

Description:	<i>Guideline for levelized cost of heat (LCoH) calculations for solar thermal applications</i>
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Introduction

In the framework of the IEA-SHC Task 54 appeared the need of assessing the costs of the heat produced by solar thermal systems over their life time to compare different designs and technological solutions with one another. The levelized cost of heat (LCoH), a measure based on the concept of levelized cost of energy, widespread in the electrical power sector, was chosen. This info sheet builds on the work of the FRoNT project [1] which laid the foundations for the application of the method to any heating technology. It aims at detailing the methodology to calculate the levelized cost of the heat substituted by solar thermal energy ($LCoH_{sol,fin}$). Furthermore, an extension of the concept is suggested to estimate the cost of the heat generated by the overall solar assisted heating system ($LCoH_{ov,fin}$), or the conventional sources of heat supply ($LCoH_{conv,fin}$).

General formulation

The LCoH for solar thermal applications can be derived from the following formula, based on [1] and [2]:

$$LCoH = \frac{I_0 - S_0 + \sum_{t=1}^T \frac{C_t(1 - TR) - DEP_t \cdot TR}{(1 + r)^t} - \frac{RV}{(1 + r)^T}}{\sum_{t=1}^T \frac{E_t}{(1 + r)^t}} \quad (1)$$

Where:

$LCoH$: levelized cost of heat in €/kWh

I_0 : initial investment in €

S_0 : subsidies and incentives in €

C_t : operation and maintenance costs (year t) in €/a

TR : corporate tax rate in %

DEP_t : asset depreciation (year t) in €/a

RV : residual value in €

E_t : final energy (year t) in kWh/a

r : discount rate in %

T : period of analysis in year

Notes: 1) Equation (1) can be calculated either with a nominal or a real (adjusted for inflation of rate i) discount rate r . The cost variables C_t , DEP_t and RV have to be adapted accordingly. As a consequence two different LCoH values can be obtained, depending on the discount rate selected: the LCoH in nominal terms and the LCoH in real terms. The LCoH in nominal

terms is always larger than the one in real terms (as $r_{nominal} > r_{real}$, for $i > 0$). Further information concerning this topic is available in [2].

2) All costs are net costs (excluding VAT).

3) The final energy is the energy reaching the final consumer's door (here household); typically the gas or oil consumption of the boiler in the household.

Different LCoH values are achieved for different system boundaries

Three different LCoH values are calculated by IEA-SHC Task 54 considering only the solar part, only the conventional part and the overall solar assisted heating system (Figure 1) distinguished by using the following acronyms:

- **LCoH_{sol,fin}**: levelized cost of the heat substituted (saved) by the solar part of the solar assisted heating system. It is the main indicator of the Task and the methodology to calculate it is described in the details in the following sections. It allows for the comparison of different solar thermal system designs and technologies as part of the overall solar assisted heating system.
- **LCoH_{ov,fin}**: levelized cost of the heat generated by the solar assisted heating system. The overall heating system is considered here. This enables a comparison of the solar assisted heating system with other heating technologies.
- **LCoH_{conv,fin}**: levelized cost of the heat supplied by the conventional part of the solar assisted heating system. It can be easily derived from the data used to calculate the LCoH_{sol,fin} and the LCoH_{ov,fin}. The last section also clarifies the method to calculate it.

The index *fin* stands for final energy, considered at the denominator of the LCoH equation, to differentiate with other studies, using the solar collector yield or the useful (solar) heat for instance.

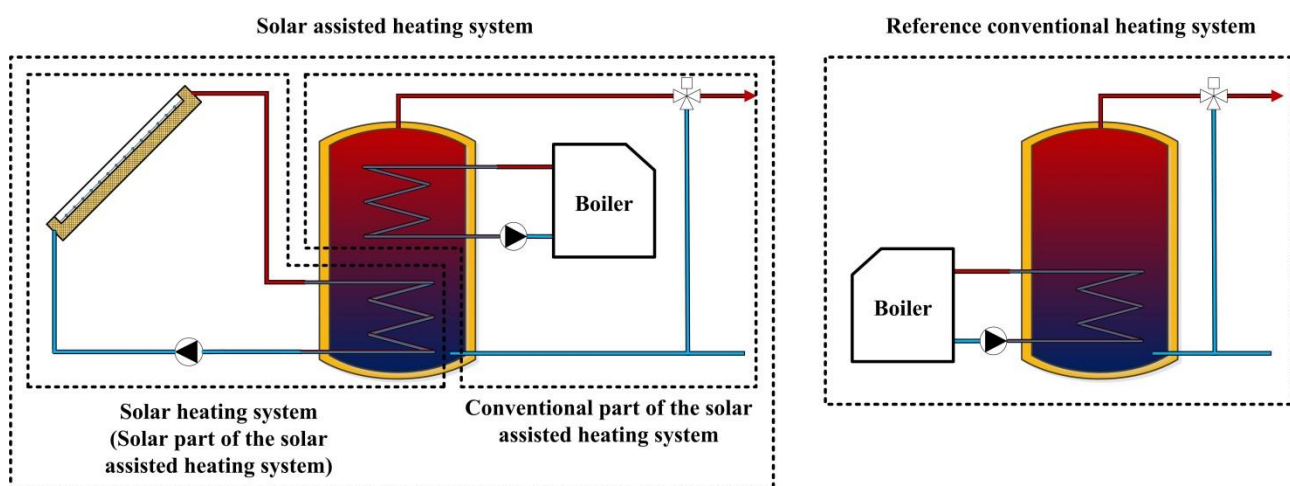


Figure 1. Schematic illustration of the terms describing the systems/system parts as considered in the Info Sheet.

Main assumptions for solar thermal applications

This section focuses on the cost of the heat substituted by solar thermal energy ($LCoH_{sol,fin}$). All cost variables (I_0 , S_0 , C_t , DEP_t and RV) only refer to the components dedicated to solar thermal heat production and integration, mainly collectors, buffer store, pumps, heat exchangers, pipe works, control unit and their installation.

The calculation of the $LCoH_{sol,fin}$ requires the definition of a reference conventional heating system (Figure 1). This conventional reference system is a heating system which would supply the same amount of energy to the end user as the solar assisted heating system, but without solar assistance. It is needed to calculate I_0 and the saved final energy E_t .

- Initial investment (I_0):
 - The cost of the storage from the conventional reference heating system and the associated installation costs SC should be subtracted from I_0 if applicable.
 - In case of building integrated solar thermal systems both for new buildings or building renovation, the cost of the building component (roof or wall section) substituted with solar thermal collectors and the associated installation costs should be subtracted from I_0 if applicable.
 - The size of the storage in the conventional reference heating system strongly depends on the application. Some guidelines might be used, as [3] for domestic hot water systems for instance.
- Subsidies and incentives (S_0):
 - The user might decide to include or not subsidies and other incentives in the calculation. In Task 54, subsidies are not considered as they vary from country to country.
- Operation and maintenance costs (C_t):
 - $C_t = O_t + M_t$ where O_t and M_t respectively corresponds to the operation and maintenance costs.
 - It is recommended to use a single fixed value for O_t and M_t (O and M):

$$C_t = O + M$$

- Operation costs (O) correspond to the power consumption of the pump and controller and depend on the electricity price, different from country to country. The running time of the pump can only be determined with numerical simulations.
- For refined calculations, it is possible to apply an electricity price index increase different from the inflation. In this case it is necessary to adjust the index for inflation if the cost variables are given in constant euros.
- Usually $0.01 \cdot I_0 < M < 0.02 \cdot I_0$ [4]. For a more detailed analysis, the values given in [5] might also be used.

- Corporate tax rate (TR) and asset depreciation (DEP_t):
 - Only apply to the industrial and commercial sectors. For the residential sector one should take $TR = DEP_t = 0$.
- Residual value (RV):
 - For residential solar thermal applications, the residual value is considered equal to zero: $RV = 0$. For the industrial and commercial sectors however positive values might be used.
 - To calculate RV , one should compare the period of analysis (T) and the technical lifetime of the different components. Each component having a different technical lifetime, its replacement should be taken into consideration when calculating RV . Typical values for assessing the technical lifetime of components might be found in [5] and [6].
- Saved final energy (E_t):
 - To allow for the comparison between different solar thermal technologies and system designs for a given reference case, the saved final energy should be used here and not the solar energy yield.

○ Following [3], $E_t = E_{conv}^{ref} - E_{aux} = \frac{Q_{conv,net}^{ref}}{\eta_{conv}^{ref}} - \frac{Q_{aux,net}}{\eta_{aux}} = \frac{Q_d + Q_{l,conv}^{ref}}{\eta_{conv}^{ref}} - \frac{Q_{aux,net}}{\eta_{aux}}$

Where:

E_{conv}^{ref} : gross (final) energy demand of the conventional (reference) heating system in kWh/a

E_{aux} : gross (final) auxiliary energy demand of the solar heating system in kWh/a

$Q_{conv,net}^{ref}$: net energy demand of the conventional heating system in kWh/a

$Q_{aux,net}$: net energy demand of the solar heating system delivered by the auxiliary heater in kWh/a

Q_d : total useful heat demand in kWh/a

$Q_{l,conv}^{ref}$: heat losses of the heat storage of the conventional (reference) heating system in kWh/a

η_{conv}^{ref} : annual utilisation ratio¹ of the heater of the conventional (reference) heating system

η_{aux} : annual utilisation ratio of the auxiliary heater of the solar heating system

- η_{conv}^{ref} and η_{aux} are highly dependent on the type of heater and on the operating conditions (notably winter vs. summer mode). However for practical reasons, $\eta_{conv}^{ref} = \eta_{aux}$ as well as a single yearly value should be considered. Values for η_{conv}^{ref} will be fixed for the solar assisted heating systems defined in Task 54, depending on the country and the type of system investigated.
- Following these assumptions:

$$E_t = \frac{Q_d + Q_{l,conv}^{ref} - Q_{aux,net}}{\eta_{conv}^{ref}}$$

¹ The annual utilisation ratio takes into consideration the steady-state efficiency of the heater as well as cyclic effect during transient phases and standby losses. Indicative values are given in [4] and [7] for instance.

- Q_d and $Q_{aux,net}$ might be determined with a simulation of the solar thermal system. $Q_{l,conv}^{ref}$ might be estimated either theoretically, for instance according to [3], or by means of a second simulation where the solar thermal loop is turned off. In the latter case, one should not forget to adapt the size of the heat storage.
- Simulations normally always estimate E_1 . A correction factor might be applied to the subsequent E_t ($t = [2..T]$) to take into consideration the ageing of the system. Unfortunately, only few analyses are available on the degradation rate of solar thermal systems. Experience shows however that each system should be considered specifically as there is so far no general criterion applying to this issue.
- Discount rate (r):
 - The discount rate is normally taken equal to the weighted average cost of capital (WACC). For single-family house systems, the total system costs are usually paid up front. In this case, $r = 0$ (real discount rate).
 - The nominal discount rate is derived from the real one with the relationship $r_{nominal} = r_{real} \cdot (1 + i) + i$, where i is the inflation rate.
- Period of analysis (T):
 - It is usually equal to the expected technical lifetime of the solar thermal system. This value is country and system dependent. For domestic systems for instance, 20 to 25 years in Germany and 25 years in Switzerland are commonly considered. In Denmark, 30 to 35 years are standard for large solar heating plants.

Under the assumptions described in this section, equation (1) can be simplified as follows for residential applications:

$$LCoH = \frac{I_0 + \sum_{t=1}^T C_t}{\sum_{t=1}^T E_t} \quad (2)$$

Where:

$LCoH$: levelized cost of heat in €/kWh

E_t : final energy (year t) in kWh/a

I_0 : initial investment in €

T : period of analysis in year

C_t : operation and maintenance costs (year t) in €/a

Cost of the heat substituted by solar thermal energy ($LCoH_{sol,fin}$) vs. cost of the heat generated by the solar assisted heating system ($LCoH_{ov,fin}$)

The methodology described in the previous section allows the calculation of the levelized cost of the heat which is substituted by solar energy ($LCoH_{sol,fin}$). A similar approach was previously applied in [8] and [9], with some differing assumptions however, which do not allow a direct comparison of the results between the studies. The indicator $LCoH_{sol,fin}$ is sufficient to compare different solar thermal technologies and system designs with each other. However to compare a solar assisted heating system with other heating technologies (heat pump, wood pellets boiler, etc.) the levelized cost of the heat generated by the overall

solar assisted heating system has to be calculated ($LCoH_{ov,fin}$). To do so the methodology described above for the calculation of each term of the LCoH equation has to be adapted as described in Table 1.

The calculation of the cost of the heat supplied by the conventional part of the solar assisted heating system ($LCoH_{conv,fin}$) could be useful for the comparison of different back-up technologies associated with a given solar thermal system. It was not the focus of IEA-SHC Task 54 to carry out this comparison, therefore the $LCoH_{conv,fin}$ is given as additional information. The $LCoH_{conv,fin}$ is obtained by subtracting the terms of the $LCoH_{sol,fin}$ to the terms of the $LCoH_{ov,fin}$ in the LCoH equation (I_0 , C_t and E_t).

Table 1. Definition of the different terms in the LCoH equation (1) for $LCoH_{sol,fin}$ and $LCoH_{ov,fin}$.

Parameter	Cost of the heat substituted by solar thermal energy ($LCoH_{sol,fin}$)	Cost of the heat generated by the solar assisted heating system ($LCoH_{ov,fin}$)
I_0	Investment costs for the solar part of the solar assisted heating system. Investment costs for the storage of the reference conventional heating system SC are deducted	Investment costs for the overall solar assisted heating system
C_t	O&M costs for the solar part of the solar assisted heating system	O&M costs for the solar assisted heating system; the costs of the energy used by the auxiliary heater need to be integrated here
DEP_t	Depreciation of the solar part of the solar assisted heating system	Depreciation of the solar assisted heating system
S_0	Subsidies for the solar part of the solar assisted heating system	All subsidies given to build the solar assisted heating system
RV	Residual value of the solar part of the solar assisted heating system	Residual value of the solar assisted heating system
E_t	Saved final energy ($E_{conv}^{ref} - E_{aux}$)	Final energy demand of the reference conventional heating system (E_{conv}^{ref})

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¹ To avoid confusion with the results of other works ([1], [8], [9]) also using the notion of LCoH for solar thermal systems, new acronyms were introduced in this Info Sheet. As previous studies have considered different assumptions for the definition of the terms of the LCoH equation, it does not make sense to compare the values they obtained with the $LCoH_{sol,fin}$, $LCoH_{conv,fin}$ and $LCoH_{ov,fin}$ values defined here. A detailed explanation of the differences between the approaches chosen in the framework of IEA-SHC Task 54 and in the Solar Heat Worldwide report [9] can be found in Info Sheet A13 [10].