energy, vol. 172, pp. 90– 101, Sep. 2018.

[7] S. Alberici et al., “Subsidies and costs of EU energy Final report,” 2014.

[8] “IEA SHC || Task 64 || Solar Process Heat.” [Online]. Available: https://task64.iea-shc.org/. [Accessed: 14-Aug-2022].

[9] "Absolicon - Production Line for T160 concentrating solar collector." [Online]. Available: https://www.absolicon.com/. [Accessed: 14-Aug-2022].

[10] "Standard Compressors/ KOBELCO COMPRESSORS CORPORATION｜KOBELCO Kobe Steel,. Ltd." [Online]. Available: https://www.kobelco.co.jp/english/products/standard_compressors/. [Accessed: 14-Aug-2022].

[11] "HTHP Symposium 2022." [Online]. Available: https://hthp-symposium.org/hthp-symposium-2022/. [Accessed: 14-Aug-2022].