Approach for a quick Pre-Dimensioning of solar process heat plants and implementation within the new VDI-Standard "Solar Thermal Process Heat"

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Abstract

The economic and ecological potential of solar process heat plants is far from being reached and mostly not known by decision makers in industry and commerce. Additionally, just a small number of engineers, energy managers, and consultants are familiar with solar process heat and its feasibility assessment. To counteract these aspects, a new standard for solar process heat systems was developed by the VDI (Association of German Engineers). This standard, which is also available in English, contains an approach for a fast feasibility assessment including pre-dimensioning and yield estimation without the need of additional tools. Furthermore, the complete planning process of solar process heat plants is specified according to the German HOAI (a legal honorarium regulation for architects and engineers) including an LCOH calculation.

Keywords: solar process heat, pre-dimensioning, planning guideline, standard

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1. Introduction

Solar process heat shows a large potential for a cost-effective decarbonisation of low temperature heat supply in industry, agriculture, and commerce. Despite a relatively small number of implemented plants, many case studies in different research projects (e.g. SolarAutomotive, EnPro or SolFood) showed that the levelized costs of heat (LCOH) using national subsidy programs are in most cases already competitive to fossil heat generation plants. Nevertheless, the potential for solar process heat is far from being reached and the market development is visible but still much too slow.

Several reasons can be found why the number of existing solar process heat plants falls far short of expectations. One finding of numerous case studies and ongoing communication with decision makers, energy managers, and planers is that both the energetic and economic potential of solar process heat for specific companies is widely underestimated. In order to assess the potential impact of a solar process heat plant without any cost intensive system simulations or time-consuming estimations, a standardized approach for pre-dimensioning with easy-to-use rules of thumb is needed. The pre-dimensioning is the basis for an economic assessment and subsequently the decision making by the customer. A validated methodology for a preliminary design of solar process heat plants was developed by Lauterbach (2014). This methodology was transferred to an easy-to-use online tool (http://designtool.solar4industry.info/) and additionally implemented within the new VDI (Association of German Engineers) standard 3988 "Solar thermal process heat", which will be published mid of 2019 (VDI, 2018). Main target groups of the VDI guideline are energy consultants and end-user companies, which do not have deeper knowledge about solar heating plants.

Kommentiert [FP1]: To reviewer 2: Sorry to hear, that the tool did not work properly for you. I just checked the link with some random inputs and it works fine for me (perhaps you can send me a screenshot or at least the browser used, perhaps there is a bug with some browsers we don't know yet?!).
The output is given on the right site in an extra table. It is changing with the input data.
The methodology described within the paper is valid for both, the VDI and the tool. The VDI works based on diagrams, the tool with interpolations based on table values in the background.

2. Prerequisites and necessary data basis for the planning of solar heating plants

For the implementation of solar heating plants several prerequisites should be met. Firstly, suitable set-up areas for the collectors should be available. In ideal cases, there are free unshaded ground areas that are not reserved for production extensions. If not, also roof areas can be used. A roof statics analysis is mandatory during the planning phase. In addition, the area to be used should be close to the selected integration points. Long pipes

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increase heat losses as well as costs and subsequently decrease solar yield and economics. This is particularly relevant for small solar heating plants (smaller than 100 m²) where the pipe length should be below 30 m.

Secondly, the company must have a relevant heat demand during summer times which is existing at least four days a week. The heat demand should be on a suitable temperature level and thus being below 150 °C or even better below 100 °C (for European regions). With appropriate technical effort, also higher temperature could be provided if there is a relevant share of beam irradiation available at the referring location.

Finally, the company should be aware and accept that in general typical payback periods in Industry of up to three years are not possible with solar heating plants. Nonetheless, due to the long operation time of solar heating plants, attractive interest rates are achieved which allows the companies to perceive solar heating plants as an investment to strengthen its competitiveness. The other way around, there is an increasing market for ESCO models which makes it possible for the companies to profit from low heat costs and a greener production without any investment. Within the preliminary analysis of the company, it is important to collect all relevant data regarding the implementation of solar heating plants. Technically, this refers to the installed fossil heat generation unit(s), the heating network, the heat consumption, and the subsequent processes needing heat. Table 1~~Table 1~~ can be used thereby as guideline for the data to be assessed.

Integration concepts

Based on the gathered information, a suitable feed-in point must be identified. In general, a distinction must be made between the central (Fig. 1, left) and the decentral or distributed (Fig. 1, right) integration. The even load profile at a central integration must be challenged with the highest temperature which is determined by the process with the highest temperature requirement. In contrast, the decentral integration can require more piping and integration effort.

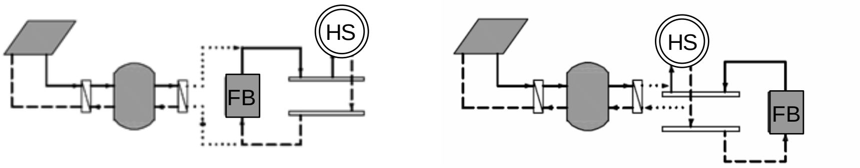

Fig. 1: Integration of a solar heating plant in the central (left) and distributed (right) level of a heat supply system, HS: heat sink, FB: fossil boiler (VDI, 2018)

Depending on the existing heat supply equipment, solar heat can be integrated in different ways. Basically, a distinction can be made between parallel and serial integration of solar heat in the existing system. With parallel integration (Fig. 2, left) a part of the returning heat transfer medium is heated by the solar heating plant to the required supply temperature and fed in again downstream of the heat generator. With serial integration (Fig. 2, right) the return flow from the conventional heat supply system is preheated with solar thermal energy before the boilers lifts the stream up to the set temperature.

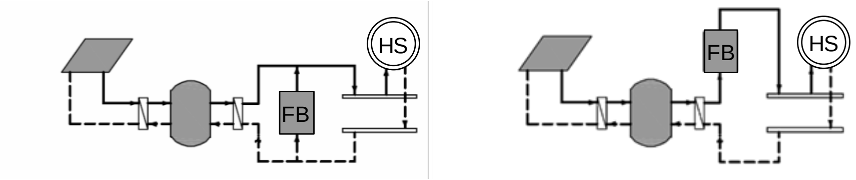

Fig. 2: Parallel (left) and serial (right) integration of the solar heating plant in the existing system (central integration), HS: heat sink, FB: fossil boiler (VDI, 2018)

The best choice for the integration point is very often not apparent and has to be balanced between the feed-in temperature, the load profile of the heat sink, and the integration effort.

Table 1: Checklist and data acquisition questionnaire with exemplary filled information (VDI, 2018)

Nr.					
0	Contact data	*Tank Cleaning "Spic & Span"*			
		Industrial Park 1, Clean City			
	Sector	☐ Industrial ☒ Commerce ☐ Agricultural ☒ Eligibility for assistance checked ☒ Conditions for assistance met			
1	Prerequisites	☒ Suitable roof surfaces and unoccupied plots available ☒ Temperature level and summer heat requirements are suitable ☒ Reasonable distance between solar plant and feed-in point ☒ Investment expectations/opportunities of company queried			
2	Energy consumption	☒ Energy consumption figures available at least in monthly resolution ☒ Production times known (company holiday, shifts, weekend) ☒ Cost of employed sources of final energy known			
3	Heat generator	☒ Technical data, number and type of existing heat generators ☒ Operating temperature and pressure ☒ Hydraulic integration			
4	Heat distribution	☒ Heat transfer medium, temperature, pressure ☒ Operating times in the summer ☒ Hydraulic circuitry and connection of heat sinks			
5.1	Heat sinks, central	**No.**	**Z1**	**Z2**	**Z3**
		Designation	*Flow heating circuit*	*Return flow heating circuit*	–
		Required temperature	*120 °C*	*90 °C*	–
5.2	Heat sinks, distributed	**No.**	**D1**	**D2**	**D3**
		Designation	*Building heating system*	*Dishwasher*	*Water heating system*
		Required temperature	*60 °C*	*80 °C*	*60 °C*
		No.	**D4**	**D5**	**D6**
		Designation	*Dryer*	–	–
		Required temperature	*140 °C*	–	–
6	Possible feed-in points for solar heat	**No.**	**Z2**	**D1**	**D3**
		Designation	*Return flow heating circuit*	*Building heating system*	*Water heating system*
		$T_{\text{flow/return}}$ **of conventional heating**	*120 °C/90 °C*	*120 °C/90 °C*	*120 °C/90 °C*
		Running time per day/week/year	*Continuous*	*Daily October–April*	*Mo–Fr*
		Heat demand on summer days	*about 2500 kWh/d*	*No summer heat requirement*	*1200 kWh/d*
		Possibilities for integrating solar heat	*Return flow boost*	*Return flow boost in building heating circuit*	*Cold water heating and feed-in into existing storage units*
		Distance to solar plant or storage unit (one way)	*10 m*	*20 m*	*30 m*
		Required temperature T_{set}	*100 °C to 130 °C*	*70 °C*	*20 °C to 70 °C*
		Max. time without heat consumption	*A few hours on weekends*	*Summer half year*	*Friday midday to Monday morning*
		Additional equipment for integration of solar heat	*Heat exchanger (WÜT) and valves/fittings*	*WÜT and valves/fittings*	*WÜT and valves/ fittings, possibly addl. storage unit*

3. Quick dimensioning approach

Especially in industrial and commercial applications, solar heat must compete with low conventional heat generation costs. To gain the maximum specific solar yield and thus the minimum solar LCOH, the solar process heat system should not produce any surplus of heat.

The design approach of the VDI 3988 is oriented on the proven approach of the VDI 6002 (Solar heating for potable water in residential buildings as well as student and retirement houses, hospitals, swimming halls, and camping sites). The solar collector area is sized to fully cover the heat demand of a typical sunny summer day at the selected integration point(s). This way, solar excess heat and stagnation are reduced to weekends or other low heat demand periods (company holidays or maintenance). Consequently, the approach enables high specific solar yields. By contrast, the possible solar fractions of this approach are comparable low. In general, this is not too much of an issue because suitable areas to situate the collectors are quite limited in Industry anyhow. At this point, it is highlighted, that the calculated collector area just indicates a first rough guess. It does not replace detailed planning in terms of simulation and optimization of the system.

With the exception of ambient temperature, a sunny summer day is comparable all over the world with a solar irradiation of 7..8 kWh/(m²·d) reaching the tilted and well oriented collector area. For that reason, the presented methodology can be used with just little modifications regarding the location all over the world. Depending on the temperature, 3..4 kWh/(m²·d) can be provided by the solar thermal system to the processes. This value is defined as dimensioning factor f_{col} (see paragraph Collector array area estimation and eq. 2).

In the same way, the presented methodology can be used independent of the heat sink or integration point. Solely, the temperature level and the load profile (5- or 7-day heat demand) influence the dimensioning and yield estimation and make the approach quite flexible.

Mean collector temperature

The central parameter in the quick dimensioning approach is the mean collector temperature ($T_{col,m}$). It is defined as follows.

$$T_{col,m} = \frac{T_{hs,flow} + T_{hs,return}}{2} + n \cdot 5K \qquad \text{(eq. 1)}$$

It represents the arithmetic mean of the flow and return temperature of the heat sink (hs). Considering the temperature drop at the heat exchangers, an additional temperature difference of 5 K per number n of the required heat exchangers between collector and heat sink is added. To give an example, a typical hot water heating process is considered. The cold-water temperature is assumed with 10 °C. The set temperature is 60 °C. In a typical solar heating plants, two heat exchangers are included in the hydraulic system, separating the collector loop and the storage charging loop as well as the storage discharging loop and the heat sink. with the given example a mean collector temperature of 45 °C is obtained.

Collector choice

Typically, the collector type is mainly chosen based on the temperature level which must be reached. For solar heating plants, the same standard collectors as for residential applications can be used. Alternatively, there are also special collector constructions with larger collector areas. This reduces the implementation effort due to scaling effects.

Flat-plate collectors (FPC) are the first choice for preheating processes. They can efficiently supply heat up to process temperatures about 80 °C. Due to their simple but robust design, they have a good price-efficiency ratio. If higher temperatures must be reached, flat-plate collectors with an additional glass cover or foil, reducing heat losses, are available on the market. These flat-plate double glass collectors (FPC-DG) are well suited for a temperature range of up to 100 °C.

If higher temperatures must be provided, evacuated tube collectors (ETC) should be used. The improved insulation enables temperatures up to 120 °C being reached with a feasible efficiency. If the collectors are equipped with a mirror on the reverse even higher process temperatures up to 150 °C can be provided (CPC).

Concentrating collectors, such as Fresnel or Parabolic trough (PTC), deliver process heat in form of steam with working temperatures between 150 and 400 °C. The VDI guideline addresses mainly the low temperature heat demand up to 150 °C. In addition to the fact, that there is only little experience with concentrating collectors in Europe with respect to standardised dimensioning and yield estimation, these collectors are only slightly treated within this guideline. This is likewise for solar air collectors which can provide hot air up to 60 °C (FPC) or up to 120 °C (ETC).

Collector array area estimation

As mentioned in the beginning, the daily heat demand in summer ($Q_{d,summer}$) is a key parameter for the dimensioning of collector gross area (A_G) and storage. The heat demand must be determined for a representative (production) day in summer. Typically, this is in average value over a longer period. Single days with significantly lower heat demand do not have to be taken into account.

The maximum possible solar collector area ($A_{col,0}$) with minimized heat surplus is determined by the following eq. 2. It represents an easy summer-working-day based energy balance between the heat consumption and the possible solar heat production.

$$A_{col,0} = \frac{Q_{d,summer}}{f_{col}} \qquad \text{(eq. 2)}$$

The dimensioning factor f_{col} is depending on the temperature level which must be reached and the collector type. It indicates the solar heat that the chosen collector can provide based on temperature level per square metre gross area. This factor is based on numerous simulations of solar heating plants for different temperatures levels, load profiles and locations (Lauterbach, 2014). Based on the calculated mean collector temperature, the dimensioning factor f_{col} can be determined by Fig. 3 (Central and Northern Europe) and Fig. 4~~Fig. 4~~ (Southern Europe). With increasing collector temperature, the specific dimensioning factor is decreasing as the collector can provide less heat due to higher heat losses. Due to the higher irradiation in Southern Europe compared to Central and Northern Europe, the solar collector can provide more heat. Thus, the specific dimensioning factor is slightly higher for Southern European countries.

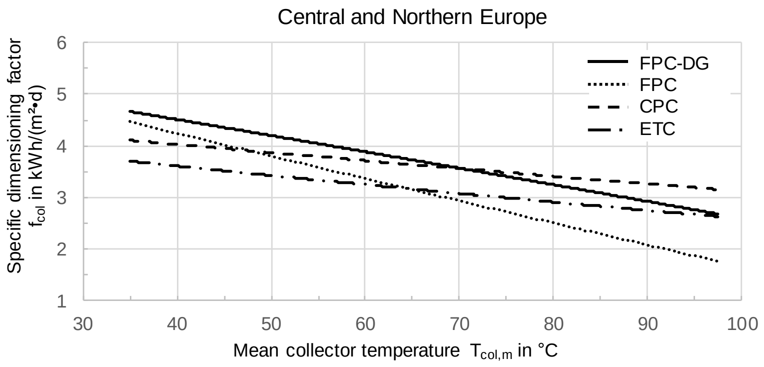

Fig. 3: Specific dimensioning factor f_{col} in kWh/(m_G^2·d) for locations in Northern and Central Europe as a function of mean collector temperature $T_{col,m}$ on the basis of Lauterbach (2014) and Solar KEYMARK test results (VDI, 2018)

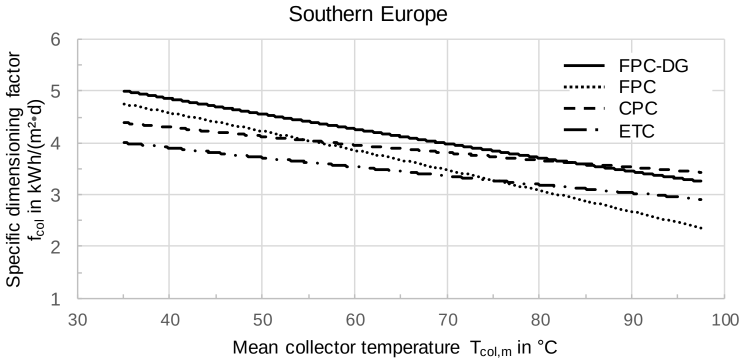

Fig. 4: Specific dimensioning factor f_{col} in kWh/(m_G^2·d) for locations in Southern Europe as a function of mean collector temperature $T_{col,m}$ on the basis of Lauterbach (2014) and Solar KEYMARK test results (VDI, 2018)

The dimensioning factor and subsequently the collector area are determined for an ideal orientation to south and a collector slope of 35 °, which is a reasonable compromise for European regions. Nevertheless, also other orientations and slopes must be taken into account, which can be done by the correction factor $f_{NA,col}$ in Fig. 5~~Fig. 5~~. With increasing collector slope, the collector area must be increased disproportionately due to the high altitude of the sun and the reduced performance of the collector on a sunny summer day.

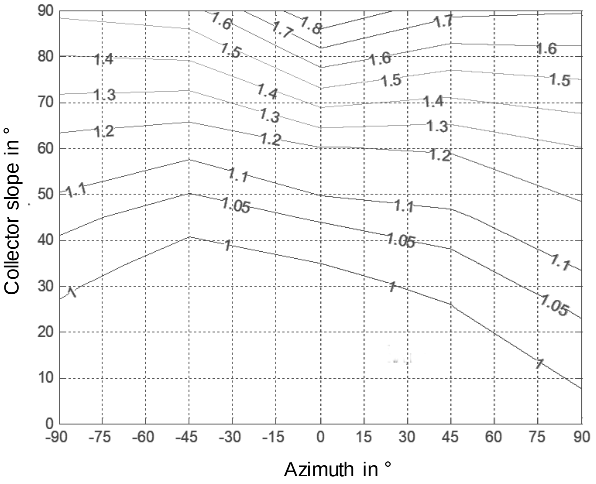

Fig. 5: Correction factor $f_{NA,col}$ in dependence of collector slope and azimuth (VDI, 2018)

The final collector gross area can be determined as follows.

$$A_{col} = A_{col,0} \cdot f_{NA,col} \qquad \text{(eq. 3)}$$

Buffer storage sizing

The buffer storage should be dimensioned so that it could store the possible solar yield of at least one day. This way, the solar yield of a sunny week-end day with low or no heat demand could be made available for the following production day with relevant heat demand. Still, the load profile of the heat demand has an influence on the suitable storage size. Therefore, the VDI 3988 provides the following rule of thumb for the first approximation.

Table 2: Specific storage volume $v_{St,spec}$ for preliminary dimensioning of the solar buffer storage unit (VDI, 2018)

Specific storage volume $v_{St,spec}$	**Properties of heat sink**	**Example**
0 ℓ/m^2	• Continuous load in weekly and daily profile • Always complete uptake of the useful solar thermal yield	District heating feed-in with solar fractions < 10 %
50 ℓ/m^2	• Inlet temperature from heat sink at cold water temperature • Required temperature, heat sink, 50 °C to 70 °C • Weekly profile: continuous, 7-day week	Heating of drinking water, preheating of boiler make-up water, daily cleaning processes
75 ℓ/m^2	• Inlet temperature from heat sink at cold water temperature • Required temperature, heat sink, 50 °C to 70 °C • Weekly profile: 5-day week	Cleaning processes on workdays, heating backup
100 ℓ/m^2	• Inlet temperature from heat sink between 20 and 60 °C • Weekly profile: 5-day week • Required temperature, heat sink > 70 °C	Heating of electroplating baths
> 100 ℓ/m^2	• Required temperature, heat sink, higher than 60 °C • Only for extreme consumption peaks	Special cleaning processes

The absolute storage volume can be calculated by multiplication with the determined collector area A_{col}.

$$V_{St} = A_{col} \cdot v_{St,spec} \qquad \text{(eq. 4)}$$

If possible, this volume should be realized with one storage. Sometimes, the conditions on site impede this and the volume has to be divided into several storages. In this case, the storages should be connected in series. It is strongly recommended to avoid more than three storages.

4. Yield estimation

The solar yield can be estimated with the mean collector temperature and the collector type by Fig. 6~~Fig. 6~~ (Central and Northern Europe) and Fig. 7~~Fig. 7~~ (Southern Europe) analogously to the dimensioning factor f_{col}. The result q_{ACO} is based on representative collector data from the Solar KEYMARK test results and 35 ° tilted and south oriented collector area. So, it represents the specific solar yield providing heat for an ideal heat sink which has unlimited heat demand at every hour of the year.

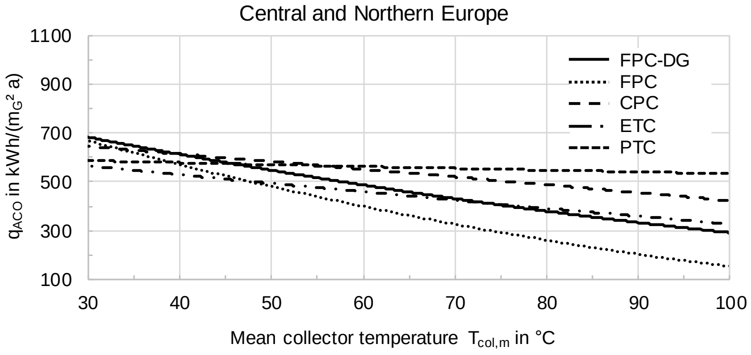

Fig. 6: Annual specific collector output q_{ACO} at constant mean collector temperature $T_{col,m}$ for Central and Northern Europe (tilt 35°, orientation south), in relation to collector area A_G (VDI, 2018)

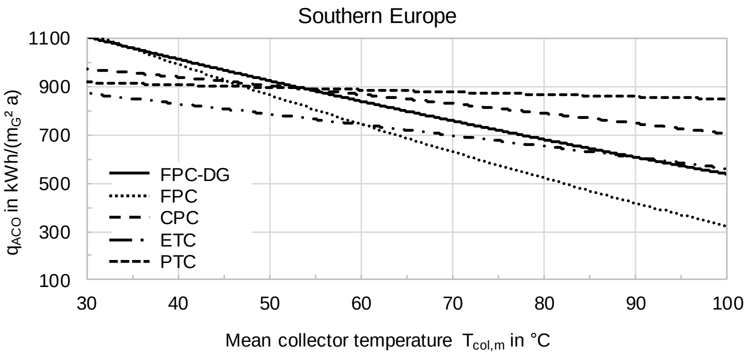

Fig. 7: Annual specific collector output q_{ACO} at constant mean collector temperature $T_{col,m}$ for Southern Europe (tilt 35°, orientation south), in relation to collector area A_G (VDI, 2018)

Typical heat sinks in Industry and Commerce are not ideal and have a specific load profile, especially during the week. Therefore, the correction factor f_{ACO} is introduced (Fig. 8~~Fig. 8~~). The correction factor f_{ACO} is always smaller than 1 because it does not only consider realistic load profiles but also heat losses (storage, pipes). With increasing process (and therefore collector) temperatures, f_{ACO} is decreasing due to increasing heat losses. Regarding f_{ACO}, it is differentiated between a 5-day- and 7-day-week which is referring to the heat load profile. Very often in Industry, there is only a relevant heat demand on five days a week. During weekend, there is only a comparably small base heat load. If the company only has a relevant heat demand on five days a week, the correction factor decreases significantly compared to a 7-day-week. This is based on the surplus of heat at a weekend which cannot be stored because of the dimensioning of the storage just for one day. With higher mean collector temperatures up to 100 °C, the difference between 5- and 7-day-week reduces. This is the consequence of the decreasing heat capacity of the storage. In consequence, the missing heat demand at weekend in a 5-day-week gets less important than the heat losses by storage and pipes.

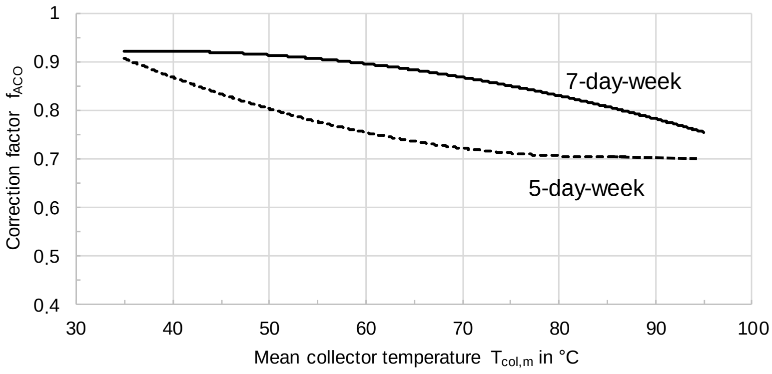

Fig. 8: Correction factors f_{ACO} for European locations as a function of the mean collector temperature $T_{col,m}$ and the weekly load profile on the basis of Lauterbach (2014) and Solar KEYMARK test results (VDI, 2018)

The effective useful specific solar yield can be determined as follows.

$$q_{sol,0} = q_{ACO} \cdot f_{ACO} \qquad \text{(eq. 5)}$$

Analogously to the dimensioning, the orientation of the collector field has to be considered here too. Therefore, the correction factor $f_{NA,sol}$ is introduced. It can be determined by Fig. 9~~Fig. 9~~ using the respective azimuth and slope.

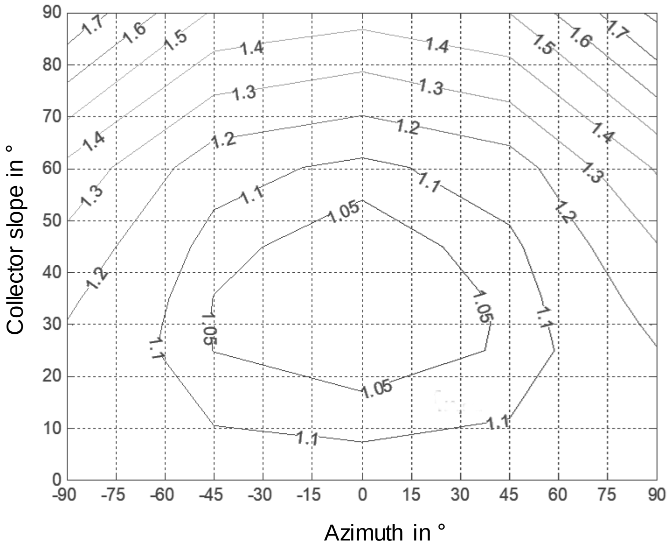

Fig. 9: Correction factor $f_{NA,sol}$ in dependence of collector slope and azimuth based on ScenoCalc-data (VDI, 2018)

The solar yield can be calculated by eq. 6 as follows.

$$q_{sol} = \frac{q_{sol,0}}{f_{NA,sol}} \qquad \text{(eq. 6)}$$

The absolute solar yield can be calculated by multiplication with the solar collector area.

$$Q_{sol} = q_{sol} \cdot A_{col} \qquad \text{(eq. 7)}$$

5. Calculation of LCOH

The calculation of the LCOH in the VDI 3988 is based on the VDI 2067 and VDI 6002 and therefore considers the demand-related costs, the operational costs and other costs like insurance. The approach is based on net present value factors for the depreciation period and the useful lifetime. In addition, the anticipated increase of the price of the fossil final energy source is included with a yearly rate.

Excluding the depreciation, the used approach leads to the same results as the calculation of the levelized costs of heat according to the IEA Task 54 (Louvet et al, 2019), which was designed for small residential applications where depreciation is not applicable. For industry and commerce in contrast, depreciation can be an important factor to make a decision for or against a solar process heat system, as the yearly depreciation rate decreases the companies' profit before taxes and is therefore leading to a lower tax burden.

The result of the used approach of the VDI 3988 reflects the total costs of the heat produced by the solar process heat system averaged over the systems useful lifetime. To achieve an economic feasible renewable energy system, the solar heat generation costs must be below the conventional generation costs. As solar process heat system does not substitute the installed capacity of the conventional heating system but is only a fuel saver, the investment costs of the conventional system are not considered.

Within the VDI 3988 the calculation is based on one equation (eq. 8) including three auxiliary variables (eq. 9, 10, 11).

$$k_{sol} = \frac{(1+c_1)\cdot K_{inv}+c_2-K_{sub}-c_3}{Q_{sol}\cdot b_{t_N}} \qquad \text{(eq. 8)}$$

with the auxilary variables

$$c_1 = f_{op} \cdot b_{t_N} \qquad \text{(eq. 9)}$$

$$c_2 = \frac{Q_{sol}}{PF_{sol}} \cdot k_{el} \cdot f_{el} \cdot b_{t_N} \qquad \text{(eq. 10)}$$

$$c_3 = DEP \cdot TR \cdot b_{t_{DEP}} \; with \; DEP = \frac{K_{inv} - K_{sub}}{t_{DEP}}. \qquad \text{(eq. 11)}$$

The calculation of the LCOH includes the investment costs (K_{inv}) as well as subsidies (K_{sub}). The variable c_1 represents the costs related to operation and maintenance. Typically, 1..2 %/a can be assumed regarding the factor f_{op}. Furthermore, $c_2$indicates the cost for electricity, using the solar seasonal performance factor PF_{sol} (70..100 for large plants), the specific price for electricity, and the interest rate for price increase (f_{el}). Finally, c_3 considers the depreciation within the calculation. DEP is the annual depreciation rate (only linear depreciation is considered) over the depreciation period t_{DEP}, which is given by national law. TR represents the tax rate (in %/100), which also is country specific.

The solar heat generation costs have to be compared with the average conventional costs (k_{conv}) over the same period. For this purpose, the following formula is stated by the VDI 3988 to calculate the conventional averaged heat costs under consideration of the annual utilization factor of the boiler (η_N , typically 70..85 %) for the conventional boiler and an anticipated price-increase rate for the respective fossil fuel (f_{foss}), whereas k_{foss}represents the actual specific price for the fossil fuel.

$$k_{conv} = \frac{k_{foss}}{\eta_N} \cdot f_{foss} \qquad \text{(eq. 12)}$$

As the calculation of LCOH is dynamic, the present-value factors have to be taken into account (b_{t_N}, $b_{t_{DEP}}$, f_{el}, f_{foss}). These factors are a function of the company specific yearly rate of return (i) and in case of f_{foss} and f_{el} also depending on the anticipated price increase. They can be found in a table given in the VDI 3988 for selected exemplary values or be calculated (see VDI 2067).

Subsequent to the economic comparison, the VDI 3988 offers an easy method to calculate the CO_2-emissions avoided by the solar process heating system. For this purpose, a table with CO_2-equivalents in kg/kWh is given based on the publications of the German Environment Agency.

6. Outlook

The new standard makes a fast and trustworthy feasibility assessment during just one phone call possible. The required data such as the daily heat demand of a selected heat sink is known by most facility managers or can easily be determined or estimated within a few minutes. This will help to spread the awareness of the economic and ecological potential of solar process heat systems. Additionally, the new standard will serve as a practical guideline for the whole planning and implementation process and therefore makes it easier for new players to enter the market.

The German subsidy program "Energy Efficiency and Renewable Process Heat in the Economy" (BMWi, 2018) contains all the relevant subsidies regarding energy efficiency and renewable heating systems for industry and commerce. As part of this, the turnkey costs of solar thermal, biomass, and heat pump energy systems receive subsidies of up to 55 %. To qualify for funding within this program, solar process heat plants must comply with the presented new VDI-standard.

In summary, the standard will help to increase the trustworthiness of solar process heat and could prove to be a decisive step towards a faster market development.

7. Acknowledgments

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9. Nomenclature

Abbreviations

FPC	Flat Plate Collector
FPC-DG	Flat Plate Collector Double Glazed
CPC	Compound Parabolic Concentrator
PTC	Parabolic Trough Collector
ETC	Evacuated Tube Collector
FB	fossil boiler
LCOH	Levelized Cost of Heat
VDI	Association of German Engineers
HOAI	honorarium regulation for architects and engineers
HS	Heat sink
ESCO	energy service company

Symbols

$A_{col,0}$	collector area (without correction factor for orientation), m²
A_{col}	collector area, m²
A_g	collector gross area, m²
b_{t_N}	present value factor over lifetime
$b_{t_{DEP}}$	present value factor over depreciation period

c_1	auxiliary variable
c_2	auxiliary variable
c_3	auxiliary variable
DEP	annual depreciation rate, €
f_{ACO}	correction factor for load profile
f_{col}	specific dimensioning factor, kWh/(m²d)
f_{el}	price increase factor electricity
f_{foss}	price increase factor fossil fuel
f_{op}	cost factor for operation and maintenance, %
η_N	annual utilization factor of the boiler, %
$f_{NA,col}$	correction factor for collector area for orientation
$f_{NA,sol}$	correction factor for solar yield for orientation
k_{conv}	levelized cost of conventional heat, €-Ct/kWh
k_{sol}	levelized cost of solar heat, €-Ct/kWh
K_{inv}	investment costs, €
K_{sub}	subsidies, €
n	number of heat exchangers
PF_{sol}	annual solar performance factor, kWh_{th}/kWh_{el}
$Q_{d,summer}$	daily heat demand in summer, kWh/d
Q_{sol}	estimated solar yield, kWh/a
q_{ACO}	estimated specific solar yield based on ideal heat sink, kWh/m²a
$q_{sol,0}$	estimated specific solar yield without corrector factor for orientation, kWh/m²a
q_{sol}	estimated specific solar yield, kWh/m²a
t_{DEP}	depreciation period, a
$T_{col,m}$	mean collector temperature, °C
$T_{hs,flow}$	flow temperature of the heat sink, °C
$T_{hs,return}$	return Temperature of the heat sink, °C
TR	tax rate, %
$v_{St,spec}$	specific storage volume, l/m²
V_{St}	storage volume, l