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Deliverable report

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Deliverable name	Report on techno-economic optimal solutions for advanced thermal energy management of Power-to-X. Assessment on potential and impact of large heat pumps combined with a thermal energy storage and district heating network in the Swiss context
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Report on techno-economic optimal solutions for advanced thermal energy management of Power-to-X. Assessment on potential and impact of large heat pumps combined with a thermal energy storage and district heating network in the Swiss context.

Technical report

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Summary

This report investigates two mechanisms to enhance flexibility and sector coupling in the Swiss energy system and to support an efficient future energy system.

Thermal energy management in Power-to-X (PtX) systems

For power-to-X, the study emphasizes the role of waste heat recovery in power-to-hydrogen and power-to-methane processes. Integrating waste heat can substantially raise exergetic efficiency, and strengthen sector coupling between electricity, synthetic hydrogen and methane, and heat.

Heat recovery increases exergetic efficiency by 3–8% on average across technologies (except Solid Oxide Electrolyzer Cell + Catalytic methanation). Solid Oxide Electrolyzer Cell+ Catalytic methanation offers the highest exergetic efficiency potential for power-to-methane due to effective internal heat reuse, resulting in an overall efficiency of 76%.

The potential and impact of large heat pumps (HPs) combined with thermal energy storage (TES) and district heating networks (DHNs).

For thermal energy storage in the Swiss context, the GeoPATH tool was developed to assess the nationwide opportunities for integrating HP+TES+DHN. The results show a high implementation potential, particularly in agricultural areas and sports grounds, where suitable locations were found in more than 97% and 65% of the cases, respectively. However, the exploitability of these areas necessitates technological improvements which are required to enable multi-use concepts for the lid of the thermal energy storage. Additionally, an area energy density of the storage larger than 600 kWh/m² supports unlocking more suitable locations.

Replacing fossil-based heating in areas of high fossil heating density in Switzerland with HP+TES+DHN could reduce national emissions by about 3.3 MtCO₂ per year (≈ 8% of the total emissions). Additionally, TES integration enables significant peak power reduction (40–70%), thereby supporting renewable electricity integration and energy system resilience.

1 Report on techno-economic optimal solutions for advanced thermal energy management of Power-to-X

1.1 General Information

The role of waste heat recovery in enhancing power-to-hydrogen (PtH) and power-to-methane (PtM) systems was analyzed in an extensive literature review, to understand the potential exergetic efficiency increase of PtH and PtM application due to heat integration.

The results have been submitted as an extended abstract to the international solar energy society solar world conference and was accepted for a poster presentation at the ISES SWC 2025. Additionally, the full paper will be published by the end of the Conference, taking place the 4-7th of November 2025.

1.2 Extended Abstract

Authors: Siegwart Malin, Thomás Verde Judit, Worlitschek Jörg, Meister Curtis

Solar World Congress 2025

THE ROLE OF WASTE HEAT RECOVERY IN ENHANCING POWER-TO-HYDROGEN AND POWER-TO-METHANE SYSTEMS

Summary

Power-to-Gas technologies offer significant potential to decouple energy demand from supply, to enhance flexibility of future renewable energy systems. This review focuses on Power-to-Hydrogen and Power-to-Methane pathways and examines the impact of waste heat recovery on their exergetic efficiency. In Proton Exchange Membrane (PEM) and Alkaline Electrolysers (AEW), approximately 25–40% of the input energy is lost as low-temperature heat (50–90 °C). Solid Oxide Electrolysis Cells (SOEC), operating with water vapor at around 800 °C, requires not only electricity input but also heat input offering potential for thermal integration by utilizing high-temperature waste heat. Integrating waste heat recovery improves mean exergetic efficiency by 6.4% for PEM/AWE, 4% for PEM/AWE + BioM, and 6.8% for PEM/AWE + CatM. The highest overall efficiency, 76.3%, is achieved in integrated SOEC + CatM systems.

Keywords: Green Hydrogen, Solar fuels, Power-To-X, Thermal integration, Waste heat utilization, Electrolysis, Methanation

1. Introduction

The increasing share of renewable energy in electricity generation leads to greater fluctuations in supply, creating mismatches between supply and demand. To mitigate these imbalances, energy storage technologies such as Power-to-Gas (PtG) are essential. PtG processes convert surplus electricity into hydrogen (PtH) or methane (PtM), enabling chemical energy storage for later use in electricity generation, industrial applications, or injection into existing gas networks.

However, PtG systems often suffer from low overall efficiency due to substantial heat losses during electrolysis and methanation. These waste heat streams are frequently underutilized, thus representing a significant potential for efficiency improvement. Despite growing interest in thermal integration, a comprehensive assessment of the impact of waste heat recovery on the exergetic efficiency across different PtH and PtM technologies remains lacking in the current literature.

2. Objective

This review summarizes the state of the art in waste heat utilization in PtH and PtM systems and evaluates its impact on exergetic efficiency. Furthermore, it explores potential synergies between available waste heat and applications requiring heat at compatible temperature levels.

3. Methodology

53 publications on PtH and PtM systems were reviewed. A subset of 12 provided sufficient data (e.g., waste heat quantity, temperature level, input electricity, gas output) for exergetic analysis and were selected for detailed exergetic analysis.

3.1 Reaction Basics

Electrolysis decomposes water into hydrogen and oxygen (eq. 1), with AEW and PEM operating around 80°C [Carmo et al., 2013], and SOEC at approximately 800°C [Laguna-Bercero, 2012]. The produced hydrogen can be further converted into methane via the Sabatier reaction (eq. 2), with catalytic methanation occurring at around 200–550°C and biological methanation at approximately 20–70°C [Götz et al., 2016].





3.2 Efficiency Metrics

For energy systems with different energy carriers, it is highly relevant to find optimal and representative comparisons. Therefore, the exergetic efficiency of the PtH and PtM systems with and without heat utilization was chosen.

Exergetic efficiency without heat utilization (w/oHU) is defined the following way, taking the nomenclature from the system diagram below (fig.1):

$$\eta_{H2,w/oHU} = \frac{m_{H2} \cdot LHV_{H2}}{E_{El,in} + Q_{in,el} \left(1 - \frac{T_{amb}}{T_{Qin}}\right)} \quad (\text{eq. 3})$$

$$\eta_{H2\&CH4,w/oHU} = \frac{m_{CH4} \cdot LHV_{CH4}}{E_{El,in} + Q_{in,el} \left(1 - \frac{T_{amb}}{T_{Qin}}\right)} \quad (\text{eq. 4})$$

The utilization Exergetic efficiency with heat utilization (wHU) is defined the following way, taking the nomenclature from the system diagram below (fig.1):

$$\eta_{H2,wHU} = \frac{m_{H2} \cdot LHV_{H2} + Q_{wH,el} \left(1 - \frac{T_{amb}}{T_{use,wH}}\right)}{E_{El,in} + Q_{in,el} \left(1 - \frac{T_{amb}}{T_{Qin}}\right)} \quad (\text{eq. 5})$$

$$\eta_{H2\&CH4,w/oHU} = \frac{m_{CH4} \cdot LHV_{CH4} + Q_{wH,el} \left(1 - \frac{T_{amb}}{T_{use,wH,el}}\right) + Q_{wH,me} \left(1 - \frac{T_{amb}}{T_{use,wH,me}}\right)}{E_{El,in} + Q_{in,el} \left(1 - \frac{T_{amb}}{T_{Qin}}\right)} \quad (\text{eq. 6})$$

Assumptions include neglecting: minor auxiliary energy needs, assuming room-temperature feedstocks, ignoring post-process gas compression, neglecting heat input for electrolysis for AEW/PEM (since it is below 3% of the energy input [Candelaresi et al., 2021]), Energy to get CO₂ neglected

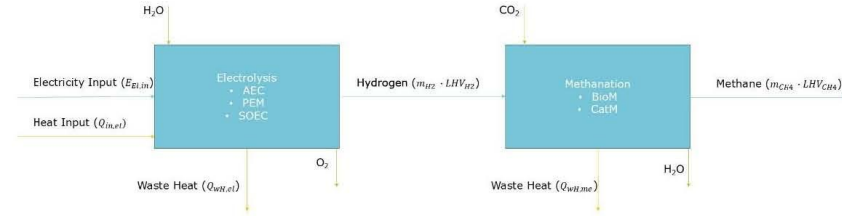


Figure 1: System Diagram, Power to Hydrogen to Methane, Definitions [own illustration]

4. Preliminary Results

The mean exergetic efficiency increase through heat recovery for PEM&AEC electrolysis is 6.4% from 67.8% to 74.2% (fig.2). For the SOEC system the efficiency increase due to heat integration has a higher increase of 26.5% due to input heat requirements. For AEW or PEM combined with CatM the mean exergetic efficiencies are 54.4% without heat integration and 61.2% with heat integration, representing a 6.8% increase. For AEW or PEM combined with BioM the mean exergetic efficiencies 48.3% without heat integration and 52.3% with heat integration which is an increase of 4%. For the SOEC combined with CatM only efficiencies with heat utilization were found in the literature, since the heat from the CatM is used internally for the SOEC. Exergetic

efficiencies range from 66.9% to 81% with a mean value of 76.3% (Fig. 2)

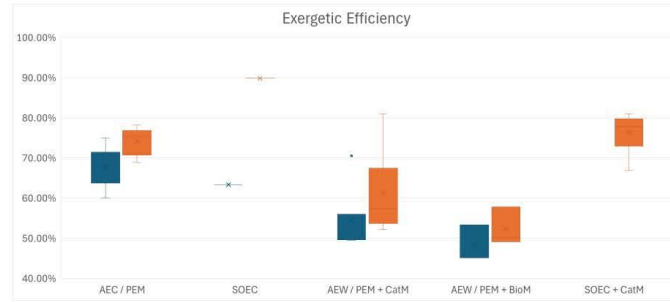


Figure 2: Exergetic efficiency of PtH and PtM process with and without heat integration [reference list will follow in the full paper submission]

Depending on the temperature range different source and sink for the heat are feasible. Low temperature waste heat can be used for district heating, swimming pool or low temperature industrial heat requirement depending on the specific availability. For high temperature waste heat especially the combination with Solid Oxide Electrolysis is favorable due to the local combination of Methanation and SOEC. Other possibilities for waste heat utilization are summarized in the graph below (fig. 3).

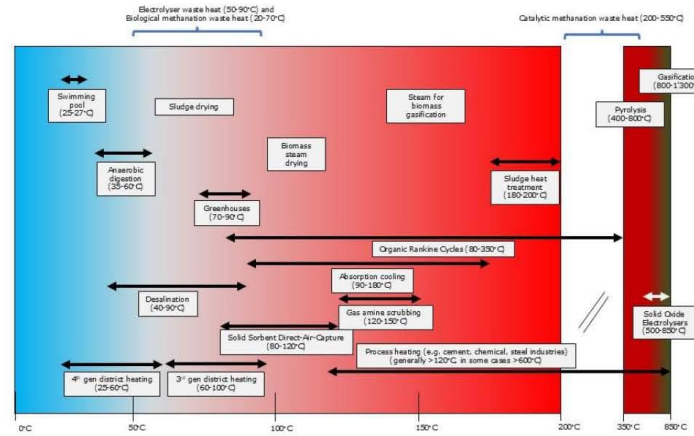


Figure 3: Overview of potential utilization of waste heat from electrolysis and methanation [own illustration]

5. Conclusion

This review highlights the critical role of waste heat utilization in improving PtG system efficiency. Key findings include:

- **Heat recovery increases exergetic efficiency by 3–8% on average** across technologies (except SOEC + CatM)
- **SOEC + CatM offers the highest exergetic efficiency potential for PtM** due to effective internal heat reuse, resulting in an overall efficiency of 76%

References:

[Candelaresi et al., 2021] Daniele Candelaresi, Linda Moretti, Alessandra Perna, and Giuseppe Spazzafumo. Heat recovery from a pting plant coupled with wind energy. *Energies*, 14, 2021.

[Carmon et al 2013] Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). A comprehensive review on PEM water electrolysis. *International Journal of Hydrogen Energy*, 38(12), 4901–4934.

[Götz et al. 2016] Götz, M., Lefebvre, J., Mörs, F., Koch, A. M., Graf, F., Bajohr, S., Reimert, R., & Kolb, T. (2016). *Renewable Power-to-Gas: A technological and economic review*. *Renewable Energy*, 85, 1371–1390.

[Laguna-Bercero 2012]. Laguna-Bercero, M. A. (2012). *Recent advances in high temperature electrolysis using solid oxide fuel cells: A review*. *Journal of Power Sources*, 203, 4–16.

2 Potential and impact of large heat pumps combined with a thermal energy storage and district heating network in the Swiss context

2.1 General Information

The second part of Deliverable D3.1.1.3 is originally titled “**Case Study on the Potential and Impact of Carnot Batteries in the Swiss Context.**” It has been converted to: “**Assessment of the Potential and Impact of Large Heat Pumps Combined with Thermal Energy Storage and District Heating Networks in the Swiss Context.**”

Initial deliverable:

Carnot batteries are systems that convert electricity into high-temperature heat, store it, and regenerate electricity on demand using technologies such as the organic Rankine cycle. While this technology attracted industry interest in the past, its low efficiency (<20%) limits its viability to specific applications where resilience in electricity production is critical.

Additionally, due to high costs, Carnot batteries currently cannot compete with alternatives like hydropower or hydrogen electrolysis with fuel cells. This perspective is also shared by industry partners such as MAN Energy Solutions, which have shifted their focus to large heat pump systems.

In contrast, coupling heat pumps with thermal energy storage systems and using the stored heat directly – rather than reconvert it into electricity – offers a more efficient and practical solution for Switzerland. Excluding the heat-to-electricity cycle found in Carnot batteries, significantly improve overall efficiency.

Long-term thermal energy storage adds flexibility by decoupling heat production from electricity availability and heat demand, enhancing system resilience. It also enables the storage of waste heat during summer, allowing heat pumps to achieve higher coefficients of performance (COP) due to elevated source temperatures or even facilitating the direct use of stored heat. However, detailed studies on where and at what scales these systems have the greatest potential in the Swiss context are currently lacking.

More information can be found in Chapter 3.

Revised proposal:

To maximize the relevance and impact of our research, we propose revising the second part of Deliverable D3.1.1.3 to focus on: “**Assessment of the Potential and Impact of Large Heat Pumps Combined with Thermal Energy Storage and District Heating Networks in the Swiss Context.**”

This revised deliverable will emphasize the more efficient aspect of Carnot batteries, the electricity-to-heat conversion combined with thermal energy storage. Using the geo-analysis tool developed within PATHFINDER WP3, we will assess the national impact potential of integrating thermal energy storage with waste heat and heat pump technologies in Switzerland.

Due to the generic nature of the GIS tool, originally designed to evaluate Carnot battery potential, the combination of heat pumps, thermal storage, and district heating networks can be analyzed by applying new boundary conditions. The key considerations for this analysis are as follows:

- **Identify target areas:** Focus on regions with high densities of fossil-based heating systems. Assuming the substitution of fossil-based systems with heat pumps, thermal energy storage, and district heating networks.
- **Constraints and feasibility:** Include factors such as:
 - Available space for thermal energy storage (e.g., exclude areas with inclinations exceeding a specified threshold).

- Land-use restrictions (e.g., sports ground areas, agricultural land, parking slots).

The analysis will estimate the maximum potential of these systems under different scenarios and perform sensitivity analyses modifying constraints or limiting values. The analysis of district heating networks focuses on centralized heating systems. Such an analysis complements the outputs of P&D nanoverbund project (WP1), where the technology mixes from the public database are used to identify clusters of houses suitable for the decentralized district heating network concept (i.e., nanoverbund).

As part of the deliverable, a summary of the Carnot battery technology with advantages and disadvantages and the reasons for not pursuing this technology further in this work package is added (Chapter 3).

2.2 Potential of large heat pumps combined with a thermal energy storage and district heating network in the Swiss context

To assess the potential and impact of large-scale heat pump integration with thermal energy storage and district heating networks in Switzerland, the GIS-based analysis tool GeoPATH was developed. GeoPATH provides a systematic framework for identifying and evaluating the maximum potential deployment of a given technology based on spatial and energetic constraints. Unlike site specific case studies, GeoPATH is designed to assess opportunities across the entire country. It combines high-resolution geographical datasets (e.g., land use, topography, slope) with energy-related indicators (e.g., heating demand, supply infrastructure) to construct a consistent and scalable evaluation methodology. The goal is to identify the geographical maximum potential of TES implementation under varying assumptions and constraints. The tool enables users to define technical and spatial boundary conditions, filter feasible regions and perform sensitivity analyses to evaluate the impact of varying assumptions on the suitability and availability of locations for deploying the given technology. This combination of nationwide scope and configurable logic renders GeoPATH a powerful instrument for strategic energy system planning in the Swiss context.

Within this analysis, areas where heating demand is dense and currently covered by fossil fuels are identified, together with nearby sites suitable for TES, specifically pit thermal energy storage (PTES). The requirements and workflow are further explained in the following chapters.

2.2.1 GeoPATH workflow

The analysis workflow in GeoPATH is structured into three main steps:

Step 1: Identification of building clusters with high heat demand and fossil heating

- Buildings with fossil-based heating systems are grouped into clusters.
- Configurable parameters include:
 - Minimum number of buildings per cluster
 - Minimum heat demand per cluster
 - Maximum distance between buildings (cluster span)

Step 2: Storage site identification

- Potential sites for thermal energy storages are identified based on:
 - Zoning category (e.g., agricultural or recreational land)
 - Maximum slope gradient (reasons high inclination angles would bring additional challenges for construction and, therefore, have not been constructed like this before). Typical values include less than 5°
 - Land area requirements, which depend on the desired coverage rate and storage density

Step 3: Linking clusters and sites

- The required area of the storage site is selected depending on the energy demand of the cluster.
- A maximum allowable distance is defined (e.g., 20 meters per kilowatt of installed capacity) to ensure technical feasibility.

For Step 3, an algorithm was developed, which will be published at CISBAT 2025 with the title “Mapping Switzerland’s energy potential: a data-driven geo-analysis of energy technologies. S. In-Albon, E. Schmitt, M. Siegwart, J. Worlitschek”. The paper is reproduced in the Annex.

Data Sources

GeoPATH utilizes a wide range of spatial datasets, primarily derived from swisstopo and is complemented by heating demand data from PATHFNDR WP2 (Sarah Schneeberger, 2025). The following data layers are considered:

- Land use (agricultural areas (geocat.ch, 2025), leisure areas (Landestopografie, swissTLM3D – Das grossmassstäbliche Topografische Landschaftsmodell der Schweiz, 2024), transportation infrastructure (Landestopografie, swissTLM3D – Das grossmassstäbliche Topografische Landschaftsmodell der Schweiz, 2024))
- Topography (slope data, elevation models, (Landestopografie, DHM25, 2024))
- Buildings (data with associated heat demand and heat source, (Sarah Schneeberger, 2025), (Landestopografie, Amtliches Verzeichnis der Gebäudeadressen, 2024))

2.2.2 Definition of selection criteria

Step 1: Formation of heat demand clusters

The goal is to replace an area of high fossil heating density with a district heating network powered by a large heat pump and thermal energy storage. Thus, building groups with high fossil heating demand density are searched and clustered. Therefore, a fossil-based heating density of 70 kWh/m² (**Arbeitsgemeinschaft QM Fernwärme, 2021**) and a maximum distance between two buildings of 200 m were considered. The minimum number of buildings to build a cluster forming a new district heating network was set to 50 buildings. This results in a total heat demand of 16.2 TWh/a divided into different clusters within Switzerland (Figure 1).

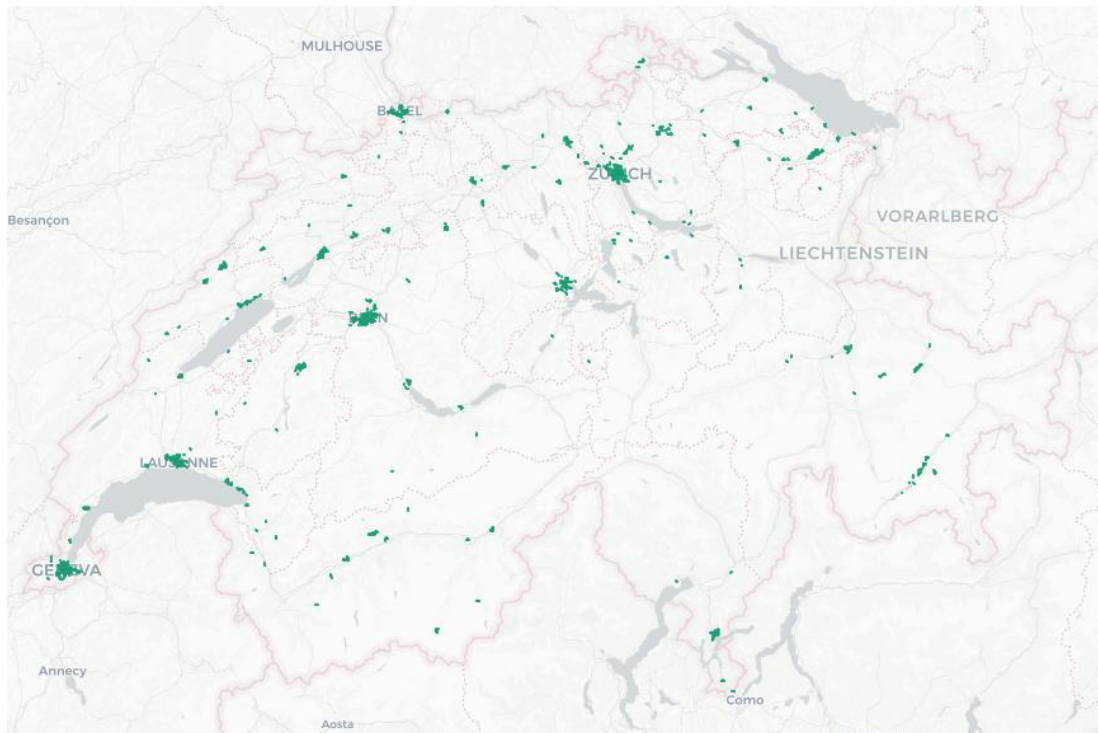


Figure 1: Locations of potential district heating networks to replace current fossil-based heating systems according to the selection criteria in Section 2.2.2.

Step 2: Storage site identification

To be able to integrate a thermal energy storage into a heat pump powered district heating network, the storage needs to be positioned which raises strong surface area requirements. Therefore, the identification of a potential storage site is vital. Here, the chosen storage technology, which determines the possible placement options, is pit thermal energy storage (PTES). PTES offer the dual benefit of high charge and discharge power combined with an elevated storage capacity compared to borehole thermal energy storage. Additionally, the PTES technology is less dependent on the geological conditions compared to technologies such as aquifer thermal energy storage.

In GeoPATH, two main conditions are applied for the storage placement potential. The first condition concerns the surface tilt. Since the employed Swiss topography data has a spatial resolution of $25 \times 25 \text{ m}^2$, even largely flat areas may display a slight slope. In the base case, a maximum angle of 5° is allowed. The impact of this selection criterion will be assessed in sensitivity analyses to investigate whether enabling PTES construction on tilted surfaces significantly increases the nationwide potential (see Table 1).

The second condition relates to land use. Only surfaces without existing buildings are considered suitable. Therefore, the following areas were considered (Table 1):

- Agricultural use area “Landwirtschaftliche Nutzungsflächen Schweiz (Bundesamt für Landwirtschaft BLW, Kantone)”
 - o Cropland (Ackerflächen)
 - o Permanent meadows and pastures (Dauerwiesen & Dauerweiden)
 - o Others were neglected after consolidation with cantonal agriculture experts. Either it is not feasible due to long lifetime of the surface plants and deep roots (Forest, Reben, Obstanlagen) or it is highly unfeasible due to natural protection (Sömmerungsflächen) or other reasons.
- Parking lot

- Airfield area
- Golf course area
- Sport ground area

For this analysis it was assumed that a PTES can be built below the above-mentioned surface. TO enable an actual placement, a multi-use of the PTES lid is a prerequisite. This condition is not state of the art today, however within the Innosuisse Flagship project SwissSTES, the multi-use of the PTES lid is investigated, and solutions are developed. Furthermore, within the same Innosuisse project the social acceptance of the PTES system depending on the multi-use are investigated. Preliminary results show that each of the possible multi-use within the survey (Sport ground, parking space, Biodiversity area) increases the social acceptance of PTES.

Considering the possible sites for the placement of a PTES in Switzerland considering only the placement conditions and neglecting the demand conditions, the largest potential lays in permanent meadows and pastures followed by cropland (Figure 2, Figure 3). The least potential is found for airfields and golf courses (Figure 5, Figure 7).

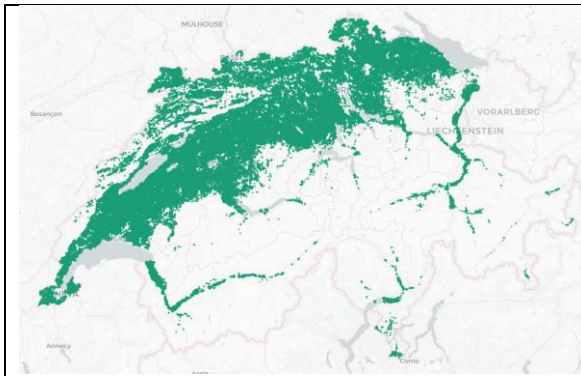


Figure 2: Possible placement for PTES on croplands.

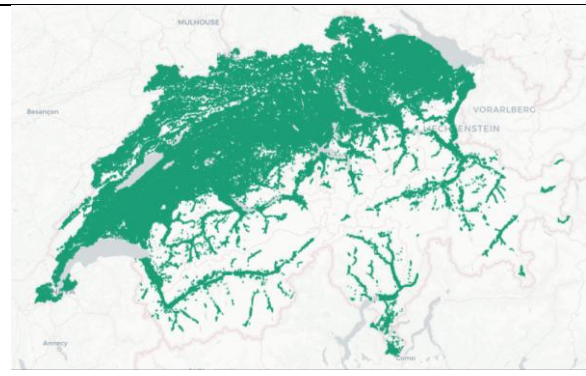


Figure 3: Possible placement for PTES on permanent meadows and pastures.

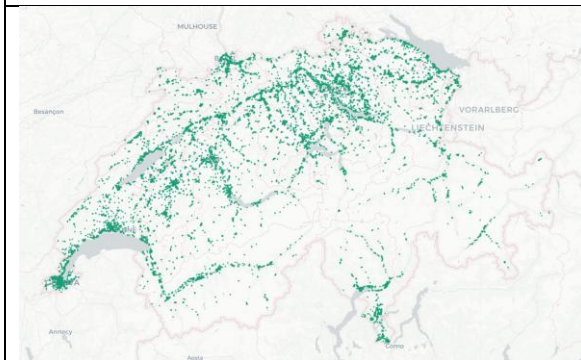


Figure 4: Possible placement for PTES on parking lots.

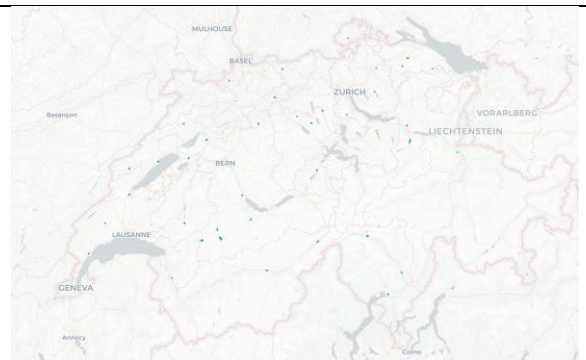


Figure 5: Possible placement for PTES on airfield areas.

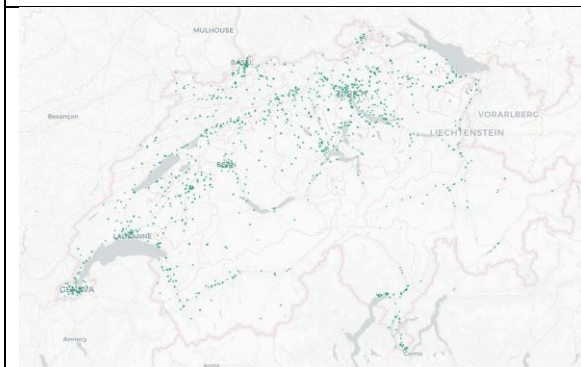


Figure 6: Possible placement for PTES on sport ground areas.

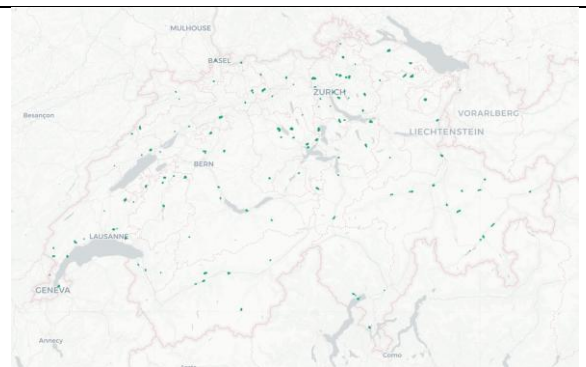


Figure 7: Possible placement for PTES on golf course areas.

Step 3: Linking Clusters and Sites

It is assumed that the PTES only covers a percentage of the demand of the district heating network. This value is varied between 5% to 30%, however the base case is assumed to be 10% (Table 1). This share defines the storage capacity required for a district heating network. Based on this capacity, the required volume assuming a temperature spread of 80 K is calculated. The surface area of PTES is estimated based on an analysis of existing PTES solutions considering the depth of the storage, the

side wall angle of the PIT, the temperature difference, and the storage medium. For the base case, a base value of 800 kWh/m² is chosen determined as follows, coming from the following calculation:

$$\frac{Q}{A} = \frac{(V \cdot c_p \cdot \Delta T) \cdot 2}{A} = \frac{(c_p \cdot \Delta T) \cdot 2}{\frac{A}{V}} = \frac{60000 \text{ m}^3 \cdot 1.163 \frac{\text{kWh}}{\text{m}^3 \text{K}} \cdot 80 \text{ K} \cdot 2}{13670 \text{ m}^2} = 817 \frac{\text{kWh}}{\text{m}^2} \approx 800 \frac{\text{kWh}}{\text{m}^2} \quad \text{*(base case specific space demand PTES)}$$

*Assumptions: Storage medium water, Delta T of 80 K, Volume and Surface area from Dronninglund (Abdulrahman Dahash, 2019), the factor 2 is considered since PTES capacity is discharged multiple times over one year.

Due to many uncertainties and specific design values for this space demand of PTES, this parameter will be varied between 400 and 1200 kWh/m² in the sensitivity study (Table 1). This analysis enables the user to quantify the relevance of increasing this value.

Additionally, the distance between DHN and PTES had to be limited, since piping cost, pumping energy and thermal losses increase with increased distances. An economical range for the piping lengths is known as 2 MWh/m*a (Arbeitsgemeinschaft QM Fernwärme, 2021) heat, leading to a possible length of 0.5 m/MWh (Table 1). This value will be varied in the sensitivity study to identify the required proximity of the PTES to the heat demand (Table 1).

Table 1: Requirements.

Requirements				
	Parameter	Description	Base case value	Range for sensitivity
Placement conditions	Tilt placement	The tilting angle of the surface. Due to the high resolution of the Swiss topography data with 25x25 m ² also mostly flat area have a small angle. Thus, in the base case, an absolute angle of 5° is allowed.	5°	[0 °, 5 °, 10 °]
	Placement	Sites which were considered suitable for PTES installation.		[Cropland, Permanent meadows and pastures, Parking lot, Airfield area, Golf course area, Sports ground area]
Energy conditions	Specific distance	What is the possible distance between DHN and PTES depending on the energy stored inside the PTES.	0.5 m/MWh	[0.3, 0.5, 0.7] m/MWh
	Storage coverage	Which share of the DHN heat demand is covered by the PTES.	0.1	[0.05, 0.1, 0.15, 0.2, 0.25, 0.30]
	Areal energy storage density	This gives the energy stored per surface area. To influence this value, either the temperature difference within the storage, the surface/volume ratio, or the material can be changed.	800 kWh/m ²	[400, 600, 800, 1000, 1200] kWh/m ²

2.3 Results

2.3.1 Results: Placement sensitivity

First, the different placement options ([Cropland, Permanent meadows and pastures, Parking lot, Airfield area, Golf course area, Sport ground area]) were evaluated while keeping all other parameters at their base case values. Based on the total Swiss heat demand of 16.2 TWh/a (Chapter 2.2.2) for the given case, the base case assumed a 10% energy coverage of the district heating network (DHN) by a PTES. This results in a maximum cumulative nationwide 1.62 TWh/a of the heating demand coming from the implemented PTES, distributed in Switzerland based on the identified location (Figure 1). With the GeoPATH it is then possible to identify for which clusters a suitable location for such a PTES can be found based on the given boundary conditions. For permanent meadows and pastures, in 97% of the cases a suitable storage site could be identified (Figure 8). Followed by cropland, where a PTES can be placed in 92% of the cases (Figure 8). Sport ground area offers fewer possibilities with about 68%, golf course area 58% and parking lots about 29% (Figure 8). On airfield areas, only 4% of the required PTES can be placed due to marginal possible locations (Figure 8).

Considering the average size of a PTES, it is visible that the mean storage capacity of the placed PTES varies depending on the placement option, being the largest on golf courses, which are often also further away from the DHN which is why a bigger storage capacity is required to connect the DHN to the PTES (Figure 9, Figure 10). The same tendency is observed for airfield areas (Figure 9, Figure 10). On the other hand parking lots tend to be very close to the DHN however often the size is very limited reaching the smallest average storage capacity (Figure 9, Figure 10).

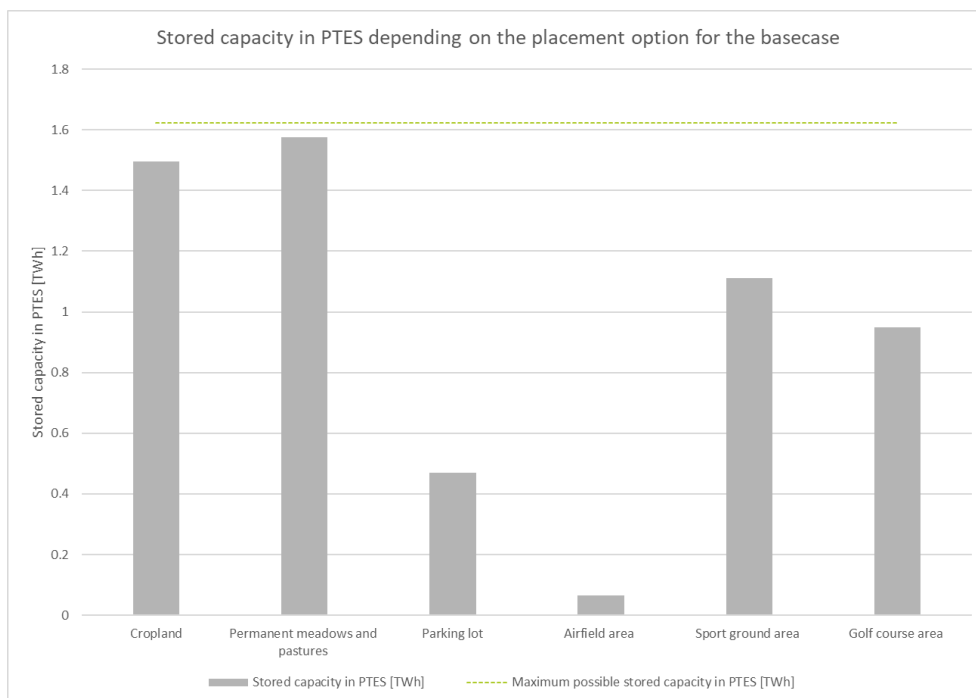


Figure 8: Total stored capacity in PTES depending on the placement option for the base case.

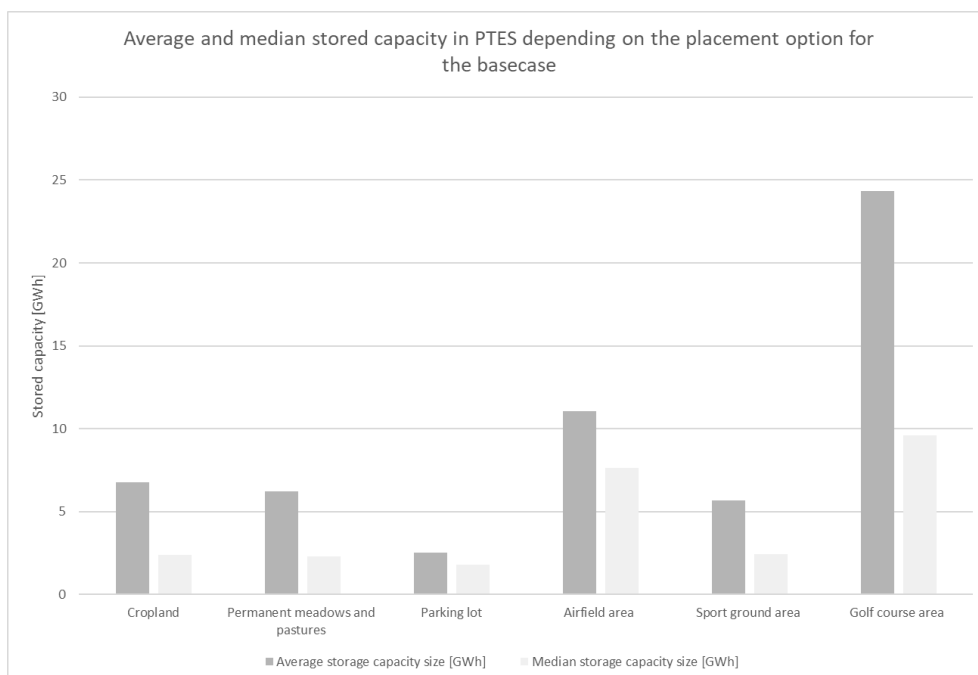


Figure 9: Average and median stored capacity in PTES depending on the placement option.

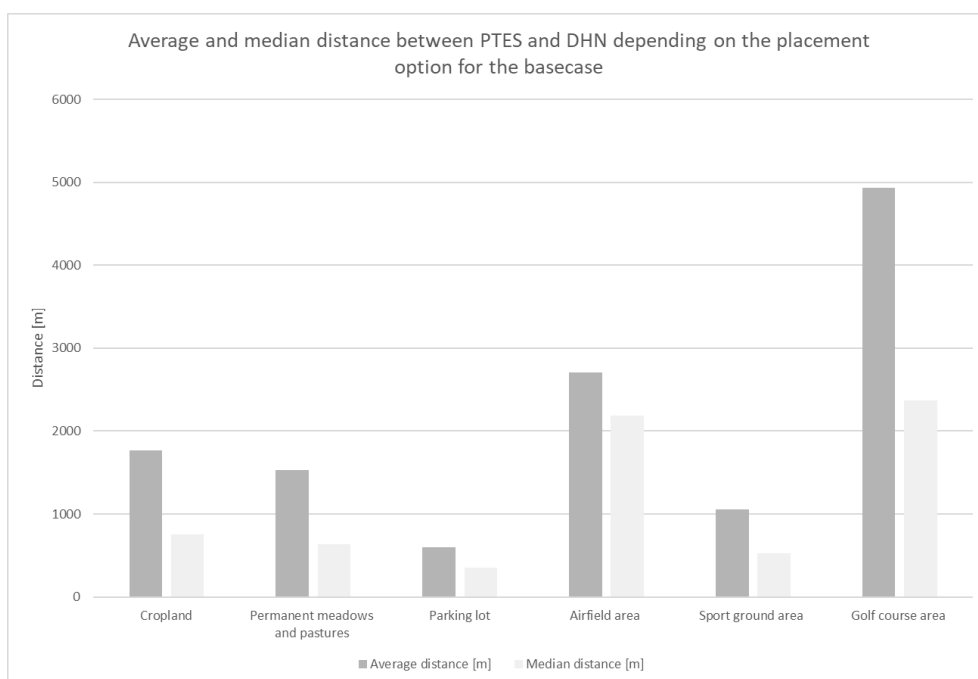


Figure 10: Average and median distance between PTES and DHN depending on the placement option.

2.3.2 Results: Sensitivity to requirements

Besides estimating the potential exploitation of the technology, GeoPATH allows to analyze the sensitivity to certain parameters, to better understand what the limiting factor for the theoretical exploitation of the technology combination of heat pump, thermal energy storage powering a district heating network.

In this chapter, for a fixed placement category, the impact of the variation of energy storage density and the PTES-DHN distance parameters was analysed as specified in Table 1.

Sensitivity on areal energy storage density

Energy storage

For cropland, the steepest increase in total storage capacity occurs between 400 kWh/m² and 600 kWh/m², with an additional $\frac{11\%}{200 \text{ kWh/m}^2}$ of the stored energy provided by the identifies sites as a share of the maximum required storage potential for the given case study. Between 600 kWh/m² and 1200 kWh/m² the share increases less than $\frac{2\%}{200 \text{ kWh/m}^2}$ (Figure 11). For permanent meadows and pastures, the pattern is similar: the maximum gradient is also between 400 kWh/m² and 600 kWh/m², with an increase of 14%, and the slope afterwards is always below $\frac{1\%}{200 \text{ kWh/m}^2}$ (Figure 11). This highlights the importance of reaching at least 600 kWh/m² areal storage density for both cropland and permanent meadows and pastures.

For sport grounds, the maximum gradient is likewise found between 400 kWh/m² and 600 kWh/m², with an increase of $\frac{16\%}{200 \text{ kWh/m}^2}$ (Figure 11). Between 600 kWh/m² and 800 kWh/m² the slope decreases to $\frac{11\%}{200 \text{ kWh/m}^2}$ and the further decreases to $\frac{10\%}{200 \text{ kWh/m}^2}$ between 800 kWh/m² and 1000 kWh/m² and to $\frac{1\%}{200 \text{ kWh/m}^2}$ between 1000 kWh/m² and 1200 kWh/m² (Figure 11). This shows a saturation for areal energy storage density higher 1000 kWh/m².

For parking lots, the maximum gradient is likewise found between 400 kWh/m² and 600 kWh/m², with an increase of $\frac{10\%}{200 \text{ kWh/m}^2}$ (Figure 11). Between 600 kWh/m² and 800 kWh/m² the slope decreases to $\frac{10\%}{200 \text{ kWh/m}^2}$ and the further decreases to $\frac{6\%}{200 \text{ kWh/m}^2}$ between 800 kWh/m² and 1000 kWh/m² and to $\frac{3\%}{200 \text{ kWh/m}^2}$ between 1000 kWh/m² and 1200 kWh/m² (Figure 11).

For golf courses, the maximum gradient is likewise found between 400 kWh/m² and 800 kWh/m², with an increase of $\frac{6\%}{200 \text{ kWh/m}^2}$ (Figure 11). Between 800 kWh/m² and 1200 kWh/m² the slope decreases to $\frac{1\%}{200 \text{ kWh/m}^2}$ (Figure 11). This indicates only marginal additional storage potential at areal densities above 800 kWh/m².

Average distance between PTES and DHN

For cropland, the average distance between PTES and DHN is mostly affected between 400 kWh/m² and 600 kWh/m², with an increase of $\frac{13\%}{200 \text{ kWh/m}^2}$ and between 600 kWh/m² and 800 kWh/m², with an decrease of $\frac{15\%}{200 \text{ kWh/m}^2}$ (Figure 11). For higher areal energy storage density, the effect is reduced and below $\frac{10\%}{200 \text{ kWh/m}^2}$ (Figure 11).

For permanent meadows and pastures the average distance between PTES and DHN between 400 kWh/m² and 600 kWh/m² increases by $\frac{10\%}{200 \text{ kWh/m}^2}$ and between 600 kWh/m² and 800 kWh/m² it decreases by $\frac{13\%}{200 \text{ kWh/m}^2}$ (Figure 11). For higher areal energy storage density, the effect is reduced and below an increase of $\frac{7\%}{200 \text{ kWh/m}^2}$ (Figure 11).

For parking lots, the average distance between PTES and DHN between 400 kWh/m² and 600 kWh/m² increases by $\frac{22\%}{200 \text{ kWh/m}^2}$ and between 600 kWh/m² and 800 kWh/m² it increases by $\frac{27\%}{200 \text{ kWh/m}^2}$ (Figure 11). For higher areal energy storage density, the effect is reduced and below $\frac{\pm 2\%}{200 \text{ kWh/m}^2}$ (Figure 11).

For sports field areas, the average distance between PTES and DHN is mostly affected between 400 kWh/m² and 600 kWh/m² and 1000-1200 kWh/m², with an increase of $\frac{16\%}{200 \text{ kWh/m}^2}$ followed by an increase of $\frac{12\%}{200 \text{ kWh/m}^2}$ and between 600 kWh/m² and 800 kWh/m² (Figure 11).

For golf course areas the change is below $\frac{6\%}{200 \text{ kWh/m}^2}$ for the whole range.

The biggest change is observed in airfield area with an increase of $\frac{37\%}{200 \text{ kWh/m}^2}$ 400 kWh/m² to 800 kWh/m² and $\frac{55\%}{200 \text{ kWh/m}^2}$ 800 kWh/m² to 1200 kWh/m² (Figure 11). This observation highlights the potential of higher storage densities to enable connections to more distant district heating networks in the case of airfield sites (Figure 12, Figure 13). As an example, with an areal storage density above 800 kWh/m², the airfield area Biel-Kappelen could be identified as a suitable storage placement for Biel (Figure 14). Hereby it is important to note that the distance of more than 15 km between the potential DHN and the area is very large and must be considered site specific if this is (economically) feasible.

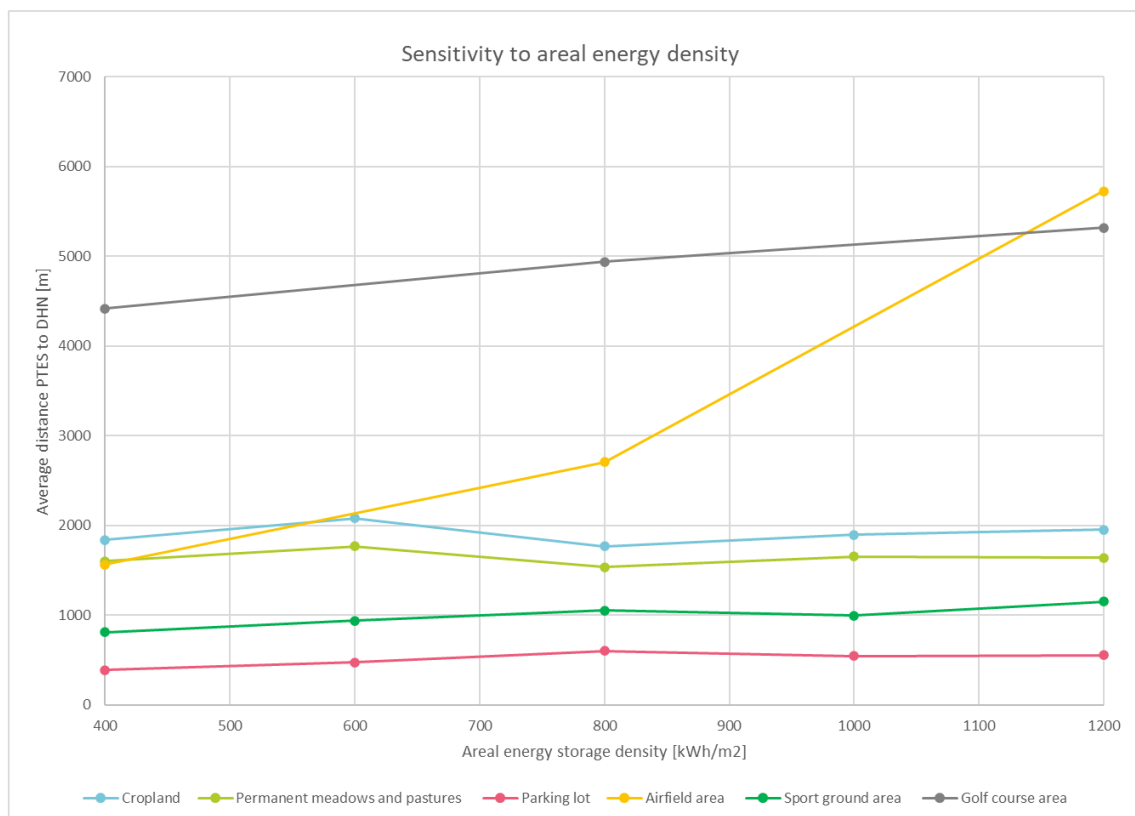
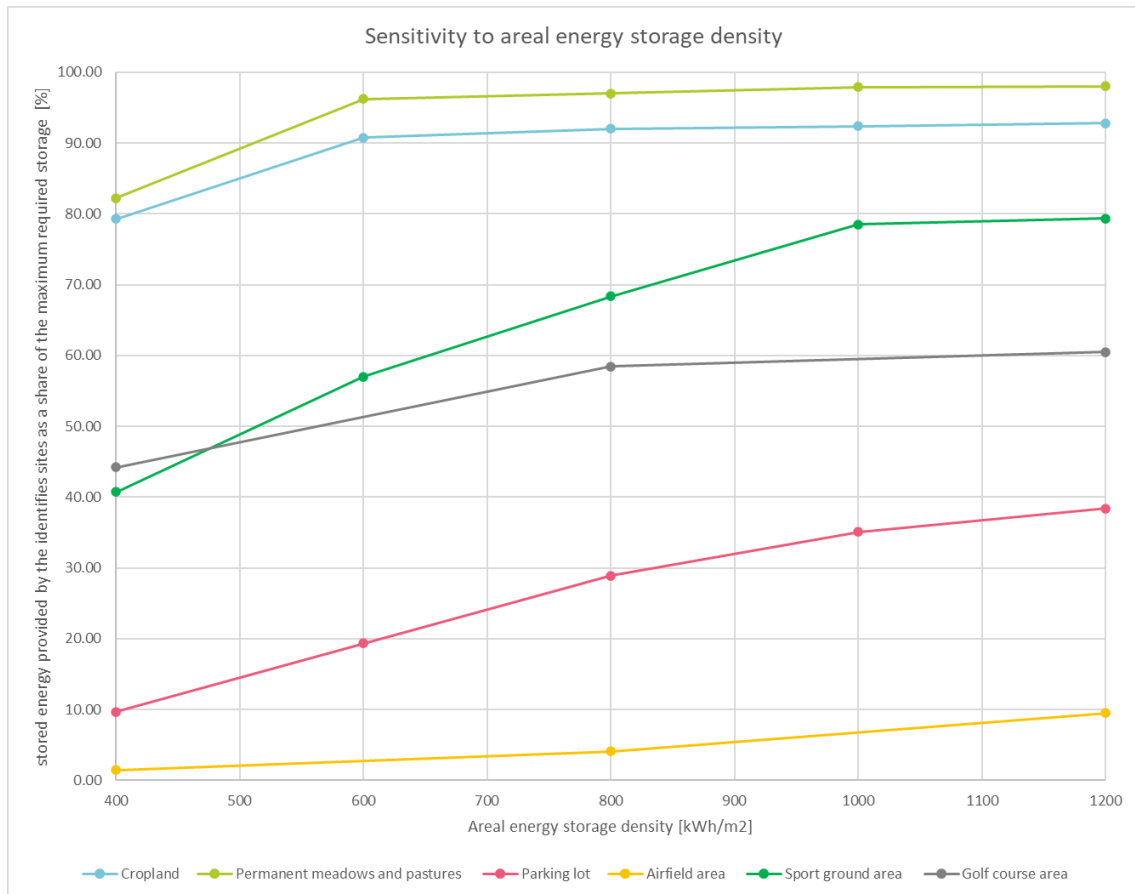


Figure 11: Sensitivity of storage capacity and average distance between PTES and district heating network on areal energy storage density.

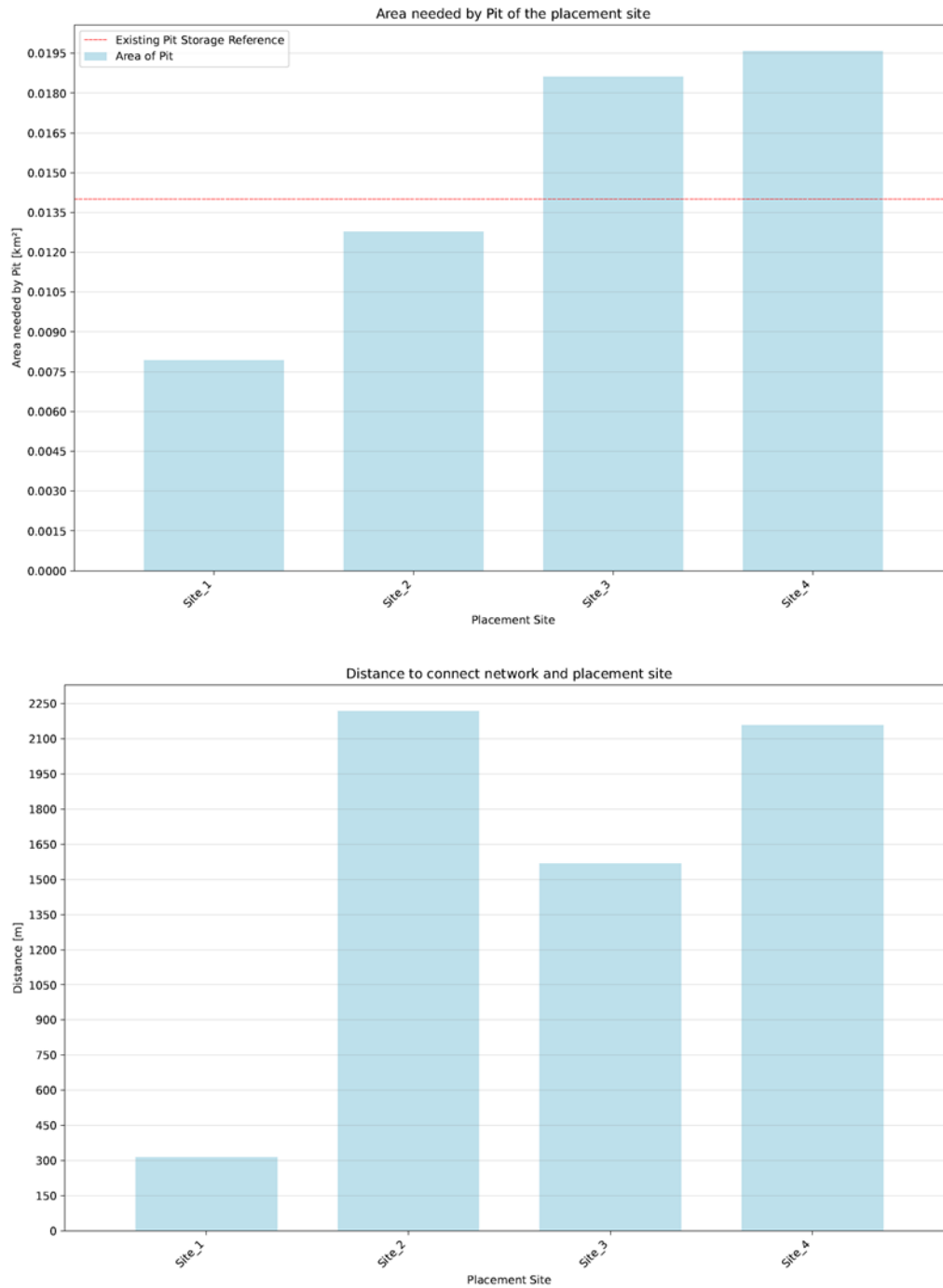


Figure 12: Each “site” is a placed PTES on airfield areas for an areal energy storage density of 400 kWh/m². With the area needed by each places PTES (upper graph) and the distance between DHN and PTES (lower graph).

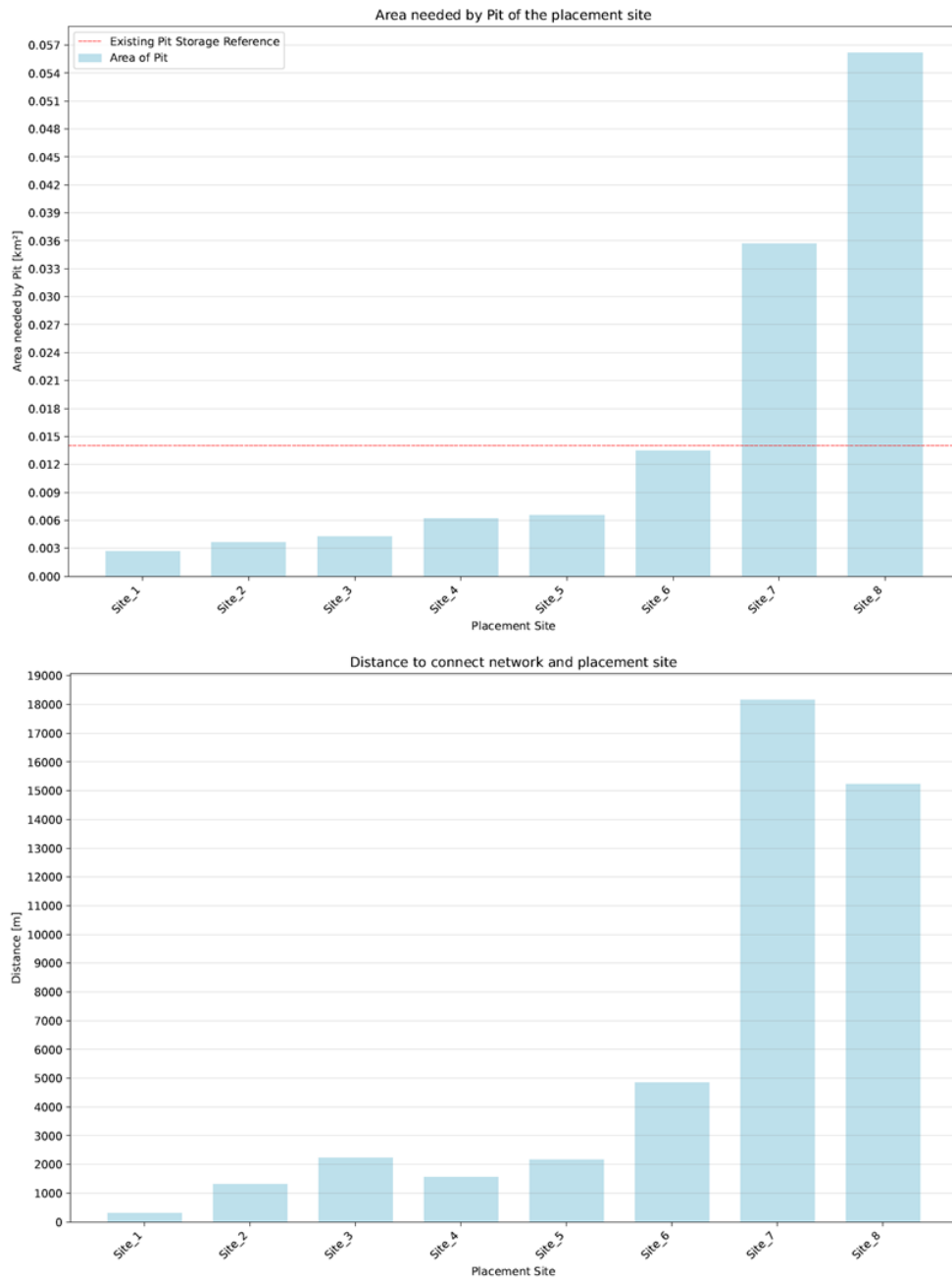


Figure 13: Each “site” is a placed PTES on airfield areas for an areal energy storage density of 1200 kWh/m². With the area needed by each places PTES (upper graph) and the distance between DHN and PTES (lower graph).

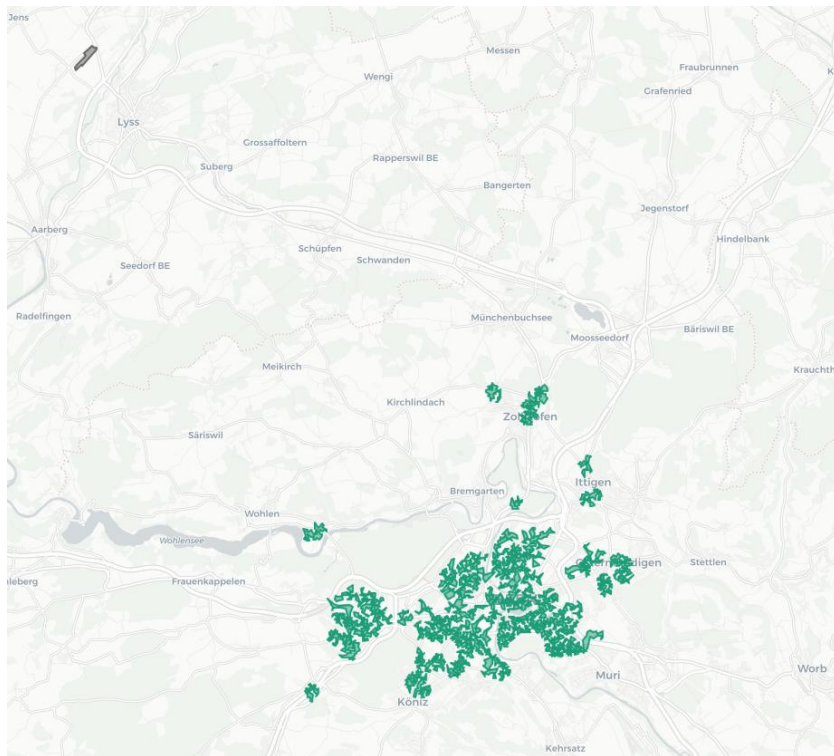


Figure 14: Airfield area Biel-Kappelen (grey) connected to the heat demand of Bern (green) for an areal energy storage density of 1200 kWh/m². (The dark grey area is the maximum available area, not the whole area required for the PTES).

Sensitivity on specific distance

Energy Storage

The effect on changing the specific distance on the total storage capacity is analyzed in PTES is analyzed.

For cropland and permanent meadows and pastures, the maximum increase in stored energy provided by the identifies sites as a share of the maximum required storage potential depending on the specific distance increase, is found between 0.3 m/MWh and 0.5 m/MWh with an increase of $\frac{5\%}{0.2 \text{ m/MWh}}$ (Figure 15). Between 0.5 m/MWh and 0.7 m/MWh the slope decreases to $\frac{2\%}{0.2 \text{ m/MWh}}$ this shows the saturation for specific distances above 0.5 m/MWh (Figure 15).

Sports ground areas show a more less variable inclination with an increase of $\frac{4\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh and $\frac{3\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh (Figure 15). Golf court areas show a very similar pattern with an increase of $\frac{6\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh and $\frac{5\%}{0.2 \text{ m/MWh}}$ between 0.5 m/MWh and 0.7 m/MWh (Figure 15). And also parking lots show a very similar pattern with an increase of $\frac{7\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh and $\frac{5\%}{0.2 \text{ m/MWh}}$ between 0.5 m/MWh and 0.7 m/MWh (Figure 15).

For airfield areas, the effect of specific distance is marginal, being smaller than $\frac{3\%}{0.2 \text{ m/MWh}}$ in any case (Figure 15).

Average distance between PTES and DHN

Further, the effect on changing the specific distance on the average PTES distance to the DHN is analyzed.

For cropland, the slope decreases from $\frac{39\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh to $\frac{19\%}{0.2 \text{ m/MWh}}$ between 0.5 m/MWh and 0.7 m/MWh, indicating stagnation. Permanent meadows and pastures show a similar trend, $\frac{50\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh to $\frac{36\%}{0.2 \text{ m/MWh}}$ between 0.5 m/MWh and 0.7 m/MWh (Figure 15). Sports ground areas show a similar trend with an average distance increase of $\frac{53\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh to $\frac{38\%}{0.2 \text{ m/MWh}}$ between 0.5 m/MWh and 0.7 m/MWh (Figure 15). The effect on parking lots is more prominent, by increasing by $\frac{101\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh to $\frac{47\%}{0.2 \text{ m/MWh}}$ between 0.5 m/MWh and 0.7 m/MWh (Figure 15).

Airfield areas show an opposite trend of an average distance increase by $\frac{24\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh increasing to $\frac{40\%}{0.2 \text{ m/MWh}}$ between 0.5 and 0.7 m/MWh (Figure 15).

For golf courses the average distance increase is $\frac{9\%}{0.2 \text{ m/MWh}}$ between 0.3 m/MWh and 0.5 m/MWh followed by a decline of $\frac{6\%}{0.2 \text{ m/MWh}}$ between 0.5 m/MWh and 0.7 m/MWh, confirming that reachable distance is not a crucial factor. The decline is due to inclusion of smaller storage sites due to higher specific distance, leading to a decrease of the average distance but increase in total energy stored (Figure 16).

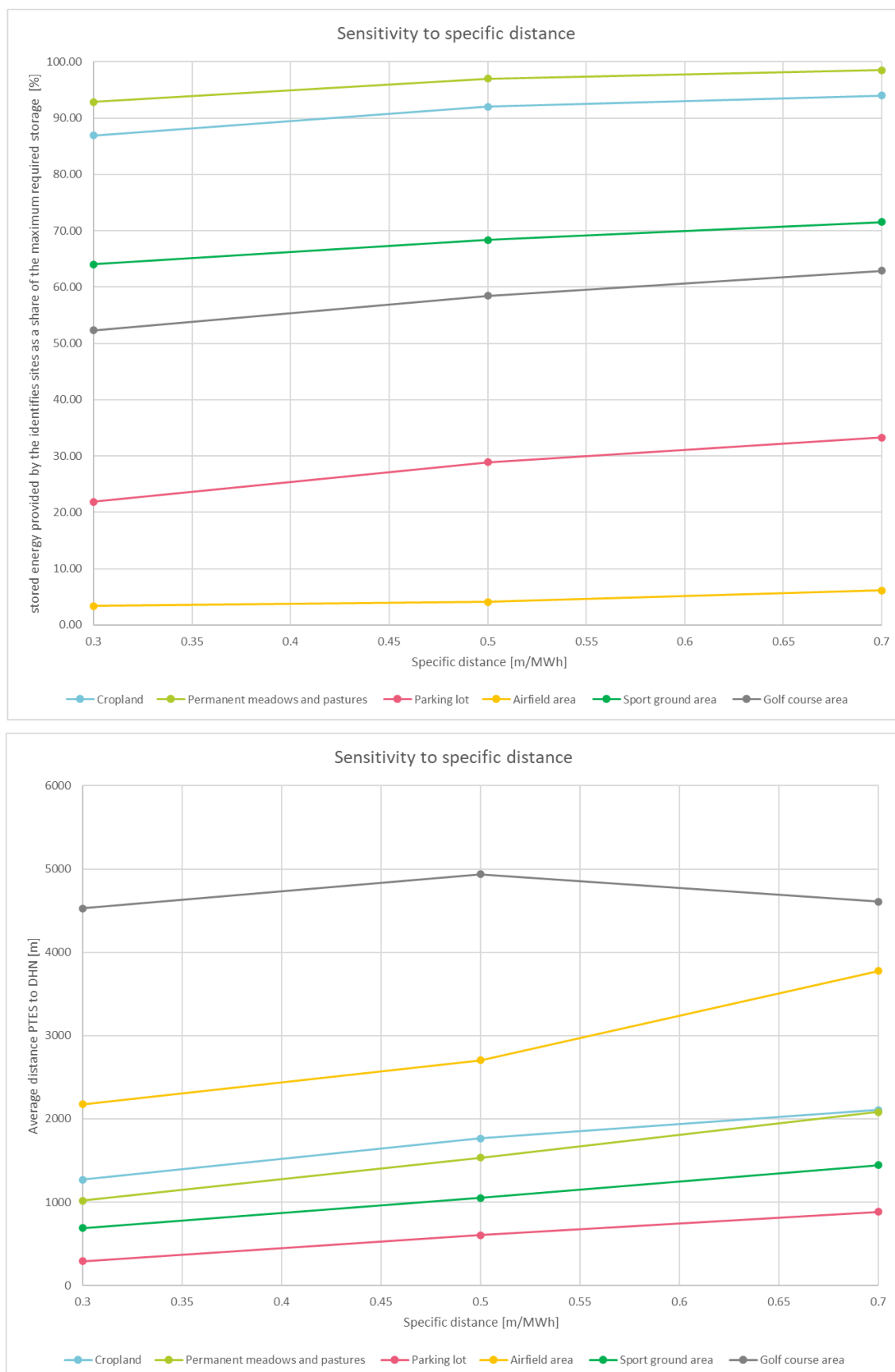


Figure 15: Sensitivity of storage capacity and average distance between PTES and district heating network to specific distance.



Figure 16: Golf court storage site identification (grey) in the region of Aarau and Olten depending on the specific distance. (The grey area is the maximum available area, not the whole area required for the PTES).

Sensitivity on storage coverage

Considering the sensitivity on the storage coverage, i.e. the share of demand covered by the PTES storage capacity, the absolute value of maximum stored heat is also changing accordingly from 0.81 TWh/a for 5% coverage to 4.86 TWh/a for 30% coverage.

For cropland, for permanent meadows and pastures and golf court areas the maximum stored energy stored by the identifies sites as a share of the maximum required storage potential is reached at a coverage of 15%, where the size enables to reach locations further away however large enough surfaces are still available to place the PTES (Figure 17).

For parking lots and sports ground areas the maximum stored energy provided by the identified sites as a share of the maximum required storage potential is reached at the lowest storage coverage of 5%, since the available surface area is the critical factor (Figure 17).

Comparing the total energy stored in PTES for a storage coverage increase from 5% to 30%, by factor 6, the increases is by factor 5.8 for airfield areas, 5.2 for cropland, 5.1 for permanent meadows and pastures, and 3.7 for sports ground areas. These factors indicate that the required increase in coverage, which would necessitate an increase of PTES size, cannot always be satisfied (Figure 18). For parking lots, the increase of the energy storage is only by a factor of 1.3, indicating that the available surface area is the main restrictive factor (Figure 18).

The average distance from PTES to DHN generally increases with storage coverage, as larger surface areas are required and therefore the storage must be placed further away. Yet non-linear behavior can also occur. For example, distances may temporarily decrease when geographical limitations exclude unsuitable sites, or when larger required PTES sizes make it feasible to connect storages at more distant but suitable locations, as observed for airfield areas (Figure 19).

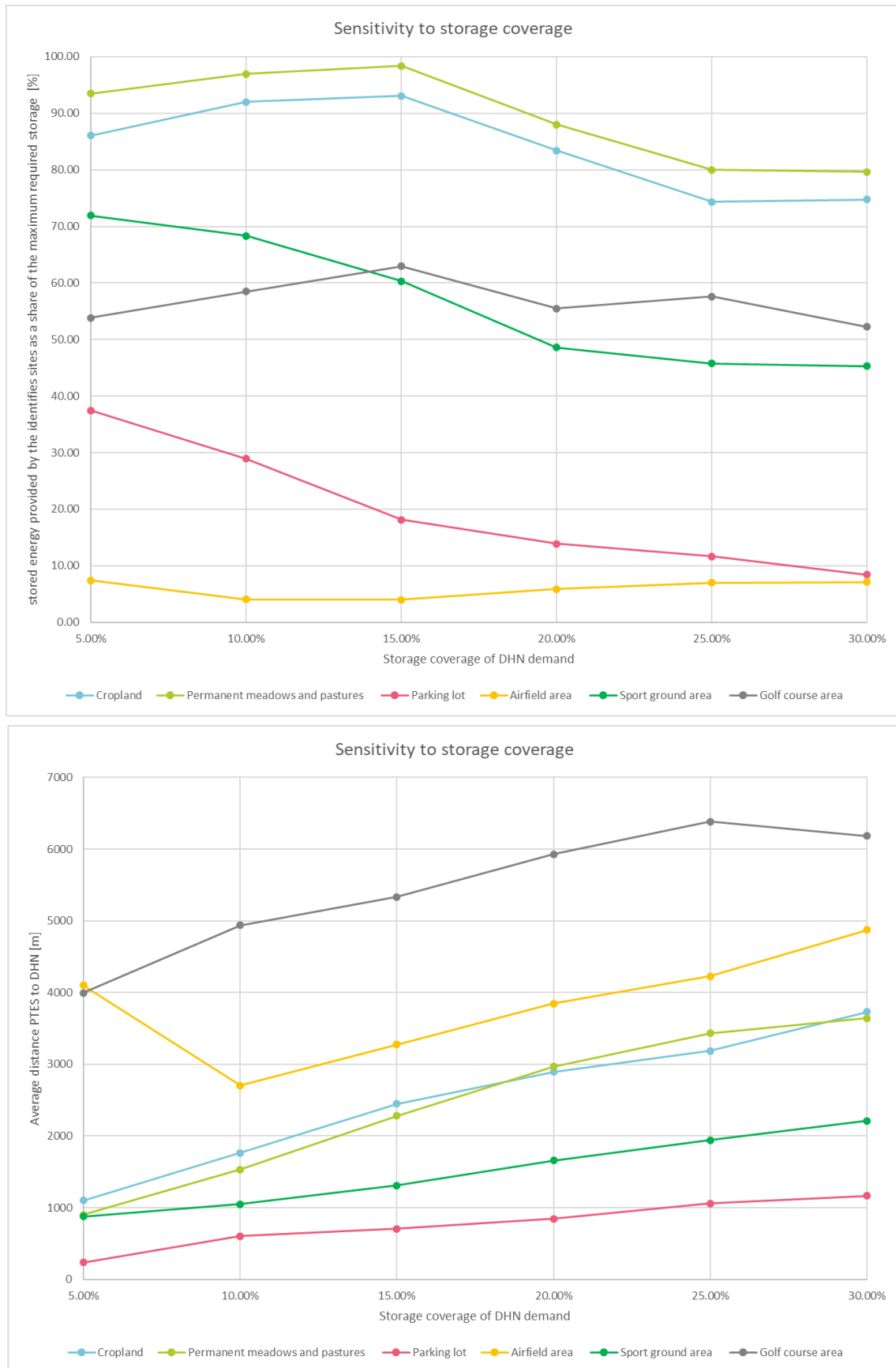


Figure 17: Sensitivity of relative storage capacity and average distance between PTES and district heating network to storage coverage.

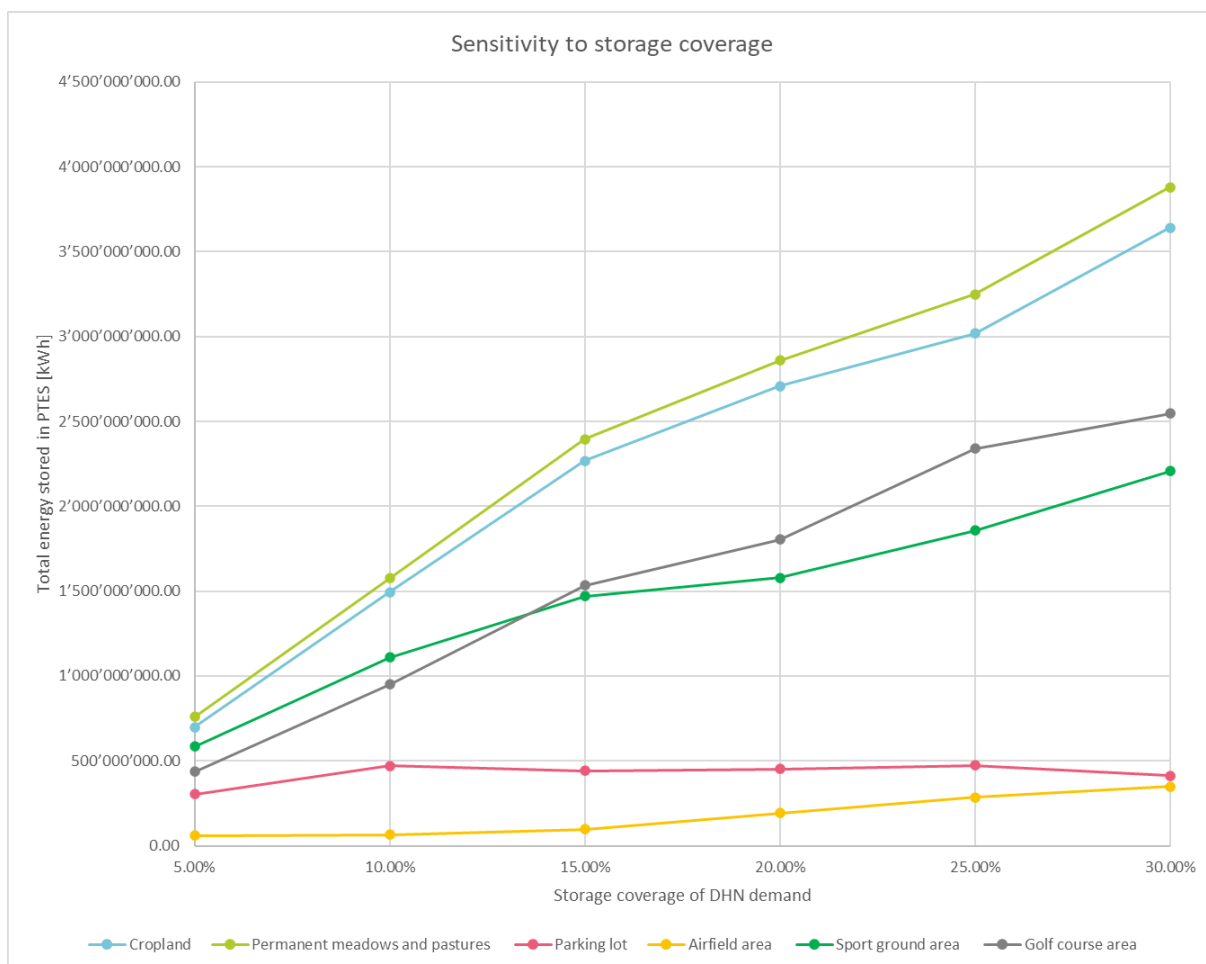


Figure 18: Sensitivity of storage capacity to storage coverage.

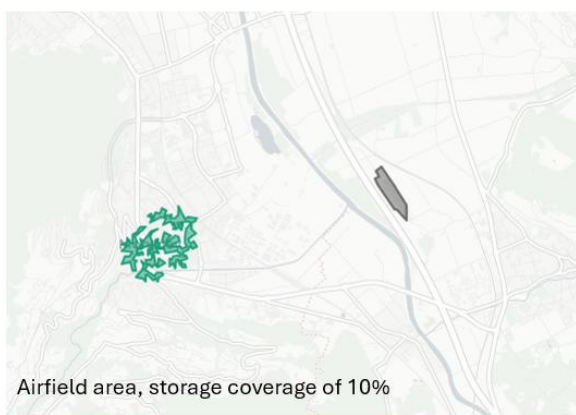


Figure 19: Storage coverage for airfield area, finding PTES (grey) for 10%, however too far away for 5% case. (The grey area is the maximum available area, not the whole area required for the PTES).

Sensitivity to surface tilt requirement

Analysis of the influence of the tilt shows that setting the tilt to 0° results in only little feasible storage locations, as such a condition is seldom met in practice (Figure 20). Increasing the limit on the permitted tilt angle from 5° to 10° has only a marginal effect on the storage potential (Figure 21). Consequently, the tilt is not considered a major influencing factor, however setting it to 0° is considered to be unfeasible.

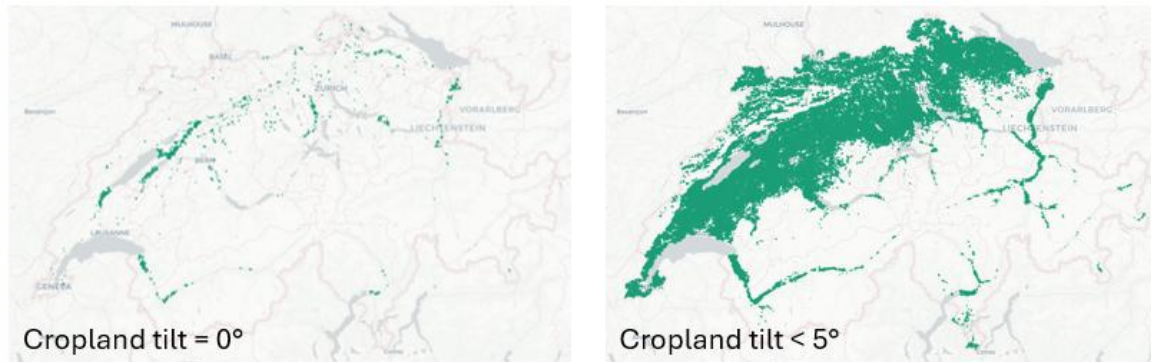


Figure 20: Possible placement site for cropland depending on the tilt.

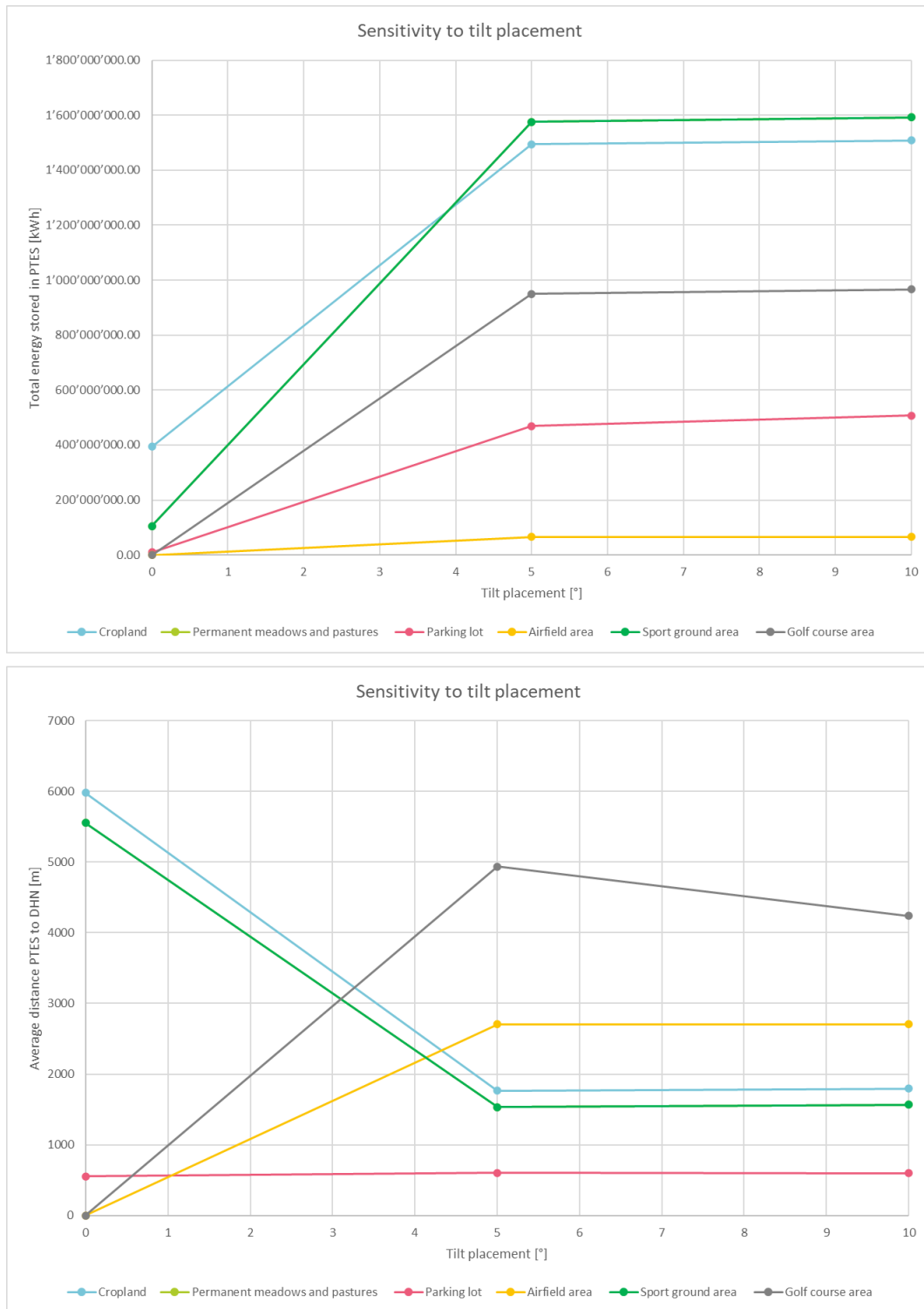


Figure 21: Sensitivity of storage capacity and average distance between PTES and district heating network to surface tilt.

2.3.3 Critical review of data

The predictive power of the GeoPATH framework is ultimately constrained by the quality, reliability, and resolution of the underlying datasets. While the framework is robust in its technical setup, its reliability is limited by the data quality.

In several instances, the available data led to outcomes that are technically valid but practically implausible. The model may generate connections that cross major obstacles like rivers (Figure 22, Left), as such constraints are not explicitly implemented for the sake of simplicity. Likewise, some resulting geometries for storage or placement areas appear fragmented or oddly shaped (Figure 22, Right), due to the permissiveness of the source data and limited spatial filtering. These outcomes reflect modelling simplifications rather than errors.

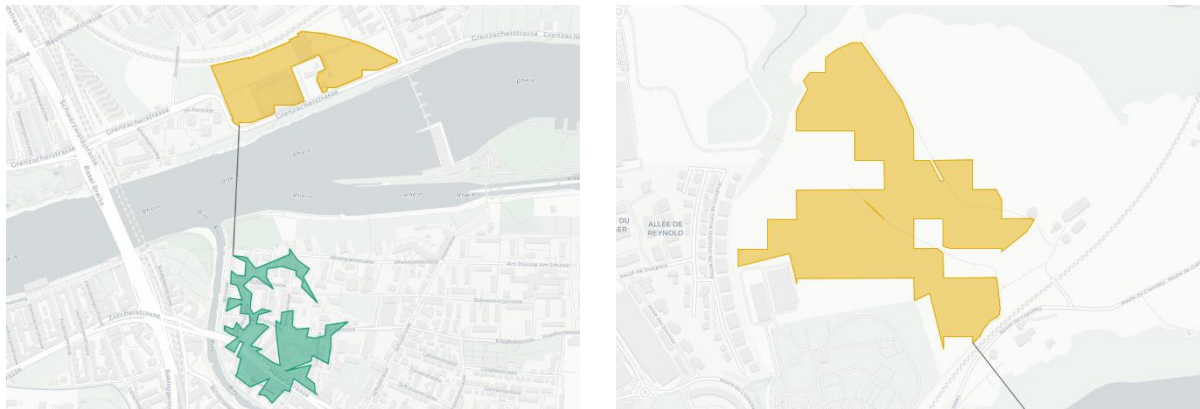


Figure 22: Left: Connection across a river without existing infrastructure. Right: Fragmented and irregular storage geometry.

Moreover, some raw data layers themselves are limited in precision. A typical case can be observed in sport areas, where geometries appear cut or misaligned with their actual land use (Figure 23). These artifacts emerge from source data generalizations and simplifications, which the framework currently accepts as-is.

These limitations highlight the importance of interpreting the results with a critical eye, particularly when assessing their practical relevance. At the same time, the outputs remain well-suited for Swiss-wide estimations, where aggregated trends and spatial patterns are more important than local detail. The observed issues also indicate improvements in data quality and preprocessing routines could lead to more realistic and reliable outcomes.



Figure 23: Sports ground area appears fragmented due to inconsistencies in the input dataset.

2.4 Conclusion

In the base case, agricultural land (permanent meadows and pastures as well as cropland) emerges as the most promising placement category: for each of these options individually, suitable PTES sites can be identified for more than 90% of the identified clusters. Activity spaces such as sports grounds and golf courses also unlock substantial potential, with feasible placement in over 50% of cases.

Realizing PTES on agricultural or activity spaces will require either adjustments to the regulatory framework or multi-use surface solutions (e.g., redesigning the PTES lid to enable continued farming or sporting activities). Deployment is therefore constrained by policy and permitting on the one hand, and by the practical limits of multi-use designs on the other. Both aspects are being advanced within the Innosuisse Flagship project SwissSTES.

The highest increase in placement option when increasing the areal energy storage density is seen for sports ground between 400 kWh/m² and 600 kWh/m², with an increase of $\frac{16\%}{200 \text{ kWh/m}^2}$. However, for all placement options the increase is the steepest between 400 and 600 kWh/m² showing that reaching an areal energy density over 600 kWh/m² is beneficial. In all cases only marginal ($< \frac{3\%}{200 \text{ kWh/m}^2}$) above 1000 kWh/m², which shows that reaching this areal storage density is only important in individual cases.

Increasing specific distance boosts stored energy most between 0.3 m/MWh to 0.5 m/MWh ($\frac{4-7\%}{0.2 \text{ m/MWh}}$ across most land uses), with clear diminishing returns beyond 0.5 m/MWh. Overall, raising specific distance past 0.5 m/MWh yields limited extra storage but can extend feasible network reach in site-dependent ways.

Considering different storage coverage rates between 5-30%, the highest share of PTES demand where a suitable location could be found under the given boundary condition occurs at 15% coverage for cropland, permanent meadows/pastures, and golf courses, but at just 5% for parking lots and sports grounds due to limited area. Total PTES energy stored scales unevenly with coverage (multipliers: airfields 5.8×, cropland 5.2×, meadows/pastures 5.1×, sports grounds 3.7×, parking lots 1.3×, compared to the theoretical expectation of 6×), showing that larger target coverage cannot always be met by available sites. Average PTES–DHN distance generally increases with coverage, though non-linear effects appear (e.g., airfields), as unsuitable sites are excluded or larger storages justify farther—but suitable—connections.

2.5 Possible impact of large heat pumps combined with a thermal energy storage and district heating network in the Swiss context

To quantify the impact, the greenhouse gas emission reduction achieved by replacing fossil heating systems with heat pumps (HP) combined with thermal energy storage (TES) was analyzed in terms of CO₂ equivalents. The assessment focused exclusively on operational emissions, comparing CO₂ emissions from fossil heating systems to those from heat pump and thermal energy storage, depending on the carbon intensity of electricity. Upstream emissions related to installation, materials, and transport were not considered.

For the fossil heating, it was assumed that 54% of the fossil heated buildings are heated by gas and 46% by oil (Figure 24). The specific emission factors were taken as 201.6 gCO₂eq/kWh for gas and 265.32 gCO₂eq/kWh for oil (BAFU, 2025), resulting in a weighted average carbon intensity of 231 gCO₂eq/kWh. The PTES storage efficiency was assumed to be 0.8 (Ioannis Sifnaios, 2022), and the HP performance was assumed to have a seasonal coefficient of performance of 3.3 (Henrik Pieper, 2020).

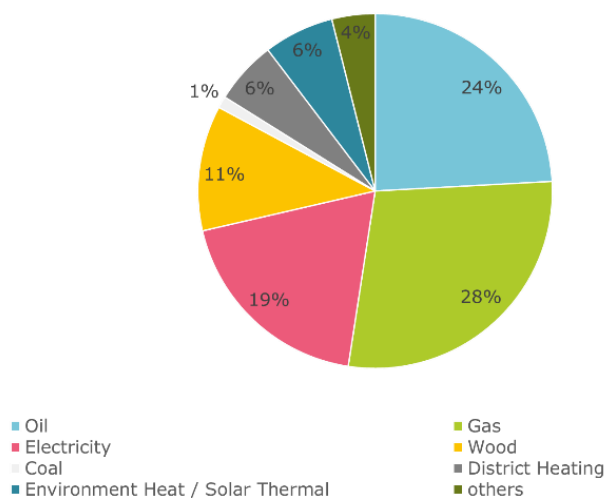


Figure 24: Final energy consumption for heating and cooling by energy source in Switzerland 2022 (Own Illustration, Data from (BFE, 2022)).

Considering the operational emissions, the relative emission reduction for the current Swiss electricity mix is above 91% with and without storage (Figure 25). In absolute terms, this contribution corresponds to a reduction of approximately 220 gCO₂eq/kWh. Due to seasonal storage losses, the case with thermal storage in district heating networks shows slightly lower performance. However, thermal storage enables better integration of renewable electricity generation, which can reduce the long-term carbon intensity of the electricity mix. This trade-off is acknowledged but not further analyzed in the present work.

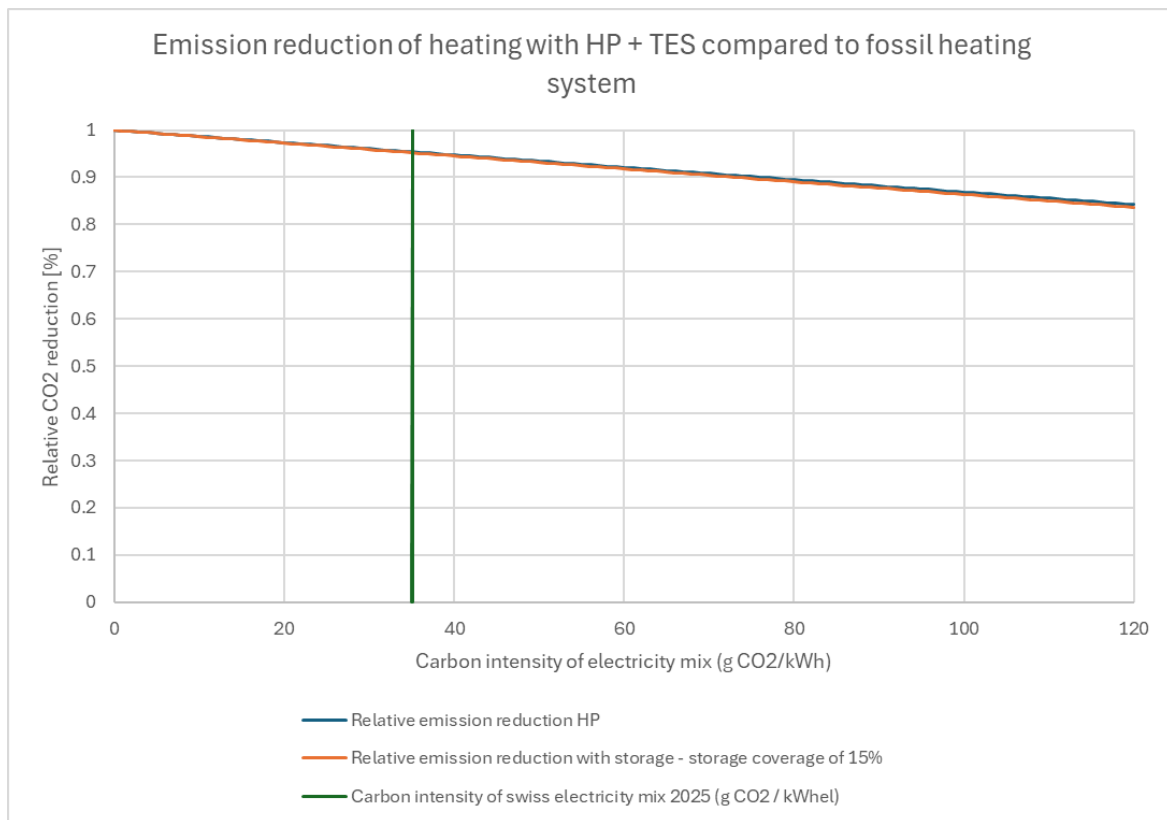


Figure 25: Emission reduction of heating with HP+TES compared to fossil heating.

Considering the replacement potential of 15 TWh/a (Section 2.2.2), the total CO₂ emission reduction potential amounts to about 3.3 MtCO₂/y. This represents 8% of the Swiss wide annual emissions (40.85 MtCO₂/y (UVEK, 2025)), underlining the high relevance of the heating sector for national decarbonization strategies.

The additional benefit of TES is the peak reduction based on the peak load. If 5% of the energy demand is covered by PTES, the peak power can be reduced by more than 40%, assuming a representative heat demand profile from a DHN (Figure 26, Figure 27). For a TES demand of 30%, the peak power can be reduced by more than 70%, showing the large potential in peak reduction due to the implementation of TES (Figure 26, Figure 27, Figure 27). Here it is assumed that the TES is able to provide the required power.

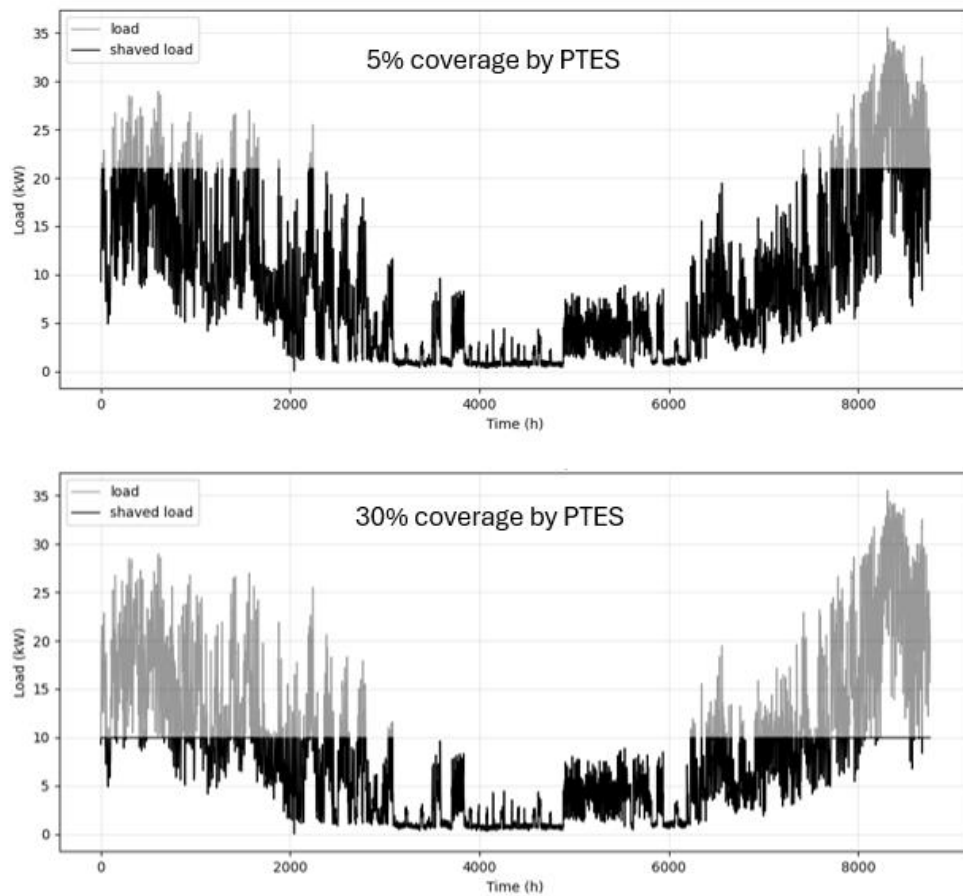


Figure 26: Peak reduction due to integration of TES.

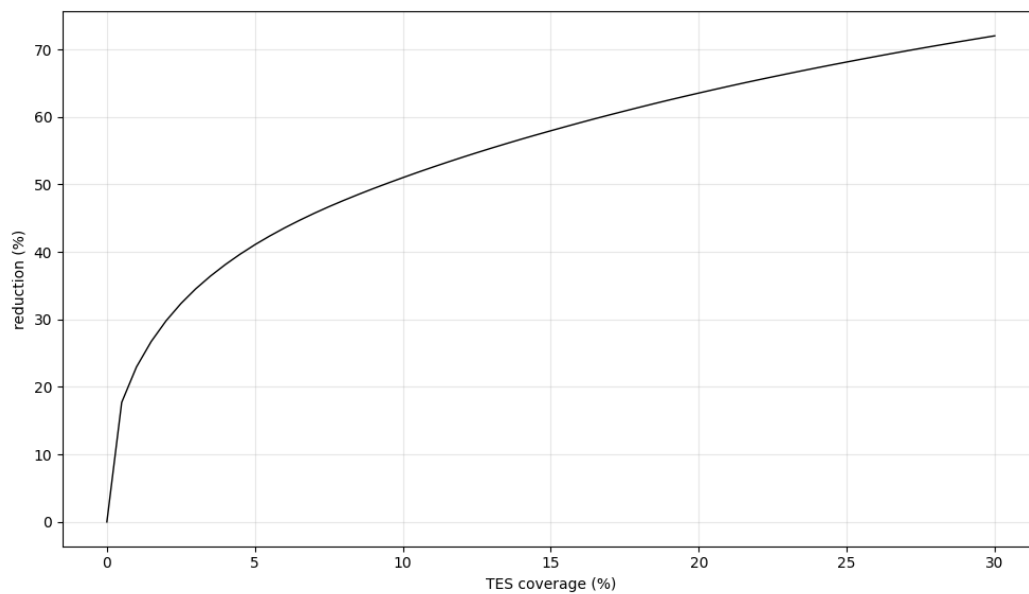


Figure 27: Relative peak power reduction based on the energy coverage by PTES of the total energy demand for a representative DHN

3 Overview Carnot Battery and its challenges

Technology:

Carnot batteries are a thermo-mechanical energy storage technology designed to convert electricity into heat, store it at different temperature levels, and reconvert it into electricity (Figure 28). Their core function relies on thermodynamic cycles, e.g. the transcritical Rankine cycle using CO₂ as a working fluid (Mercangöz, 2012) or Brayton cycles using air (Ting Liang, 2023). The used temperature levels range from low temperatures in liquid air based systems to high temperatures exceeding 500°C. At moderate temperature levels cold storage at 0°C is combined with heat storage at above 100°C. During charging, electricity typically drives a high-temperature heat pump to charge a thermal energy storage (TES) unit. In the discharge phase, the stored heat is converted back to electricity via a power cycle such as an Organic Rankine Cycle (ORC), with a portion of the heat typically lost as low-temperature waste heat in the process. From an energy system perspective, Carnot batteries provide sector coupling between electricity and heat. They enable the storage of surplus renewable electricity and release it either as electricity or as heat, contributing to grid flexibility and decarbonization of the heating sector. Typical design targets for Carnot batteries range from 2–50 MW_{el} power and 10–100 MWh_{th} of storage capacity (International Energy Agency (IEA) Task 36, 2022).

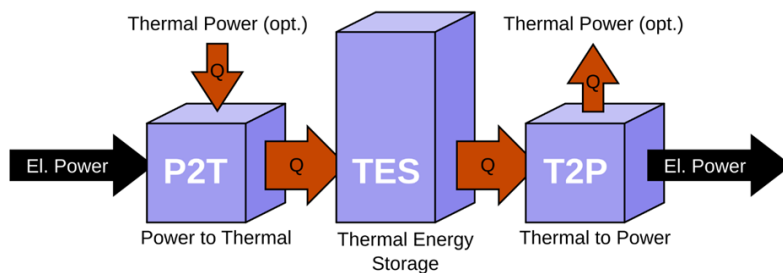


Figure 28: A simplified scheme of a typical Carnot Battery system.

Key Challenges:

- **Short storage time:** Carnot batteries are typically optimized for optimized for daily cycles (International Energy Agency (IEA) Task 36, 2022).
- **Low round-trip efficiency (RTE):** The RTE can theoretically reach up to 72% under favorable conditions (Andrew Smallbone, 2017). However, prototype results showed significantly lower RTE in practice. The CHESTER project reported RTEs between 17.9% and 37.2%, primarily limited by losses in the electricity reconversion process (K. Theologou, 2024). The charging process uses low-temperature heat into stored high-grade heat without waste losses. In contrast, the discharging power cycle inherently generates low-temperature waste heat due to thermodynamic constraints, which can be recovered if coupled to a low-temperature heat network.
- **Storage material:** Database for suitable storage material for high and low temperature levels is missing (International Energy Agency (IEA) Task 36, 2022).

- *Economic viability*: Cost of storage material must be reduced (International Energy Agency (IEA) Task 36, 2022).
- *Low TRL level*: between 3-5 if charged with a HP (International Energy Agency (IEA) Task 36, 2022).

Conclusion

Research in the field of Carnot Batteries is performed on various aspects. Nevertheless, especially regarding medium temperature ranges like applied with CO₂ driven heat pump processes, achievable round trip efficiencies are poor and allow for very niche applications only. Therefore, as stated in Chapter 2.1, more potential is seen in a consequent use of flexible power to heat applications with integrated heat storages, i.e. neglecting the second step of Carnot batteries reconverting heat to power.

4 References

Abdulrahman Dahash, F. O. (2019). Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems. *Applied Energy*, vol. 239, 296-315.

Andrew Smallbone, V. J. (2017). Levelised Cost of Storage for Pumped Heat Energy Storage in comparison with other energy storage technologies. *Energy Conversion and Management*, vol. 152, 221-228.

Arbeitsgemeinschaft QM Fernwärme, N. T. (2021). *Planungshandbuch Fernwärme (Version 1.3a, leicht überarbeitet vom 3. Mai 2021)*. P.108 Table 6.3. Zürich: Verenum AG, EnergieSchweiz.

BAFU, B. f. (2025). *CO₂-Emissionsfaktoren des Treibhausgasinventars der Schweiz*. Bundesamt für Umwelt BAFU.

BFE, B. f. (2022). *Analyse der Schweizerischen Energieverbrauch 2000-2022 nach Verwendungszweck*. Bundesamt für Energie.

geocat.ch. (2025, 09 30). Retrieved from geonetwork:
<https://www.geocat.ch/geonetwork/srv/ger/catalog.search#/metadata/ae183bc4-5c91-467e-89bc-85f390340efb>

Henrik Pieper, T. O. (2020). Comparison of COP estimation methods for large-scale heat pumps used in energy planning. *Energy Volume 205*.

International Energy Agency (IEA) Task 36. (2022). *Carnot Batteries - Technology Briefing*. IEA.

Ioannis Sifnaios, A. R. (2022). Performance comparison of two water pit thermal energy storage (PTES) systems using energy, exergy, and stratification indicators. *Journal of Energy Storage*, vol. 52 part B, 104947.

- K. Theologou, M. J. (2024). CHESTER: Experimental prototype of a compressed heat energy storage and management system for energy from renewable sources. Energy Conversion and Management. *Energy Conversion and Management*, vol. 311, 118519.
- Landestopografie, B. f. (2024, 01 08). *Amtliches Verzeichnis der Gebäudeadressen*. Retrieved from swisstopo: <https://www.swisstopo.admin.ch/de/amtliches-verzeichnis-der-gebaeudeadressen>
- Landestopografie, B. f. (2024, 01 08). *DHM25*. Retrieved from swisstopo: <https://www.swisstopo.admin.ch/de/hoeihenmodell-dhm25>
- Landestopografie, B. f. (2024, 03 08). *swissTLM3D – Das grossmassstäbliche Topografische Landschaftsmodell der Schweiz*. Retrieved from swisstopo: https://www.swisstopo.admin.ch/de/landschaftsmodell-swisstlm3d?utm_source=chatgpt.com
- Mercangöz, M. &. (2012). Electrothermal energy storage with transcritical CO₂ cycles. *Energy*. 45, 407–415.
- Sarah Schneeberger, C. M. (2025). Estimating the heating energy demand of residential buildings in Switzerland using only public data. *Energy and Buildings*.
- Ting Liang, T. Z. (2023). Liquid air energy storage technology: a comprehensive review of research, development and deployment. *Progress in Energy*.
- UVEK, B. (2025). *Kenngrossen zur Entwicklung der Treibhausgasemissionen in der Schweiz*. Bundesamt für Umwelt BAFU.
- Wikipedia. (2025, 08 20). Retrieved from Carnot Battery: https://en.wikipedia.org/wiki/Carnot_battery

Annex

Mapping Switzerland’s energy potential: a data-driven geo-analysis of energy technologies

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Abstract. The decarbonization of Switzerland’s energy system requires not only new technologies but spatially grounded decision-making tools that reflect regional differences in existing infrastructure and their energy requirements. This study presents a key component of the GIS-based energy planning framework *GeoPATH*, focused on a novel Demand-Supply Allocation Model. The model enables spatially explicit matching of decentralised energy supply and demand objects under a user-defined, energy-dependent distance constraint. Two algorithmic approaches are introduced: a Direct Allocation Model for one-to-one matching and a more flexible Multi-Stage Allocation Model that accounts for intermediate infrastructure nodes. To evaluate the behaviour of different allocation strategies, the model is applied to a national-scale case study examining the potential of heat recovery from wastewater treatment plants into existing fossil-fuel-based district heating networks. The impact of the allocation strategy (e.g., closest, furthest, most efficient) and input sorting (ascending vs. descending) is assessed using spatial and statistical metrics. Results show that while outcomes vary with spatial context and sorting, the model performs robustly across scenarios. The closest-ascending strategy is recommended due to its computational efficiency, realism, and high infrastructure reuse. Although not intended as a planning tool, the allocation model offers valuable insights for energy system design, policy prioritization, and regional scenario development.

1. Introduction

With its net zero emissions target, Switzerland is pursuing a sustainable, flexible and resilient energy system by 2050. Given its high population density and limited energy resources, Switzerland relies on innovative technologies and strategic sector coupling to increase system-wide efficiency and flexibility. When complemented with energy storage, such an approach can promote a sustainable and resilient energy grid. To accelerate the application of such technologies, it is essential to identify the spatial and systemic constraints that limit their deployment. For this purpose, the *GeoPATH* tool has been developed. *GeoPATH* is a Geographic Information System (GIS) based energy system analysis tool designed to evaluate and map the national deployment potential of specific technologies and sector-coupling energy applications. *GeoPATH* is built upon high-resolution spatial data from SwissTopo and energy datasets created during the development of *GeoPATH*. It allows for the definition of flexible boundary conditions, including:

- Energy requirements (e.g., industrial waste heat, e-charging stations, fossil heating systems)
- Topographical constraints (e.g., slope of terrain, zoning, erosion risk)

- Network conditions (e.g., transmission distance, capacity limits, spatial density)

The core functionalities of *GeoPATH* are structured around three analytical modules:

- (i) Object Clustering (spatial aggregation of objects)
- (ii) Demand-Supply Allocation (matching of energy sources and sinks)
- (iii) Placement Assessment (evaluation of technology installation sites)

The present study focuses on the second module—the Demand-Supply Allocation—and presents a newly developed algorithm specifically designed to address the geospatial, multi-stage, and constraint-driven nature of the problem.

2. Demand-Supply Allocation

The Demand-Supply Allocation model in *GeoPATH* aims to optimally match spatially distributed demand objects d , each with annual energy demand values $v(d_i)$ to supply objects s . The matching process respects a maximum allowable transmission distance D_{max} , which dynamically depends on the amount of energy transmitted between demand and supply objects. Such dynamic constraints reflect realistic considerations including thermal energy losses, economic feasibility thresholds, and network capacity limitations. Classical graph-theory-based algorithms—such as bipartite matching [1], maximum-flow [2], or minimum-cost flow models [3] — are insufficient for this problem, as they typically fail to address critical real-world complexities. The novel algorithm proposed here explicitly overcomes the following limitations:

- Dynamically determined maximum transmission distances based on transmitted energy.
- Handling of intermediate infrastructure nodes that simultaneously act as demand.
- Implementing efficient pruning methods to quickly eliminate infeasible allocations, thereby ensuring computational efficiency.

2.1. Direct Allocation Model

The Direct Allocation Model addresses simplified scenarios where each supply object directly meets a demand object without intermediate steps. To ensure realistic allocations, the algorithm considers spatial constraints, specifically an energy-dependent maximum transmission distance $D_{max}(v)$. For each demand objects d_i , all feasible supply objects within the allowable distance are first identified:

$$S_i = \{s_j \in S \mid d(i, j) \leq D_{max}(v(d_i)), v(s_j) \geq v(d_i)\} \quad (1)$$

The algorithm then selects a specific allocation from these feasible candidates based on one of four defined strategies:

- (i) Closest allocation: Select the closest feasible supply object to reduce transmission distances, promoting network realism:

$$s_i^* = \arg \min_{s_j \in S_i} d(i, j) \quad (2)$$

- (ii) Furthest allocation: Select the most distant feasible supply object, aiming to maximize overall demand coverage. This approach is preserving nearby supply resources for smaller local demands:

$$s_i^* = \arg \max_{s_j \in S_i} d(i, j) \quad (3)$$

- (iii) Most efficient allocation: Select the allocation offering the highest value per unit distance, prioritizing economic efficiency by optimizing the ratio of demand value to distance:

$$s_i^* = \arg \max_{s_j \in S_i} \frac{v(d_i)}{d(i, j)} \quad (4)$$

- (iv) Most inefficient allocation: Selects allocations with the lowest value-to-distance ratio, favoring small demands over long distances to illustrate a worst-case scenario:

$$s_i^* = \arg \min_{s_j \in S_i} \frac{v(d_i)}{d(i, j)} \quad (5)$$

After each assignment, the available energy values of the supply and demand objects are updated to reflect their remaining capacity and unmet demand. This allocation process alternates iteratively between demand and supply perspectives, updating capacities at each step, until no further changes occur and convergence is reached. The entire procedure is executed with ascending and descending energy value-based sorted object lists - which prioritizes small (ascending) or big (descending) demands and supplies first - selecting the allocation set that maximizes total matched demand:

$$M^* = \arg \max_{M_1, M_2} \sum_{(d_i, s_j) \in M_k} v(d_i(s_i^*)) \quad (6)$$

As part of Section 3, this study compares the presented four distinct allocation strategies, closest, furthest, most efficient and most inefficient, in terms of distances of allocations and the realism of the resulting network scenarios.

2.2. Multi-Stage Allocation Model

The Multi-Stage Allocation Model generalizes the direct allocation approach by incorporating intermediate nodes, which act either solely as additional demand points or as passive connectors without assigned values. Unlike direct allocation, the multi-stage model evaluates allocations by exploring indirect, multi-node paths. Formally, feasible allocation paths are determined by recursively evaluating connections through intermediate nodes. Each feasible link between consecutive nodes is spatially filtered via a k-dimensional tree (KDTree) [4] to ensure compliance with the dynamically-defined energy-dependent maximum transmission distance $D_{max}(v)$. At each intermediate level l , for each object i , the set of feasible connections S_i^l includes all valid nodes j at level $l + 1$ satisfying distance and capacity constraints:

$$S_i^l = \{j \mid d(i, j) \leq D_{max}(v(d_i)), v(j) \geq v(d_i)\} \quad (7)$$

Importantly, the maximum allowable distance is dynamically updated level-by-level throughout each allocation, accounting for allocation distance already used and the additional demand collected at intermediate nodes. Furthermore, allocation paths between nodes that have been previously utilized remain available for subsequent allocations without requiring additional distance allowance, reflecting realistic infrastructure-sharing conditions. Each allocation path $P = (i, j, k, \dots, n)$ extending across multiple levels from an initial node to a final node, is evaluated cumulatively according to two metrics:

- Total transferred energy along the entire path P :

$$V(P) = \sum_{x \in P} v(x) \quad (8)$$

- Total transmission length along the entire path P :

$$L(P) = \sum_{(x, y) \in P} d(x, y) \quad (9)$$

After recursively exploring all feasible allocations via depth-first search [5], the optimal allocation path P^* is selected according to one of the previously introduced allocation strategies (closest, furthest, most efficient, or most inefficient). The algorithm iteratively alternates between demand-first and supply-first perspectives until convergence, when no further feasible allocations are identified. The multi-stage model, though computationally more intensive due to spatial filtering and recursive evaluation, enables accurate representation of realistic allocation scenarios involving intermediate connection points.

3. Results

To evaluate the effects of allocation strategies and sorting directions, the Multi-Stage Allocation Model was applied to a specific use case. Here, the demand objects are building heat loads currently met by heating oil boilers. Intermediate nodes represent district heating networks (DHNs), whose fossil-fueled peak boilers contribute additional heat demand to be replaced within the allocation model. The supply is provided by wastewater treatment plants serving as thermal sources for heat pumps. All allocations respect an energy-dependent maximum distance constraint defined as $D_{max} = 0.05$ m/kWh. The following subsections analyze results based on the chosen allocation strategy and sorting direction (ascending vs. descending).

3.1. Influence of Allocation Strategy

The comparison of the four allocation strategies—closest, furthest, most efficient, and most inefficient—reveals two clear behavioral groupings. The closest and most efficient strategies produce very similar results, as do the furthest and most inefficient. Closest and most efficient result in shorter allocation distances, with fewer long-distance outliers (see Figure 1). In contrast, combinations involving descending sorting with either the furthest or most inefficient strategy generate considerable outliers, with individual allocation distances exceeding 40 kilometers. Despite these differences in distance, all strategies form networks of similar overall size in terms of total demand covered. However, closest and most efficient strategies tend to connect more objects located close to each other, which results in significantly more infrastructure reuse. This leads to more spatially coherent and realistic network structures, particularly when paired with ascending sorting. When comparing the distribution of the connected energy demand, no significant differences are found between the strategies, indicating that the selection method influences the spatial characteristics of the network more than the total number of matched objects.

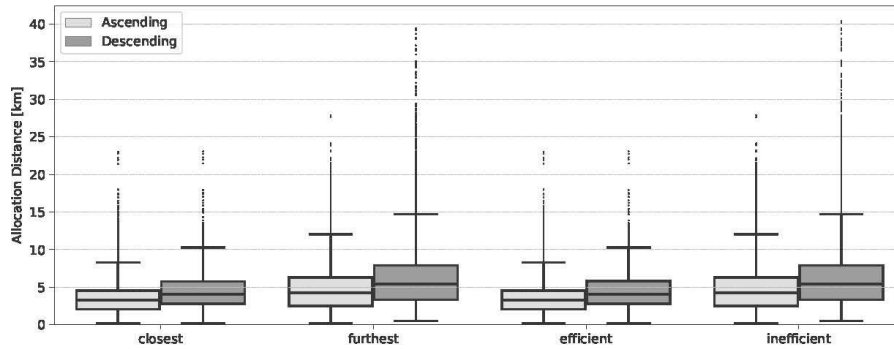


Figure 1. Distribution of allocation distances by strategy and sorting direction.

3.2. Influence of Sorting Direction

The results show that the sorting order has a notable impact on network structure and allocation efficiency. With ascending sorting, networks exhibit compact and realistic spatial patterns, characterized by shorter allocation distances, fewer extreme outliers, and notably higher infrastructure reuse. Smaller, nearby demand nodes aggregate around shared intermediate nodes, resulting in densely interconnected and realistic networks. Conversely, descending sorting prioritizes allocation to fewer but larger, more distant demands. This leads to longer allocation distances, lower reuse of network paths, and fragmented spatial structures with limited connectivity. Regarding allocated energy values, descending sorting logically results in larger average allocations per node, whereas ascending sorting distributes the same total energy across more nodes with smaller individual demands. A spatial comparison between ascending and descending sorting (Figure 2) highlights these differences clearly, showing the spatial efficiency and realism benefits of ascending sorting over descending sorting. Across all strategy and sorting combinations, the total allocated demand remained stable, suggesting that the model produces consistent outcomes under varying configurations.

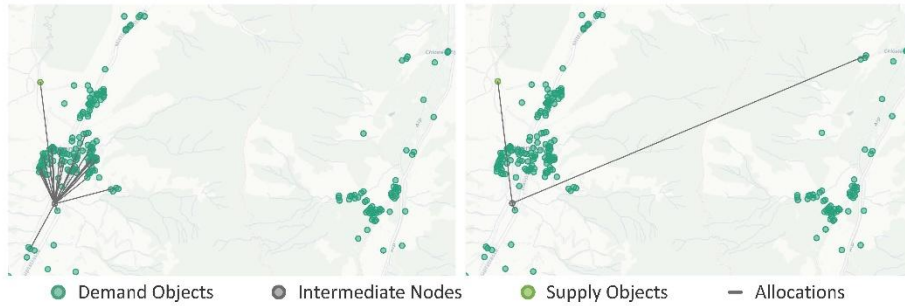


Figure 2. Comparison of network maps using the "closest" strategy and ascending (left) and descending (right) sorting.

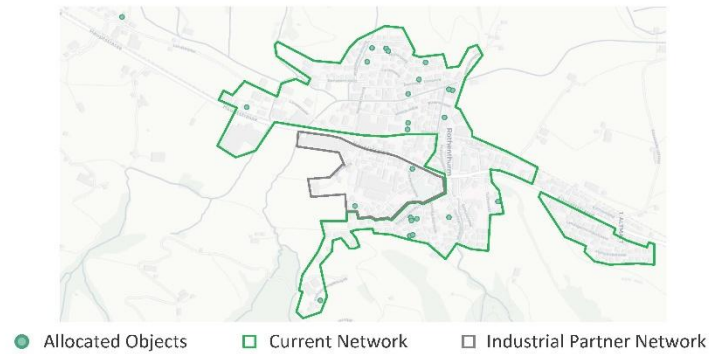


Figure 3. Comparison of allocated objects from "closest" strategy and ascending algorithm to traditional planning of the local district heating network owner [6].

3.3. Comparison to Traditional Planning

Most households allocated by the algorithm match closely with the existing district heating network, confirming its practical applicability (Figure 3). Some identified households, however, lie within the area served by the neighboring industrial partner's network; although these are unavailable to the main network, their allocation still highlights their potential suitability for district heating integration. An existing remote area connected to the current network but not recognized by the algorithm indicates that traditional planning includes additional factors—such as potential long-term urban development—that are not purely spatial considerations. Thus, while the algorithm performs robustly regarding spatial allocations, it inherently excludes political and private motivations influencing real-world planning decisions.

4. Conclusion

The results of the allocation tests show clear differences in network structure and efficiency depending on the chosen strategy and sorting logic. Strategies based on spatial proximity (closest) or value-to-distance efficiency (efficient) produced significantly shorter and more compact allocation paths compared to furthest or inefficient strategies. Likewise, ascending sorting—which prioritizes small demands and supplies first—led to more realistic network structures, higher reuse of allocation paths, and better spatial clustering. Although total demand coverage remained similar across all configurations, the combination of the closest strategy with ascending sorting delivered the most spatially coherent and infrastructure-efficient results. The developed allocation model proved to be robust across scenarios, as indicated by the consistent total demand coverage across all tested strategies and sorting configurations. This supports its reliability for exploratory spatial analysis, even under varying assumptions. The closest strategy was ultimately selected as the preferred default, as it depends less on absolute demand or supply values. This is particularly important given the uncertainties in energy data relative to the well-documented and highly reliable spatial geospatial data. Relying more on geospatial data thereby increases the robustness of the outcomes. While current distance calculations are based on the shortest path between two objects, they do not account for real-world constraints such as topography or road networks. Incorporating network-based distances would improve spatial accuracy but is not yet implemented due to the associated computational cost. Nevertheless, the model offers a practical and scalable solution for assessing spatial allocation patterns, especially when supported by high-quality geospatial input data.

Credit authorship contribution statement

Simon In-Albon: Methodology, Software, Validation, Writing - Original Draft
Emma Schmitt: Software, Data Curation
Malin Siegwart: Methodology, Supervision
Jörg Worlitschek: Project administration, Funding acquisition

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References

- [1] Kuhn H W 1955 *Naval Research Logistics Quarterly* **2** 83–97 ISSN 0028-1441
- [2] Edmonds J and Karp R M 1972 *Journal of the ACM* **19** 248–264 ISSN 0004-5411
- [3] Ahuja R K, Magnanti T L and Orlin J B 1993 *Network flows : theory, algorithms, and applications / Ravindra K. Ahuja, Thomas L. Magnanti, James B. Orlin* (Englewood Cliffs, N.J.: Prentice Hall) ISBN 9780136175490
- [4] Bentley J L 1975 *Communications of the ACM* **18** 509–517 ISSN 0001-0782
- [5] Tarjan R 1972 *SIAM Journal on Computing* **1** 146–160 ISSN 0097-5397
- [6] 18052025 Wärmeverbund rothenthurm: Mit fernwärme klimaneutral heizen URL <https://www.waermeverbund-rothenthurm.ch/>

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