Life cycle impact assessment for a district heating project with seasonal storage

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

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1 Abstract

A life cycle impact assessment (LCIA) was conducted for a solar district heating community project under construction in Bracht, Germany. It incorporates solar thermal collectors, a seasonal heat storage unit powered through an included electric heat pump, a supplemental biomass boiler as a backup solution for when there is no heat available from the solar based system, and a transport 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 through optimization of the system's operating conditions remains. The key opportunities include using renewable electric energy for the heat pump, and reducing heat losses in storage and transport 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 and related work

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 [1]. 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 [2], 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 [1]. Process heating uses a similar setup but is designed for industrial applications, which typically require higher temperatures. Studies such as [3] 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 [4]. According to [5], 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 GWth, covering roughly 800 km² of collector area [5]. 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 [1]. This introduces a trade-off, as the remote location requires laying additional underground piping.

In scientific literature, only a small number of LCIA case studies for district heating systems exist, such as those for the systems in Milan [6] and Marseille [7]. Life cycle impact assessment, particularly based on the ReCiPe method, has been used to evaluate the environmental impact of different STC-powered district heating configurations in [8]. The findings indicate that larger systems serving many households tend to have a lower environmental impact per unit of energy delivered. In [9], the authors present an LCIA study of a STC plant connected to the Geneva district heating network.

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 [10]. However, the environmental impact of the project has not yet been examined in detail. This gap forms the focus of the present study.

3 Methodology and research questions

The LCIA was performed using the SimaPro 9.6.0.1 software [11]. The foreground data was collected from various online sources and combined with background data from the Ecoinvent v3 database [12] and the UVEK LCI database version DQRv2:2025 [13]. The environmental impacts were assessed using the mid-point level Environmental Footprint (EF) method [14], the Ecological Scarcity 2021 (v1.04) method [15] at the single score level with UVEK LCI weighting set, and the IPCC 2021 GWP100 methodology [16].

The research questions were formulated as follows:

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 a heat pump 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 transport pipe system. The hypothesis is that the seasonal storage component will lower the environmental impact.

The following chapters will cover all the necessary stages of the LCIA: goal and scope definition in Section 4, inventory analysis in Section 5, impact assessment in Section 6, and interpretation in Section 7.

4 Goal and scope

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

For the present LCIA, the specific goals are to address the research questions outlined in Section 3. The scope of the assessment encompasses a district heating project initiated and

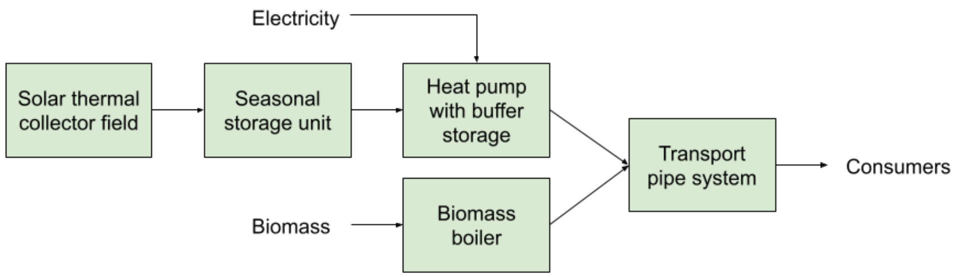

Figure 1: System overview for the Bracht community district heating network.

operated by a cooperative composed of future household consumers and the local municipal council. As illustrated in Figure 1, the system includes the following key components:

- solar thermal collector (STC) field,
- seasonal storage unit (SSU),
- heat pump component powered with 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,
- heat transport distribution network that supplies to residential consumers,
- and receiver units installed in each participating household.

The lifetime of the district heating system is assumed to be 50 years. There are at least 180 consumer households expected, 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.

The system diagram shown in Figure 2 describes the product system and its boundaries. The functional unit is defined to be 1 MegaJoule (MJ) of thermal energy provided to the consumer directly at the consumer site 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 that the comparison will be performed against.

5 Life cycle inventory (LCI)

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 [17]. 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.

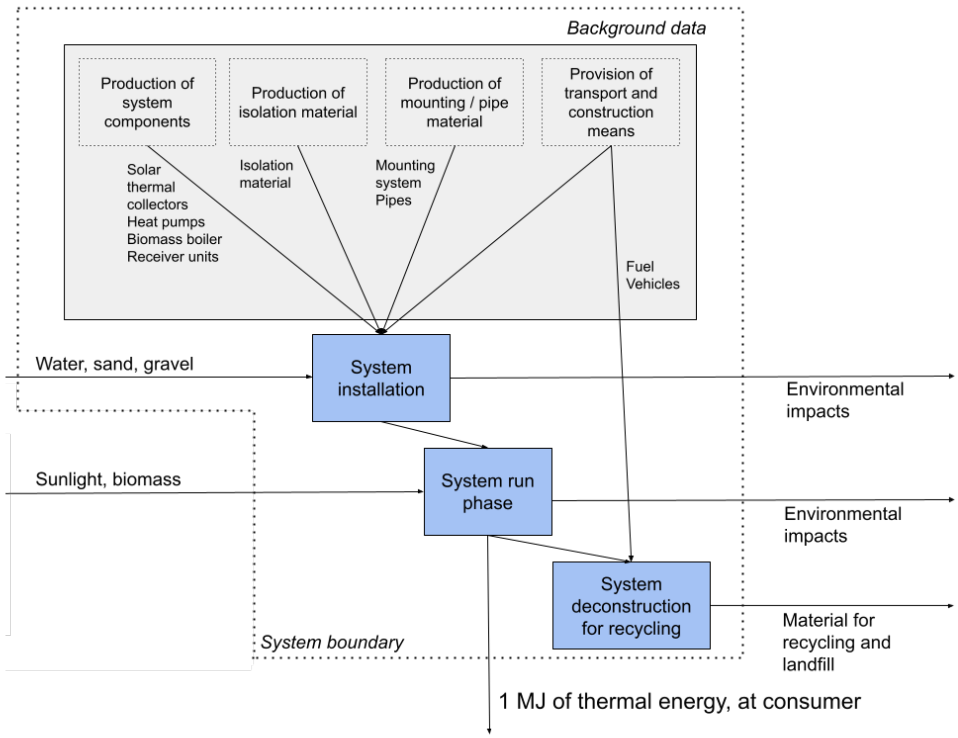

Figure 2: System diagram for the Bracht community district heating network.

The comparison datasets and the heat transport network were modelled based on UVEK LCI data [13], an existing resource for conducting LCIAs 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.

5.1 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 [18].

Table 1

Component	Years	Multiplier	Source
Solar thermal collectors	30	1.67	[19]
Seasonal storage unit	30	1.67	[18]
Heat pumps	20	2.5	[20]
Heat buffer storage	20	2.5	[19]
Heat installation facility	50	1	[21]
Heat exchange stations at consumer	20	2.5	[18]
Heat transport network	50	1	[18]

5.2 Electrical power requirements and loss coefficient assumptions

Performance data from [22] 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 [23], 2.700 MWh per year are expected to reach end-user households. This implies a total system loss of approximately 40%, accounting for thermal losses in the storage unit and distribution piping.

The energy distribution for heating supply for the Bracht plant is reported in [24] as follows:

- 67 % from stored solar thermal energy (approximately 2.258 MWh),
- 26 % from biomass sources (approximately 904 MWh), and
- 6 % from the electricity grid (approximately 209 MWh)

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.

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 7.3.1. Given this assumption, the implied thermal loss within the seasonal storage unit would be approximately 50% to align with the reported figures from [23]. These assumptions 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 7.3.

6 Results

The system model, as detailed in Section 9.2.1, was implemented using SimaPro [11]. This model served as the foundation for generating LCIA results using the Environmental Footprint (EF) method [14] and the Ecological Scarcity 2021 (v1.04) method [15]. The corresponding results derived from these assessments are presented in this section.

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 3. They show that biomass (27.3 %) and electricity (35.8 %) 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 [24]. Only one-third of the energy delivered to end consumers originates from biomass and electricity.

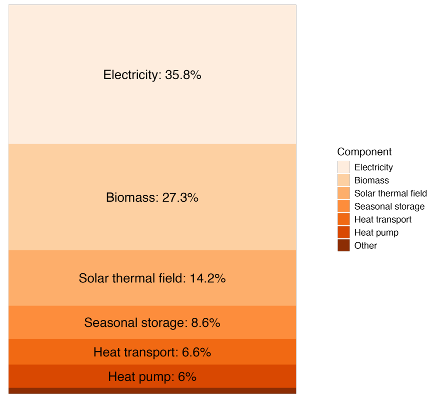

Figure 3: Relative environmental impact for components of Bracht community district heating system (Ecological Scarcity 2021, v1.04, UVEK LCI weighting)

For a more detailed view of the environmental impact by individual damage categories, Figure 4 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 to climate change and fossil resource use. Similar effects can be seen for the solar thermal collector.

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 5), an option explored in more detail in Section 7.2. Strategies to reduce biomass consumption by improving thermal efficiency, such as lowering heat loss coefficients, are examined in Section 7.3.

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 5, 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,

Figure 4: Relative environmental impact of Bracht community district heating network system components for the six most relevant damage categories (Environmental Footprint Method).

applying the UVEK LCI weighting set.

The results are expressed in environmental impact points (Pt) per kilowatt-hour (kWh) of heat delivered. They reveal that the heat produced by the Bracht plant with 170 Pt per kWh 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 5), and to a lesser extent by the seasonal storage unit and the solar thermal collectors (cf. Figure 4).

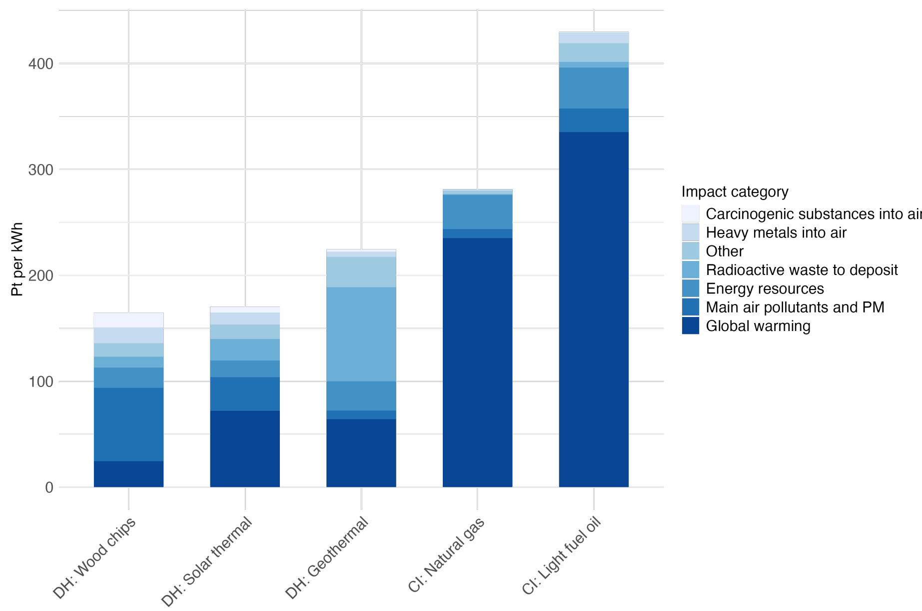

Figure 5: Comparison of environmental impact of Bracht community district heating network to other energy sources for district heating such as wood chips and heat pump, and to consumer installations such as gas and oil burners (Ecological Scarcity 2021 v1.04, UVEK LCI weighting).

The lowest environmental impact with 165 Pt per kWh 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 225 Pt per kWh of heat, to the largest extent from impact on radioactive waste to deposit. Gas and oil based consumer installations fare significantly worse with 281 Pt and 430 Pt per kWh of heat, dominantly from impact on climate change.

As before, Figure 6 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 5, 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 5, *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 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.

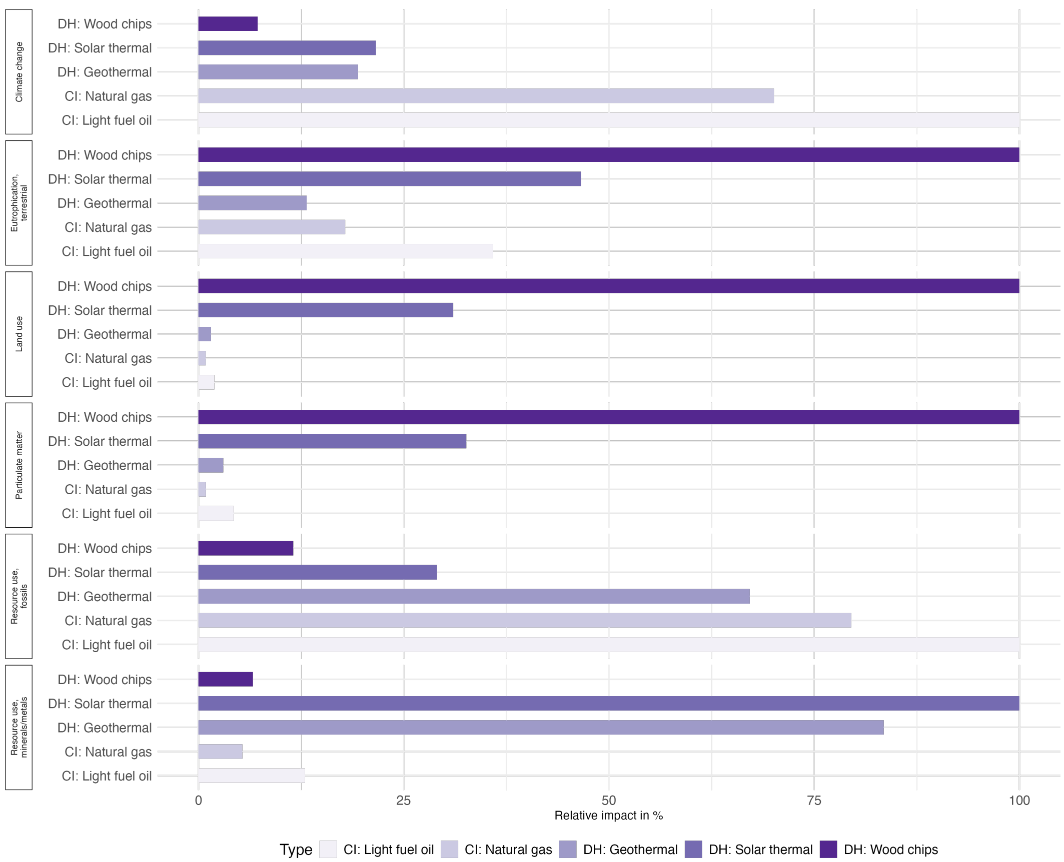

Figure 6: Damage assessment for the most relevant categories using the Environmental Footprint Method, visualized as relative environmental impacts in comparison. See Figure 10 for the results for categories omitted in the given chart.

7 Interpretation and discussion

This chapter discusses the results introduced in Section 6. 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 7.1, 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 saving potential from using lower-emitting (see Section 7.2) or less energy resources (see third research question and Section 7.3), sensitivity analyses for source of electricity and loss coefficients for the heat loss in the seasonal storage unit and the transport pipes were performed. The combined results from both sensitivity analyses are summarized in Section 7.4.

7.1 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 of 50 kW power. The best possible assumption in this situation was that the two large heat pump 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 3).

The UVEK data for the other energy sources for district heating (wood chips, heat pump) uses an 11 % assumption for transport pipe heat loss, which means that the solar thermal data with a 20% assumption as mentioned in Section 5.2 was disadvantaged in the comparison in Figure 5. The effect of these assumptions on the results will be investigated in Section 7.3.

Worth mentioning is that the UVEK data for transport system district heat has a lifetime assumption of 30 years whereas the Bracht transport system setup assumes 50 years. This is acceptable since the heat transport system showed only minor impact of 6.6 % on the overall results (see Figure 3).

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.

System deconstruction was modeled 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 2).

7.2 Sensitivity analysis: Source of electricity

The results as presented in Figure 5 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 modeled based on the ENTSO-E production mix [13]. 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 the Swiss Federal Office of Energy's Energy Perspectives 2050+ report [25] and its accompanying resources including charts [26] and data tables [27]). Particularly relevant are the projections for the expected winter electricity production mix at five-year intervals from 2025 to 2060, as depicted in Figure 7.

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 adress this, an additional dataset from the World Bank [28] was emplyed to determine the country-wise distribution of 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.

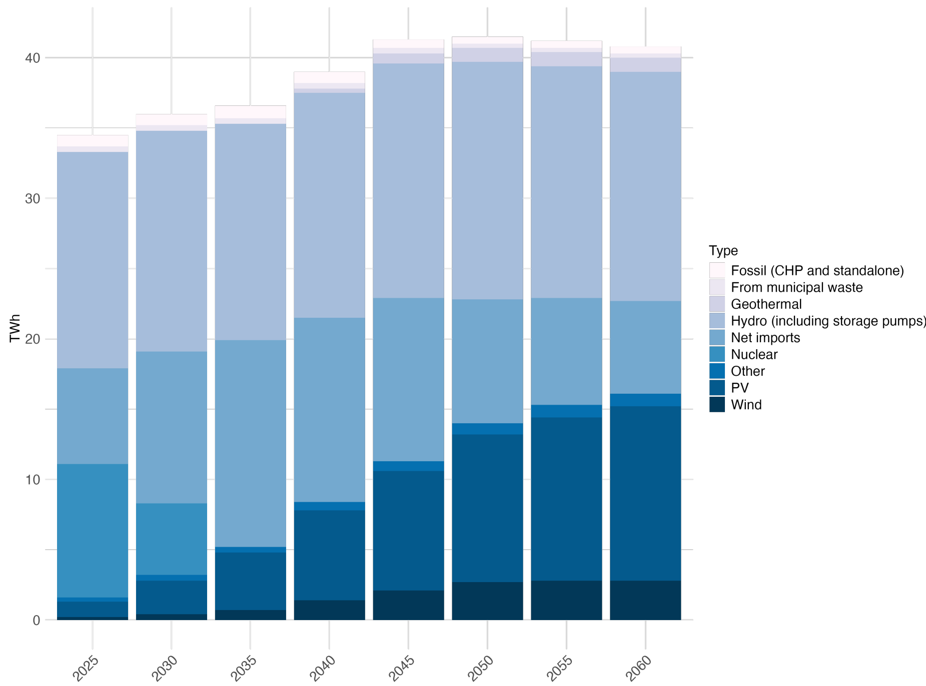

Figure 7: Expected production mix for winter period (6 months) in Switzerland from 2025 to 2060 (Source: Swiss Federal Office for Energy).

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 to an average of 130 Pt per kWh of heat over the complete lifetime of the plant.

To reduce this impact further, the Bracht plant could consider to purchase renewable electricity. Using exclusively wind power would lower the environmental impact to 113 Pt per kWh of heat, while relying solely on hydro power would result in 115 Pt per kWh. 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 109 Pt per kWh of heat.

7.3 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 coefficients assumptions will be assessed in Section 7.3.1 and Section 7.3.2.

7.3.1 Pipe heat loss

As summarized in [29], 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 planned supply temperature of 85 degrees °C is relatively high and 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 [30].

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 [31] 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 planned to be supplied via biomass, which would correspond to a 9 % reduction in ecological impact from 170 Pt per kWh to 155 Pt per kWh 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.

7.3.2 Seasonal storage unit heat loss

In [32], the authors report a 26 % loss of heat production in the storage unit amounted to of heat production. The Energy Transition Model [31] suggests 30 % as a sensible default for modelling heat loss in the storage unit. Another study [33] provides a comprehensive review and finds that 30% to 50% heat loss 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 6.

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 [34], which is out of scope for the given work. As a simplification, a rough estimate of the heightened energy requirements was carried out based 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 begin 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 modeled in SimaPro to learn about the implications on environmental impact. Like in the default model, the ENTSO-E production mix was assumed. For scenario (A) with updated assumptions, a 15 % reduction from 170 Pt per kWh of heat to 146 Pt per kWh of heat can be achieved. For scenario (B) with a doubled insulating cover for the seasonal storage unit, a 9 % reduction to 155[1] Pt per kWh of heat can be achieved. This confirms the environmental impact savings potential of operating conditions improvements.

7.4 Combined results from sensitivity analysis

As discussed in the previous sections, two main opportunities for optimization have been identified: (1) using renewable energy to operate the heat pump and (2) reducing heat losses in the system to decrease the need for supplemental biomass. However, improving insulation leads to increased electricity demand for the heat pump which in turn amplifies the benefits of using renewable energy.

[1]This is coincidentally the exact same result as already obtained in Section 7.3.1.

Given the interdependence of these two factors, this section presents the combined results. The analysis is based on the IPCC 2021 GWP100 methodology [16], with outcomes expressed in grams of CO_2-equivalents per kWh, to enable comparison with widely recognized tools such as [35]. However, it is important to note that heat and electricity are different energy forms, which should be considered when interpreting direct comparisons. As the results for wind and hydro power were nearly identical, hydro was excluded from this analysis for the sake of clarity. Scenario (A) from Section 7.3.2 was chosen for the comparison as the representative scenario for heat loss optimization. The results are presented in Figure 8. The chart reveals that, according to the IPCC methodology, scenario (A) performs worse than the baseline due to increased electricity demand met by the ENTSO-E production mix. However, this impact can be mitigated by using wind energy, which in turn yields the best results among the scenarios compared by bringing down the numbers substantially, from 72 g CO_2-eq for the ENTSO-E based baseline to 31 g CO_2-eq for the heat loss optimized scenario together with renewable energy from wind.

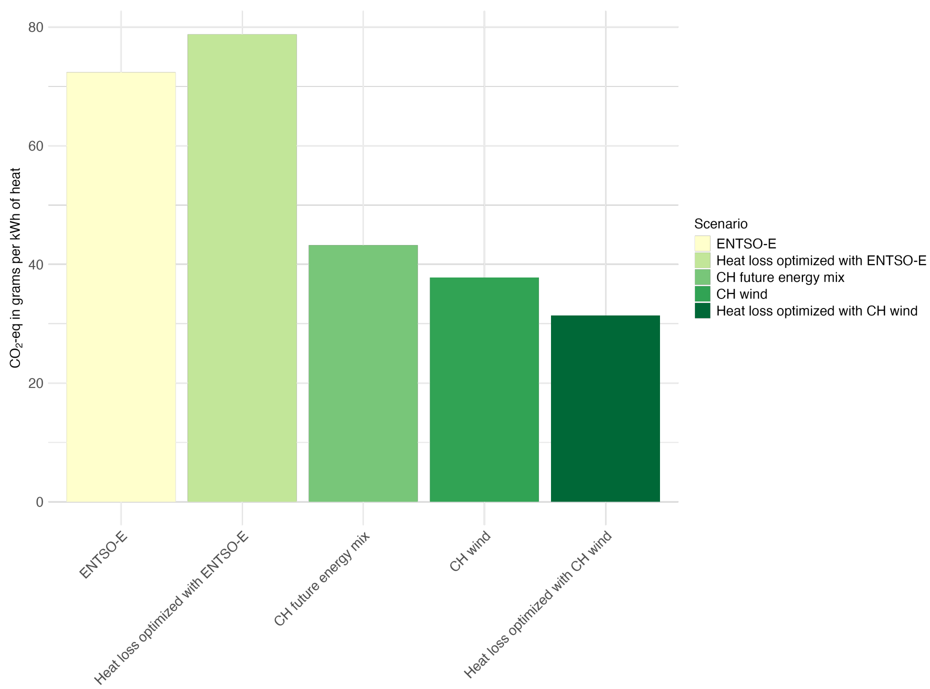

Figure 8: Environmental impact in grams of CO_2-eq per kWh of heat (IPCC 2021 GWP100).

8 Summary and conclusion

A Life cycle impact assessment 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 heat transport network supplies the thermal energy to 180 residential consumers. The system's energy supply is expected to be 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 transport network and an implied 50 % loss for the seasonal storage unit.

Results indicate that biomass and grid electricity 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 STC-based district heating system with seasonal storage shows the second lowest environmental impact at approximately 170 Pt per kilowatt-hour (kWh) of heat, based on analysis using the Ecological Scarcity 2021 (v1.04) method. This is similar to district heating using wood chips (165 Pt/kWh), lower than a geothermal heat pump district heating system (225 Pt/kWh), and significantly lower than gas boilers (281 Pt/kWh) and oil boilers (430 Pt/kWh).

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 of 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. 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 be entering 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)	[36]
Type	Flat-plate collectors Vitosol 100-F XF13 Viessmann	[36] [37] [22]
Land use	23.500 m^2	[36]
Mounting infrastructure material	15 t steel	[17]
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 9.

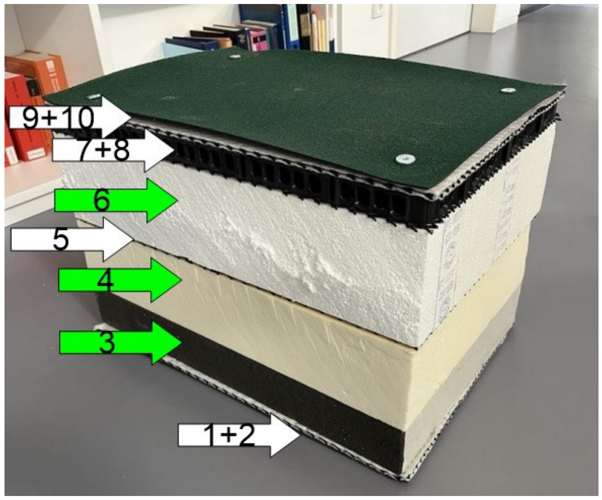

Figure 9: Floating cover profile. Source: Bracht community.

Table 5

Dimension	Value	Source
Volume	26’600 m^3	[24]
Resource: water	26’600 m^3 filled from local source	[38]
Cover layer 1, 10	Polyethylen (HDPE) sealing membranes 1.5 mm, 1.5 kg / m^2	[38], estimated weight
Cover layer 2, 9	Fleece (0.1 kg / m^2) laminated plastic grid (HDPE, 0.5 kg / m^2)	[38], estimated weight
Cover layer 3	Foam glass, 8.33 kg / m^2	[38]
Cover layer 4	Polyurethane (bauder foam): 3.125 kg / $m2$	[38]
Cover layer 5, 7, 8	Airing gap made of plastic grid, 0.5 kg / m^2 each	[38], estimated weight
Cover layer 6	Polystyrene (XPS), 3 kg / m^2	[38]
Floating cover dimensions	70 m x 70 m = 4900 m^2	[39]
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	[38], 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	[39]
Ground liner weight	2.5 kg / m^2	Assumption
Production country	China	Assumption

Dimension	Value	Source
Transport per container ship	8000 km	Assumption
Transport per lorry	1000 km	Assumption
Required construction process	Excavator 26.600 m^3	[24]

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)	[36] [40]
Electricity requirements	209 MWh per year	Own calculation, see Section 5.2
Buffer storage	ca. 200 m^3 = 200'000 l	[24]
Biomass boiler	Mawera boiler with 700 kW thermal power	[36]
Controller	Vitocontrol 200-M	[36] [41]
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 data for the sensitivity analysis process 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.

9.3 Supplemental charts

In this section, supplemental charts are presented for completeness reasons. Figure 10 complements Figure 6 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

Figure 11 documents the time plan that was followed for this project. The live version 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 10: Damage assessment using the Environmental Footprint Method, visualized as relative environmental impacts in comparison.

# weeks	Nov 26, 2024	Jul 8, 2025		
		Burndown		
Tasks	**Start date**	**End date**	**Timeline (gray = past, yellow = active, green = future, red = overdue)**	**Status**
Attend disposition colloquium	Nov 26, 2024	Nov 26, 2024		Complete
Project meeting #1 - Elke, René	Jan 8, 2025	Jan 8, 2025		Complete
Perform inital literature research	Jan 8, 2025	Jan 15, 2025		Complete
Check existence of background data in Ecoinvent/KBOB/UVEK	Jan 15, 2025	Jan 29, 2025		Complete
Perform screening LCA	Jan 29, 2025	Feb 19, 2025		Complete
Create required data questionaire	Feb 17, 2025	Feb 19, 2025		Complete
Research online data sources to fill the questionnaire	Jan 29, 2025	Mar 19, 2025		Complete
Project meeting #2 - Elke, René	Feb 19, 2025	Feb 19, 2025		Complete
Create time plan	Feb 26, 2025	Mar 2, 2025		Complete
Document research question and hypothesis	Mar 1, 2025	Mar 8, 2025		Complete
Create draft of research agreement based on template	Mar 1, 2025	Mar 8, 2025		Complete
Send out draft of research agreement for feedback	Mar 3, 2025	Mar 8, 2025		Complete
Create system diagram and functional unit (LCA part 1)	Feb 19, 2025	Mar 14, 2025		Complete
Define goal and scope (LCA part 1)	Feb 19, 2025	Mar 14, 2025		Complete
Finalize and sign research agreement	Mar 8, 2025	Mar 14, 2025		Complete
Create inventory analysis (LCA part 2)	Feb 13, 2025	Mar 30, 2025		Complete
Project meeting #3 - Elke, René	Mar 19, 2025	Mar 19, 2025		Complete
Perform impact assessment (LCA part 3) and interpretation (LCA part 4)	Mar 24, 2025	May 30, 2025		Complete
Send out impact assessment results	Apr 22, 2025	Apr 22, 2025		Complete
Project meeting #4 (Discuss results) - Elke, René	Apr 28, 2025	Apr 29, 2025		Complete
Perform sensitivity analysis	May 19, 2025	May 30, 2025		Complete
Project meeting #5 (Discuss results) - Elke, René	May 27, 2025	May 28, 2025		Complete
Finalize literature study	May 27, 2025	May 30, 2025		Complete
Prepare final paper draft for review and proofreading	May 27, 2025	Jun 1, 2025		Complete
Finalize the paper	Jun 23, 2025	Jun 29, 2025		Upcoming
Hand in paper in Complesis	Jun 29, 2025	Jun 29, 2025		Upcoming
Prepare slides for presentation	Jul 1, 2025	Jul 8, 2025		Upcoming
Test run presentation	Jul 2, 2025	Jul 8, 2025		Upcoming
Attend defence colloquium	Jul 8, 2025	Jul 8, 2025		Upcoming
Give presentation	Jul 8, 2025	Jul 8, 2025		Upcoming

Figure 11: Gantt chart used for time planning.

References

[1] Euroheat & Power, "28/03/2023: The rise of solar district heating." https://www.youtube.com/watch?v=ngNgVxTT2y4, 2023.

[2] Swiss Federal Office of Energy, "District heat." https://www.bfe.admin.ch/bfe/en/home/supply/energy-efficiency/district-heat.html, 2020.

[3] C. Jeandaux, J.-B. Videau, and A. Prieur-Vernat, "Life cycle assessment of district heating systems in europe: Case study and recommendations," *Sustainability*, vol. 13, no. 20, p. 11256, 2021.

[4] Wikipedia, "Solar thermal collector." https://en.wikipedia.org/wiki/Solar_thermal_collector, 2025.

[5] W. Weiss and M. Spörk-Dür, "Solar heat world wide," International Energy Agency, White paper DOI: 10.18777/ieashc-shww-2024-0001, 2024. Available: https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2024.pdf

[6] J. Famiglietti *et al.*, "Environmental life cycle assessment scenarios for a district heating network. An italian case study," *Energy Reports*, vol. 7, pp. 368–379, 2021.

[7] M. Vauchez, J. Famiglietti, K. Autelitano, M. Colombert, R. Scoccia, and M. Motta, "Life cycle assessment of district heating infrastructures: A comparison of pipe typologies in france," *Energies*, vol. 16, no. 9, p. 3912, 2023.

[8] M. H. Abokersh, M. Vallès, L. F. Cabeza, and D. Boer, "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*, vol. 267, p. 114903, 2020.

[9] J. Solano, M. Frossard, S. Lasvaux, and A. Duret, "Life cycle assessment of the new solar thermal power plant SolarCAD II connected to a district heating network in geneva, switzerland," in *Journal of physics: Conference series*, IOP Publishing, 2023, p. 152005.

[10] J. Kelch, O. Kusyy, J. Zipplies, J. Orozaliev, and K. Vajen, "Comparison of solar district heating and renovation of buildings as measures for decarbonization of heat supply in rural areas," *Solar Energy Advances*, vol. 4, p. 100060, 2024.

[11] PRé Sustainability, *SimaPro 9.6 database manual: Methods library*. 2024. Available: https://simapro.com/wp-content/uploads/2024/04/DatabaseManualMethods.pdf

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

[13] Federal Office for the Environment (FOEN), "UVEK LCI database DQRv2:2025." 2025.

[14] European Commission, "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, 2021.
[15] Federal Office for the Environment (FOEN), "Swiss eco-factors 2021 according to the ecological scarcity method: Methodological fundamentals and their application in switzerland." 2021. Available: https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/economy-and-consumption-publications/publications-economy-and-consumption/eco-factors-switzerland.html
[16] F. J. Dentener *et al.*, "Tables of historical and projected well-mixed greenhouse gas mixing ratios and effective radiative forcing of all climate forcers," in *Climate change 2021: The physical science basis. Contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change*, V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds., Cambridge, UK; New York, NY, USA: Cambridge University Press, 2021, pp. 2139–2151. doi: 10.1017/9781009157896.017.
[17] City of Rauschenberg, "Solarwärme Bracht eG, Stadtteile Bracht und Bracht-Siedlung." https://www.solarwaerme-bracht.de/, 2025.
[18] J. Kelch, O. Kusyy, J. Orozaliev, and K. Vajen, "Abschlussbericht weiterentwicklung und optimierung des konzepts einer solaren nahwärmeversorgung für ländliche gebiete am beispiel von bracht-dorf," Universität Kassel, Technical report EF960 0039/2021 20008503, 2022.
[19] R. Große, C. Binder, S. Wöll, R. Geyer, and S. Robbi, "Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU," Publications Office of the European Union, 2017.
[20] S. Wolf, "Integration von Wärmepumpen in industrielle Produktionssysteme: Potenziale und Instrumente zur Potenzialerschließung," 2017.
[21] V. VDI, "VDI 2067 Blatt 1" Wirtschaftlichkeit gebäudetechnischer Anlagen-Grundlagen und Kostenberechnung." Düsseldorf, 2012.
[22] TÜV Rheinland, "Annex to solar keymark certificate." https://www.dincertco.de/logos/011-7S3003%20F.pdf, 2021.
[23] City of Rauschenberg, "Solarwärme Bracht eG, FAQ und häufig gestellte Fragen." https://www.solarwaerme-bracht.de/faq/, 2025.
[24] B. Epp, "High solar heat fraction solutions supported by heat pumps," *Solarthermalworld.org*, 2024, Available: https://solarthermalworld.org/news/high-solar-heat-fraction-solutions-supported-by-heat-pumps/
[25] Bundesamt für Energie (BFE), "Energieperspektiven 2050+," Bundesamt für Energie, 2020. Available: https://www.bfe.admin.ch/bfe/de/home/politik/energieperspektiven-2050-plus.html

[26] Bundesamt für Energie (BFE), “Energieperspektiven 2050+: Entwicklung der stromproduktion,” Bundesamt für Energie, 2020. Available: https://www.uvek-gis.admin.ch/BFE/storymaps/AP_Energieperspektiven/index3.html?lang=de&selectedSzenario=ZB&selectedVariant=AJB&selectedNuclear=50

[27] Swiss Federal Office of Energy (SFOE), “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, 2020.

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

[29] S. Werner, “International review of district heating and cooling,” *Energy*, vol. 137, pp. 617–631, 2017.

[30] H. Lund *et al.*, “District heating and cooling: Review of technology and potential enhancements,” *Energy*, vol. 68, pp. 1–11, 2020, doi: 10.1016/j.energy.2014.05.045.

[31] Quintel, “Energy Transition Model (ETM).” https://energytransitionmodel.com/scenario/supply/heat_ht/transport-and-distribution-losses, 2025.

[32] P. Penttinen, J. Vimpari, and S. Junnila, “Optimal seasonal heat storage in a district heating system with waste incineration,” *Energies*, vol. 14, no. 12, p. 3522, 2021.

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

[34] V. S. AG, “Polysun simulation software.” https://www.velasolaris.com, Winterthur, Switzerland, 2012.

[35] E. M. ApS, “Electricity maps.” 2025. Available: https://app.electricitymaps.com/map/72h/hourly

[36] Viessmann Climate Solutions, “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, 2024.

[37] Viessmann Climate Solutions, “Großflächen-Solarthermie für die Nah- und Fernwärme.” https://energiekonsens.de/media/pages/media/6a0997554c-1640096559/2-viessmann-nah-und-fernwaerme-mit-solarthermie.pdf, 2021.

[38] City of Rauschenberg, “Solarwärme Bracht eG, Genossenschaftsunterlagen: Floating Cover.” https://www.solarwaerme-bracht.de/unterlagen-der-genossenschaft/, 2025.

[39] Top Agrar, “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, 2025.

[40] Carrier Klimatisierungs- und Heizsysteme - Deutschland, “AquaForce - Hochtemperatur Wasser/Wasser-Wärmepumpe mit Kältemittel HFO R-1234ze.” https://www.carrier.com/commercial/de/de/produkte/heizung/wasser-wasser-waermepumpen/61xwhze/, 2025.

[41] Viessmann Climate Solutions, “Regelungsprogramm für Mittel- und Großkessel.” https://www.viessmann.de/de/loesungen/gewerbe-und-industrie/regelung-mittelkessel-grosskessel.html, 2025.