

Description:	Guideline for levelized cost of heat (LCoH) calculations for solar thermal applications
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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. Furthermore, an extension of the concept is suggested to estimate the cost of the heat generated by the entire solar assisted heating system, or the conventional sources of heat supply.

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 €

TR : corporate tax rate in %

DEP_t : asset depreciation (year t) in €

RV : residual value in €

E_t : saved final energy (year t) in kWh

r : discount rate in %

T : period of analysis in years

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 distinguished by using the following acronyms:

- **LCoHs**: levelized cost of the heat substituted (saved) by the solar part of the 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 the comparison of different solar thermal system designs and technologies as part of the complete heating system.
- **LCoHo**: overall levelized cost of the heat generated by the solar assisted heating system. The complete heating system is considered here. This enables a comparison of the solar assisted heating system with other heating technologies.
- **LCoHc**: levelized cost of the heat supplied by the conventional part of the solar assisted heating system or by a conventional system alone (in this case LCoHc and LCoHo are equal). It is the twin of the LCoHs and can be easily derived from the data used to calculate the LCoHs and the LCoHo. The last section also clarifies the method to calculate it.

Main Assumptions for Solar Thermal Applications

This section focuses on the cost of the heat substituted by solar thermal energy (LCoHs). 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 LCoHs requires the definition of a conventional reference heating system. This conventional reference system is a heating system which would supply the same amount of energy to the end user as the solar thermal 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 system and the associated installation costs 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 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.
- 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 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], $E_t = E_{conv} - E_{aux} = \frac{Q_{conv,net}}{\eta_{conv}} - \frac{Q_{aux,net}}{\eta_{aux}} = \frac{Q_d + Q_{l,conv}}{\eta_{conv}} - \frac{Q_{aux,net}}{\eta_{aux}}$

Where:

E_{conv} : gross (final) energy demand of the conventional (reference) heating system in kWh
 E_{aux} : gross (final) auxiliary energy demand of the conventional (reference) heating system in kWh
 Q_d : total heat demand in kWh
 $Q_{l,conv}$: heat losses of the heat storage of the conventional (reference) heating system in kWh

solar heating system in kWh

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

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

η_{conv} : 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} 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, $\eta_{conv} = \eta_{aux}$ as well as a single yearly value should be considered. Values for $\eta_{conv} = \eta_{aux}$ will be fixed within the reference solar thermal systems defined in Task 54. They will depend on the country and the kind of reference heating system used.
- Following these assumptions:

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

- Q_d and $Q_{aux,net}$ might be determined with a simulation of the solar thermal system. $Q_{l,conv}$ 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.

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.

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

$$LCoH = \frac{I_0 - S_0 + \sum_{t=1}^T \frac{C_t}{(1+r)^t}}{\sum_{t=1}^T \frac{E_t}{(1+r)^t}} \quad (2)$$

Where:

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

E_t : saved final energy (year t) in kWh

I_0 : initial investment in €

r : discount rate in %

S_0 : subsidies and incentives in €

T : period of analysis in years

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

Cost the Heat Substituted by Solar Thermal Energy (LCoHs) vs. Cost of the Heat Generated by the Solar Assisted Heating System (LCoHo)

The methodology described in the previous section allows the calculation of the levelized cost of the heat which is substituted by solar energy (LCoHs). A similar approach was previously applied in [8] and [9], with some differing assumptions however, which does not allow a direct comparison of the results between the studies. It 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 total heat generated by the solar assisted heating system has to be calculated (LCoHo). 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 (LCoHc) 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 LCoHc is given as additional information. The LCoHc is obtained by subtracting the terms of the LCoHs to the terms of the LCoHo in the LCoH equation (I_0 , C_t and E_t).

Table 1. Definition of the different terms in the LCoH equation (1) for LCoHs and LCoHo.

Parameter	Cost of the heat substituted by solar thermal energy (LCoHs)	Cost of the heat generated by the solar assisted heating system (LCoHo)
I_0	Investment costs for the “solar related components” of the entire heating system	Investment costs for the entire heating system
C_t	O&M costs related to the “solar related components” of the entire heating system	O&M costs for the entire heating system; the costs of the energy used by the auxiliary heater need to be integrated here
DEP_t	Depreciation of the “solar related components” of the entire heating system	Depreciation of the entire heating system
S_0	Subsidies for the “solar related components” of the entire heating system	All subsidies given to build the entire heating system
RV	Residual value of the “solar related components” of the entire heating system	Residual value of the entire heating system
E_t	Saved final energy	Final energy demand

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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 LCoHs, LCoHc and LCoHo 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].