CSP for a cost effective process heat generation at high latitudes

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Foreword

The common view about CSP is that it is well suited only for applications in high DNI geographical areas, while in lower DNI areas PV is a better choice,

This is generally true if one takes into account the electricity generation and has no concern about the dispatch-ability. This preference is due to the extremely low cost of PV and to its ability to harvest the global solar radiation, instead of relying only on the direct normal radiation. In low DNI areas, as well as in zones experiencing frequent direct sun radiation blockages by clouds, PV plants are preferred.

However, if the plant duty is to supply heat at high temperature to power an industrial process, the CSP can play an important role, even in geographical areas where the generation of electricity by this mean would not be convenient in respect of PV.

In this study an application of CSP, at high latitude, in a geographical location with limited DNI, dedicated to supply heat at high temperature to an industrial process, has been analyzed. The Levelized Cost of Heat has been evaluated and compared to the values offered by other competing technologies.

Location

The selected geographic location is *Cabauw*, a village located mid way between Rotterdam and Utrecht. This location has been mentioned some time ago as one possible site of interest.

The TMY [1]data for this site were recovered from the site

https://ec.europa.eu/jrc/en/PVGIS/tools/tmy

Latitude: 51.970001 N

Longitude: 4.920000 E

1 TMY: Typical Meteorological Year

Fig 1 Selected location

DNI

The site DNI[2] resulting from the TMY records is 961 $kWh/m^2/y$ corresponding to an average value of 2.63 $kWh/m^2/day$,
This value fits well with SOLARGIS maps and is rather usual for the Netherlands.
Analyzing the records, 226 days show daily DNI greater than 1 kWh/m^2 . About one half of the days of the year has more than 2 $kWh/m^2/day$.
The daily DNI distribution is shown in fig. 2

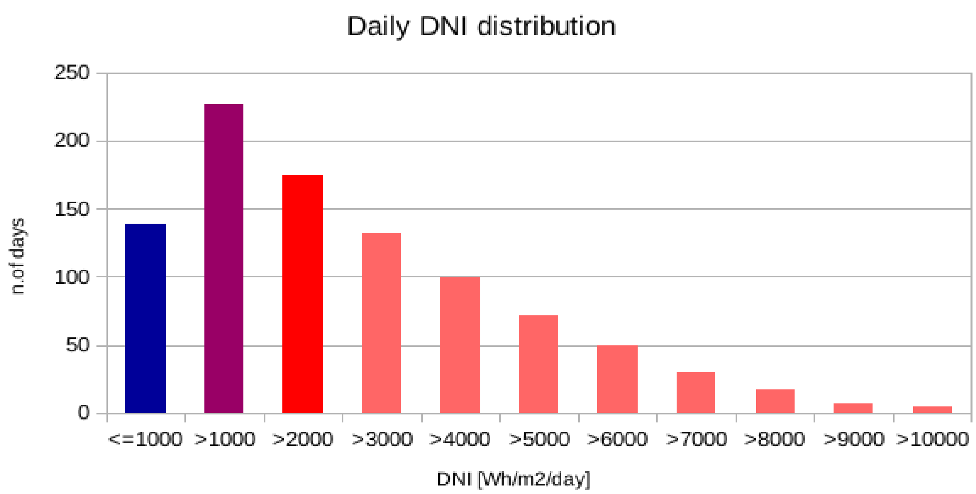

Fig 2 - Daily DNI distribution

2 DNI: Direct Normal Irradiation

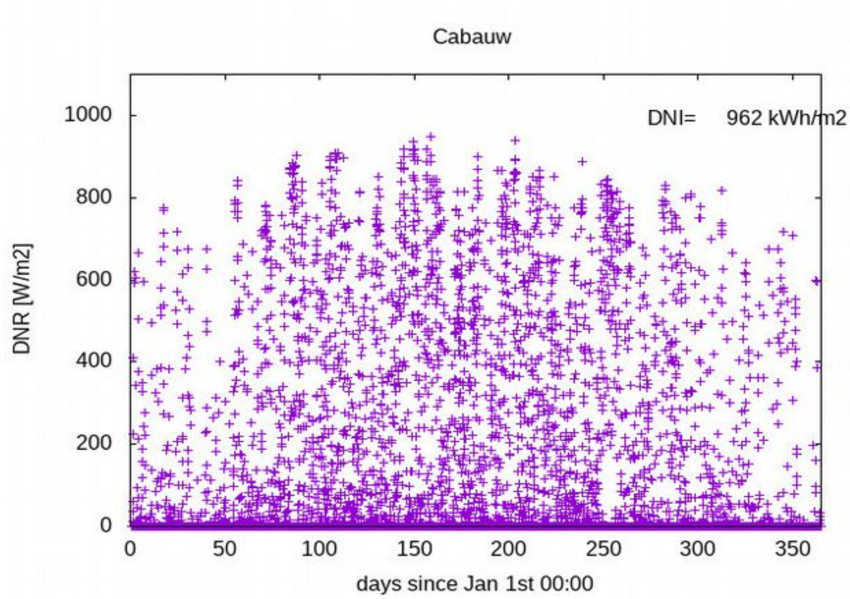

Fig 2B - whole year DNR plot from TMY records

In the best days the DNI is as high as 10 kWh/m^2/day with a peak DNR[3] of 960 W/m2, indicating clear sky conditions, well suited for CSP[4] installations. Fig 3 shows the DNR values for three days centered on day 149 (May 29th), where the best daily DNI value is listed in TMY file.

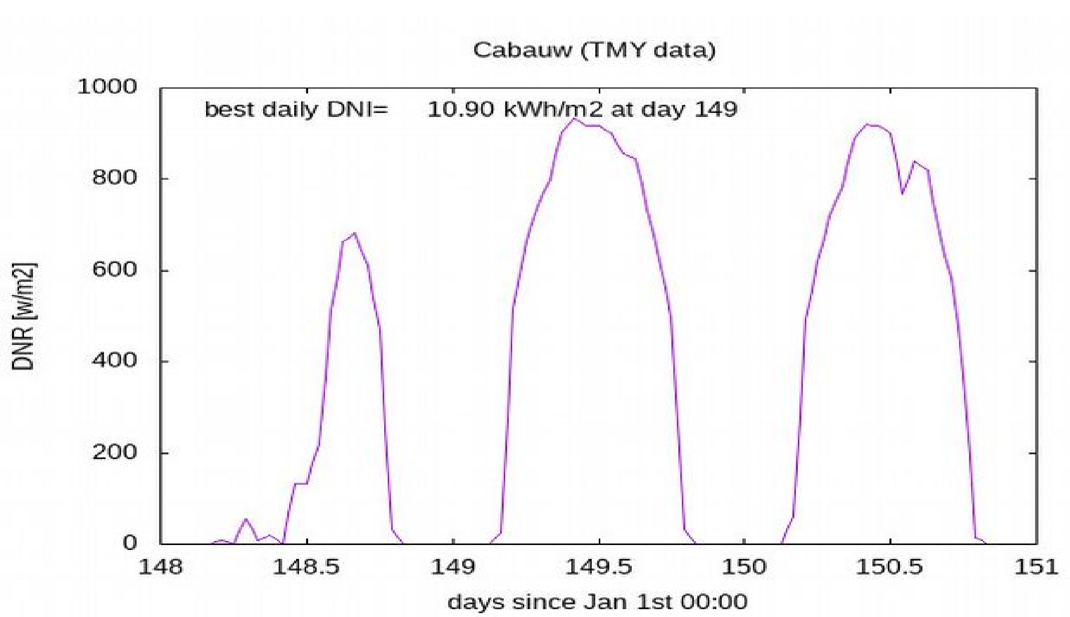

Fig 3 - DNR at best DNI days

3 DNR: Direct Normal Radiation

4 CSP: Concentrated Solar Power

Generally speaking, this is a rather sunny location and it is expected that a CSP plant would be able to produce useful heat for a great number of days, even if not for the whole day. Provisions should be made for an adequate heat storage, or a backup heat source, if the user application requires an uninterrupted heat supply.

Ambient temperature

In the TMY file the ambient temperature at the site goes below zero degrees Celsius few times per year in January and December with a minimum temperature of -5°C . However, these data are from a TMY file, that means that, although they are derived from the observations of several past years, they are not an historical record of the same period of time. Temperatures outside the displayed range of values are therefore possible. Care must be taken in the design of the plant, in the choice of the HTF[5], and in drafting the overall plant operational procedures, in order to allow a smooth operation, clear of adverse effects due to the possible freezing of the HTF in the tubes (backup heaters, HTF dump, etc.). Even in this case, HTF freezing at this site is much more than a remote possibility during the winter and must be considered.

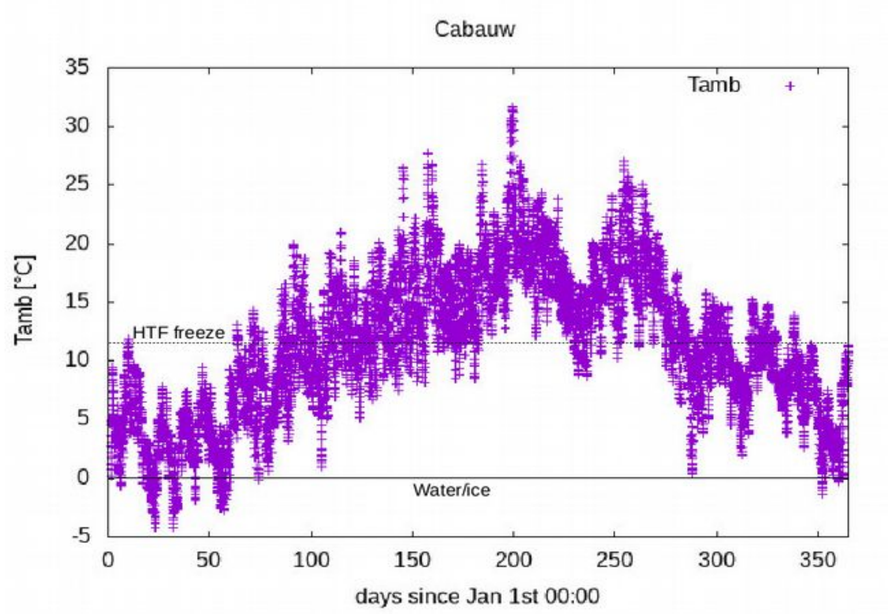

Fig 4 - Site Temperature

5 HTF: Heat Transfer Fluid

Wind

Parabolic troughs, as well as LFR fields, are subject to issues regarding a correct operation in presence of strong winds. Wind reduces the precision of the aiming and, consequently, the collector efficiency. Strong winds can severely affect the solar collector structures causing damages and even their destruction.

Typical operating procedures for PT[6] plants foresee the moving of the troughs to the stowage position, aiming the troughs to a suitable angle where the resistance to the wind induced forces is the highest.

These plants consider generally go to stowage when wind speed exceeds a limit varying from 10 to 15 m/s. This depends on the size and on the mechanical design of the parabolic collector. The decision about the opportunity of going to stowage depends also on other parameters, as the presence of wind gusts.

Furthermore the performance of the collectors is affected by the wind in various ways, mechanical deformations, vibrations and others, causing the partial defocusing of the optics. A wind speed of 5-7 m/s is considered a limit for a non degraded collector performance.

These values are typical for a 6 m wide parabolic trough, smaller troughs are generally less prone to wind effects, but it depends of their mechanical design.

The mirrors in LFR[7] plants are located very near the ground and the expected wind effects on them are low; no safety aiming strategy is therefore normally needed. However the HCE’s are suspended high above the mirrors, unprotected from the wind. The supporting structure is subject to vibrations and movements induced by the wind. The HCE position should be assured to remain within 10 to 20 cm distance[8] from the exact design position.

The wind speeds resulting from the TMY records are shown in fig. 5

6 PT: Parabolic Trough

7 LFR: Linear Fresnel Reflector

8 typ. values for a single HCE with secondary concentrator placed 10 m above mirrors

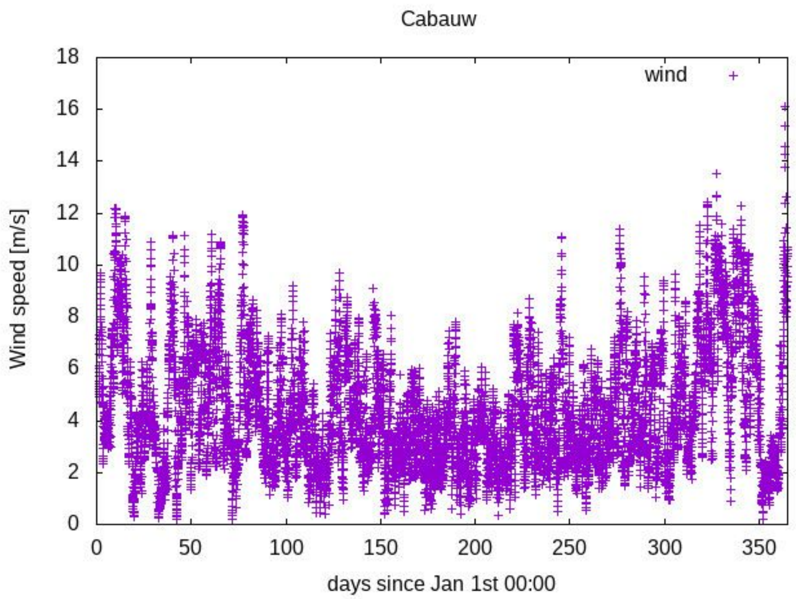

Fig 5 - Site wind speed

While during most of the year the wind remains below the 7 m/s limit, at least once per month we observe high-wind episodes, lasting up to several days, with wind speed in the range 7 to 16 m/s. January, November and December are windy months in the TMY records, with wind speed almost always above 7 m/s.

Only 72 hours in the whole TMY year show a wind speed below 1 m/s (~2 knots). Never a 0 m/s value.

A total of 118 days in a year have wind speeds above 7 m/s during daytime and 27 days show wind speed values higher than 10 m/s, which will force to move the troughs to stowage position, during daytime.

Generally speaking, this is not a comfortable site for CSP solar collectors.

Care must be taken in selecting a robust design and perhaps the choice of a narrower trough could be useful.

Simulation

The reference CSP plant used for the simulation is a parabolic trough, depicted in figure 7A and 7B. The HCE's[9] used in the mirror field are the standard vacuum insulated tubes normally used in the conventional PT plants. If the output temperature of the mirror field is below 180°C other lower cost devices could be used, but this is not taken into consideration here. Instead the standard 6 m wide parabolic collector equipped with standard HCE's has been taken into account, whose performance is well established.

9 HCE: Heat Collecting Element

The A) solution uses direct heating of pressurized water, which can be used directly in the end user application. In this case the output temperature is limited by the pressure limit of the tube (10 bar).
Although a careful flow control is needed to handle and stabilize possible fluid phase change while in HCE, this can be easily handled with a flash drum at the end of the line.
As the HCE losses in this temperature range are low, a narrower collector (say 3 to 4 m wide) could be used with a possible lower cost (to be confirmed).

The B) solution uses an intermediate HTF[10] as a heat vector towards the final user. In this case the output temperature can be higher, always within the operational range of the HTF. If the output temperature is below 300°C, a number of non-toxic, not-flammable, HTF can be used with a low environmental impact of the plant. The standard HCE's in this range of temperature shows low losses, but a full size (6 m wide) collector is recommend.

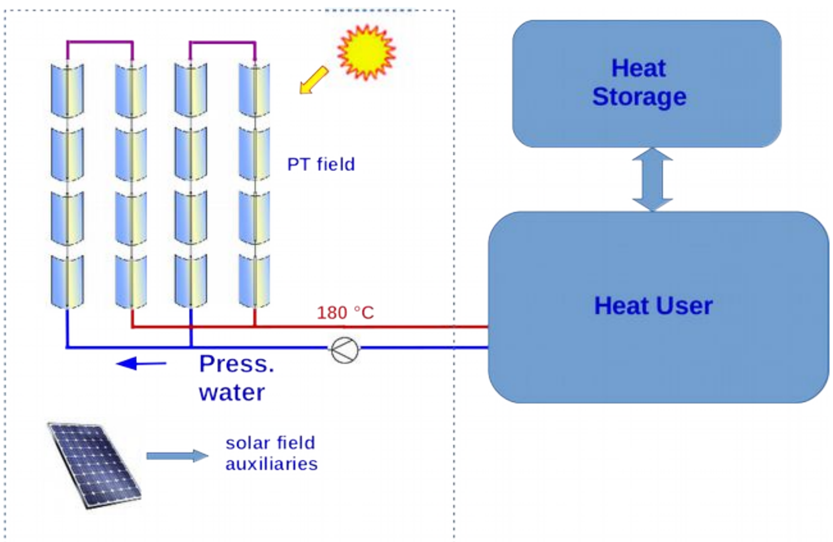

Fig 7A - PT plant (water)

10 HTF: Heat Transfer Fluid

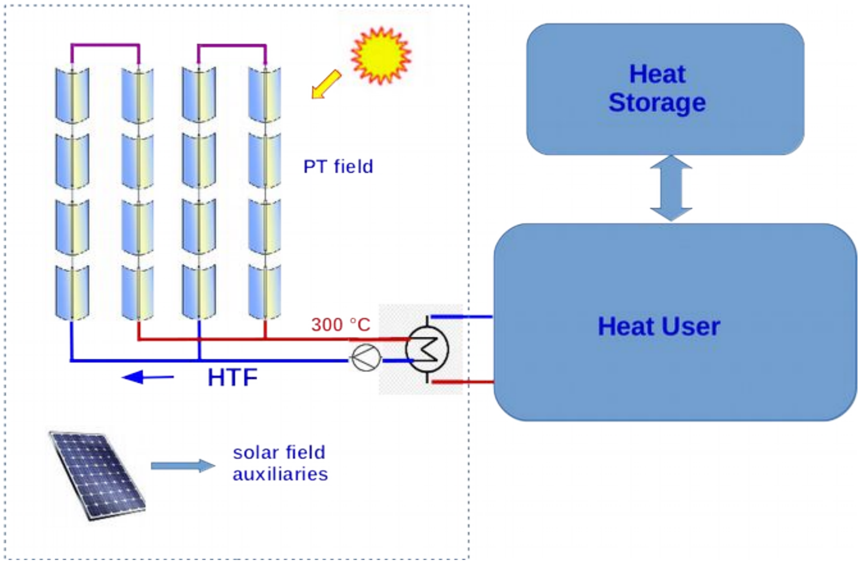

Fig 7B - PT plant (intermediate HTF)

When ambient temperature goes below the water freezing point some sort of countermeasures should be used to prevent damages. If it is not possible to heat up the tubes, by electrical means or with forced flow of warm fluid, one should need emptying the tubes.
Oil HTF has a higher freezing point (10 – 15 °C). However, the standard recovery procedure foresees heating up the oil with the first available solar radiation of the day.
The mirror field of the reference plant has been sized to give ~2.5 MW peak thermal power. This is obtained with the use of 6 “standard” PT collectors (6m wide, 100m long)

Cumulative active collector area	3600 m^2
total tube length	600 m
Mirror efficiency (reflectivity & dusting)	0.81
avg. HCE losses	100 W/m

A second solution using an LFR collector field has been analyzed, depicted in fig 7C. The area of the LFR field has been adjusted in order to give, using the same TMY records, the same yearly energy output as the PT plant[11].

11 within 2%

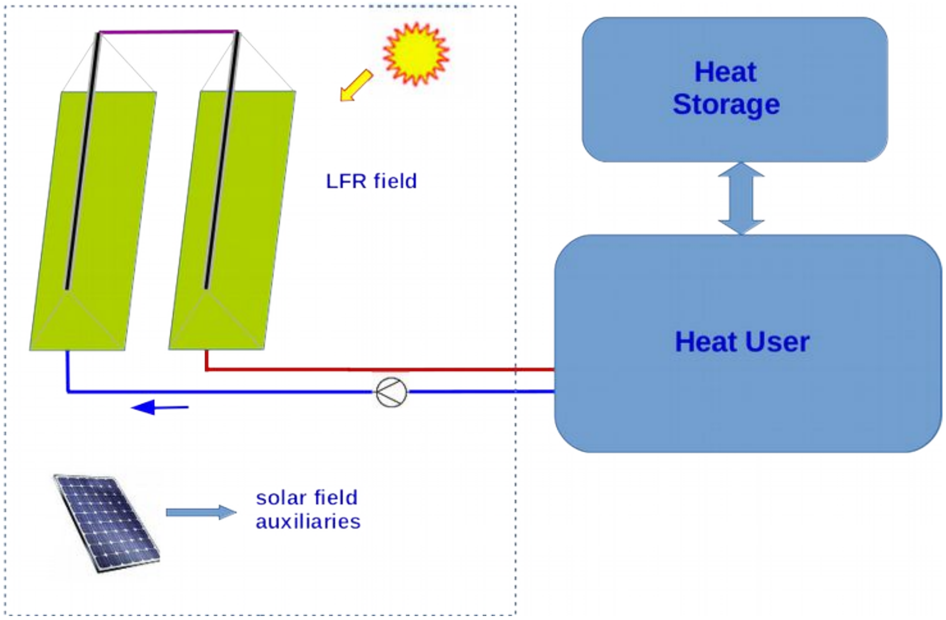

Fig 7C - LFR plant

The resulting plant is a 6400 m^2 collector built with two 200 m long sub-fields.
The plant is supposed to use the same HCE type of the PT plant. The LFR collector is 16 m wide with the receiver tube suspended 10 m above the mirrors.

Finally, an equivalent PV[12] plant has been envisaged, sized to produce the same yearly energy output as the reference PT plant. The yearly production of a PV plant (1000 kWh/kWp) has been derived from SOLARGIS[13] data, available for the selected location .
It is supposed that the whole energy output will be used in an electric heater to heat up the fluid in the end user application.
A further option foresees the use of a heat pump with COP=2[14].
The cost of the hardware of the CSP plants is practically the sole cost of the solar field. It is initially assumed that the cost of auxiliaries (inclusive of connecting pipes, pumps and valves as well as dedicated PV for the auxiliaries, if any) is negligible in respect of the solar collectors. However, the total cost is increased by 20% to take into account EPC cost for CSP plants.
A PV plant cost of 1100 €/kWp has been assumed. It includes all the auxiliaries and the electric heat generator as well as the EPC.
In case a heat pump is used the cost is increased by the cost of the heat pump equipment, which is assumed to be 200 €/kW [3].

12 PV: Photovoltaic
13 https://solargis.com/
14 COP=2 is considered a suitable value for a comparison of Heat Pumps with other CSP solutions with the same working temperatures.

Considerations about CSP solar field cost

Reliable recent data regarding the solar field cost are not easily available from the manufacturers. Nevertheless an analysis has been performed starting from all the available economic data regarding the most recent CSP plants built in China. They are expected to sufficiently reliable being based upon plants actually built and operating. They are also significantly lower than the cost experienced in the plants built in Europe and in other parts of the world as shown in fig 8.

A future development of CSP in Europe cannot avoid taking into account these new cost levels, which hopefully could have a dynamic not different from what happened since 2007 for PV panels.

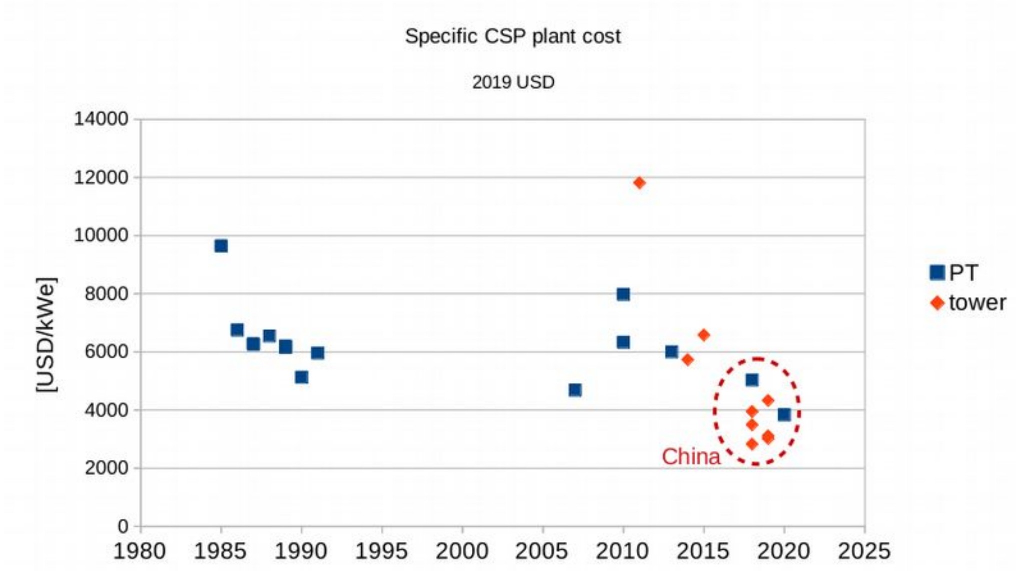

Fig 8 – CSP plant specific cost evolution

The data related to many Chinese CSP plants have been analyzed with a methodology explained in another document [5]. The results are summarized in TAB I with separate figures for low and high estimates,

The bottom line of the table is for an LFR plant using, instead of an evacuated tube HCE, a simple metal tube, or tube bundles, as seen in some manufacturers' designs. The future cost of the solar field for PT and LFR is expected to be nearer to the lowest of these figures.

However, as a result of the present global market difficulties, related mainly to the increase of transportation cost, but also to the manufacturing of some components, an increase of the prices could happen.

TAB I

Estimated solar field cost		
	High	**Low**
PT [€/m²]$^{(1)}$	248	212
LFR w HCE [€/m²]$^{(2)}$	126	91
LFR [€/m²]$^{(3)}$	103	82

Solar collector system efficiency

The optical efficiency of a PT collector system with a N-S axis is fundamentally different from an LFR one. The differences are due to the orientation of the reflecting structures which in the former case are reduced to a constant area surface, oriented normally to the plane of incoming solar beam radiation, while in the LFR case the equivalent reflecting surface has to be projected in a plane normal to the direction of the incoming radiation. The resulting IAM[15] of an LFR is always lower that of a PT (except at solar noon, at which time they have the same value). Moreover The IAM of a PT collector is exactly 1 when the sun azimuth is EAST or WEST, independently of the latitude. In the northern hemisphere this happens twice a day between spring and fall equinoxes. The yearly integral of AI for an LFR collector field is therefore always lower than that of a PT with the same reflecting area.
These consideration must be combined with the insolation data to compute the solar energy actually collected in both cases.
Anyhow, the total collector surfaces can be adjusted in order to obtain the same yearly integral value, with a surface of the LFR field adequately larger than the PT one.
If the LFR field cost is sufficiently lower than a PT, this is a cost effective solution.

Land cost

The cost of land in the location selected for this study is much higher than in low populated areas or semi desert lands where many CSP plants are normally built. This consideration, connected to the different land occupation of different solar technologies, leads to an additional adjustment of the techno-economical comparison.
Because of the high land occupation of PV panels in respect of CSP, for the same collected solar energy, higher land cost will penalize PV applications.
The cost of land in the Netherlands can be as high as 50k€/ha to 80 k€/ha (see fig. 9).

15 IAM: Incident Angle Modifier

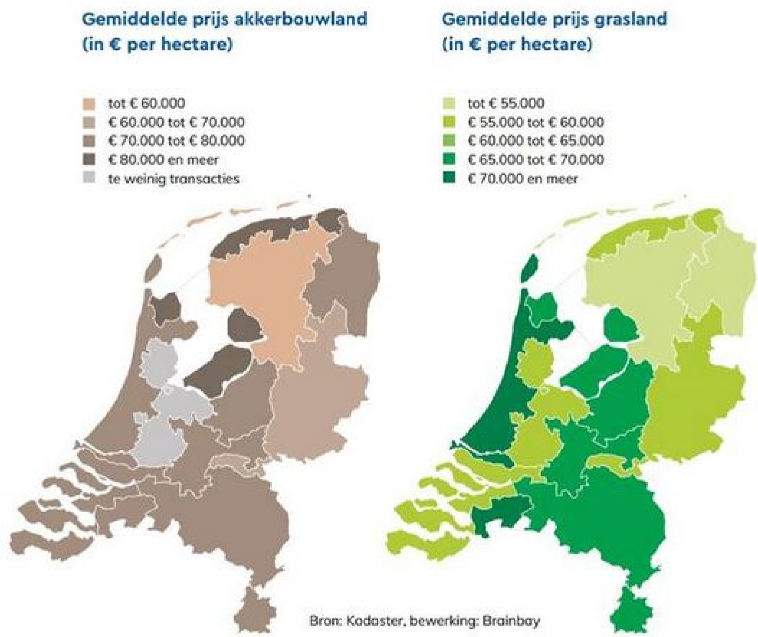

Fig 9 - cost of land in The Netherlands[16]

Table II show the computed land occupation and the associated cost for the solar technologies considered here. Land occupation for a PV plant has been assumed 2.8 ha/MWp[17].

TAB II

Plant land coccupation and cost			
Plant	***Land occ. [ha]***	***Land cost [k€] @50 k€/ha***	***Land cost [k€] @80 k€/ha***
PT (reference plant)	0.72	36	57.6
LFR equivalent plant	0.64	32	51.2
PV equivalent plant	6.33	316	506
PV+HP equivalent plant	3.16	158	253

the equivalent plants produce the same yearly output energy as the reference plant

In fig 10 is shown the plant cost splitting between plant hardware, land and EPC. EPC is assumed to be 15% of investment for CSP and 10% for PV plants.[18]
Fig 10 is related to a 50 k€/ha land cost.

16 source: https://www.nvm.nl/agrarisch-landelijk/agrarische-grondprijzen/ (accessed 26/01/22)
17 This is computed for the latitude of the selected location, with a 14% PV panel efficiency.
18 the EPC is calculated excluding the land cost

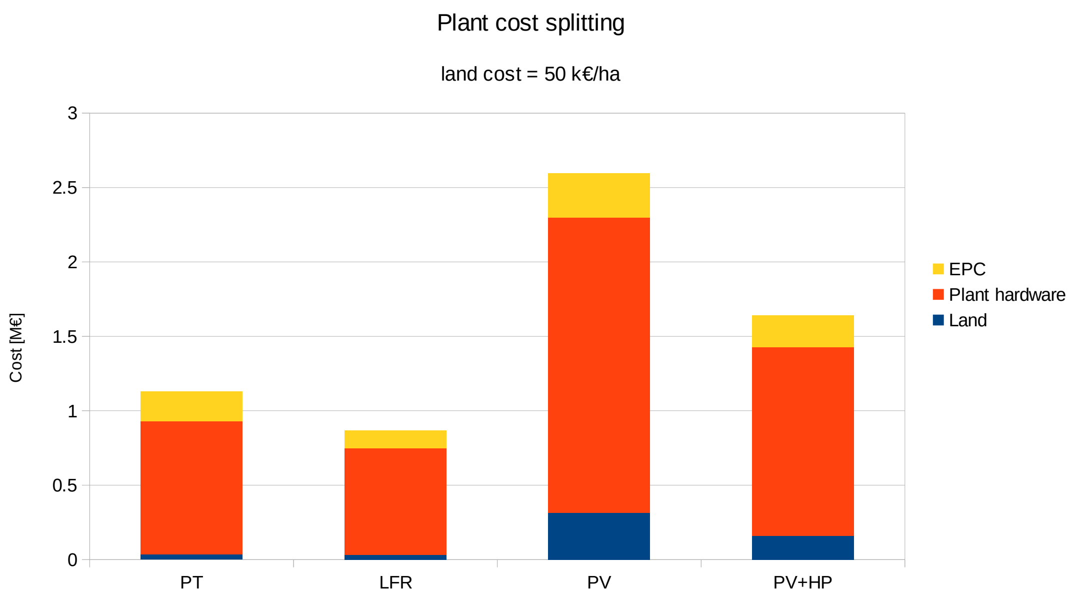

Fig 10 Plant cost splitting

Results

The simulation results are summarized in tables TAB II to TAB V

TAB III

PT plant (reference)			
		High est.	**Low est.**
PT plant area	[m²]	3600	
DNI	[kWh/m²/y]	961	
harvested solar energy	[MWh/y]	3459	
PT plant net energy out	[MWh/y]	2202	
yearly avg. collector field efficiency		0.64	
PT collector cost	[€/m²]	248	212
estimated PT plant cost	[M€]	1.070	0.879
estimated land cost	[M€]	0.032	0.032
Total cost	[M€]	1.103	0.911
LCOH (3)	[€/kWh]	0.042	0.034

TAB IV

LFR plant					
		High est.		**Low est.**	
		HCE	**Tube**	**HCE**	**Tube**
LFR plant area	[m²]	6400			
DNI	[kWh/m²/y]	961			
harvested solar energy	[MWh/y]	6149			
LFR plant net energy out	[MWh/y]	2180			
yearly avg. collector field efficiency		0.34			
LFR field cost	[€/m²]	126	103	91	82
estimated fresnel plant cost	[M€]	0.821	0.756	0.671	0.606
estimated land cost	[M€]	0.030	0.030	0.030	0.030
Total cost	[M€]	0.851	0.786	0.701	0.636
LCOH (3)	[€/kWh]	0.032	0.030	0.027	0.024

TAB V

PV plant		
PV plant size	[kWp]	2202
PV plant energy out	[MWh/y]	2202
PV cost	[k€/kWp]	1100
estimated PV plant cost	[M€]	2.144
estimated land cost	[M€]	0.316
Total cost	[M€]	2.460
LCOH (3)	[€/kWh]	0.099

TAB VI

PV plant (With heat pump)		
Heat pump COP		2
PV plant electric energy out	[MWh/y]	1101.0
PV plant size	[kWp]	1101
PV cost	[k€/kWp]	1100
estimated PV plant cost	[M€]	1.267
estimated land cost	[M€]	0.157
Total cost	[M€]	1.423
LCOH (3)	[€/kWh]	0.057

TAB VII

(3) LCOH conditions			
		PT/LFR	***PV***
interest rate		5.00%	5.00%
O&M (fraction of initial inv. per year)		2.00%	1.00%
Plant life	[y]	30	25

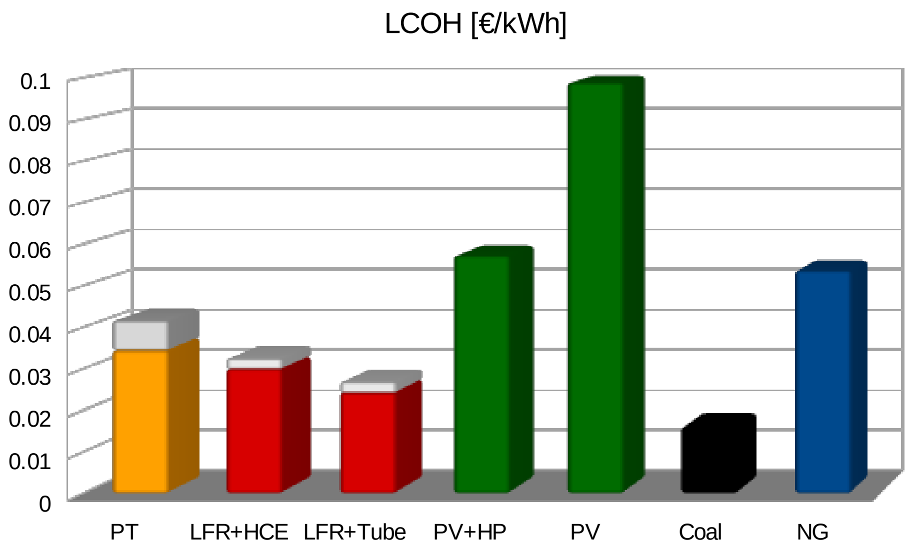

Fig 11 - LCOH comparison

The LCOH[19] of the different solutions has been computed together with those of conventional boilers using Coal and Natural Gas[20]. All the LCOH values do not take into account any heat storage device which could be necessary in case the user process needs a steady state heat supply. Although the LFR plant energy conversion efficiency is lower than the PT plant and it requires a larger mirror area, the much lower mirror field specific cost, makes this solution the most attractive, with an LCOH value around 2.4 Euro cents/kWh.

This value is to be compared with LCOH typical values from Coal (1.6 cents/kWh[2])[21] and Natural Gas (5.4 cents/kWh).

NG LCOH has been computed from NG prices as of June 2021 (TTF gas index), before the last huge increase in fuel prices[22], that hopefully will be recovered.

Fig 11 shows the overall LCOH comparison. The white areas on the top of PT and LFR columns are the spread between the "low" and "high" solar field cost estimates.

Among all the analyzed options, LFR plant is therefore the best one, although the windy site could force to peculiar design choices that could slightly rise the investment.

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19 LCOH: Levelized Cost Of Heat

$$LCOH = \frac{I_0 + \sum_{i=0}^{N} OM/(1+r)^i}{\sum_{i=0}^{N} E_i/(1+r)^i}$$

20 All the LCOH values do not take into account any heat storage device which could be necessary in case the target process needs a steady state heat supply

21 Coal prices had a peak at 3.9 Euro cents/kWh in Jan 2022

22 computed LCOH for NG had a peak of about 22 Euro cents/kWh in December 2021 and is presently at 12 Euro cents/kWh

A preliminary evaluation for the selected site shows that roughly 9% of the total collectible solar energy is lost due to loss of efficiency or even forced shutoff of the mirror field due to the wind conditions in a PT plant. This would rise the LCOH values for these PT plants by 10%, which, however, does not modify substantially the above considerations. The effect of wind on LFR plants should be much less than that of PT. This case should be analyzed in much more detail prior to compute the final economic convenience.

Among the solar plants dedicated to deliver process heat, those using PV have the lowest economic convenience, even if coupled with a heat pump equipment.

Although the DNI of the site is not exciting, the use of a CSP plant to obtain process heat is economically convenient in respect of the use of Gas.

Conclusions

The use of CSP plants to harvest solar thermal energy to be used as process heat at intermediate temperature levels (180 – 300 °C), with DNI values experienced in the Netherlands, at high latitude, is a viable option.

Both PT and LFR technologies are offering LCOH values much lower than Natural Gas fired boilers.

With the present high coal prices[21] the LFR solution is preferable even when compared with Coal fired boilers.

Special attention should be given to the mechanical design of the CSP in order to account for the wind, whose intensity at the selected location is generally high and long lasting.

LFR technology is the solution which offer the best economic opportunity with an LCOH value roughly less than one half of a Natural Gas fired boiler, with values down to 2.4 Euro cents per kWh.

PV technologies have LCOH values always higher than a CSP. Even if coupled with a heat pump, the resulting LCOH value is much higher than a PT plant, and 4 times higher than an LFR plant.

The DNR of the site is good, with excellent sky clearness, but even in sunny days it is rather discontinuous, due to very frequent cloud passing events. If a steady state heat production is needed a suitable heat storage system is to be provided, together with an adequate sizing of the solar field.

References:

[1] Eckhard Lüpfert et al. - “Experimental Analysis of Overall Thermal Properties of Parabolic Trough Receivers” - Journal of Solar Energy Engineering - MAY 2008, Vol. 130 / 021007-1

[2] Victor Nian a, * Qie Sun b Zhanyu Ma c Hailong L - “A comparative cost assessment of energy production from central heating plant or combined heat and power plant” - CUE2016-Applied Energy Symposium and Forum 2016:

[3] Paul Scheihing, “High Temperature (Industrial) Heat Pumps: An Untapped US Industrial Process Energy Efficiency Opportunity” - Low Temperature Industrial Processes Workshop, February 3, 2021

[4] Johan Lilliestam et al. “The Dragon Awakens: Will China Save or Conquer Concentrating Solar Power?” July 2019 AIP Conference Proceedings 2126(1):130006

[5] G.Liberati “Evaluation of most recent PT and LFR solar field cost”