A Methodological Framework for Calculating the Levelized Cost of Heat for Solar Thermal Applications in Residential Buildings

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Abstract

The levelized cost of heat (LCoH) is becoming an important economic metric for economic assessment of heating systems in the thermal engineering literature. Yet published values are hardly comparable because studies adopt different – and often implicit – system boundaries for both energy and costs. This paper reports about a methodological framework that resolves this deficiency for heating systems in residential buildings. Starting from the energy balance defined in building standards, boundaries for the reference energy are identified along the supply chain, from primary energy to end-use heat demand. Similarly, four nested "levels of analysis" are specified for costs. As a result of the investigations, a nomenclature is proposed to differentiate the LCoH values from each other. The influence of boundary choices is illustrated with an example, with the heat supply of a multi-family house as application. Depending on the selected boundaries, the ranking of the technical solutions compared can reverse, and absolute LCoH values vary significantly. The study therefore recommends (i) adopting heat demand as the default reference energy, (ii) selecting the level of analysis that captures only those components that differ between technical solutions, and (iii) reporting the chosen boundaries explicitly using the proposed nomenclature. The framework lays the foundation for harmonised techno-economic assessments within the wider scientific community.

Keywords: Solar thermal systems; Levelized cost of heat; Domestic applications

1. Introduction

1.1. General introduction

This work was carried out as part of Task 71 of the IEA SHC (International Energy Agency Solar Heating and Cooling) Programme and is part of an international effort to harmonise the calculation of economic indicators for assessing the economic efficiency of solar thermal systems, and more broadly, heating systems in general. IEA SHC Task 71, entitled "Life Cycle and Cost Assessment for Heating and Cooling Technologies", deals more generally with the environmental and economic assessment of heating and cooling systems. This work falls within this framework and focuses on the economic indicator chosen in Task 71, the levelized cost of heat (LCoH), for building applications.

Buildings are only one part of the applications considered in Task 71, which also includes industrial applications. District heating systems are also considered in more detail in Task 71. For more information on applications not covered in this document, readers are referred to IEA SHC Task 71 website, where the results of the work of the expert group are published (IEA SHC, 2025).

This work on the LCoH for heating applications in buildings is the result of a process that began as part of the previous IEA SHC Task 54 entitled "Price Reduction of Solar Thermal Systems" (IEA SHC, 2018). It aims to summarise and illustrate the results of previous publications, notably in an article written by the authors of this work (Louvet and Vajen, 2025). The present paper is structured around the slides from the presentation given at the Solar World Congress 2025 in Fortaleza and aims to convey the main messages on the topic of LCoH for heating applications in buildings.

1.2. Introduction to the levelized cost of heat

The LCoH is an economic indicator used in thermal engineering, adapted from the levelized cost of energy (LCoE) widely used in the electricity sector. The purpose of the LCoH is to compare the economic value of

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different technical solutions that provide the same energy service. In its general form (see equation in Figure 1), the LCoH is defined as the ratio of life-cycle costs to a discounted reference energy E_t over a given period of analysis. Depending on the scope of analysis, life-cycle costs in the numerator can encompass, the initial investment, operation and maintenance costs, replacement costs, disposal costs, the residual value at the end of the period of analysis, subsidies and other proceeds. These expenditures and earnings are summed using standard net-present-value discounting to account for their different time values. The denominator contains the reference energy characterising the heating service which is likewise discounted over time.

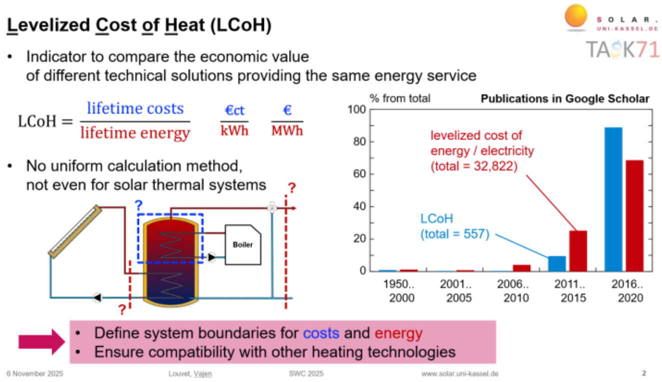


Figure 1: Definition of the levelized cost of heat and presentation of the underlying methodological difficulties and objectives.

The results of a meta-analysis conducted using Google Scholar are presented in Figure 1. It shows the number of publications containing the terms “levelized cost of energy” or “levelized cost of electricity” and “levelized cost of heat” in the database for the period 1950-2020. It illustrates that references to LCoE far exceed those to LCoH, although mentions of LCoH have grown markedly over the last decade (as have references to LCoE). A more in-depth analysis reveals that the term “solar” appears in 86 % of publications containing the term “levelized cost of heat”, highlighting the importance of the indicator for solar applications. Louvet et al. (2019) list several relevant works in the field of solar thermal energy using the LCoH as an economic indicator and show that there is no standard approach in the literature for calculating the LCoH of solar thermal systems in households. As shown in the hydraulic scheme in Figure 1, there are several possible locations where the reference energy could be counted. The same applies to costs, i.e. the components that should or should not be included in the calculations. This is a core difficulty for LCoH calculations, which motivates the development of a harmonised methodology for heating applications, including solar thermal collectors but also all other technologies. Without a precise definition of the system boundaries, both for costs and energy, reported LCoH values become non-comparable. This will be exemplified in this contribution.

2. System boundaries for energy

This section focuses on the denominator of the LCoH equation, i.e. the energy to be considered for LCoH calculations. The approach is based on a detailed analysis of energy streams in buildings, notably to identify losses along the distribution chain. To this end, the energy balance of buildings for heating purposes defined in the European standard DIN EN 832 (DIN, 2003a) is taken as a basis.

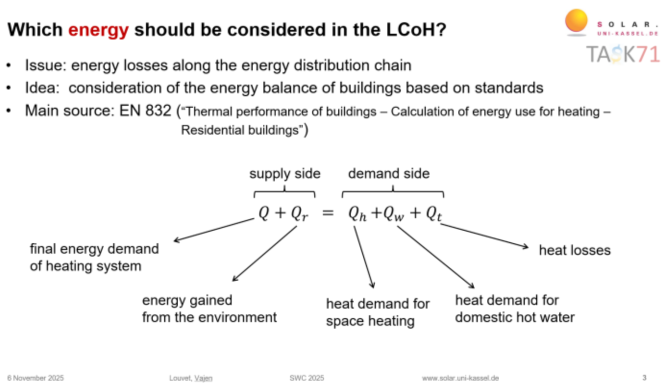
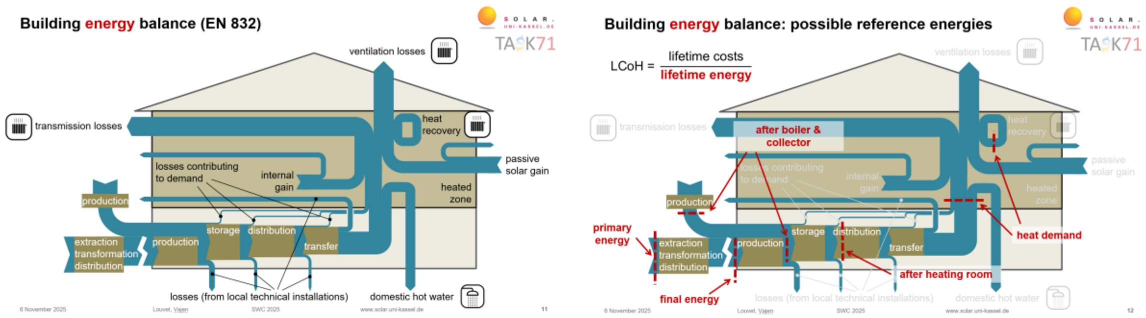


Figure 2: Main equation of the energy balance of a building for heating purposes as defined in DIN EN 832 (DIN, 2003a).

Figure 2 shows the main equation for the energy balance of a building for heating purposes as defined in the standard. The balance distinguishes between supply and demand. On the supply side (left-hand term), Q denotes the final energy delivered to the building (e.g. fuel, electricity, district heat) and Q_r refers to the energy gained from the environment (e.g. heat from solar thermal collectors or heat pumps). On the demand side, Q_h corresponds to the heat demand for space heating (SH), Q_w to the heat demand for domestic hot water (DHW), and Q_t to the heat losses from the technical installations (detailed in Figure 3). Auxiliary electricity consumption for pumps, fans, etc. is not part of the energy balance in DIN EN 832.

Figure 3(a) provides a more detailed graphical representation of the energy balance for heating purposes, as proposed by DIN EN 832. Along the supply chain inside and outside the building, a distinction is made between production (e.g. solar collectors or gas boiler), storage, distribution and transfer (e.g. floor heating system). The heat supplied aims to cover the total useful heat demand, which includes the heat demand for DHW and for SH (which aims to cover transmission and ventilation losses). It should be noted that, unlike DIN EN 832, heat recovery from air handling units (AHUs) is also considered part of the heat demand for SH. This allows, in specific cases, a comparison of technical solutions with and without heat recovery, or with differently designed AHUs.

Part of the heat demand is covered by passive solar gains and internal gains (heat losses from appliances). Some of these gains are lost in the sense that they cause the room temperature to exceed the required set point temperature. Losses from the technical installations are divided between those that contribute to covering the space heating demand and those that do not. Like lost passive solar gains and lost internal gains, losses from the "transfer" block correspond to the room temperature exceeding the set point. It is caused by the inertia and control inaccuracy of the components transferring the energy from the other technical installations to the heated zone.



(a) (b)

Figure 3: Schematic representation of energy streams for heating purposes in a building with a single heated zone (a), based on DIN EN 832 (DIN, 2003a). Possible positions where the reference energy might be counted along the energy distribution chain (b). Illustrations based on the German standard DIN V 4701-10 (DIN, 2003b).

Figure 3(b) highlights reasonable positions that may be chosen as reference energy in the LCoH equation. With the exception of primary energy, all the others have been used as "reference" energies in various LCoH studies published in the literature (Louvet et al., 2019), which once again highlights the need for harmonisation. The figure also implicitly shows that the definition of "useful heat" is open to debate. A common approach is to define useful heat as the heat transferred to the heat distribution system at the heating room outlet (the "after heating room" boundary in the figure). This is the definition that was chosen in Task 71. As illustrated, this energy differs from the actual heat demand (the "heat demand" boundary in the figure), which is another reasonable quantity to define as "useful heat". In Task 71, the "useful heat" defined at the "after heating room" boundary is chosen as reference energy. This is reasonable for many case studies, but depending on the scope of the analysis, it is shown in the following that in some cases another reference energy should be chosen. Defining the reference energy at the "heat demand" boundary allows for more cases to be covered. The choice made in Task 71 is motivated by the fact that the Task focuses on the heating system itself and not on the building. The distribution system and the transfer system are considered to "belong" more to the building than to the heating system itself. Furthermore, there is an underlying assumption within the Task that defining "heat demand" as the boundary for energy necessarily implies considering the costs of the distribution and transfer systems, which obviously requires additional effort to collect the data. This is common practice in life cycle assessments (LCAs), which, together with LCoH, constitute the other topic of the Task. Given that the Task also aims to harmonise the LCA and LCoH calculation methodologies as much as possible, the choice of the "after heating room" boundary as reference energy (i.e. as functional unit for LCA calculations) was considered a good solution. For LCoH, the authors of this report consider that there is no obligation to overlap the boundaries for costs and energy, so that choosing "heat demand" as boundary for energy does not necessarily imply taking into account the costs of the distribution and transfer systems. More generally, it is recommended to focus on the costs of the components that vary between the technical solutions compared, as detailed in the section 3 on costs. This avoids unnecessary work.

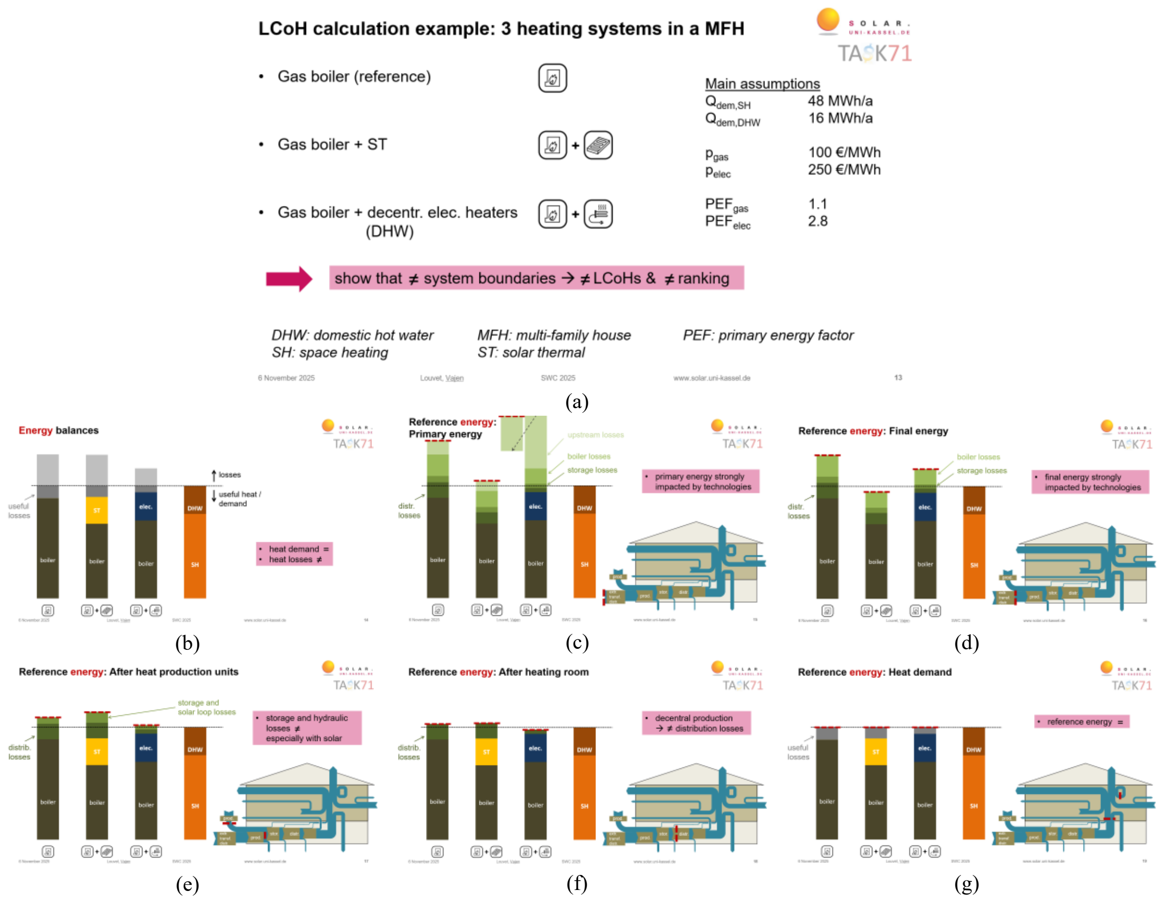


Figure 4: Presentation of the three exemplary technical solutions defined in this study (a). Energy balances (b) as well as reference energies for different boundaries for energy for the three systems (c) to (g).

Three exemplary technical solutions are defined in this study to highlight the impact of the system boundaries for energy and costs (in a later section) on LCoH calculation results and that the fact that different rankings of solutions can be obtained, even when the energy service provided is identical. The defined technical solutions are presented in Figure 4(a). The application chosen is the supply of heat for DHW and SH in a multi-family house (MFH). The demand for DHW amounts to 16 MWh/a and that for SH to 48 MWh/a. The three technical solutions compared, are a central gas boiler ("ref"), a central gas boiler combined with solar thermal collectors (STC) ("boil + ST") and a central gas boiler for SH combined with decentralised (i.e. in each apartment) instantaneous electric water heaters for DHW ("boil + elec"). A natural gas price of 100 €/MWh (based on gross calorific value – GCV) and an electricity price of 250 €/MWh are considered. Primary energy factors of 1.1 and 2.8 are applied to natural gas and electricity respectively. Additionally, the ratio between the GCV and the net calorific value (NCV) of natural gas is taken equal to 1.11. It should be noted that no numerical simulation was performed to compute the energy streams presented in the following. Instead, the yearly values of the streams were calculated based on estimated rates, which are summarised in Table 1.

Figure 4(b) shows the overall energy balances for each technical solution. The bar on the right indicates the total heat demand, which is identical for all solutions. The technologies contribute differently to covering the heat demand depending on the solution. Losses from the technical installations contribute to covering part of the total heat demand ("ref" 11 %, "boil + ST" 10 % and "boil + elec" 6 %). The share is significantly lower in the "boil + elec" solution, as the total losses from the technical installations are lower due to the absence of losses related to DHW distribution. Losses from the technical installations that do not contribute to the total heat demand are shown at the top of the bars for each technical solution.

Table 1: Main assumptions considered for the calculation of the energy streams for the three technical solutions compared in this study.

Parameter	Value
Losses of the solar collector loop	5 % of the yearly solar collector yield
Useful solar yield	10 % of the yearly heat demand for SH and 65 % of the yearly heat demand for DHW
Production losses (boiler)	15 % of the yearly final energy consumption of the boiler, based on NCV (losses of which 25 % contribute to covering the SH demand)
Storage losses	5 % of the yearly total distribution losses and yearly heat demand covered centrally (solutions “ref” and “boil + elec”) 7 % of the yearly total distribution losses and yearly heat demand covered centrally (solution “boil + ST”)
Storage losses covered by STC (“boil + ST” only)	40 % of the yearly storage losses
Distribution losses	DHW distribution (incl. circulation): 40 % of the yearly heat demand for DHW (losses of which 30 % contribute to covering the SH demand) SH distribution: 5 % of the yearly heat demand for SH (losses of which 40 % contribute to covering the SH demand)
Distribution losses covered by STC (“boil + ST” only)	35 % of the yearly DHW distribution losses and 10 % of the yearly SH distribution losses

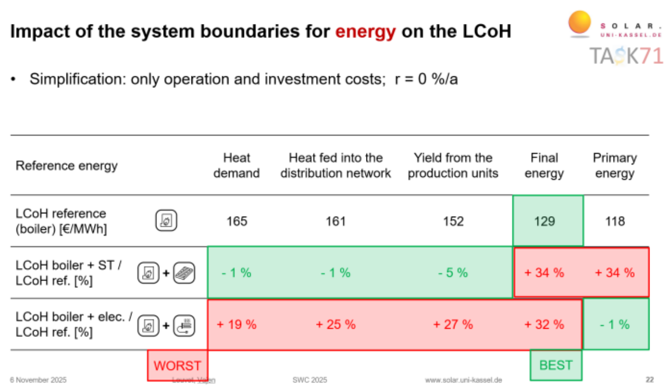


Figure 5: Results of the LCoH calculations for the three technical solutions considered and different reference energies. For each reference energy, the best and worst technical solutions in terms of LCoH are marked in green and red, respectively.

The following Figure 4(c) to (g) show the reference energy value E_t for the three technical solutions when counted at different points in the distribution chain, namely primary energy (c), final energy (d), after the production units (e), after the heating room (f) and heat demand (g). Primary energy and final energy depend heavily on the technologies considered and lead to significantly different E_t values between the three solutions. When considering the heat at the outlet of the production units, storage losses as well as losses between the production unit and the storage differ, especially for decentralised DHW production without DHW storage (“boil + elec” solution) and for solar heating technologies with long piping distances between production and storage (“boil + ST” solution). Further down the distribution chain, after the heating room, the difference in E_t is negligible in this example for purely centralised solutions (“ref” and “boil + ST”), while in the “boil + elec” solution, distribution losses are lower which explains the lower reference energy. Finally, taking the heat demand as reference energy leads to the same E_t for the three technical solutions.

Figure 5 shows the results of the LCoH calculations for the three technical solutions considered and the different reference energies presented in Figure 4. For a given technical solution, the costs are identical for all reference energies. The LCoH calculations presented in this work are greatly simplified. Only investment and operation costs are considered, and the discount rate is set at 0 %/a. The period of analysis is 20 years. The investment costs considered are rough estimates made for the illustrative purposes of this study and are not intended to represent the current economic reality. They are listed in Table 2 and include all costs required for the functioning of the system, i.e. main components (collectors, boiler, storage, etc.), small parts (pipes, pumps, valves, etc.) as well as installation costs.

Table 2: Investment costs of the main components considered in this study.

Component	Investment cost
Central boiler system	30.000 €
Solar heating system	45.000 €
Distribution system (SH)	15.000 €
Distribution system (DHW)	25.000 €
Transfer system (convectors)	64.000 €
Decentral electric heaters	14.400 €

In the LCoH calculation results presented in Figure 5, the LCoH is expressed in €/MWh for the reference solution (“ref”). For the other two solutions, “boil + ST” and “boil + elec”, the results are presented relative to the results for the reference solution. Considering only the reference solution, throughout the energy supply chain from heat demand to primary energy, an increasing amount of heat losses are integrated into the reference energy. This is why the LCoH decreases as the reference energy, in the denominator of the equation, increases (for the same costs). For each reference energy, the best technical solution is marked in green and the worst in red. Interestingly, depending on the reference energy chosen, the ranking of the technical solutions changes. “boil + ST” is the most cost-effective solution when calculating the LCoH using the heat demand, the heat fed into the MFH distribution network and the yield from the production units as reference energy. This changes when final energy is taken as reference energy, as “ref” becomes the most cost-effective solution, while the “boil + elec” solution becomes the best with primary energy.

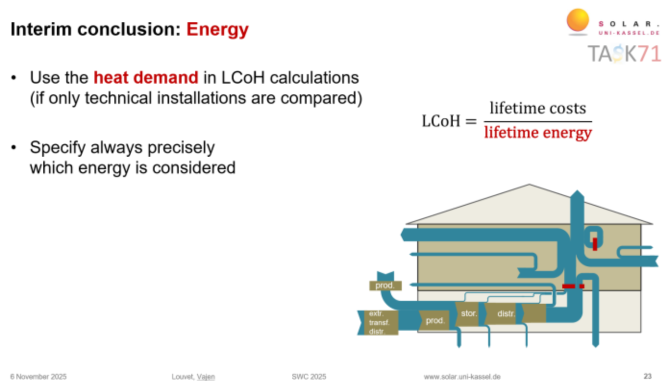


Figure 6: Key messages regarding the choice of the boundary for energy in LCoH calculations.

The key messages regarding the choice of the boundary for energy in LCoH calculations are summarised in Figure 6. For meaningful comparisons, the reference energy must be the same for all technical solutions being compared. For this reason, it is recommended to use the heat demand as reference energy in LCoH calculations. It is possible to place the boundary for energy further upstream in the distribution chain (as is the case in Task 71) if the losses from the technical installations, between the point considered and the heat demand, are the same for all technical solutions compared. It is important to note that the fact that the reference energy must be the same between the technical solutions compared implies that LCoH is not a suitable indicator for evaluating energy efficiency measure, for instance to compare solutions with or without building insulation. In these cases, workarounds should be found, for example by using the heat demand of the reference system as the reference energy for all technical solutions or by using another fixed quantity in the denominator, such as the heated floor area, instead of energy. Furthermore, it is essential to specify precisely which energy is used in the denominator and where the boundary lies when reporting the results of LCoH calculations. This enables reproducibility and comparability with other studies.

3. System boundaries for costs

With regards to costs, the system boundaries must define which components are included and which are excluded from the LCoH calculations. The concept of *level of analysis* is introduced, and the main levels of analysis identified are presented in Figure 7(a) to (d). The four levels of analysis presented are constructed like nesting dolls. Components outside the boundaries of a level of analysis are assumed to be identical and their costs are therefore not considered. It should be noted that only the main components are shown in Figure 7. Small parts such as pipes, pumps and heat exchangers should also be considered when relevant. Conversely components situated within the boundaries of a given level of analysis, but which are identical across all technical solutions compared do not necessarily need to be included. This simplifies the analysis. For costs too, for the sake of reproducibility and comparability, it is important to document the components included in a given study clearly and in as much detail as possible.

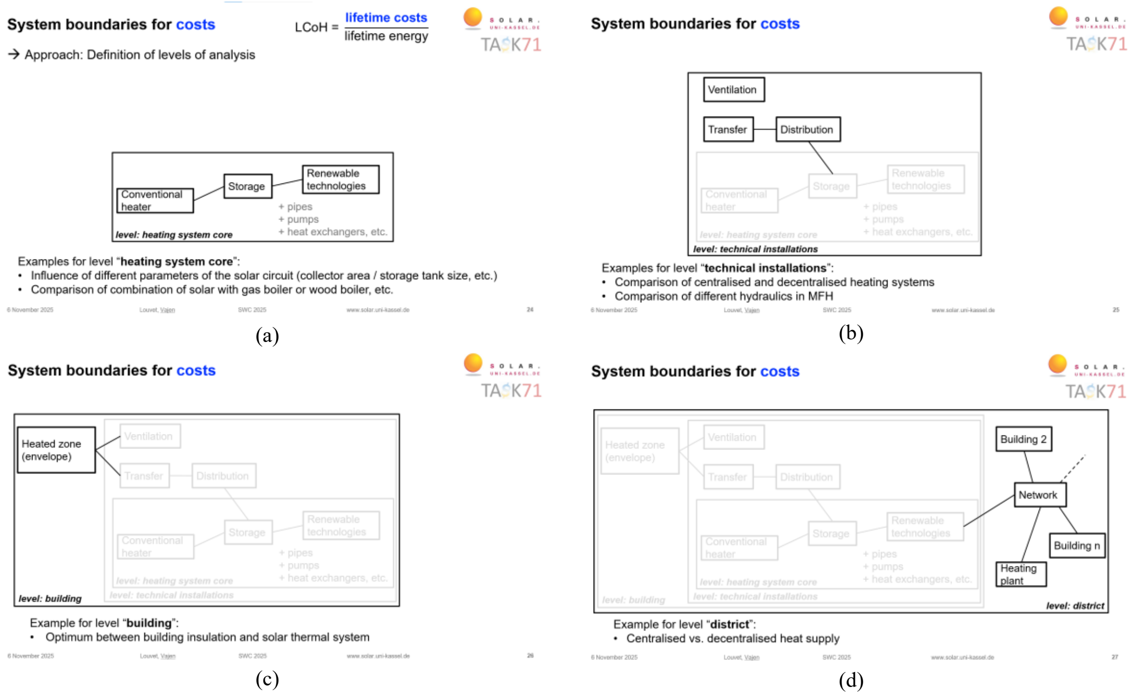
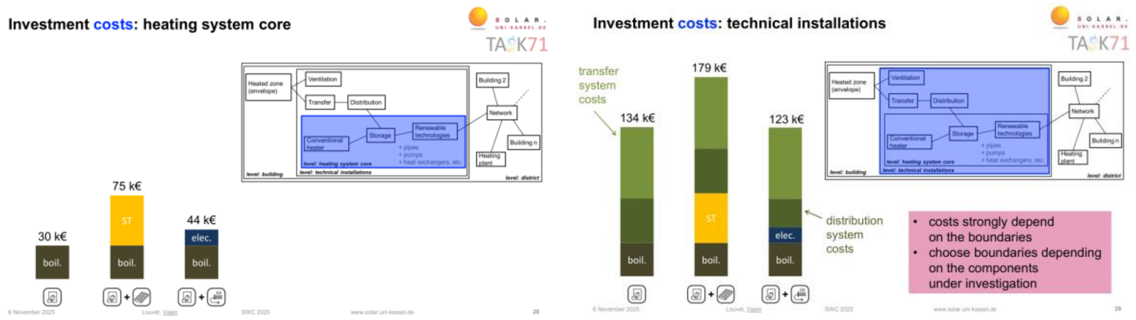


Figure 7: Graphical illustration of the four levels of analysis as system boundaries for costs in LCoH calculations.

The lowest level, *heating system core* (Figure 7(a)), comprises the heat production unit(s) and the heat storage, together with associated auxiliaries such as pumps, valves, heat exchangers, etc. This level is appropriate, for instance, when the objective is to evaluate design parameters of the solar thermal subsystem or to compare combinations such as solar with a gas boiler versus solar with a biomass boiler. The level *technical installations* (Figure 7(b)) extends the boundary to include the distribution and transfer systems and, where applicable, the AHU. It is for example suited for comparing centralised and decentralised heating solutions or for comparing different hydraulic solutions in MFHs. The level *building* (Figure 7(c)) encompasses the heated zone and its envelope. This boundary is appropriate, for example, for determining the optimum between insulation thickness and solar thermal system size. However, as specified in section 2, at this level the heat demand may vary between the technical solutions compared, so workarounds need to be found when performing a comparative economic analysis. The outermost boundary, the level *district* (Figure 7(d)), adds multiple buildings, a distribution network and centralised heating plant(s) and is suitable for the analysis of district heating networks. It enables, for instance, a comparison between centralised and decentralised heat supply at the neighbourhood level.

Figure 8(a) and (b) present a summary of the investment costs at the levels *heating system core* and *technical installations* of the three exemplary systems already introduced in section 2. Single costs have already been summarised in Table 2. As expected, the total investment costs depend strongly on the level of analysis chosen, so that, as with energy, it is always important to specify where the boundary lies in a given study.



(a) (b)

Figure 8: Investment costs for the three exemplary technical solutions considered in this study at the levels *heating system core* and *technical installations*.

The impact of the level of analysis on the LCoH values is presented in Figure 9 for the three technical solutions. Heat demand is chosen as reference energy. The other calculation assumptions are the same as for the examples presented in section 2. With a “higher” level of analysis, the LCoH increases as expected, due to the inclusion of additional costs. At both levels considered, there is no change in ranking. The “boil + ST” solution is the most cost-effective and the “boil + elec” solution the least. However, there is a significant change between the two levels of analysis for the “boil + elec” solution. While at the level *heating system core*, the LCoH of the “boil + elec” solution is 19 % higher than that of the “ref” solution, at the level *technical installations*, it is only 5 % higher and the LCoH of the three solutions are very close to each other. One of the advantages in terms of costs of decentralised electric water heaters is the absence of a distribution network for DHW in the building. This advantage is not reflected at the level *heating system core*, as the costs of distribution systems are not included in the analysis, unlike at the level *technical installations*. When comparing only the “ref” and “boil + ST” solutions, there is no relative difference between the two levels of analysis, as the distribution and transfer systems are the same in both solutions. In this case, it is not advisable to carry out the analysis at the level *technical installations*, due to the additional effort required.

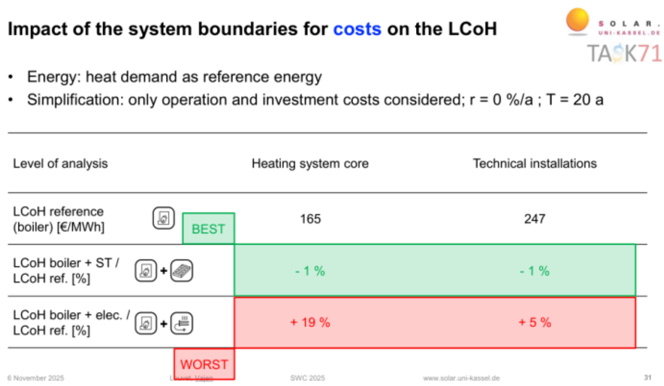


Figure 9: Results of the LCoH calculations for the three technical solutions considered and different levels of analysis, i.e. different boundaries for the costs. For each level of analysis, the best and worst technical solutions in terms of LCoH are marked in green and red, respectively.

4. Proposed nomenclature

To differentiate between LCoH values, a nomenclature comprising three subscripts is proposed, as detailed in Figure 10. The subscript e specifies the reference energy as detailed in section 2, and the subscript l designates the level of analysis for costs as presented in section 3. The subscript p, only relevant at the level *heating system core*, is also introduced. It refers to the system part and enables the heat cost of individual technologies to be calculated at this level, for instance the cost of "solar" heat or the cost of the heat produced by the backup gas boiler.

For a given study, some if not all system boundaries are usually fixed and do not vary. From a practical point of view, it is therefore not recommended to write out all the subscripts explicitly, unless necessary, to avoid overloading the text of a document. Most important is to clearly state at the beginning of the document what the system boundaries are for the rest of the work.

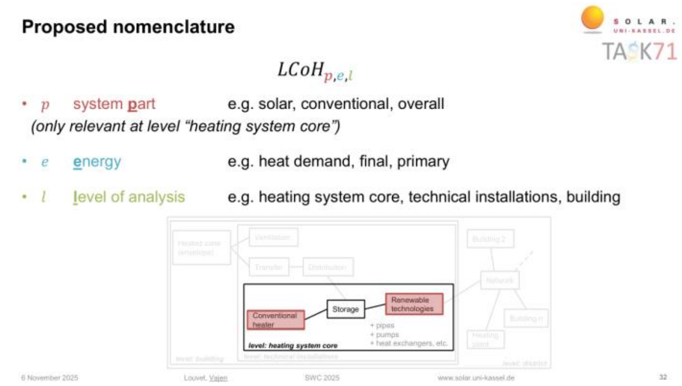


Figure 10: Proposed nomenclature to differentiate between LCoHs calculated with different system boundaries.

5. Conclusions

The main conclusions of this study are summarised in Figure 11. The choice of system boundaries determines the outcome of any LCoH calculation. With regard to the denominator of the LCoH equation, it is important that the reference energy remains the same between the technical solutions compared. For this reason, it is recommended to choose heat demand as the reference energy, as it fulfils this condition in the largest number of cases. Other reference energies may be appropriate, provided that the condition "the reference energy remains the same between the technical solutions compared" is met. It is important to clearly state the assumptions made for the energy boundary in a given study to ensure reproducibility and comparability. The same advice applies to costs, included in the numerator of the LCoH equation. The levels of analysis introduced in section 3 should be useful in this regard by providing a general framework. However, each system has its own particularities, so it is important to specify as detailed as possible the components that are included.

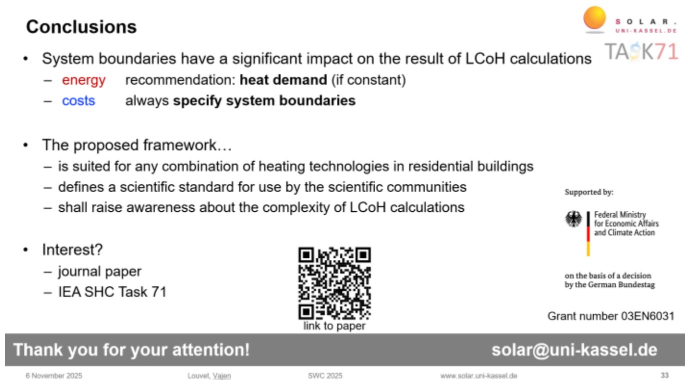


Figure 11: Main conclusions of the study.

The framework proposed in this work for LCoH calculations is accompanied by a nomenclature that allows for a concise presentation of the choices made for the system boundaries. This framework is suitable for any combination of heating technologies in residential buildings and sets a scientific standard for use by scientific communities. Beyond facilitating comparison, this framework draws attention to the inherent complexity of LCoH calculations. In Task 71, the work presented here for residential buildings has been extended in more detail to district heating systems and process heat applications. Readers are therefore invited to refer to the publications of the Task for further information (IEA SHC, 2025).

6. Acknowledgments

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7. References

DIN, 2003a. Wärmetechnisches Verhalten von Gebäuden – Berechnung des Heizenergiebedarfs – Wohngebäude. German version EN 832:1998 + AC:2002 (No. DIN EN 832:1998 + AC:2002). Beuth Verlag, Berlin, Germany.

DIN, 2003b. Energetische Bewertung heiz- und raumlufttechnischer Anlagen im Bestand – Teil 10: Heizung, Trinkwassererwärmung, Lüftung. DIN V 4701-10:2003-08 (No. DIN V 4701-10:2003-08). Beuth Verlag, Berlin, Germany.

IEA SHC, 2025. Task 71 – Life Cycle and Cost Assessment for Heating and Cooling Technologies [WWW Document]. IEA SHC || Task 71 || Life Cycle and Cost Assessment for Heating & Cooling Technologies. URL https://task71.iea-shc.org/ (accessed 11.6.25).

IEA SHC, 2018. Task 54 – Price Reduction of Solar Thermal Systems [WWW Document]. URL https://task54.iea-shc.org/ (accessed 11.11.22).

Louvet, Y., Fischer, S., Furbo, S., Giovannetti, F., Helbig, S., Köhl, M., Mugnier, D., Philippen, D., Veynandt, F., Vajen, K., 2019. Economic comparison of reference solar thermal systems for households in five European countries. Solar Energy 193, 85–94. https://doi.org/10.1016/j.solener.2019.09.019

Louvet, Y., Vajen, K., 2025. Levelized cost of heat for solar thermal applications in households. Solar Energy 285, 113100. https://doi.org/10.1016/j.solener.2024.113100