Life cycle assessment for a district heating project with seasonal storage

A case study analysis for a community project based in Bracht, Rauschenberg, Hessen, Germany

Elke Michlmayr

1 Abstract

A life cycle assessment (LCA) was conducted for a solar district heating community project under construction in Bracht, Germany. The system incorporates solar thermal collectors, a seasonal heat storage unit powered by an integrated electric heat pump, a supplemental biomass boiler as a backup solution for periods when no heat is available from the solar-based system, and a district heating network to supply residential consumers.

The assessment used standard environmental impact methods such as the Ecological Scarcity method to evaluate the system over a 50-year lifetime. Despite supplying the majority of the energy, the solar thermal component with seasonal storage contributed less than 30% to the overall environmental impact. The supplemental biomass and the required electricity sourced from the grid accounted for roughly two-thirds of the total impact, even though they provided only one-third of the energy.

The results are encouraging and show that the Bracht system is environmentally favorable compared to many alternatives. However, substantial potential for improvement remains through optimization of the system's operating conditions. Key opportunities include using renewable electricity for the heat pump and reducing heat losses in storage and the district heating network to minimize, or even completely eliminate, the need for supplemental biomass. This is achievable by optimizing settings such as the system's operating temperature.

2 Introduction

Heating is a key contributor to energy consumption, accounting for roughly half of all energy used in the EU, with 60% of that energy still generated from fossil fuels as stated by Euroheat

& Power (2023). District heating is a system in which a central heating plant supplies heat to multiple households through a network of pipes. It works in two main ways, either by utilizing surplus heat from sources such as waste incineration plants to provide heating for residential areas and service centers as described by Swiss Federal Office of Energy (2020), or by relying on dedicated energy sources such as biomass or solar thermal collectors. There are approximately 6,000 district heating systems operating across the EU according to Euroheat & Power (2023). Process heating uses a similar setup but is designed for industrial applications, which typically require higher temperatures. Studies such as Jeandaux et al. (2021) have shown that using a centralized heating system with a heat distribution network results in a lower environmental impact compared to standalone heating units installed at each consumer's site.

Solar thermal collectors (STCs) are devices that absorb solar radiation and convert it into heat. There are several types of STCs, including flat plate collectors, unglazed water collectors, and evacuated tube collectors. These systems are often combined with heat pumps to bridge the temperature gap between the water produced by the solar field and the temperature required by the district heating delivery system as explained in Wikipedia (2025). According to Weiss and Spörk-Dür (2024), there are more than 300 large-scale district heating systems worldwide powered by STCs, and over 1.200 STC systems that provide industrial process heat.

Solar thermal collectors are a mature technology. In 2023, the total operational solar thermal capacity reached 560 GW_{th}, covering roughly 800 km^2 of collector area as documented by Weiss and Spörk-Dür (2024). STC-provided capacity varies seasonally depending on available sunlight. In some cases, STCs are used only during certain parts of the year, for example to allow a biomass-powered plant to shut down during summer when it would otherwise operate at extremely low capacity.

STCs can be combined with short-term heat storage that acts as a buffer, or with seasonal heat storage tanks, sometimes referred to as pit thermal energy storage (PTES). These include underground hot water basins that store excess heat from the warm season for use in the cold season. However, this setup involves heat losses.

If space limitations or land costs require it, STCs can be installed at a distance from consumers and heat plants, with pipelines connecting them. An example is Priština, where the distance is around 4 km as detailed by Euroheat & Power (2023). This introduces a trade-off, as the remote location requires laying additional underground piping.

For the community district heating project in Bracht, the economic viability in comparison to conventional energetic renovation measures has been assessed in a previous study by Kelch et al. (2024). However, the environmental impact of the project has not yet been examined in detail. This gap forms the focus of the present study. The following chapters will cover the remaining stages of the LCA: goal and scope definition in Section 3, life cycle inventory analysis (LCI) in Section 4, life cycle impact assessment (LCIA) in Section 5, and result interpretation in Section 6.

3 Goal and scope

The goal and scope definition is a fundamental step in any life cycle assessment (LCA), as it provides a clear description of the product system under study, its system boundaries, and a definition of the functional unit that reflects the output of the system in a consistent and measurable way.

The scope of the assessment encompasses a district heating project initiated and operated by a cooperative composed of future household consumers and the local municipal council. The system includes the following key components:

- solar thermal collector (STC) field,
- seasonal storage unit (SSU),
- heat pump component powered by electricity from the grid with buffer storage unit,
- biomass combustion unit serving backup heat when stored heat is unavailable,
- facility to house the heat pump and the biomass combustion unit,
- district heating distribution network that supplies heat to residential consumers,
- and receiver units installed in each participating household.

The lifetime of the district heating system is assumed to be 50 years. At least 180 households are expected to join the community district heating as paying consumers, which is roughly 60% of all households that exist in the local community. The plant is currently under construction and on track to be operational for the 2025 winter heating period.

For the present LCA, the specific goals are to address the following research questions:

1. What is the relevance of the additional electricity required in the setup and the supplemental biomass boiler with respect to the overall environmental impact? The hypothesis is that the additional electricity and biomass required will amount to a sizable part of the overall environmental impact.
2. How does the STC-based system with seasonal heat storage compare to other heating technologies in terms of environmental impact? The comparison will include district heating from other sources that would be available in small communities (such as heat pumps or wood chips), and consumer side heating installations such as oil or gas boilers. The hypothesis is that the STC-based system will have a lower environmental impact compared to other district heating setups and to fossil energy based consumer installations.
3. What is the environmental impact contribution of the seasonal heat storage unit in the production, construction, and use stages in the life cycle? A sensitivity analysis will be performed to assess the benefits of the STC-based system with a seasonal heat storage component included under several assumed loss coefficients for the storage component and the district heating pipe system. The hypothesis is that the seasonal storage component will lower the environmental impact.

3.1 Functional unit

The functional unit is defined as 1 megajoule (MJ) of thermal energy delivered to the consumer directly at the point of use during the heating period. Using MJ instead of kilowatt-hours of thermal energy (kWh_{th}) ensures consistency with the UVEK processes for other forms of district heating in SimaPro, against which the comparison will be performed.

3.2 System boundary

The system diagram shown in Figure 1 describes the product system and its boundaries.

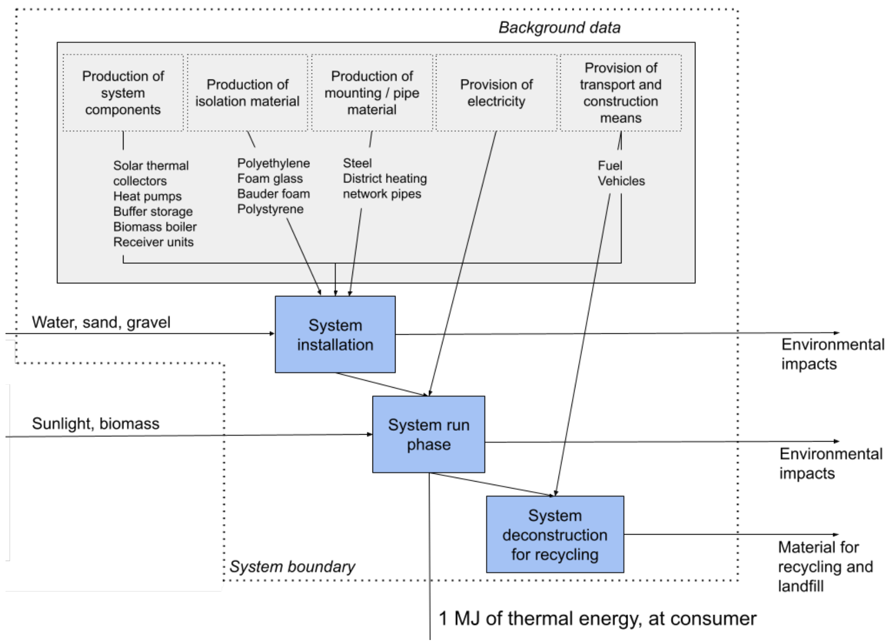

Figure 1: System diagram for the Bracht community district heating network.

3.3 Databases, software, and data sources

The LCA was performed using the SimaPro 9.6.0.1 software by PRé Sustainability (2024). The foreground data was collected from various online sources and combined with background data from the Ecoinvent v3 database by Wernet et al. (2016) and the UVEK LCI database version DQRv2:2025 by the Federal Office for the Environment (FOEN) (2025).

3.4 Selected LCIA methods

The environmental impacts were assessed using the midpoint level Environmental Footprint (EF) 3.1 method by the European Commission (2021), and the Ecological Scarcity 2021 (v1.04) method by the Federal Office for the Environment (FOEN) (2021) at the single score level with UVEK LCI weighting set.

3.5 Allocation

The cut-off approach as defined by the International Organization for Standardization (2006) was employed.

4 Life cycle inventory

This section outlines the foundational data used to support system modelling. Extensive project-related information for the Bracht community district heating system is available on the project website published by the City of Rauschenberg (2025c). This was used as a key source for detailed LCI data. It provided detailed data on the solar thermal collector field, the seasonal storage unit, and heat preparation systems comprising the heat pump, buffer storage, installation facility, and consumer installations.

The comparison datasets and the district heating network were modelled based on UVEK LCI data by the Federal Office for the Environment (FOEN) (2025), an existing resource for conducting LCAs of energy systems and infrastructure within Switzerland and the broader European context provided by the Swiss Federal Office of Energy (abbreviated in English as SFOE, and in German as UVEK). For electricity input, the modelling assumed the European Network of Transmission System Operators for Electricity (ENTSO-E) production mix, also provided in the UVEK dataset, to ensure the model reflects conditions typical of a plant operating within the European region.

Additional LCI details for all components are provided in Section 9.1. Detailed specifications and parameters of the resulting system model are described in Section 9.2.1. The remainder of this section outlines the key assumptions regarding component lifetimes, expected electricity demand, and thermal loss coefficients.

4.1 Component lifetimes

The planned lifetime for the Bracht plant is 50 years. The assumed individual component lifetimes and the resulting relevant multipliers are shown in Table 1. The assumed individual component lifetimes are in line with the assumptions used in Kelch et al. (2022).

Table 1

Component	Years	Multiplier	Source
Solar thermal collectors	30	1.67	(Große et al., 2017)
Seasonal storage unit	30	1.67	(Kelch et al., 2022)
Heat pumps	20	2.5	(Wolf, 2017)
Heat buffer storage	20	2.5	(Große et al., 2017)
Heat installation facility	50	1	(VDI, 2012)
Heat exchange stations at consumer	20	2.5	(Kelch et al., 2022)
District heating network	50	1	(Kelch et al., 2022)

4.2 Electrical power requirements and loss coefficient assumptions

Performance data from TÜV Rheinland (2021) provides several estimates of the annual output for the solar thermal collectors used in this project. These estimates vary by geographic location and desired output temperature. The most geographically relevant data point is for Würzburg, with an output of 5.283 kWh per collector per year at a target output temperature of 75 degrees Celsius (°C). Given a total of 855 collectors, the estimated gross thermal energy production is approximately 4.517 MWh per year.

According to the project documentation by the City of Rauschenberg (2025a), 2.700 MWh per year are expected to reach end-user households. This implies a total system loss of approximately 40% in total, accounting for thermal losses in two places: in the storage unit, and in the heat distribution network used for heat transmission to consumers.

Since detailed methods for the loss estimates used in the Bracht assumptions were not provided in the public documentation, the modelling described in this document assumes a 20% loss coefficient as the default for the heat transmission pipe network. The relevant literature and further rationale for the choice are presented in Section 6.3.1. Given this assumption, the implied thermal loss within the seasonal storage unit would be approximately 50% to align with the reported figures from City of Rauschenberg (2025a).

Consequently, roughly half of the solar thermal collector production of 4.517 MWh per year, which amounts to 2.258 MWh per year, is available for consumption from the seasonal storage unit. The available heat will be augmented with extra energy from biomass (26 %) and from the electricity grid (6 %) as reported in Epp (2024). The total amount of energy supplied to the district heating network is approximately 3.370 MWh per year:

- 67 % from stored solar thermal energy (approximately 2.260 MWh),
- 26 % from biomass sources (approximately 900 MWh), and
- 6 % from the electricity grid (approximately 210 MWh)

After discounting district heating network losses that will happen during heat transmission, an amount of 2.700 MWh per year is available for consumption in the participating end-user households. It is noted that the distribution totals 99 instead of 100, likely due to rounding, but since this is information from the original source and the difference is small, it was adopted without modification.

The loss assumptions as described in this chapter were incorporated into the system model as the default values. More background and a detailed discussion of thermal loss coefficients and their influence on system performance is presented in the sensitivity analysis in Section 6.3.

5 Results

The system model, as detailed in Section 9.2.1, was implemented using SimaPro by PRé Sustainability (2024). This model served as the foundation for generating LCA results using the Environmental Footprint (EF) 3.1 method by the European Commission (2021) and the Ecological Scarcity 2021 (v1.04) method by the Federal Office for the Environment (FOEN) (2021). The results derived from these assessments are presented in this section.

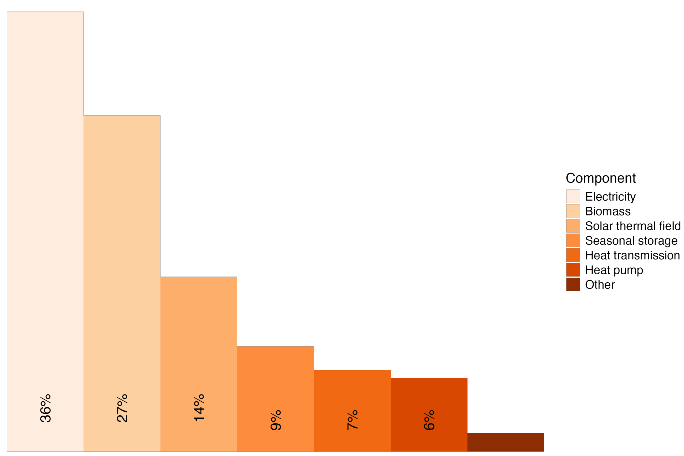

Figure 2: Relative environmental impact for components of Bracht community district heating system (Ecological Scarcity 2021, v1.04, UVEK LCI weighting)

To address the first research question regarding the environmental impact of the additional electricity and the supplemental biomass burnt in the wood boiler, the relative influence of the individual components of the solar thermal district heating system on overall environmental impact was evaluated using the Ecological Scarcity 2021 (v1.04) method. The assessment was conducted at the single-score level, applying the UVEK LCI weighting set to define the relative importance of the different damage categories. The results are presented in Figure 2.

They show that biomass (27 %) and electricity (36 %) have a very large impact. They are responsible for nearly two-thirds of the environmental impact of the overall system. The solar thermal based part of the system with solar thermal field, seasonal storage, and heat pump is responsible for less than 30 % of the overall environmental impact, although they supply two-thirds of the total energy production as documented by Epp (2024). Only one-third of the energy delivered to end consumers originates from biomass and electricity.

For a more detailed view of the environmental impact by individual damage categories, Figure 3 presents the drilled-down individual results for the most relevant impact categories *Climate change*, *Particulate matter*, *Eutrophication (terrestrial)*, *Land use*, *Resource use (minerals and metals)*, and *Resource use (fossils)*. The figure shows that biomass combustion is the dominant contributor to land use, particulate matter, and terrestrial eutrophication. In contrast, electricity use is the primary driver of impacts for fossil resource use and climate change. The environmental impact for minerals and metals resource use is most significantly influenced by heat preparation and the solar thermal collectors. The seasonal storage unit is not dominant for any damage category, but some contributions are visible in climate change and fossil resource use. Similar effects can be seen for the solar thermal collector.

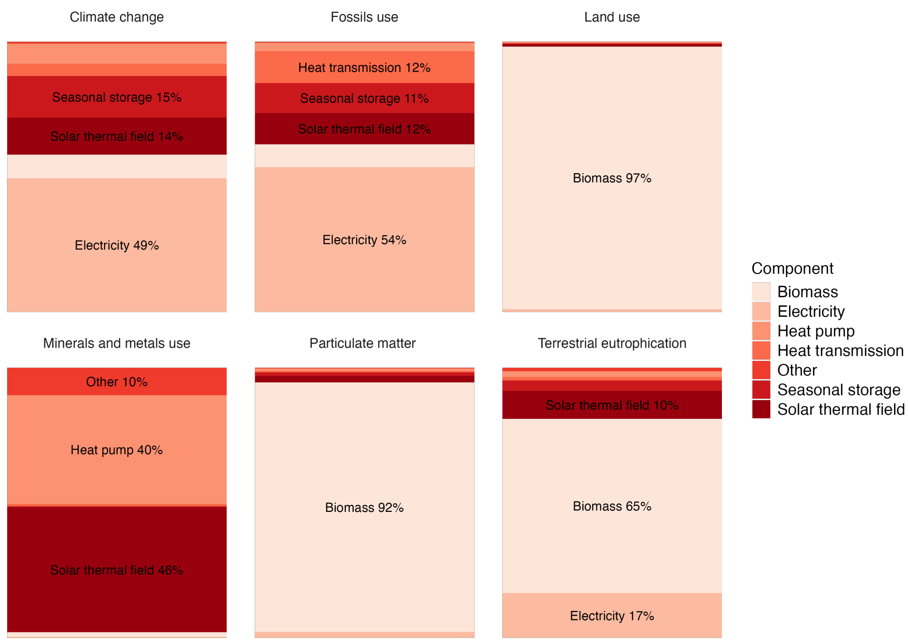

Figure 3: Relative environmental impact of Bracht community district heating network system components for the six most relevant damage categories (Environmental Footprint 3.1 method, version 3.1).

In summary, the electricity and biomass used to operate and supplement the system are the primary contributors to the overall environmental impact. Electricity consumption is unavoidable due to the operation of the heat pump. However, its impact can potentially be mitigated by sourcing electricity from renewable sources instead of the ENTSO-E production mix (as described in Section 4), an option explored in more detail in Section 6.2. Strategies to reduce biomass consumption by improving thermal efficiency, such as lowering heat loss coefficients, are examined in Section 6.3.

To address the second research question, the environmental impact of heat generated by the solar thermal collector based district heating system with seasonal heat storage was compared to that of other heating technologies. The results, presented in Figure 4, show a comparison of the environmental impacts of STC-based district heating with other district heating (DH) options commonly available in small communities, such as central systems based on wood chips (biomass) or geothermal heat pumps as the energy source. Additionally, the analysis includes consumer-side heating installations (CI), such as oil and gas boilers. The assessment was conducted using the Ecological Scarcity 2021 (v1.04) method at the single-score level, applying the UVEK LCI weighting set.

The results are expressed in environmental impact points (Pt) per megajoule (MJ) of heat delivered. They reveal that the heat produced by the Bracht plant with 47 Pt per MJ of heat shows the second lowest environmental impact compared to other heating technologies. The largest contributor is the *Global warming* category (which is comparable to the *Climate Change* damage category in the Environmental Footprint method). This is dominantly caused by the electricity required (ENTSO-E production mix as discussed in Section 4), and to a lesser extent by the seasonal storage unit and the solar thermal collectors (cf. Figure 3).

The lowest environmental impact with 46 Pt per MJ of heat is returned for the district heating system based on wood chips as the energy source, even with the impact on main air pollutants and particulate matter (PM) having a significant impact on the overall results for this setup. The district heating system based on a geothermal heat pump as the energy source has the third lowest impact with 62 Pt per MJ of heat, to the largest extent from impact on radioactive waste to deposit. Gas- and oil-based consumer installations fare significantly worse with 78 Pt and 119 Pt per MJ of heat, primarily from impact on climate change.

As before, Figure 5 presents the individual results for the most relevant damage categories, comparing them relative to the highest value in each category, which is shown as the longest bar representing 100% relative impact. This analysis confirms the findings from Figure 4, clearly demonstrating that oil and gas boilers have extremely high impacts in the *Climate change* category with 100% and 70%, respectively. Additionally, the oil and gas boilers exhibit the highest fossil resource use, at 100% and 80%. A clear trade-off exists because each heating technology performs worst in different impact categories. For example, the district heating network using wood chips shows lower climate change impacts but the highest relative impacts in *Terrestrial eutrophication*, *Land use*, and *Particulate matter* (PM). While PM impact was visible in Figure 4, *Terrestrial eutrophication* and *Land use* impacts were not significant in the single score results. Similarly, solar thermal and geothermal-based district heating systems have the highest relative impacts in *Minerals and metals resource use*, at 100% and 83%, respectively. These trade-offs imply that selecting a heating technology depends on which

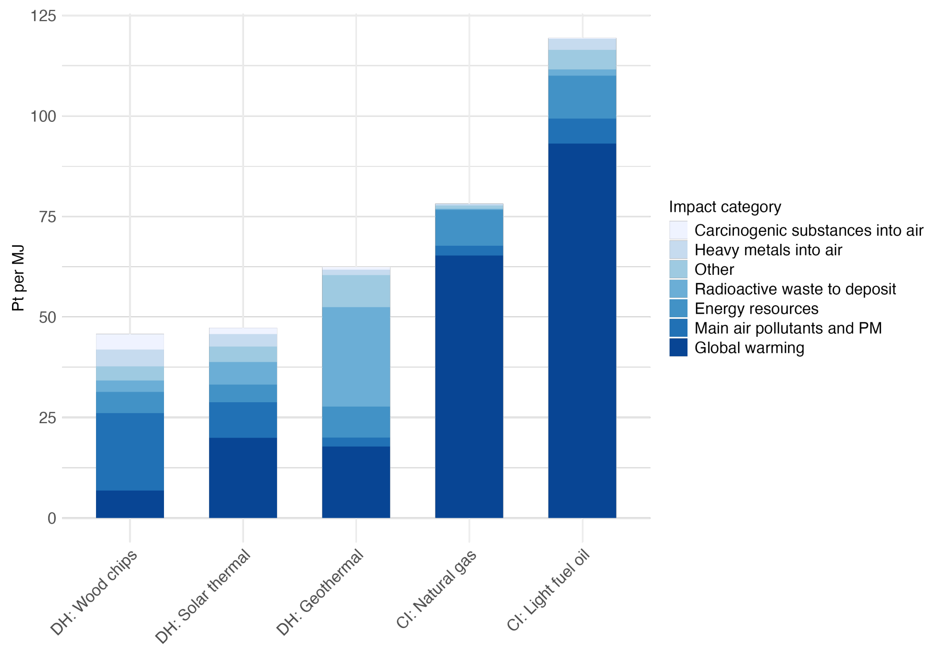

Figure 4: Comparison of environmental impact of Bracht community district heating network to other energy sources for district heating such as wood chips and heat pump, and to consumer installations such as gas and oil burners (Ecological Scarcity 2021 v1.04, UVEK LCI weighting).

environmental impacts are prioritized for a given use case. This highlights the need to weigh and balance different categories manually, or to rely on a single score method if applicable.

6 Interpretation and discussion

This chapter discusses the results introduced in Section 5. They revealed that the district heating system based on solar thermal energy and seasonal storage compares favorably to other means of heating. However, in the given modelling, with limitations as documented in Section 6.1, it exhibits higher environmental impact compared to the district heating system based on wood chips as the energy source. The electricity and the supplemental biomass required were found to be the two top single contributors to the overall results. To understand the savings potential from using lower-emitting (see Section 6.2) or less energy resources (see third research question and Section 6.3), sensitivity analyses for source of electricity and loss coefficients for the heat loss in the seasonal storage unit and the district heating pipes were performed. The combined results from both sensitivity analyses are summarized in Section 6.4.

6.1 Modelling limitations

Data availability was generally satisfactory with one notable exception for the modelling of the heat pumps used in the system (see Section 9.1.3 for specifications). There are two heat pumps with 630 kW max electrical input power each used in the system, but in the UVEK data, the largest sized heat pump available has a maximum power of 50 kW. The best possible assumption in this situation was that the two large heat pumps have the same impact as 25 units of the 50 kW heat pump, but this is likely leading an overestimation of the resource use for minerals and metals. This is acceptable since with 6 %, the heat pump showed only minor impacts on the overall results (see Figure 2).

The UVEK data for the other energy sources for district heating (wood chips, heat pump) uses an 11 % assumption for district heating pipe heat loss, which means that the solar thermal data with a 20% assumption as mentioned in Section 4.2 was disadvantaged in the comparison in Figure 4. The effect of these assumptions on the results will be investigated in Section 6.3.

Worth mentioning is that the UVEK data for district heating has a lifetime assumption of 30 years whereas the Bracht district heating network setup assumes 50 years. This is acceptable since the district heating system showed only a minor impact of 7 % on the overall results (see Figure 2).

There was a problem with the weights for the damage category *Water resources, net balance* in the UVEK LCI weighting set that required excluding this category from the analysis.

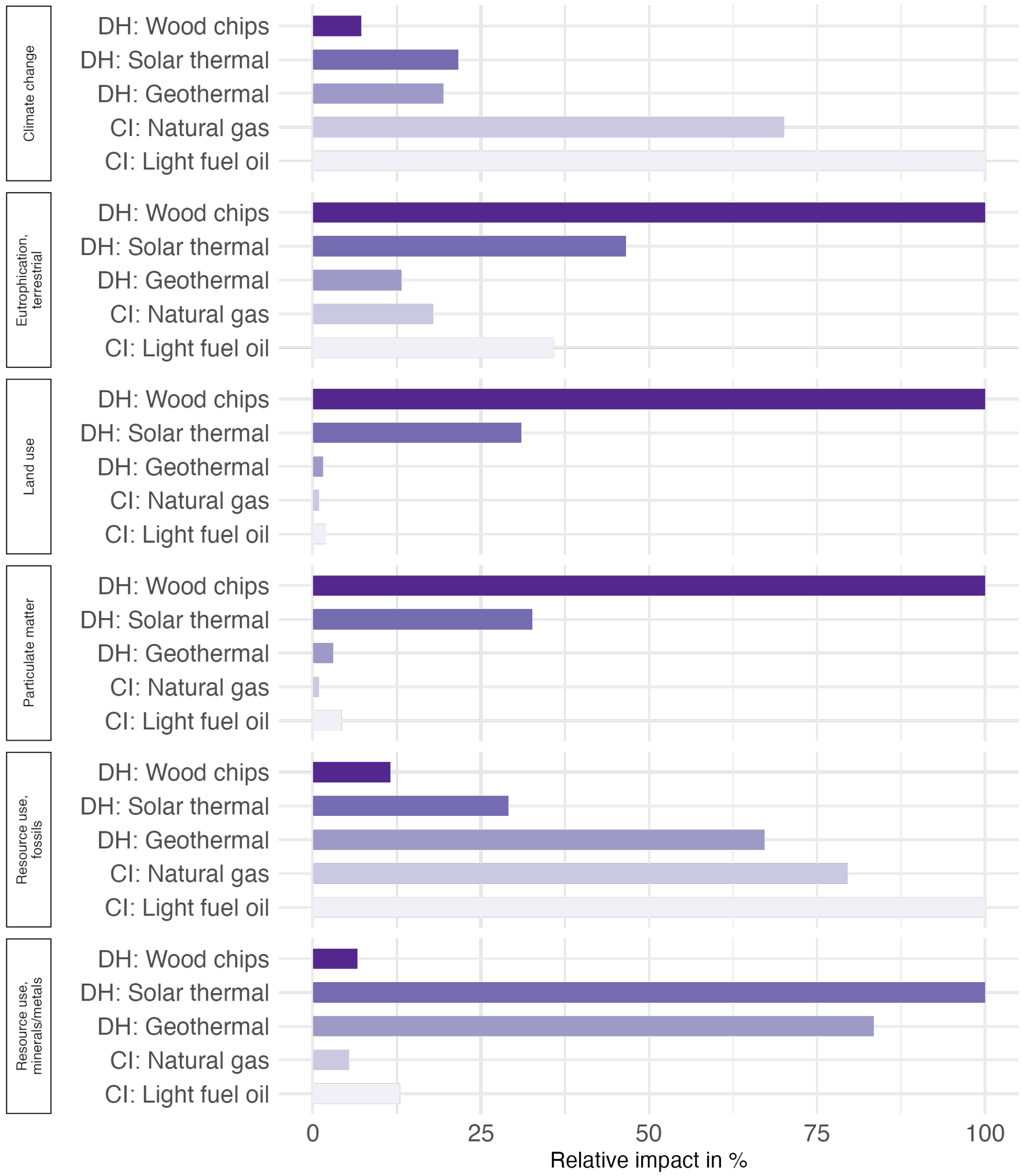

Figure 5: Damage assessment for the most relevant categories using the Environmental Footprint 3.1 method, visualized as relative environmental impacts in comparison. See Figure 9 for the results for categories omitted in the given chart.

System deconstruction was modelled only for the major infrastructure components, specifically the solar thermal collector field and the seasonal storage unit. The model includes the disposal of plastic materials used for sealing and insulation in the seasonal storage unit, assuming treatment via municipal waste incineration. For the remaining system components, the deconstruction processes were included in the model, but final disposal or material recovery for these components was not considered within the scope of this analysis (cf. system diagram in Figure 1).

6.2 Sensitivity analysis: Source of electricity

The results as presented in Figure 4 indicate that the dominant environmental impact arises from the electricity demand of the system, which originates from the heat pump. In the default model, the electricity mix was modelled based on the ENTSO-E production mix by the Federal Office for the Environment (FOEN) (2025). This includes a built-in assumption that the electricity production mix will remain constant over the lifetime of the plant. In this section, the effects of the default choice for the modelling as well as potentially achievable savings by using lower-emitting electricity are assessed.

There are two specific aspects of the given use case that need to be considered:

- Electricity consumption primarily occurs during the winter months, when electricity production conditions differ significantly from those in the summer months (e.g., reduced output of photovoltaic systems).
- The plant is assumed to have a lifetime of 50 years, which means it is expected to be decommissioned around 2075. Given the European Union's commitment to achieving net-zero greenhouse gas emissions by 2050, significant changes in the environmental impact of electric energy can be anticipated over the plant's operational period.

While attempting to assess the impact of future grid decarbonization, it became apparent that no readily available dataset exists with projections about the future energy grid in Europe that could be directly applied for the analysis. Consequently, the remainder of this section focuses on the planned future for the Swiss energy grid. The most reliable sources of information are provided by Swiss Federal Office of Energy (SFOE) (2020a) (charts: Swiss Federal Office of Energy (SFOE) (2020b); data tables: Swiss Federal Office of Energy (SFOE) (2020c)). Particularly relevant are the projections for the expected winter electricity production mix at five-year intervals from 2025 to 2060, as depicted in Figure 6.

Based on this data, the anticipated energy mix over the operational lifetime of the Bracht plant was calculated as summarized in Table 2. Since no projections are available beyond 2060, the values from 2060 were assumed to remain constant through 2075. Detailed information about the origin and type for Switzerland's imported electricity during the winter was missing from the primary dataset. To address this, an additional dataset from the World Bank World Bank (2023) was employed to determine the country-wise distribution of

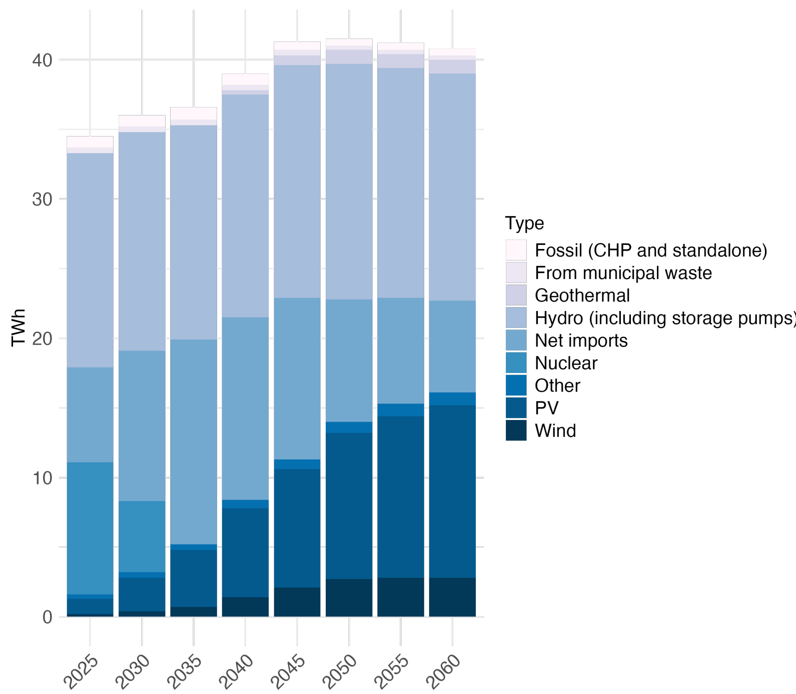

Figure 6: Expected production mix for winter period (6 months) in Switzerland from 2025 to 2060 (Source: Swiss Federal Office for Energy).

electricity imports. According to this dataset, electricity imports in 2023 originated primarily from France (60.2%), Germany (23.1%), Austria (14.4%), and Italy (2.3%). The low voltage production mix in these countries was assumed for modelling. There was no specific data for geothermal and waste water based electricity available. These were substituted with hydro power based electricity, due to its comparable environmental impact profile.

Table 2

Type	%	Avg. MWh per year
Hydro (with storage pumps)	41.81 %	87.4
Net imports	22.38 %	46.8
PV	20.30 %	42.4
Wind	4.59 %	9.6
Nuclear	3.45 %	7.2
Fossil (CHP and standalone)	1.73 %	3.6
Other	1.70 %	3.6
Geothermal	1.42 %	3.0
From municipal waste	0.92 %	1.9
Bio gas	1.18 %	2.5
Biomass	0.26 %	0.5
From waste water	0.26 %	0.5

Based on the numbers from Table 2 and evaluated using the Ecological Scarcity 2021 (v1.04) method, the environmental impact of operating such a plant in Switzerland is estimated at an average of 36 Pt per MJ of heat over the complete lifetime of the plant.

To reduce this impact further, the Bracht plant could consider purchasing renewable electricity. Using exclusively wind power would lower the environmental impact to 31 Pt per MJ of heat, while relying solely on hydro power would result in 32 Pt per MJ. In both cases, the environmental footprint associated with the plant's electricity demand would be largely offset. For comparison, in a hypothetical scenario with no electricity requirement at all, the environmental impact would be 30 Pt per MJ of heat.

6.3 Sensitivity analysis: Loss coefficients

Heat is harder to transport than electrical power since even good insulation cannot avoid losses of radiating heat. There are two main areas where heat losses occur in the setup: in the pipes, and in the seasonal storage unit. Therefore, the loss coefficients assumed for the pipes and for the storage unit are highly relevant to the modelling. The impact of changes in these loss coefficient assumptions will be assessed in Section 6.3.1 and Section 6.3.2.

6.3.1 Pipe heat loss

As summarized in Werner (2017), the key parameters affecting heat loss in district heating pipes include the length of the network which depends on the transmission distance relative to demand, the system age, and the operating temperature. The relevant heat loss coefficients reported range between 5 % and 35 %. The Bracht setup involves a relatively long transmission distance of 8800 meters due to its rural context. The supply temperature of 85 degrees °C is relatively high, which will contribute to increased thermal losses. In contrast, modern district heating systems can operate with lower supply temperatures between 50 and 70 degrees °C to minimize heat loss and improve efficiency as described by Lund et al. (2020).

The rationale behind selecting a default heat loss rate of 20 % for the Bracht setup reflects the combined negative impact of the long transmission distance and high operating temperature on system performance. However, several sources assume lower loss rates. For example, the open source Energy Transition Model Quintel (2025) suggests a 15 % default loss figure based on real world data for modern district heating networks. The Swiss Federal Office of Energy UVEK assumes an even lower rate of approximately 11 % in its district heating data.

If the Bracht system was optimized to achieve heat loss rates comparable to the UVEK assumption, e.g. by lowering the operating temperature, annual efficiency gains of about 300 MWh could be realized. This would remove one-third of the requirements that are planned to be supplied via biomass, which would correspond to a 9 % reduction in ecological impact from 47 Pt per MJ to 43 Pt per MJ of heat produced according to the Ecological Scarcity 2021 (v1.04) method at the single score level with UVEK LCI weighting. The most significant reductions can be achieved in the *Main air pollutants and particulate matter (PM)* category, primarily due to the reduced combustion of biomass.

6.3.2 Seasonal storage unit heat loss

In Penttinen et al. (2021), the authors report a 26 % loss of heat production in the storage unit. The Energy Transition Model by Quintel (2025) suggests 30 % as a sensible default for modelling heat loss in the storage unit. Another study by Xiang et al. (2022) provides a comprehensive review and finds that 30% to 50% heat losses are common for Pit Thermal Energy Storage and that the majority of losses are caused through the top of the system, where the floating cover is located.

Given these reference numbers from literature, the 50 % loss assumption that was used for the Bracht plant is on the conservative side. For the sensitivity analysis, the assumption made is that it can potentially be lowered to 30% based on two different scenarios: (A) without any changes in the setup but an understanding that the original assumptions were not accurate, and (B) by doubling the floating cover for the top of the seasonal storage unit which will provide better insulation. Sides and bottom of the seasonal storage unit remain unchanged.

In both scenarios, a significantly higher amount of energy is available from the seasonal storage unit because of the lower heat loss as shown in Table 3. In the original scenario, out of the 4.517 MWh produced by the solar thermal collectors, an amount of 2.259 MWh remains available from the seasonal storage unit after accounting for assumed losses. When heat losses are reduced, the available energy increases substantially to 3.162 MWh. The difference of 900 MWh is equal in size to the contribution that was expected to be supplied via biomass combustion in the default model. Therefore, the opportunity exists to lower the environmental impact of the system by removing the parts that stem from biomass. These have a significant impact as shown in Section 5.

Table 3

Scenario	Dimension	Value	Assumed loss	Electricity requirements
all	Produced	4.517 MWh	-	
default	Available	2.259 MWh	50%	209 MWh (Factor 0.092)
(A) and (B)	Available	3.162 MWh	30%	293 MWh (Factor 0.092)

However, the higher availability of energy in the seasonal storage unit results in a modified heat supply curve and in heightened electrical energy requirements for the heat pump since it will be used more extensively in the system instead of the biomass boiler. An in-depth analysis of the implications would require additional modelling tools such as AG (2012), which is out of scope for the given work. As a simplification, a rough estimate of the heightened energy requirements was carried out based on the factor between energy from the seasonal storage unit and energy from electricity from the original assumptions (see Table 3): 209 MWh divided by 2.258 MWh, which returns a 9.2 % electricity requirement factor. Note that this corresponds to a COP of 11, which is indicative for a highly performant system. This was considered plausible, because the initially very high temperature in the seasonal storage unit (85 degrees °C) at the beginning of the heating periods means that the heat pump will not be required to bridge the temperature gap until the temperatures are falling to lower levels. The rough estimate based on the electricity requirement factor as described results in a 293 MWh electricity demand for the heat pump (40 % increase).

Both scenarios were modelled in SimaPro to learn about the implications on environmental impact. The Ecological Scarcity 2021 (v1.04) method was employed. Like in the default model, the ENTSO-E production mix was assumed. For scenario (A) with updated assumptions, a 15 % reduction from 47 Pt per MJ of heat to 40 Pt per MJ of heat can be achieved. For scenario (B) with a doubled insulating cover for the seasonal storage unit, a 9 % reduction to 43[1] Pt per MJ of heat can be achieved. This confirms the environmental impact savings potential of operating conditions improvements.

[1]This is coincidentally the exact same result as already obtained in Section 6.3.1.

6.4 Combined results from sensitivity analysis

As discussed in the previous sections, two main opportunities for optimization have been identified: (1) reducing heat losses in the system to decrease the need for supplemental biomass, and (2) using renewable energy to operate the heat pump. Interestingly, there are dependencies between these two factors. Reducing heat losses increases the amount of energy available from the seasonal storage unit. As a result, less biomass is required. However, more electricity may be needed to operate the heat pump, since a larger amount of energy must be processed. Depending on the environmental impacts of the selected electricity mix compared to those of the chosen biomass, the overall effect of reducing heat losses in the seasonal storage system could, counterintuitively, be negative.

As the results for wind and hydro power were nearly identical in the previous section, hydro was excluded from this analysis for the sake of clarity. Scenario (A) from Section 6.3.2 was chosen for the comparison as the representative scenario for heat loss optimization. As before, the Ecological Scarcity 2021 (v1.04) method was employed.

The optimization potential results are presented in Figure 7. As already shown, optimizing heat loss in the seasonal storage unit can lower the impact from 47 Pt per MJ of heat to 40 Pt per MJ of heat (15 % reduction). The impact when operating the plant using the future energy mix in Switzerland (CH) is estimated at an average of 36 Pt per MJ of heat (23 % reduction). When using Swiss wind energy, the impact will be lowered to 31 Pt per MJ of heat (34 % reduction). The best result with 18 Pt per MJ of heat can be achieved by combining heat loss optimization with Swiss wind energy to operate the heat pump, which reduces environmental impact by 61 %.

7 Related work

In scientific literature, while several LCA case studies for district heating systems exist, only a small number focus on solar thermal collector based systems.

Famiglietti et al. (2021) conducted a life cycle assessment of a district heating extension intended to serve a large new development in Milan. The goal was to determine whether this option would offer environmental advantages over individual heat pumps, using the Environmental Footprint 3.0 method. The results showed that, based on the energy source used for the district heating network in 2021, the environmental impact in the *Climate change* damage category was 208 g CO_2-eq per kWh_{th}, which is significantly higher than that of individual heat pumps. In comparison, the climate change impact assessed using the Environmental Footprint 3.1 method for the Bracht plant was 201 g CO_2-eq per kWh_{th}. This is noteworthy, considering the substantial difference in system scale (a small community of single-family houses vs. a large-scale urban development). However, after the planned transition to renewable energy sources for the Milan district heating system by 2030, the

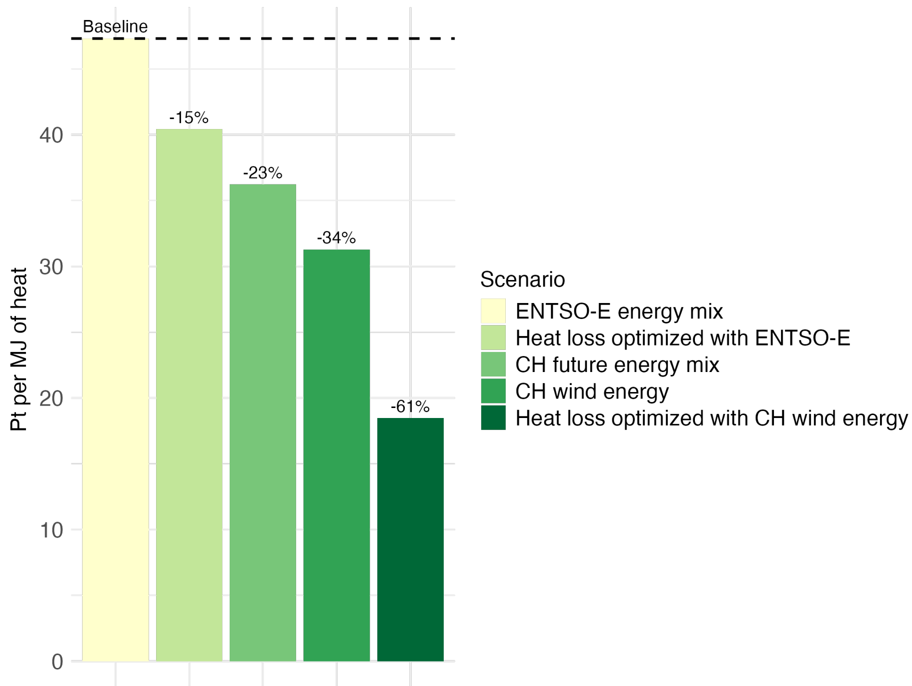

Figure 7: Environmental impact in Pt per MJ of heat (Ecological Scarcity 2021 v1.04, UVEK LCI weighting).

environmental impacts of both options are expected to converge: 89 g CO_2-eq per kWh_{th} for district heating versus 81 g CO_2-eq per kWh_{th} for individual heat pumps. This aligns with the findings from this study, where the use of renewable energy sources for system operation leads to significant reductions in environmental impact.

Vauchez et al. (2023) analysed several options for a district heating network case study for Marseille with a focus on the heat transmission part of the system (instead of the energy source and seasonal storage, which was the focus of this study). Their findings revealed significant differences in the environmental impacts of the materials used for the pipe system. Polyethylene foam was found to have the lowest environmental impact for the insulation materials evaluated.

Life cycle assessment was used to evaluate the environmental impact of various solar thermal collector–powered district heating configurations with seasonal storage in Abokersh et al. (2020). The study aimed to identify the optimal number of large multi-apartment buildings (10, 25, 50, 100) to connect to the system as district heat consumers for a new plant planned in Madrid. It found that larger systems serving more households generally result in a lower environmental impact per unit of energy delivered. The analysis employed the ReCiPe method at the single-score level, as described by Huijbregts et al. (2017), to compare different system sizes relative to each other. However, this approach makes direct comparison with the present study's results infeasible, as the metrics used are not aligned and no absolute numbers are included in Abokersh et al. (2020).

In Solano et al. (2023), the authors present a Life Cycle Assessment (LCA) of a solar thermal collector-powered plant connected to the Geneva district heating network. Unlike the Bracht system, the Geneva plant does not include a seasonal storage unit. The environmental impact of the directly consumed solar heat is reported as 46 points (Pt) per kilowatt-hour (kWh) of thermal energy, which is equivalent to approximately 13 Pt per megajoule (MJ). The Ecological Scarcity method was applied, although the exact version was not specified. In comparison, the environmental impact of the Bracht system is significantly higher at 47 Pt per MJ. This difference can largely be explained by variations in functional units and system boundaries. For the Geneva system, the functional unit is one kilowatt-hour of solar heat injected into the district heating network by the SOLARCAD II power plant. Transmission losses and downstream infrastructure are not included in the assessment. In contrast, the Bracht system includes seasonal storage, and a large share of the delivered heat, approximately two thirds, comes from supplementary sources such as biomass and electricity from the grid. These supplemental sources, which significantly contribute to the environmental impact, are not considered in the LCA conducted by Solano et al. (2023).

8 Summary and conclusion

A Life Cycle Assessment (LCA) was conducted for a solar district heating community project located in Bracht, Rauschenberg, Germany. This project combines solar thermal collectors with a seasonal storage unit to preserve heat produced in summer until the heating period in fall and winter. A district heating distribution network supplies the thermal energy to 180 residential consumers. The system's energy supply is expected to come to the largest share from stored solar thermal energy, partly from biomass, and partly from the electricity grid. Default modelling assumptions included a 20 % heat loss coefficient for the district heating network and an implied 50 % loss for the seasonal storage unit.

Results indicate that biomass and grid electricity employed in the use phase are the primary contributors to the overall environmental impact, accounting for approximately two-thirds of the total, despite supplying only one-third of the energy delivered. The solar thermal collectors contribute less than 15 % to the overall environmental impact. Analysis by damage categories shows biomass combustion significantly contributes to land use, particulate matter, and terrestrial eutrophication, while electricity use is the main driver for fossil resource use and climate change.

Comparing the Bracht system to other heating technologies, the solar thermal collector based district heating system with seasonal storage shows the second lowest environmental impact at approximately 47 Pt per megajoule (MJ) of heat, based on analysis using the Ecological Scarcity 2021 (v1.04) method. This is similar to district heating using wood chips (46 Pt/MJ), lower than a geothermal heat pump district heating system (62 Pt/MJ), and significantly lower than gas boilers (78 Pt/MJ) and oil boilers (119 Pt/MJ).

Sensitivity analyses for the inputs biomass and electricity were performed to demonstrate the effects of generalizations and uncertainties in input data on the results, and to evaluate the potential for reducing environmental impact. The conclusion is that, while the Bracht solar district heating system compares favorably to many conventional and alternative heating technologies in terms of environmental impact, further improvements to the operating conditions are possible to achieve even lower environmental impact.

Significant opportunities lie in sourcing lower-emission electricity for heat pump operation, which would help mitigate the environmental impact associated with the current and future electric grid mix. Purchasing renewable energy for the operation of the heat pump achieves highly significant improvements.

Furthermore, improving heat loss coefficients, particularly reducing the significant heat loss in the seasonal storage unit, could allow the system to meet consumer demand without any combustion of supplemental biomass over the winter heating period, which would also achieve sizable savings in environmental impact. However, since improving insulation can lead to increased electricity demand for the heat pump, careful analysis is required. The first step towards achieving this is to use dedicated modelling tools to fully understand the impact of the different operating conditions on the energy balance, to validate the preliminary findings of this study. In addition, since the plant will enter the operational phase in late 2025, further analysis can be supported with run-time data collected from the functional system.

9 Appendix and supporting information

This section documents the supporting information related to the life cycle inventory in Section 9.1, the data used for modelling in Section 9.2, supplemental charts in Section 9.3, and the project organization in Section 9.4.

9.1 Life cycle inventory

There are several components described in the following sections: solar thermal collector, seasonal storage unit, and heat preparation.

9.1.1 Solar thermal collector (STC)

The relevant data for the solar thermal collector can be found in Table 4.

Table 4

Dimension	Value	Source
Size	11’638 m^2 (855 x 13.6 m^2)	(Viessmann Climate Solutions, 2024)
Type	Flat-plate collectors Vitosol 100-F XF13 Viessmann	(Viessmann Climate Solutions, 2024) (Viessmann Climate Solutions, 2021) (TÜV Rheinland, 2021)
Land use	23.500 m^2	(Viessmann Climate Solutions, 2024)
Mounting infrastructure material	15 t steel	(City of Rauschenberg, 2025c)
Collector weight	50 kg / m^2	Own assumption
Production country	China	Own assumption
Transport per container ship	8000 km	Own assumption
Transport per lorry	1000 km	Own assumption

9.1.2 Seasonal storage unit (SSU)

The relevant data for the seasonal storage unit can be found in Table 5. A picture of the floating cover can be found in Figure 8.

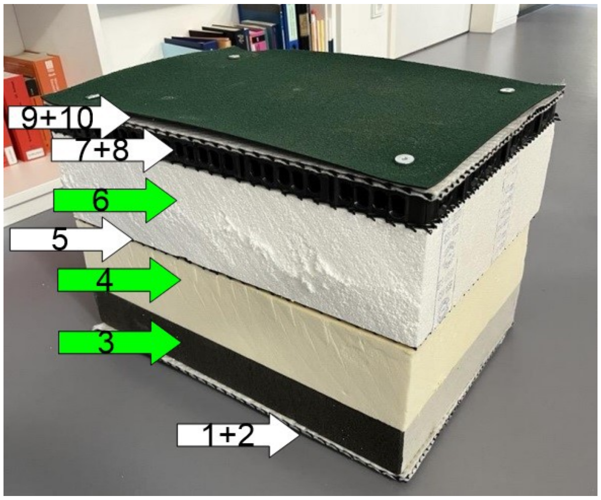

Figure 8: Floating cover profile. Source: Bracht community.

Table 5

Dimension	Value	Source
Volume	26'600 m^3	(Epp, 2024)
Resource: water	26'600 m^3 filled from local source	(City of Rauschenberg, 2025b)
Cover layer 1, 10	Polyethylen (HDPE) sealing membranes 1.5 mm, 1.5 kg / m^2	(City of Rauschenberg, 2025b), estimated weight
Cover layer 2, 9	Fleece (0.1 kg / m^2) laminated plastic grid (HDPE, 0.5 kg / m^2)	(City of Rauschenberg, 2025b), estimated weight
Cover layer 3	Foam glass, 8.33 kg / m^2	(City of Rauschenberg, 2025b)

Dimension	Value	Source
Cover layer 4	Polyurethane (bauder foam): 3.125 kg / $m2$	(City of Rauschenberg, 2025b)
Cover layer 5, 7, 8	Airing gap made of plastic grid, 0.5 kg / m^2 each	(City of Rauschenberg, 2025b), estimated weight
Cover layer 6	Polystyrene (XPS), 3 kg / m^2	(City of Rauschenberg, 2025b)
Floating cover dimensions	70 m x 70 m = 4900 m^2	(Top Agrar, 2025)
Floating cover weight	2 * (1.5 + 0.1 + 0.5) + 8.33 + 3.125 + 1.5 + 3 = 20.155 kg / m^2	Calculation
Ground liner	Polyethylen (HDPE), 2.5mm, 2.5 kg / m^2	(City of Rauschenberg, 2025b), estimated weight
Ground liner dimensions	Bottom 20 m x 20 m, vertical height 15 m, surface area on each of the four sides 5250 m^2	(Top Agrar, 2025)
Ground liner weight	2.5 kg / m^2	Assumption
Production country	China	Assumption
Transport per container ship	8000 km	Assumption
Transport per lorry	1000 km	Assumption
Required construction process	Excavator 26.600 m^3	(Epp, 2024)

9.1.3 Heat preparation

The relevant data for the heat preparation unit can be found in Table 6.

Table 6

Dimension	Value	Source
Heat pump	2x Carrier Aquaforce 61XWH-ZE (630 kW max electrical input power)	(Viessmann Climate Solutions, 2024) (Carrier Klimatisierungs- und Heizsysteme Deutschland, 2025)
Electricity requirements	209 MWh per year	Own calculation, see Section 4.2
Buffer storage	ca. 200 m^3 = 200'000 l	(Epp, 2024)
Biomass boiler	Mawera boiler with 700 kW thermal power	(Viessmann Climate Solutions, 2024)
Controller	Vitocontrol 200-M	(Viessmann Climate Solutions, 2024) (Viessmann Climate Solutions, 2025)
Heat installation facility	50 m^2	Own assumption

9.2 Data

In this section, the data that was created for the model is documented.

9.2.1 SimaPro data

Table 7 and Table 8 show the parameters and calculated parameters that were defined as helpers for modelling the solar thermal based district heating process in Simpapro.

The data for the process *district heat, at consumer, solar thermal, 1MW/MJ/RER U* is kept in an external spreadsheet accessible here. The input data for the adapted processes created for the electricity sensitivity analysis can be found in a separate tab accessible here.

Table 7

Name	Value	Comment
Plant-size-m2	23500	The total size of the plant in sqm
STC-size-m2	11638	The total size of the STC panels in sqm
STC-weight-per-m2	50	The weight of the STC per sqm
STC-prod-MWh-per-a	2700	Production from the STC per year in MWh
Lifetime	50	The lifetime of the plant in years
MWhtoMJ	3600	Conversion from MWh to MJ
Mult30To50	1.67	Multiplier for components with 30 years lifetime
Mult20To50	2.5	Multiplier for components with 20 years lifetime
SSU-volume-m3	26600	The volume of the SSU
SSU-top-m2	4900	The size of the SSU at the top (floating cover) in sqm
SSU-side-m2	5250	The size of the SSU at each of the four sides in sqm
SSU-bottom-m2	5400	The size of the SSU at the ground in sqm
Steel-kg	15000	The weight of the required steel for the STC foundation
Freight-ship-dist-km	8000	The transport distance per freight ship in km
Lorry-dist-km	1000	The transport distance per lorry in km

Table 8

Name	Value	Comment
STC-prod-MJ-lifetime	STC-prod-MWh-per-a * Lifetime * MWhtoMJ	The total production from the STC over the plant lifetime in MJ
STC-weight-t-total	(STC-size-m2 * STC-weight-per-m2 * Mult30To50 + Steel-kg) / 1000	The total transport weight of the STC over the plant lifetime in tons
SSU-ground-m2	SSU-bottom-m2 + 4 * SSU-side-m2	The total size of the SSU that is touching the ground on the bottom and sides in sqm

For the comparison, the following SimaPro processes were employed (all of them part of the UVEK dataset):

- *district heat, at consumer, borehole heat pump, 50kW/MJ/CH U*
- *district heat, at consumer, wood chips in industrial furnace, 1MW/MJ/CH U*
- *heat, light fuel oil, at boiler 10kW, average/CH U*
- *heat, natural gas, at boiler condensating modulating, 15kW/CH U*

For the electricity sensitivity analysis, the following SimaPro processes were employed for comparison:

- *electricity, low voltage, production from hydro power, at grid/CH U*
- *Electricity, at wind power plant/CH U*

9.2.2 Loss coefficients and energy requirements

The loss coefficients and energy requirements numbers were calculated in a spreadsheet accessible here.

9.2.3 Results data

The data for producing the charts for this report is kept in a spreadsheet accessible here, with one or more tabs in the spreadsheet for each figure. It also contains tabs for result numbers mentioned in the textual description with a chart.

9.3 Supplemental charts

In this section, supplemental charts are presented for completeness reasons. Figure 9 complements Figure 5 with the results for the damage categories that were considered less relevant for the use case.

9.4 Project organization

In this section, the time plan and the meeting notes are documented.

9.4.1 Time planning

The time plan that was followed for this project can be found here.

9.4.2 Meeting notes

The notes for the meetings can be found here. Access is given upon request. Contact in case of permission issues: Elke Michlmayr.

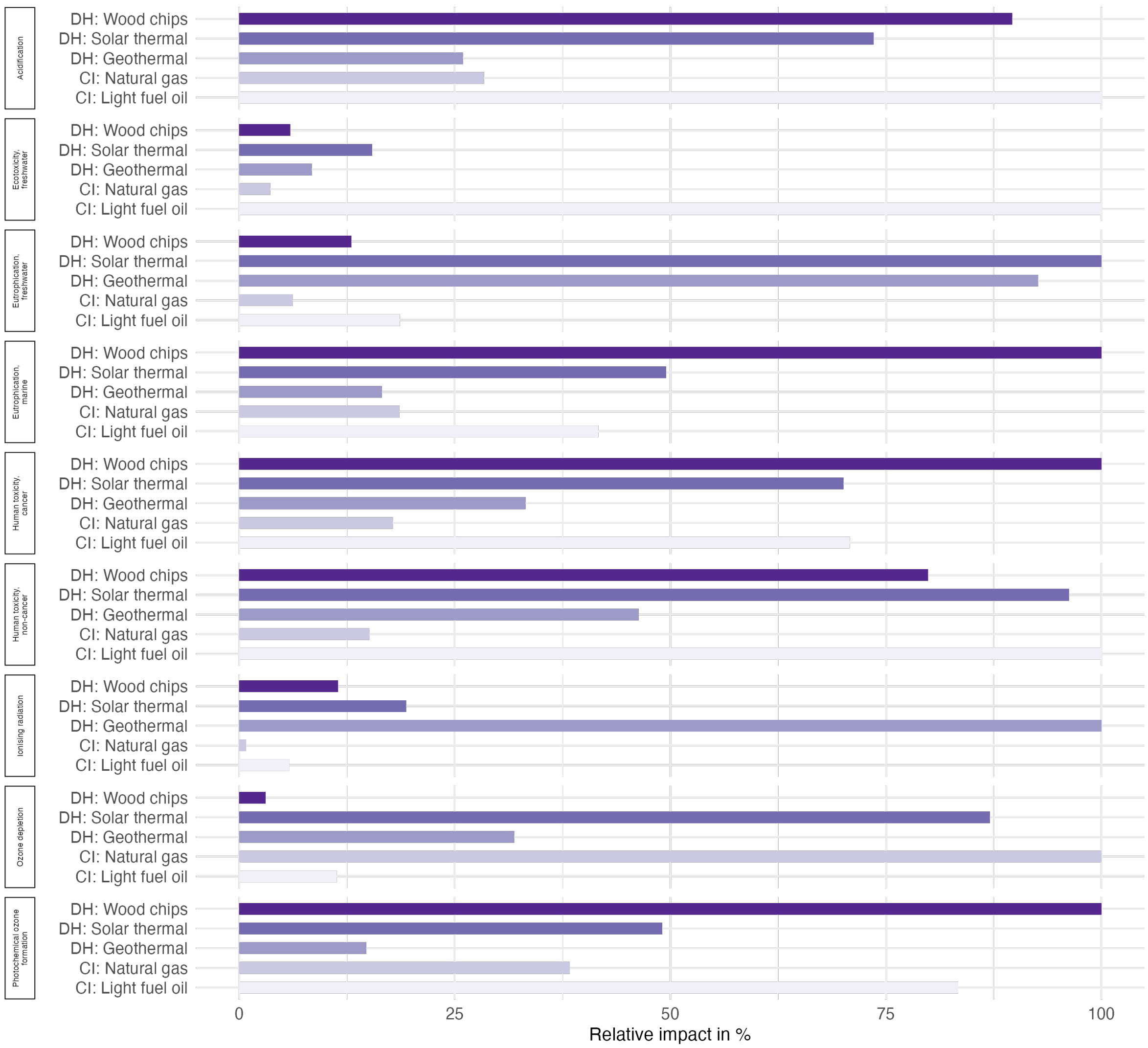

Figure 9: Damage assessment using the Environmental Footprint 3.1 method, visualized as relative environmental impacts in comparison.

10 Acknowledgements

Thanks to René Itten for supervising this work and for the valuable feedback on earlier versions of the paper, which significantly improved the final outcome. Thanks also to Michael Götz for providing the UVEK LCI database used in this study. Thanks to Nils Ratnaweera for teaching me how to create charts with ggplot and how to use Git(hub), Quarto and Markdown. And last but not least, thanks to Daija Angeli for highlighting the importance of considering the future energy mix in the electricity sensitivity analysis.

References

Abokersh, M. H., Vallès, M., Cabeza, L. F., and Boer, D. (2020). A framework for the optimal integration of solar assisted district heating in different urban sized communities: A robust machine learning approach incorporating global sensitivity analysis. *Applied Energy*, *267*, 114903.

AG, V. S. (2012). *Polysun simulation software*. https://www.velasolaris.com.

Carrier Klimatisierungs- und Heizsysteme Deutschland. (2025). *AquaForce Hochtemperatur Wasser/Wasser-Wärmepumpe mit Kältemittel HFO R-1234ze*. https://www.carrier.com/commercial/de/de/produkte/heizung/wasser-wasser-waermepumpen/61xwhze/.

City of Rauschenberg. (2025a). *Solarwärme Bracht eG, FAQ und häufig gestellte Fragen*. https://www.solarwaerme-bracht.de/faq/.

City of Rauschenberg. (2025b). *Solarwärme Bracht eG, Genossenschaftsunterlagen: Floating Cover*. https://www.solarwaerme-bracht.de/unterlagen-der-genossenschaft/.

City of Rauschenberg. (2025c). *Solarwärme Bracht eG, Stadtteile Bracht und Bracht-Siedlung*. https://www.solarwaerme-bracht.de/.

Epp, B. (2024). *High Solar Heat Fraction Solutions Supported by Heat Pumps*. https://solarthermalworld.org/news/high-solar-heat-fraction-solutions-supported-by-heat-pumps/.

Euroheat & Power. (2023). *28/03/2023: The rise of solar district heating*. https://www.youtube.com/watch?v=ngNgVxTT2y4.

European Commission. (2021). *Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279.

Famiglietti, J., Gerevini, L., Spirito, G., Pozzi, M., Dénarié, A., Scoccia, R., and Motta, M. (2021). Environmental life cycle assessment scenarios for a district heating network. An italian case study. *Energy Reports*, *7*, 368–379.

Federal Office for the Environment (FOEN). (2021). *Swiss eco-factors 2021 according to the ecological scarcity method: Methodological fundamentals and their application in switzerland*. https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/

economy-and-consumption-publications/publications-economy-and-consumption/eco-factors-switzerland.html
Federal Office for the Environment (FOEN). (2025). *UVEK LCI database DQRv2:2025*.
Große, R., Binder, C., Wöll, S., Geyer, R., and Robbi, S. (2017). *Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU*. Publications Office of the European Union.
Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., Hollander, A., Zijp, M., and Zelm, R. van. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, *22*, 138–147. https://doi.org/10.1007/s11367-016-1246-y
International Organization for Standardization. (2006). *Environmental Management — Life Cycle Assessment — Requirements and Guidelines* (ISO 14044:2006). International Organization for Standardization; https://www.iso.org/standard/38498.html.
Jeandaux, C., Videau, J.-B., and Prieur-Vernat, A. (2021). Life cycle assessment of district heating systems in europe: Case study and recommendations. *Sustainability*, *13*(20), 11256.
Kelch, J., Kusyy, O., Orozaliev, J., and Vajen, K. (2022). *Abschlussbericht Weiterentwicklung und Optimierung des Konzepts einer solaren Nahwärmeversorgung für ländliche Gebiete am Beispiel von Bracht-Dorf* (Technical Report EF960 0039/2021 20008503). Universität Kassel.
Kelch, J., Kusyy, O., Zipplies, J., Orozaliev, J., and Vajen, K. (2024). Comparison of solar district heating and renovation of buildings as measures for decarbonization of heat supply in rural areas. *Solar Energy Advances*, *4*, 100060.
Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., and Mathiesen, B. V. (2020). District heating and cooling: Review of technology and potential enhancements. *Energy*, *68*, 1–11. https://doi.org/10.1016/j.energy.2014.05.045
Penttinen, P., Vimpari, J., and Junnila, S. (2021). Optimal seasonal heat storage in a district heating system with waste incineration. *Energies*, *14*(12), 3522.
PRé Sustainability. (2024). *SimaPro 9.6 database manual: Methods library*. https://simapro.com/wp-content/uploads/2024/04/DatabaseManualMethods.pdf
Quintel. (2025). *Energy Transition Model (ETM)*. https://energytransitionmodel.com/scenario/supply/heat_ht/transport-and-distribution-losses.
Solano, J., Frossard, M., Lasvaux, S., and Duret, A. (2023). Life cycle assessment of the new solar thermal power plant SolarCAD II connected to a district heating network in Geneva, Switzerland. *Journal of Physics: Conference Series*, *2600*, 152005.
Swiss Federal Office of Energy. (2020). *District heat*. https://www.bfe.admin.ch/bfe/en/home/supply/energy-efficiency/district-heat.html.
Swiss Federal Office of Energy (SFOE). (2020a). *Energieperspektiven 2050+*. Bundesamt für Energie. https://www.bfe.admin.ch/bfe/de/home/politik/energieperspektiven-2050-plus.html
Swiss Federal Office of Energy (SFOE). (2020b). *Energieperspektiven 2050+: Entwicklung der stromproduktion*. Bundesamt für Energie. https://www.uvek-gis.admin.ch/BFE/storymaps/AP_Energieperspektiven/index3.html?lang=de&selectedSzenario=

ZB&selectedVariant=AJB&selectedNuclear=50

Swiss Federal Office of Energy (SFOE). (2020c). *Energy perspectives 2050+: Scenario results ZERO basis (ZIP dataset)*. https://www.bfe.admin.ch/bfe/de/home/politik/energieperspektiven-2050-plus.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTA0MzQ=.html.

Top Agrar. (2025). *Hessisches Dorf baut riesiges Wasserbecken für eigene Solarthermieanlage*. https://www.topagrar.com/energie/news/hessisches-dorf-baut-riesiges-wasserbecken-fur-eigene-solarthermieanlage-20010847.html%0A.

TÜV Rheinland. (2021). *Annex to solar keymark certificate*. https://www.dincertco.de/logos/011-7S3003%20F.pdf.

Vauchez, M., Famiglietti, J., Autelitano, K., Colombert, M., Scoccia, R., and Motta, M. (2023). Life Cycle Assessment of District Heating Infrastructures: A Comparison of Pipe Typologies in France. *Energies*, *16*(9), 3912.

VDI, V. (2012). *VDI 2067 Blatt 1" Wirtschaftlichkeit gebäudetechnischer Anlagen-Grundlagen und Kostenberechnung*. Düsseldorf.

Viessmann Climate Solutions. (2021). *Großflächen-Solarthermie für die Nah- und Fernwärme*. https://energiekonsens.de/media/pages/media/6a0997554c-1640096559/2-viessmann-nah-und-fernwaerme-mit-solarthermie.pdf.

Viessmann Climate Solutions. (2024). *Energiewende: Solarthermie und Erdspeicher decken rund 70 Prozent des Wärmebedarfs im hessischen Bracht*. https://www.viessmann-climatesolutions.com/de/newsroom/unternehmen/erstes-klimaneutrales-mit-solarwaerme-versorgtes-dorf.html.

Viessmann Climate Solutions. (2025). *Regelungsprogramm für Mittel- und Großkessel*. https://www.viessmann.de/de/loesungen/gewerbe-und-industrie/regelung-mittelkessel-grosskessel.html.

Weiss, W., and Spörk-Dür, M. (2024). *Solar heat world wide* [White paper]. International Energy Agency. https://doi.org/10.18777/ieashc-shww-2024-0001

Werner, S. (2017). International review of district heating and cooling. *Energy*, *137*, 617–631.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. (2016). The ecoinvent database version 3 (part i): Overview and methodology. *The International Journal of Life Cycle Assessment*, *21*, 1218–1230.

Wikipedia. (2025). *Solar thermal collector*. https://en.wikipedia.org/wiki/Solar_thermal_collector.

Wolf, S. (2017). *Integration von Wärmepumpen in industrielle Produktionssysteme: Potenziale und Instrumente zur Potenzialerschließung*.

World Bank. (2023). *Switzerland - electricity imports (product code 271600) in 2023*. World Integrated Trade Solution (WITS), World Bank. https://wits.worldbank.org/trade/comtrade/en/country/CHE/year/2023/tradeflow/Imports/partner/ALL/product/271600

Xiang, Y., Xie, Z., Furbo, S., Wang, D., Gao, M., and Fan, J. (2022). A comprehensive review on pit thermal energy storage: Technical elements, numerical approaches and recent applications. *Journal of Energy Storage*, *55*, 105716.