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CORRELATION-BASED PRE-ASSESSMENT OF THE LEVELIZED COST OF HEAT OF LOW-TEMPERATURE INDUSTRIAL HEAT SUPPLY TECHNOLOGIES

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Summary

Low-temperature industrial process heat (< 100 °C) can be supplied by several efficient and low-carbon technologies, yet these options are often not fully considered in early project phases due to limited familiarity and the effort required for techno-economic assessments. This paper presents a correlation-based approach for the rapid pre-assessment of the levelized cost of heat (LCoH) of four heat supply technologies: solar thermal collectors, heat pumps for waste heat utilisation, biomass boilers, and natural gas boilers as reference or backup systems.

The approach relies on harmonised methodological assumptions and explicitly defined system boundaries, ensuring direct comparability between technologies. Generic contour plots express the LCoH as a function of two dominant parameters per technology, complemented by additional correlations that allow key parameters, such as solar collector yield and full-load hours, to be estimated without detailed simulations. The full-load hour correlations are further extended to hybrid systems combining solar thermal collectors with one or several dispatchable heat generator(s). A sensitivity analysis complements the results by quantifying the impact of discount rate, service life, and fuel or electricity prices on the LCoH of each technology. Overall, the results support early-stage decision-making by allowing stakeholders to quickly compare technology options on a consistent basis and to identify promising solutions for more detailed analysis.

Keywords: industrial process heat, levelized cost of heat, solar thermal, heat pump, biomass boiler

Field of application for the findings: techno-economic pre-assessment and technology screening for low-temperature industrial heat supply projects

Addressed audience: industrial energy managers, engineering consultants, and researchers working on the decarbonisation of industrial process heat

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1. Introduction

Industrial process heat and space heating in industrial buildings account for 20 % of global energy consumption and a significant share of global CO_2 emissions (Bellevrat and West, 2018). For applications below 100 °C, commercially available technologies such as solar thermal collectors, heat pumps using waste heat, and biomass boilers can significantly reduce fossil energy use and emissions.

In practice, technology selection is often driven primarily by economics, but promising options may not be considered early because of limited familiarity among decision-makers, and because of the lack of simple methods that allow a quick assessment of the economic competitiveness of alternative heat supply options without performing detailed simulations and cost calculations.

This paper addresses this gap by presenting correlation-based methods that enable a rapid pre-assessment of the heat cost of the three low-temperature industrial heat supply technologies introduced above. Natural gas boilers are additionally investigated as backup or reference technology. The results are derived from a report currently in publication within the framework of Task 71 of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme, Subtask D (Louvet and Pag, 2026). Not all details from the report are reproduced here, so that the reader may refer to the full report for additional information. The analysis follows the harmonised methodological guidelines developed within the same Task 71, Subtask B (Itten et al., 2025), ensuring consistent assumptions and system boundaries and allowing direct comparison between technologies.

2. Methodological framework and assumptions

2.1. LCoH equation and system boundaries

The economic assessment is based on the levelized cost of heat (LCoH), calculated with eq. (1), which relates the life-cycle costs (LCC) of a system to a discounted reference energy E_t over the analysis period T, with r the nominal discount rate.

$$LCoH = \frac{LCC}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \tag{1}$$

The life-cycle costs are expressed with eq. (2), where I_0 is the initial investment, S_t subsidies, O_t operation costs, M_t maintenance costs, R_t replacement costs, D_t disposal costs, P_t proceeds, and RV the residual value.

$$LCC = I_0 - \sum_{t=0}^{T} \frac{S_t}{(1+r)^t} + \sum_{t=1}^{T} \frac{O_t+M_t+R_t+D_t}{(1+r)^t} - \sum_{t=1}^{T} \frac{P_t}{(1+r)^t} - \frac{RV}{(1+r)^T} \tag{2}$$

System boundaries are defined in accordance with IEA SHC Task 71, Subtask B (Itten et al., 2025), corresponding to the functional unit FU-HSW with simplifications: the assessed technologies are considered part of the main heat supply system of an industrial site, feeding heat into its main distribution network (Fig. 1). Costs (system boundary in pink) include turnkey supply of the heat generation technology, thermal storage, and hydraulics up to the feed-in point, covering material, installation, and planning costs. Costs of the distribution network itself and of building-level substations are excluded. Regarding useful energy (system boundary in green), 10 % distribution losses are assumed between the generator outlet and the reference energy boundary, so that the reference energy E_t is expressed with eq. (3), where $Q_{gen,tot}$ is the yearly thermal yield of the respective technology.

$$E_t = 0.9 \cdot Q_{gen,tot} \tag{3}$$

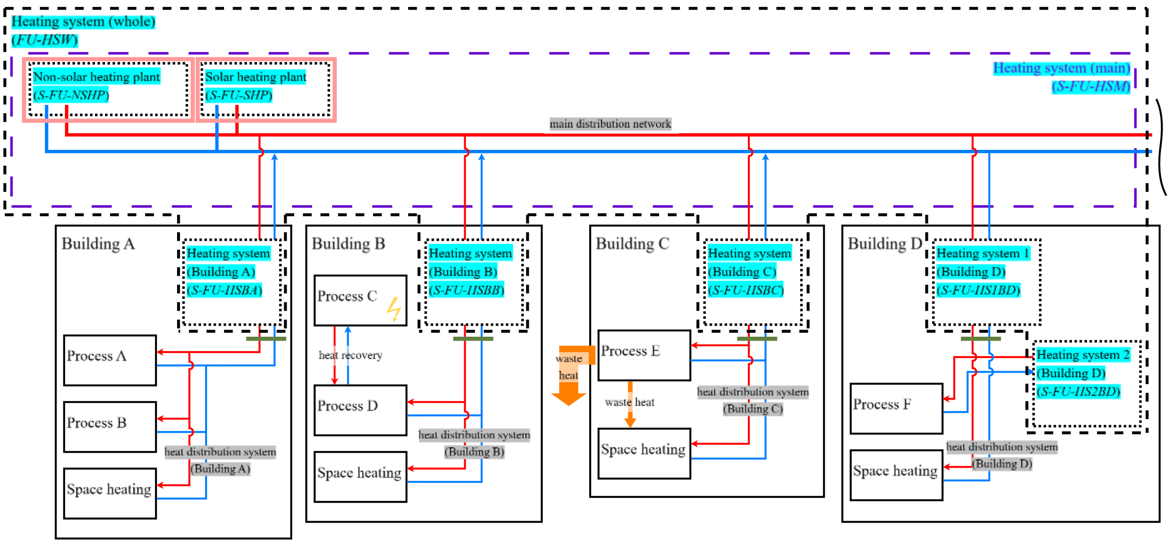


Fig. 1: System boundaries for LCA and LCoH calculations for process heat systems as defined in IEA SHC Task 71, Subtask B (Itten et al., 2025). The system boundaries for costs and energy considered in this study are added in pink and green, respectively.

2.2. General and technology-specific assumptions

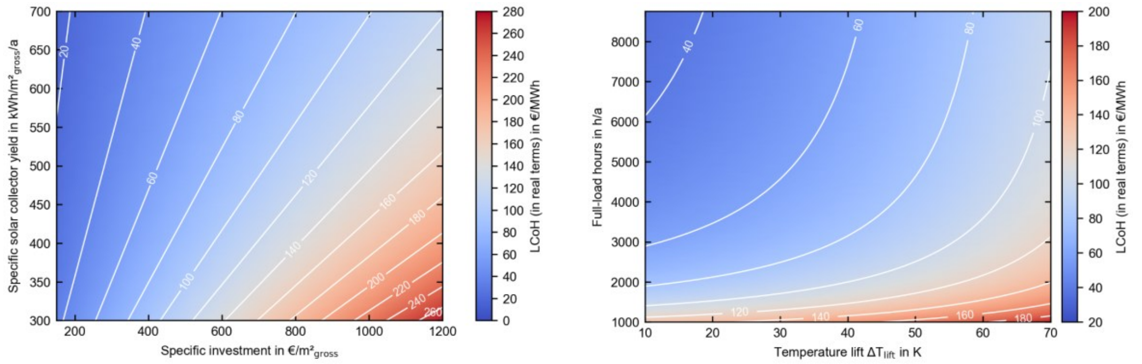
To ensure comparability, a period of analysis T of 30 years, a nominal discount rate r of 5.5 %/a, and an inflation rate of 2 %/a are assumed for all technologies. Country-specific subsidies S_t, disposal costs D_t and VAT are excluded to maintain broad applicability, and proceeds P_t are not considered as none of the four technologies co-generates heat and electricity. Tab. 1 summarises the technology-specific assumptions. The fuel prices are based on gross calorific value (GCV).

Tab. 1: Summary of the main technology-specific assumptions used for the LCoH calculations.

Parameter	Solar thermal	Heat pump	Biomass boiler	Gas boiler
Investment	investigated param.	1,000 €/kWth	investigated param.	investigated param.
Maintenance	0.75 %/a of invest.	2.5 %/a of invest.	6 %/a of invest.	3 %/a of invest.
Aux. electricity consumption	1.4 kWh/100 kWh yield	0.5 kWh/100 kWh yield	2.2 kWh/100 kWh yield	0.5 kWh/100 kWh yield
Fuel / elec. price	150 €/MWh (elec.)	150 €/MWh (elec.)	35 €/MWh (biomass) 150 €/MWh (elec.)	65 €/MWh (gas) 150 €/MWh (elec.)
Nominal fuel / elec. price increase rate	2.5 %/a (elec.)	2.5 %/a (elec.)	2 %/a (biomass) 2.5 %/a (elec.)	2 %/a (gas) 2.5 %/a (elec.)
Service life of the main components	30 years	20 years	15 years	20 years

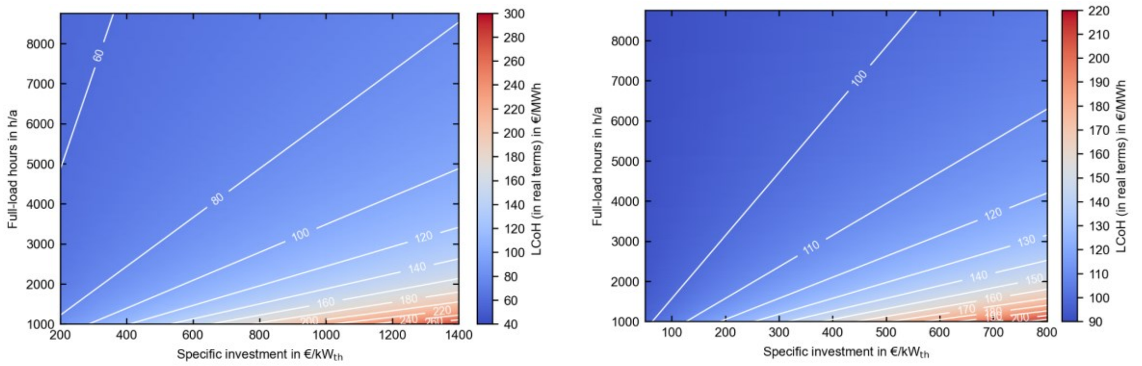
3. Contour plots for four heat supply technologies

For each technology, the LCoH is expressed using generic contour plots as a function of two dominant parameters: specific investment ($€/m^2_{gross}$) vs. specific collector yield ($kWh/(m^2_{gross}\cdot a)$) for solar thermal collectors; temperature lift (K) vs. full-load hours (h/a) for heat pumps; and specific investment ($€/kW_{th}$) vs. full-load hours (h/a) for biomass and natural gas boilers. These contour plots allow a rapid estimation of the LCoH once approximate values for the two parameters are known. Fig. 2 shows the contour plots for solar thermal collectors (a) and heat pumps for waste heat utilisation (b), while Fig. 3 shows the contour plots for biomass boilers (a) and natural gas boilers (b), all under the assumptions summarised in Tab. 1.



(a) *(b)*

Fig. 2: Contour plots of the LCoH for heating systems with solar thermal collectors (a) and heat pumps for waste heat utilisation (b) in process heat applications, under the assumptions considered in this work.



(a) *(b)*

Fig. 3: Contour plots of the LCoH for heating systems with biomass boilers (a) and natural gas boilers (b) in process heat applications, under the assumptions considered in this work.

For heat pumps and boilers, additional sensitivity analyses are conducted to assess the impact of electricity and fuel prices; these are presented in section 5.

4. Correlation-based estimation of key parameters

In practical applications, one of the two parameters required for the contour plots (solar collector yield or full-load hours) cannot be determined without simulation. Additional correlations are provided to overcome this limitation.

4.1 Solar thermal collector yield

Solar collector yields are estimated using correlations from the VDI 3988 guideline (VDI, 2020), derived from TRNSYS simulations (Klein et al., 2006) for five collector types (flat-plate collectors (FPCs), high-temperature FPCs, evacuated tubular collectors, compound parabolic collectors, and parabolic troughs) across two climate zones, Northern/Central Europe (average of Copenhagen and Würzburg) and Southern Europe (average of Toulouse and Madrid). Fig. 4 shows the maximum specific yearly yield for the five collector types in Northern/Central Europe (a) and Southern Europe (b), for a constant heat demand profile and optimal collector orientation. Correction factors, not detailed here for the sake of brevity, are further provided in the full report for non-optimal weekly load profiles and collector tilt/azimuth angles.

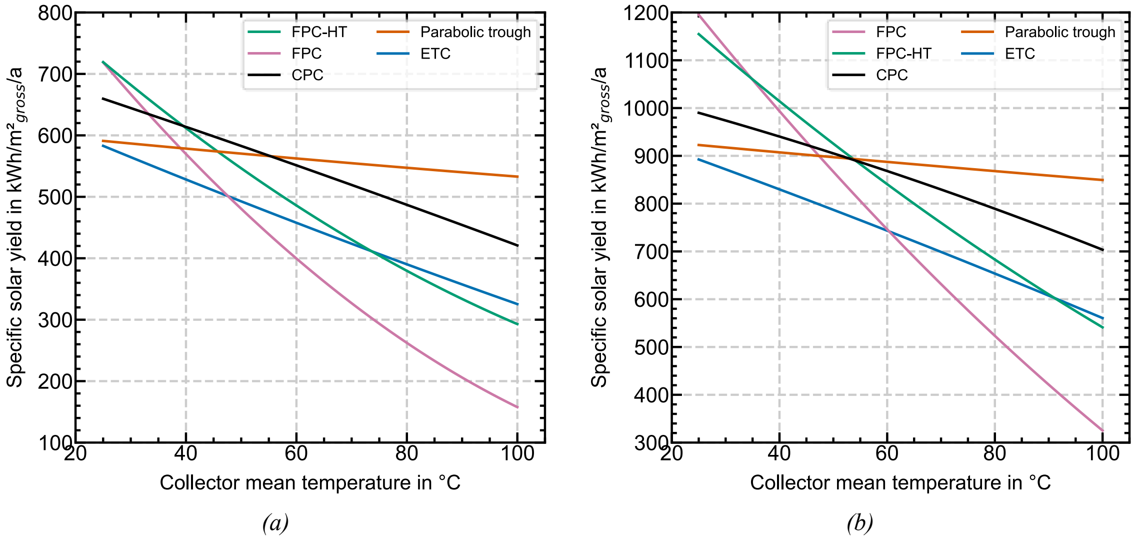
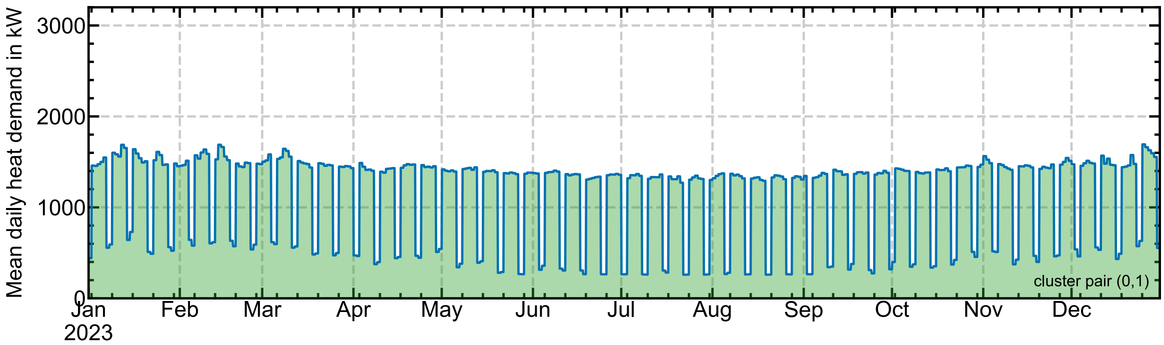


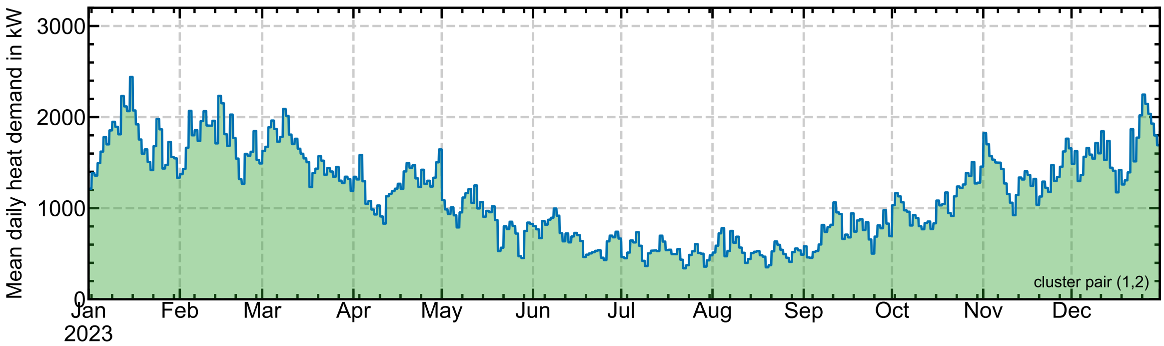
Fig. 4: Maximum yearly yield of five types of solar thermal collectors for the climate zones Northern and Central Europe (a) and Southern Europe (b). Data from the VDI 3988 guideline (VDI, 2020).

4.2 Heat demand profiles

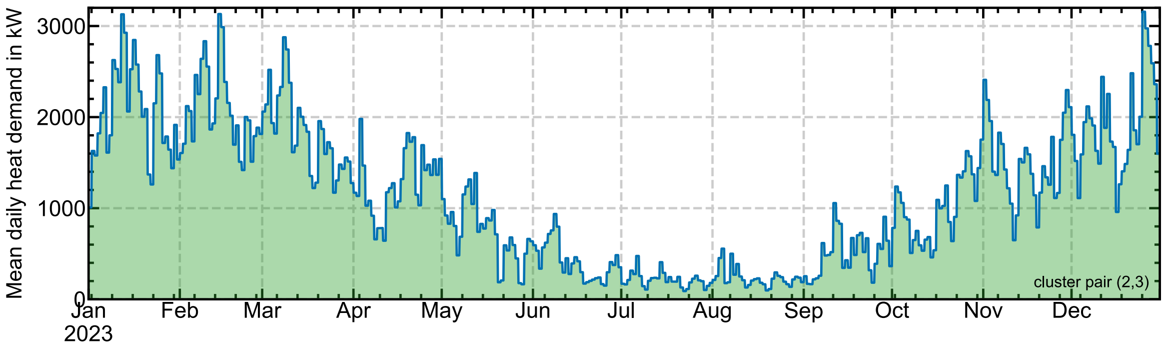
Estimating FLHs requires representative industrial heat demand profiles, defined using the methodology developed in IEA SHC Task 64 (Jesper et al., 2021; Pag et al., 2021) from the clustering of nearly 800 German industrial gas consumption profiles with hourly resolution. Combining a cluster for weekdays with a cluster for weekend days yields a yearly heat demand profile; only the three most common cluster pairs, (0,1), (1,2) and (2,3), are considered here. Fig. 5 illustrates the resulting yearly heat demand profiles for these three cluster pairs, computed for a total yearly heat demand of 10 GWh and the weather data of Copenhagen. Seasonality increases from (a) to (c): with the pair (0,1) the demand is relatively constant throughout the year (only dropping on weekends), while the winter-to-summer demand ratio reaches about 3 for the pair (1,2) and about 10 for the pair (2,3).



(a)



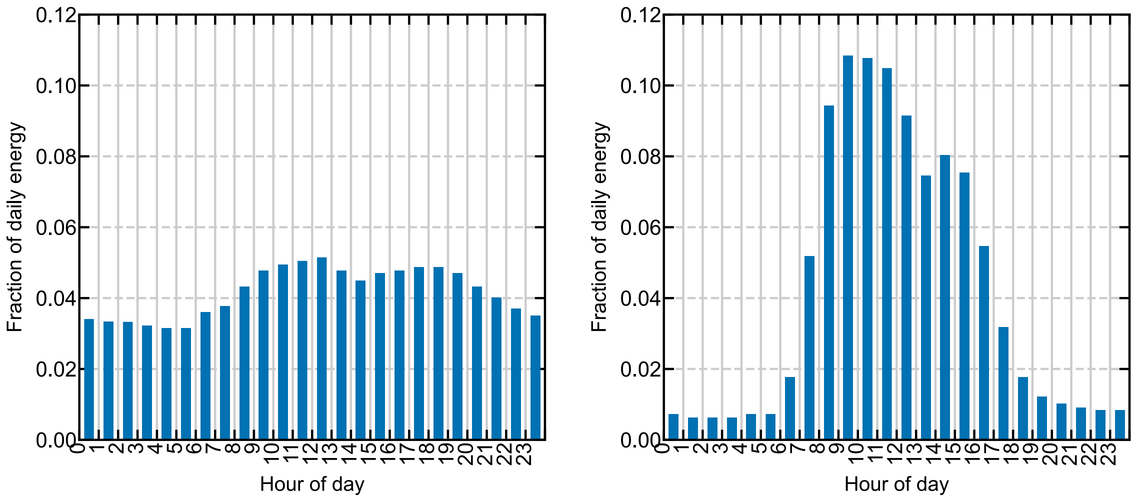
(b)



(c)

Fig. 5: Yearly heat demand profiles resulting from the cluster pairs (0,1) (a), (1,2) (b) and (2,3) (c), calculated for a total yearly heat demand of 10 GWh and the weather data of Copenhagen.

In addition to the yearly profile, the distribution of the daily heat demand over the 24 hours of the day is considered using two daily profiles, a "constant" and a "daytime" profile (Fig. 6). With the "constant" profile (a), heat demand varies only slightly over the day, while with the "daytime" profile (b) most of the demand is concentrated during usual working hours, between 7 a.m. and 5 p.m. Combining the three yearly profiles with the two daily profiles yields six representative heat demand profiles with hourly resolution, used throughout the FLH correlations presented below.



(a) *(b)*

Fig. 6: Daily heat demand characteristics for a "constant" profile (a) and a "daytime" profile (b).

4.3 Full-load hours of dispatchable heat generators

Based on the heat demand profiles introduced above, characteristic curves relate FLHs to the ratio r_{dim} of installed nominal capacity ($\dot{Q}_{\text{gen,nom}}$) to peak heat demand ($\dot{Q}_{\text{dem,peak}}$). Fig. 7 shows these curves for Northern and Central Europe: as expected, FLHs decrease as the relative size of the heat generator increases, and this decrease is faster for more seasonal demand profiles and for the more variable "daytime" daily profile.

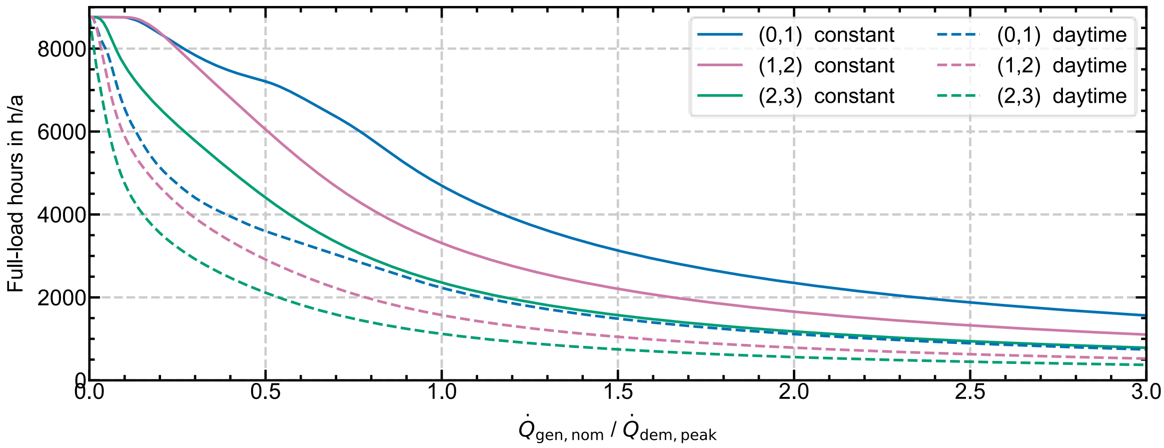


Fig. 7: Full-load hour characteristic curves for dispatchable heat generators in Northern and Central Europe, for the combinations of the three yearly heat demand profile clusters and two daily profiles.

4.4 Hybrid systems with solar thermal collectors

The approach is extended to hybrid systems combining solar thermal collectors with one or more dispatchable heat generators. A simplified hourly solar yield allocation method (based on an irradiance threshold and a linear distribution above it) and a simplified energy-based storage model are used to estimate how solar thermal integration reduces the operating hours of the other heat generators. The resulting FLH characteristic curves depend on the heat demand profile, the collector type, and the operating temperature level of the solar thermal system. Fig. 8 illustrates exemplary FLH characteristic curves of a dispatchable heat generator combined with flat-plate collectors for Northern and Central Europe and a "constant" daily heat demand profile. In the legend, the tuples (e.g. (0,1)) denote the combinations of weekday and weekend heat demand profile clusters, while the indicated temperatures correspond to the mean solar collector temperature. For a given r_{dim} ratio and a given heat demand profile, the number of full-load hours increases with the mean collector temperature, as lower temperatures allow the solar thermal system to cover a larger share of the heat demand.

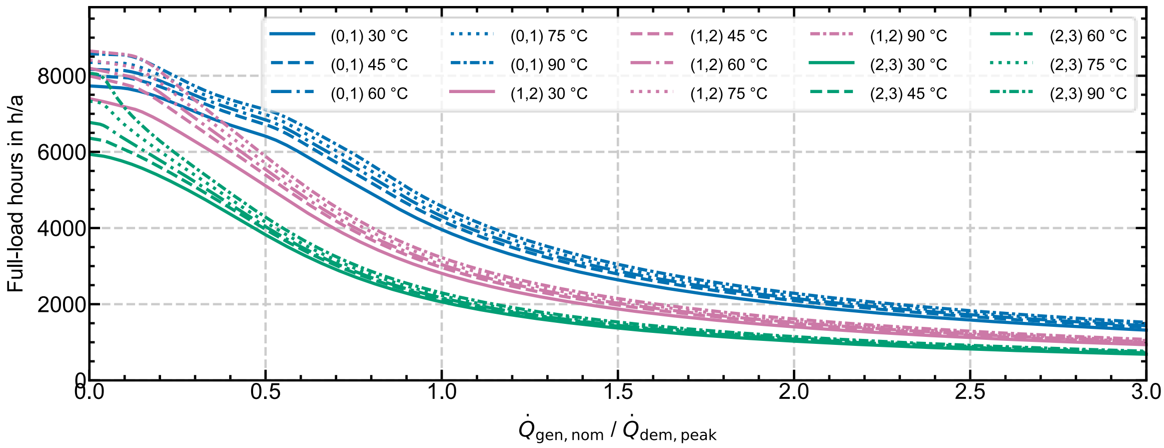
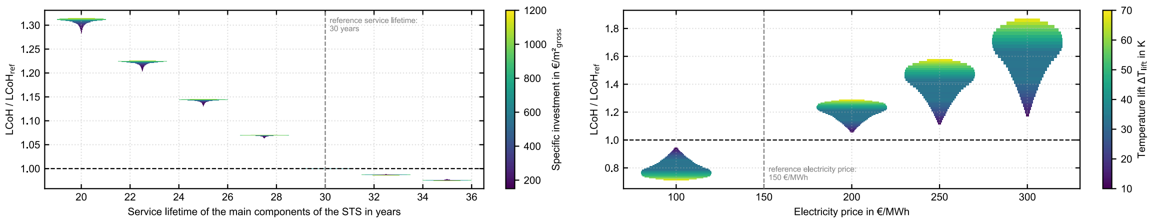


Fig. 8: Full-load hour characteristic curves for dispatchable heat generators combined with flat-plate collectors in Northern and Central Europe for a "constant" daily heat demand profile.

5. Sensitivity analysis

Beyond the two parameters shown in the contour plots (Figs. 2 and 3), further parameters influence the LCoH. Their impact is assessed through a sensitivity analysis, using violin plots that show, for each varied parameter value, the distribution of LCoH ratios (relative to the reference case) for all system configurations composing the mesh of the corresponding contour plot; the colour scale indicates the value of a third parameter (e.g. investment cost or temperature lift) for the most represented systems in each slice. Two examples are shown in Fig. 9, for the impact of the service life of the main components on the LCoH of solar thermal systems (a) and the impact of the electricity price on the LCoH of heat pump systems (b).



(a) *(b)*

Fig. 9: Sensitivity of the LCoH of solar thermal systems to the service life of the main components (a) and of heat pump systems to the electricity price (b).

For solar thermal systems, reducing the service life of the main components from 30 to 20 years increases the LCoH by 28 to 32 %, while extending it to 35 years decreases the LCoH by only 2 to 3 %; a lower discount rate of 3 %/a decreases the LCoH by 22 to 25 %, while a higher rate of 8 %/a increases it by 26 to 29 %, with systems of higher specific investment generally more sensitive to both parameters. For heat pumps, the sensitivity to investment cost and electricity price strongly depends on the temperature lift: a specific investment of 500 €/kW$_{th}$ (vs. 1,000 €/kW$_{th}$) changes the LCoH by -7 to -41 %, and 1,500 €/kW$_{th}$ by +7 to +41 %; an electricity price of 100 €/MWh (vs. 150 €/MWh) changes the LCoH by -7 to -30 %, and 300 €/MWh by +17 to +87 %. The nominal discount rate has a comparatively small effect on heat pumps (-1 to -12 % at 3 %/a, +2 to +14 % at 8 %/a). For biomass boilers, the LCoH varies close to linearly with the biomass price (-11 to -49 % at 15 €/MWh, +11 to +49 % at 55 €/MWh) and is only weakly affected by the discount rate (-1 to -8 % at 3 %/a, +1 to +9 % at 8 %/a). Natural gas boilers show the highest sensitivity to fuel price among the four technologies (-29 to -68 % at 20 €/MWh, +29 to +69 % at 110 €/MWh) but, like biomass boilers, a low sensitivity to discount rate (-1 to -8 % at 3 %/a, +1 to +9 % at 8 %/a), the lowest of all four technologies. Tab. 2 summarises the full ranges observed across all technologies and parameters.

Tab. 2: Summary of the sensitivity analysis results for the four technologies (impact relative to the reference LCoH, calculated with the value of the parameters presented in Tab. 1).

Technology	Parameter varied	Range studied	LCoH impact (low end)	LCoH impact (high end)
Solar thermal	Service life	20..35 years	+28 to +32 % (20 yr)	-2 to -3 % (35 yr)
Solar thermal	Nominal discount rate	3..8 %/a	-22 to -25 % (3 %/a)	+26 to +29 % (8 %/a)
Heat pump	Specific investment	500..1,500 €/kW$_{th}$	-7 to -41 % (500 €/kW$_{th}$)	+7 to +41 % (1,500 €/kW$_{th}$)
Heat pump	Electricity price	100..300 €/MWh	-7 to -30 % (100 €/MWh)	+17 to +87 % (300 €/MWh)
Heat pump	Nominal discount rate	3..8 %/a	-1 to -12 % (3 %/a)	+2 to +14 % (8 %/a)
Biomass boiler	Biomass price	15..55 €/MWh	-11 to -49 % (15 €/MWh)	+11 to +49 % (55 €/MWh)
Biomass boiler	Nominal discount rate	3..8 %/a	-1 to -8 % (3 %/a)	+1 to +9 % (8 %/a)
Gas boiler	Gas price	20..110 €/MWh	-29 to -68 % (20 €/MWh)	+29 to +69 % (110 €/MWh)
Gas boiler	Nominal discount rate	3..8 %/a	-1 to -8 % (3 %/a)	+1 to +9 % (8 %/a)

6. Conclusions and outlook

This paper presents a set of harmonised correlations that enable a rapid pre-assessment of the LCoH of four low-temperature industrial heat supply technologies, namely solar thermal collectors, heat pumps for waste heat utilisation, biomass boilers, and natural gas boilers, as well as their combinations. The correlations allow stakeholders to quickly compare options on a consistent basis, identify non-competitive solutions early, and focus planning efforts where detailed analyses are most valuable.

The sensitivity analysis shows that the economic performance of the technologies is influenced by key parameters such as discount rate, service life, temperature lift, and fuel or electricity prices, underlining the importance of transparent assumptions and consistent system boundaries when comparing results. The LCoH values estimated with the presented correlations are directly comparable with one another, as they rely on a harmonised methodology, but should not be compared with values obtained using different system boundaries or assumptions.

Future work could extend the methodology to additional technologies (e.g., direct electric boilers, geothermal, air-source heat pumps), broaden climate coverage for solar thermal, and verify the correlations against data from realised industrial projects. For additional correlations and details regarding the calculations, the reader may refer to the full report produced in the framework of IEA SHC Task 71 and currently in publication (Louvet and Pag, 2026).

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