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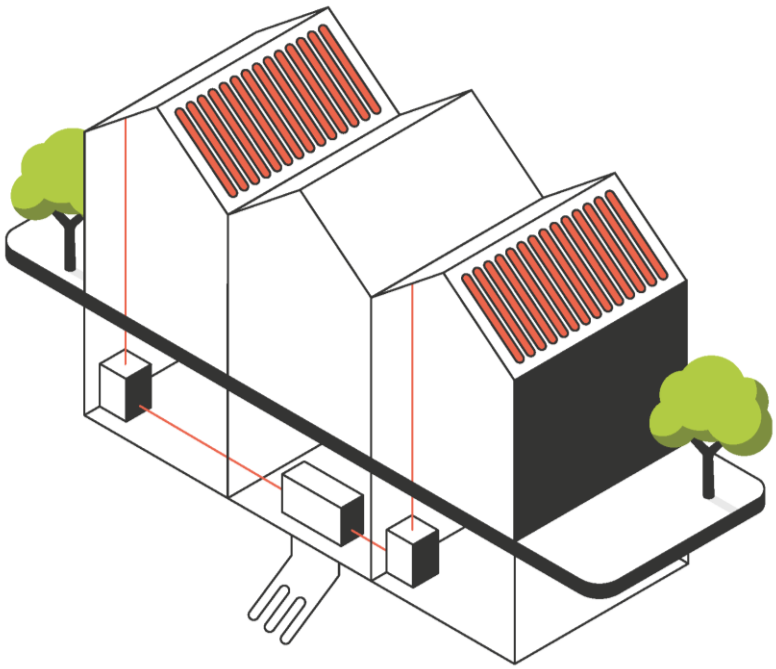
Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

Final report from 27.10.2025

SWEET P+D nanoverbund

nanoverbund



Source: ©IWB

sweet swiss energy research for the energy transition



Date: 27.10.2025

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
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SFOE contract number: SI/502655-01

This project is partially funded by the SFOE's pilot and demonstration programme and is part of the SWEET consortium PATHFNDR project portfolio.

SWEET Call: 1-2020
Consortium's website: https://sweet-pathfndr.ch/

The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.

Summary

Building heating systems are designed to provide sufficient heating for the coldest days of the year. So, for most parts, they are underutilized. Retrofitting thermal connections between nearby buildings leads to a more locally efficient use of energy, as the most efficient heating system(s) can supply heat to all buildings. These connected buildings with adapted control (dubbed a “nanoverbund”) can also offer greater flexibility to upper-layer distribution grid operators or energy providers. Especially in heterogeneous building energy systems, energy storage and conversion technologies can benefit all parties/stakeholders. A pilot site installation of three buildings in the city of Basel shall be operated by a flexibility-aware control scheme to demonstrate the potential of the nanoverbund concept. Additionally, a stakeholder ecosystem study is conducted to understand the key aspects of each party involved. The nanoverbund concept is especially applicable in cases where large, centralized distribution systems are unavailable. District heating relies on a central source and unidirectional heat flow, while nanoverbund allows bidirectional flows with prosumers. It can start small and grow, unlike centralized district systems that need large-scale planning from the start, potentially delaying setup. With such a decentralized, shared infrastructure, end users can access heat-as-a-service without owning a heat pump. This project is part of the SWEET PATHFNDR project portfolio, leveraging synergies in outcomes and findings.

The main insights from this project are the following:

- The nanoverbund concept has considerable potential for scaling in Switzerland. About 82,870 building clusters across the country have been identified as suitable for this approach, with the potential to reduce CO_2 emissions by 239 million tons.
- Study of the pilot site shows that 84% to 90% of fossil heat demand in the connected buildings could be supplied by the shared heat pump. However, the development of advanced control was challenged by the difficulty in modeling the thermal network and internal control logic, limited observability, and restricted control over only shared components.
- The results of economic and ecological assessment show that decentralized heat prosumer communities, in whole or in part, are viable for 14 out of 23 scenarios with improved performance. The analysis also indicates that individual households' budget limits may prevent community formation. This shows coordinated electrification using shared community infrastructure can benefit society.
- Interview-based qualitative analysis provides insights into how previously independent residential heating systems can be interconnected to utilize their interdependencies effectively. These interdependencies and the prerequisites necessary for interdependent heating systems are outlined in the study.
- The nanoverbund concept supports residential decarbonization by adding flexibility and minimizing user discomfort during the energy transition. The upscaling of nanoverbund increases grid load and may require DSOs to prevent voltage issues, but end-users are less affected by curtailment due to backup heating options.

Résumé

Les systèmes de chauffage des bâtiments sont conçus pour fournir une chaleur suffisante pendant les jours les plus froids de l'année. Ainsi, ils sont sous-utilisés la plupart du temps. Le raccordement thermique entre bâtiments voisins permet une utilisation locale plus efficace de l'énergie, car le système de chauffage le plus performant peut alimenter tous les bâtiments. Ces bâtiments connectés, avec un contrôle adapté (appelé « nanoverbund »), peuvent également offrir une plus grande flexibilité aux gestionnaires de réseau ou aux fournisseurs d'énergie. En particulier, la présence de systèmes énergétiques hétérogènes permet d'utiliser les technologies de stockage et de conversion d'énergie au bénéfice de toutes les parties prenantes. Un site pilote comprenant trois bâtiments dans la ville de Bâle sera exploité avec une commande tenant compte de la flexibilité afin de démontrer le potentiel du concept de nanoverbund. En parallèle, une étude de l'écosystème des acteurs est menée pour comprendre les enjeux propres à chaque partie impliquée. Le concept de nanoverbund est particulièrement pertinent dans les zones dépourvues de réseaux de distribution centralisés. Contrairement au chauffage à distance, qui repose sur une source centrale et un flux de chaleur unidirectionnel, le nanoverbund permet des flux bidirectionnels avec des prosommateurs. Il peut démarrer à petite échelle et se développer progressivement, contrairement aux systèmes centralisés nécessitant une planification d'envergure dès le départ. Grâce à cette infrastructure partagée et décentralisée, les utilisateurs peuvent accéder à la chaleur comme un service, sans posséder de pompe à chaleur. Ce projet fait partie du portefeuille SWEET PATHFNDR et exploite les synergies entre les résultats et les enseignements.

Les principaux enseignements du projet sont les suivants :

- Le concept de nanoverbund présente un fort potentiel de déploiement en Suisse. Environ 82 870 regroupements de bâtiments ont été identifiés comme adaptés, avec un potentiel de réduction de 239 millions de tonnes de CO_2.
- L'étude du site pilote montre que 84 % à 90 % de la demande de chaleur fossile des bâtiments connectés pourraient être couverts par la pompe à chaleur partagée. Cependant, le développement d'un contrôle avancé a été freiné par la difficulté de modéliser le réseau thermique et la logique interne, la visibilité limitée et le contrôle restreint des composants partagés.
- L'évaluation économique et écologique montre que les communautés décentralisées de prosommateurs thermiques sont viables, totalement ou partiellement, dans 14 des 23 scénarios avec de meilleures performances. L'analyse indique aussi que les contraintes budgétaires des ménages peuvent freiner la formation de telles communautés. Cela démontre qu'une électrification coordonnée avec une infrastructure partagée peut bénéficier à la société.
- L'analyse qualitative basée sur des entretiens met en évidence comment des systèmes de chauffage auparavant indépendants peuvent être interconnectés pour exploiter efficacement leurs interdépendances. Ces interdépendances et les conditions préalables nécessaires à de tels systèmes interconnectés sont détaillées dans l'étude.
- Le concept de nanoverbund soutient la décarbonation du secteur résidentiel en ajoutant de la flexibilité et en minimisant l'inconfort des utilisateurs pendant la transition énergétique. Le déploiement à grande échelle du nanoverbund augmente la charge sur le réseau et peut nécessiter des mesures de la part des gestionnaires de réseau pour éviter les problèmes de tension, mais les utilisateurs finaux sont moins touchés grâce aux options de chauffage de secours.

Zusammenfassung

Heizsysteme in Gebäuden sind so ausgelegt, dass sie auch an den kältesten Tagen des Jahres ausreichend Wärme liefern. Daher sind sie die meiste Zeit unterausgelastet. Die Nachrüstung thermischer Verbindungen zwischen benachbarten Gebäuden führt zu einer lokal effizienteren Energienutzung, da das effizienteste Heizsystem Wärme an alle Gebäude liefern kann. Diese verbundenen Gebäude mit angepasster Regelung (als „Nanoverbund“ bezeichnet) können zudem zusätzliche Flexibilitätspotenziale für Verteilnetzbetreiber oder Energieversorger bereitstellen. Besonders bei heterogenen Gebäudesystemen können Energiespeicher- und Umwandlungstechnologien zum Vorteil aller Beteiligten genutzt werden. Eine Pilotinstallation mit drei Gebäuden in der Stadt Basel wird mit einem flexibilitätsbewussten Regelungskonzept betrieben, um das Potenzial des Nanoverbund-Konzepts zu demonstrieren. Zusätzlich wird eine Stakeholder-Analyse durchgeführt, um die wichtigsten Aspekte der beteiligten Parteien zu verstehen. Das Nanoverbund-Konzept eignet sich besonders für Fälle, in denen große, zentralisierte Verteilnetze fehlen. Während Fernwärme auf einer zentralen Quelle und einem unidirektionalen Wärmefluss basiert, erlaubt der Nanoverbund bidirektionale Flüsse mit Prosumenten. Er kann klein beginnen und wachsen, im Gegensatz zu zentralen Systemen, die von Beginn an groß geplant werden müssen und dadurch den Aufbau verzögern. Durch eine solche dezentrale, gemeinsam genutzte Infrastruktur können Endnutzer Wärme als Dienstleistung beziehen, ohne selbst eine Wärmepumpe besitzen zu müssen. Dieses Projekt ist Teil des SWEET PATHFNDR-Portfolios und nutzt Synergien in Ergebnissen und Erkenntnissen.

Die wichtigsten Erkenntnisse des Projekts sind:

- Das Nanoverbund-Konzept hat ein erhebliches Skalierungspotenzial in der Schweiz. Etwa 82’870 Gebäudeverbünde im Land wurden als geeignet identifiziert, mit einem Potenzial zur Einsparung von 239 Millionen Tonnen CO_2.
- Die Untersuchung des Pilotstandorts zeigt, dass 84 % bis 90 % des fossilen Wärmebedarfs der verbundenen Gebäude durch die gemeinsame Wärmepumpe gedeckt werden könnten. Die Entwicklung einer fortgeschrittenen Regelung wurde jedoch durch die Schwierigkeit der Modellierung des thermischen Netzes und der internen Logik, die begrenzte Beobachtbarkeit sowie die eingeschränkte Steuerung gemeinsamer Komponenten erschwert.
- Die wirtschaftliche und ökologische Bewertung zeigt, dass dezentrale Wärme-Prosumergemeinschaften ganz oder teilweise in 14 von 23 Szenarien mit verbesserter Leistung machbar sind. Die Analyse weist auch darauf hin, dass Budgetbeschränkungen einzelner Haushalte die Bildung solcher Gemeinschaften verhindern könnten. Dies zeigt, dass eine koordinierte Elektrifizierung mit gemeinsamer Infrastruktur der Gesellschaft zugutekommen kann.
- Die qualitative Analyse auf Basis von Interviews liefert Einblicke, wie zuvor unabhängige Heizsysteme miteinander verbunden werden können, um ihre Wechselwirkungen effektiv zu nutzen. Diese Abhängigkeiten und die notwendigen Voraussetzungen für vernetzte Heizsysteme werden in der Studie beschrieben.
- Das Nanoverbund-Konzept unterstützt die Dekarbonisierung des Wohnsektors, indem es Flexibilität hinzufügt und den Nutzerkomfort während des Übergangs erhält. Eine Skalierung des Nanoverbunds erhöht zwar die Netzlast und erfordert Maßnahmen der Verteilnetzbetreiber zur Spannungsstabilisierung, doch sind Endnutzer dank Backup-Heizsystemen weniger von Leistungsbegrenzungen betroffen.

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Abbreviations

ASHP	Air Source Heat Pump
BAU	Business-as-usual
DHW	Domestic Hot Water
DN	Distribution Network
DSO	Distribution Grid Operator
EBC	Energy in Buildings and Communities Programme
GSHP	Ground Source Heat Pump
HP	Heat Pump
ICT	Information and communications technology
IWB	Industrielle Werke Basel
MPC	Model Predictive Control
RBC	Rule-Based Control
RBD	Swiss Register for Buildings and Dwellings
SH	Space Heating
TES	Thermal Energy Storage
VNB	Verteilnetzbetreiber
WP	Work Package
ZEV	Zusammenschluss zum Eigenverbrauch / Prosumer community

1 Introduction

1.1 Background information and current situation

The thermal energy demand of buildings and industries accounts for a significant share of global energy consumption. Most heating energy demands are still met by natural gas or oil heating systems in buildings. Increasingly, heat pumps contribute to the variety of possible building energy systems. Each of these heating systems is sized to provide sufficient heating power on the coldest days of the year, with an additional capacity reserve. Thus, for most of the year, heating systems are not utilized to 100%. Furthermore, neighboring buildings can have differing heating systems installed. Even if buildings are built simultaneously and identically in shape and size, over time, the owner must replace heating technologies, leading to a diverse set of heating systems installed in proximity. In most buildings, including row houses (multiple single- or multi-family houses situated in a row or in proximity), each house has its own heating system. Different carriers provide energy at varying costs and result in different ecological footprints and levels of availability, but all energy carriers are consumed to meet heat demand, regardless of their sustainability or potential scarcity. In case of a (electric) blackout or natural gas shortage, some buildings potentially might become uninhabitable.

One way to resolve this issue is to thermally connect nearby buildings to couple heating systems with different energy carriers and thus provide a so far untapped flexibility potential to the connected buildings, dubbed a “nanoverbund”, and to the energy system. There is an advantage in being able to flexibly switch energy sources from both individual and societal perspectives to enhance energy system resilience and enable participation and arbitrage across different energy markets. The operational strategy of the coupled heating systems plays a crucial role, as it determines which energy carrier is used to supply the connected buildings. With such coordinated utilization of the heating systems, a flexible operation can be advertised to or coordinated with the distribution grid operators for each connected grid. The flexibility potential of the connected nanoverbund case is greater than the flexibility potential of the individual buildings separated, as the possible exchange between energy carriers and consumers increases the possibilities in the energy flows. Historically, electricity and gas supply security were high. However, energy shortages caused by geopolitical events highlight the need for flexible, robust systems to reduce stress on the energy network. During a blackout or gas shortage, some buildings may become uninhabitable. The nanoverbund concept proposes retrofitting existing buildings not connected to district heating into small networks with multiple sources and loads. Thermally connecting nearby buildings, called a “nanoverbund,” can couple heating systems with different energy carriers, adding flexibility to the energy system. The connected nanoverbund's flexibility surpasses individual buildings' potential due to increased energy exchange, improving energy flow optimization. Coordinated operation allows flexible management with distribution grid operators.

Compared to district heating (Fern- / Nahwärmeverbund), the nanoverbund is modular, flexible, and community-oriented. District heating systems are local but rely on a centralized heating source and unidirectional heat distribution. In contrast, the nanoverbund allows bidirectional heat flows, with house owners acting as prosumers (both producers and consumers of heat). A nanoverbund can start small, with just two households, and grow over time, making it easier to set up. In comparison, district heating requires centralized planning across a larger community from the beginning, which can potentially extend the commissioning timeline. Moreover, the ownership models of the infrastructure differ: nanoverbund are often owned and managed by the participating households. At the same time, district heating systems are typically run by a central operator, leading to different legal and regulatory implications.

Before the project began, a pilot installation of a nanoverbund with three single-family houses was set up in the city of Basel. This pilot, led by IWB, the distribution grid operator for Basel, is physically complete and operating using a basic control scheme. This project has strong connections with SFOE

SWEET PATHFNDR[1] project. For instance, PATHFNDR WP2 investigates the potential flexibility of sector-coupled buildings that integrate mobility and building energy demand. Several studies address the mathematical modeling of building energy systems (including heating systems and thermal connections) and building energy demand. On the building systems side, PATHFNDR WP3 develops technology descriptions and high-fidelity models. PATHFNDR WP6 focuses on business opportunities for stakeholders during the technology transition, particularly through sector coupling in mobility.

This project aims to: 1. Identify suitable neighborhoods (containing residential buildings only) for the nanoverbund concept. 2. Implement flexible building operations. 3. Optimize the mix and technology for a sustainable nanoverbund/heat prosumer community and evaluate the economic and ecological benefits. 4. Understand stakeholders' motivations and value propositions. 5. Quantify and evaluate the benefits of aggregated flexibility at the DSO level. The overall system configuration is shown in Figure 1, consisting of three row houses with interconnected heat systems. The remaining sections will refer to this configuration for detailed investigation.

1.2 Structure of this report

This report is organized as follows. Section 2 summarizes the technical boundary conditions and potential sites for implementing the nanoverbund concept across Switzerland. Section 3 focuses on unlocking operational flexibility through an optimal control framework to reduce costs and CO_2 emissions. Section 4 evaluates the economic and ecological merits of the nanoverbund. Section 5 analyzes how previously independent stakeholders can be aligned to leverage interdependence. Section 6 examines how flexibility at the DSO level can be reliably harnessed. Finally, Section 7 provides conclusions and future outlooks.

2 Modeling and case definition

This section aims to identify the technical boundary conditions necessary for the successful deployment of the nanoverbund concept and to identify potential implementation sites across Switzerland. The nanoverbund concept has been developed and patented by IWB (https://patents.google.com/patent/CH720288B1) based on similar concepts developed in the HVAC industry. Additionally, based on estimated heating demand profiles for individual buildings, the share of fossil heating that can be covered by heat pump overcapacity was quantified. This allowed for an estimation of both the emission reduction potential and the increase in the share of renewable energy in the heating supply. The results of the screening of suitable neighborhoods are necessary for the upscaling study in Section 4.

[1] **https://sweet-pathfndr.ch/** and **https://www.aramis.admin.ch/Grunddaten/?ProjectID=48860**

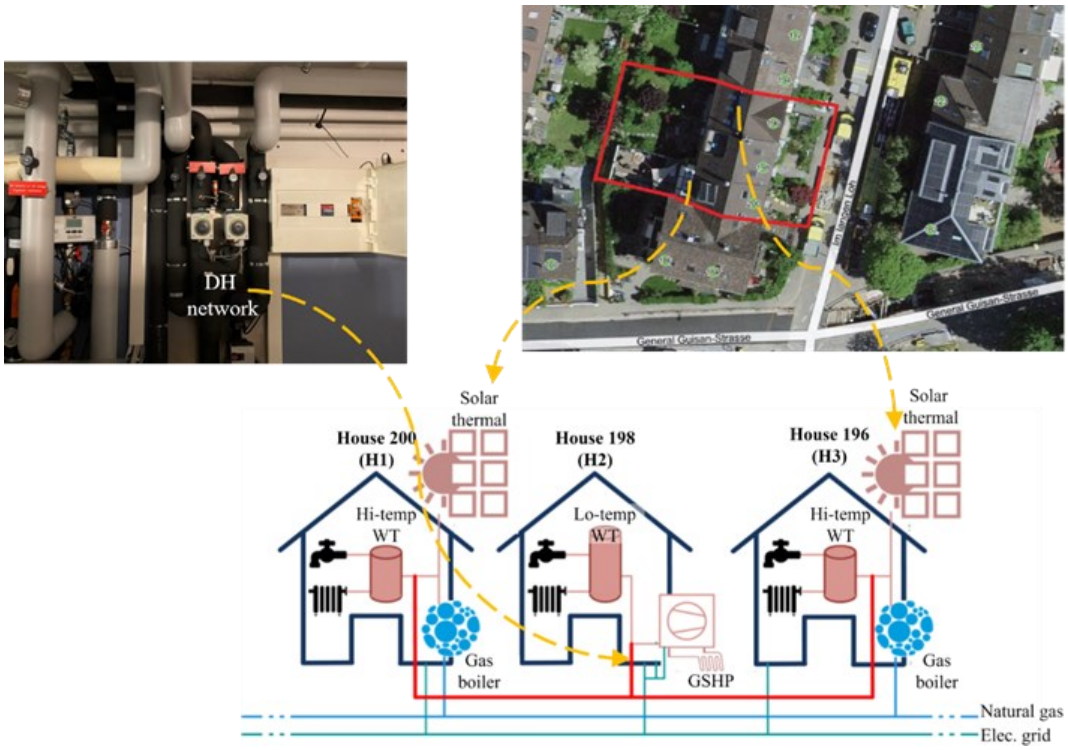


Figure 1. Overall system configuration of the neighborhood.

2.1 Methodologies

2.1.1 The nanoverbund concept

To identify suitable buildings for a nanoverbund, several criteria must be considered. These include the combination of building types, their heat demand profiles, the heat pump capacity, and spatial proximity (to reduce losses and excavation costs). Clusters of buildings already connected to a district heating network are excluded from consideration. The methodological framework developed within this P&D project for estimating the CO_2 reduction potential of the nanoverbund was tested and validated using a pilot site in the city of Basel. The economic aspect can be found in the section 4. This site is described in more detail below, before presenting the method and results of the Swiss-wide potential analysis.

2.1.2 Pilot site case study

The pilot site consists of three residential buildings, as shown in Figure 1: Building 198 is equipped with a geothermal heat pump, while Buildings 196 and 200 are heated with gas systems. The buildings are connected via pipelines, allowing the heat pump to distribute heat across all three buildings. In 2023, the individual heat consumptions for the three buildings was 10.9 MWh, 10 MWh, and 12.5 MWh, respectively.

In [1], the Federal Office of Energy recommends dimensioning the heat pump power at the design temperature by dividing the consumed oil by a factor of 265 l/kW, if the heat pump is only providing space heating and no hot water. From [2], it follows that 1 liter of fossil oil is equivalent to 10 kWh of heat. This information is used to construct the heating curve of the house. Assuming a design ambient temperature of -10°C and no heating demand above 12°C ambient temperature, heating curves for each building were approximated via linear interpolation. These curves, in combination with hourly ambient temperature data from Meteostat [3], enabled the calculation of annual heating demand. The

modelled results were then compared to the actual measured data: 42% and 41% of the measured demand for buildings 196 and 200 were captured by the model, while 76% was captured for building 198. Due to uncertainties regarding the assumed design temperature and the specific heat pump specifications, a scaling factor was derived from the measured-to-modelled demand ratios. This scaling factor enabled a recalculation of the heating curves to reflect actual conditions better. The final heating curves are illustrated in Figure 2.

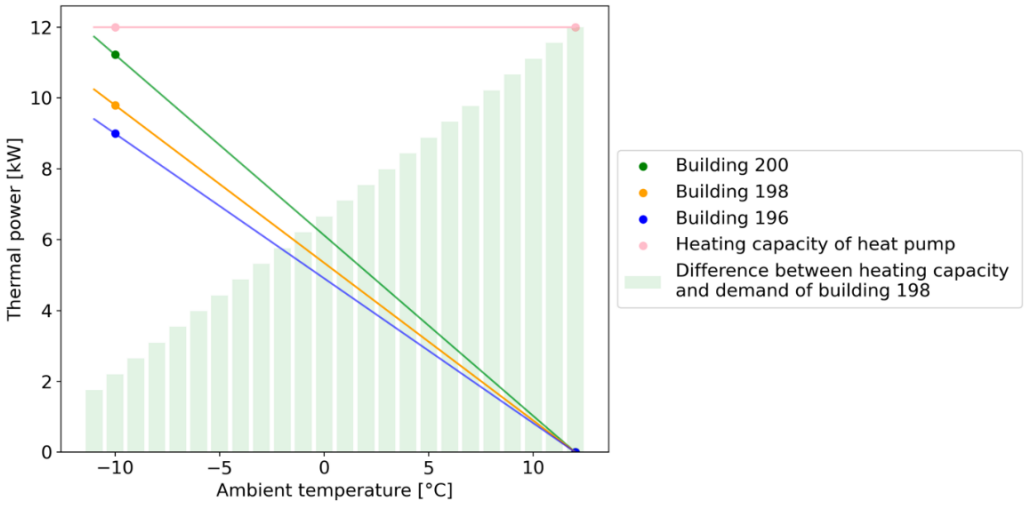


Figure 2. Heating capacity and heating curve for the considered buildings, based on data from the pilot side.

The geothermal Optiheat OH 1-8es heat pump, with a probe depth of 230 m, was characterized using its datasheet and ground temperature data (~20°C) from northern Switzerland. A minimum heating capacity of 12 kW was estimated. The difference between heating demand and capacity at various ambient temperatures was calculated to estimate surplus power up to the assumed 12°C heating limit. These are visualized in Figure 2. To determine the fraction of the total heat demand that could be met by the installed heat pump, the model aggregated available power and building demand across the 2023 climate data. The results, displayed in Figure 3, indicate that approximately 84% of the fossil-fuelled load can be replaced. Full coverage is achieved when ambient temperatures exceed approximately 4°C.

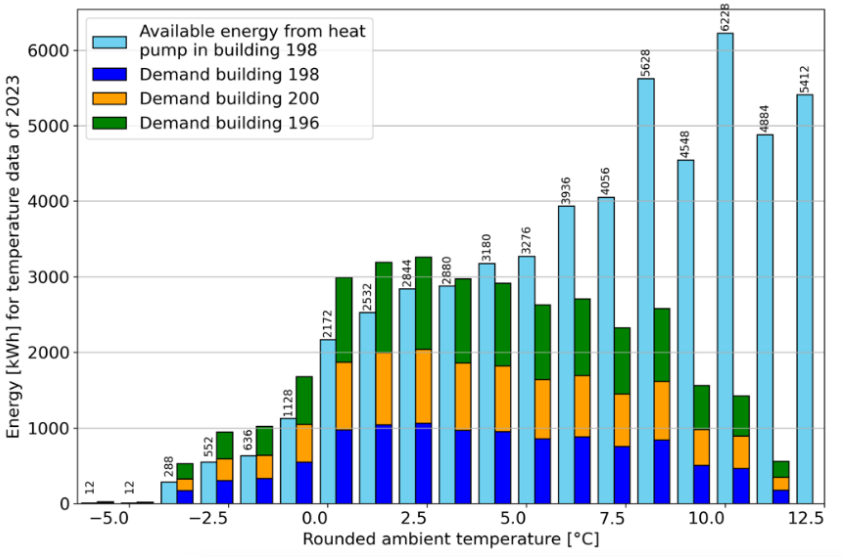


Figure 3. Overview for 2023 of available energy for the heat pump and heat demands for the three buildings in the pilot site.

Based on the emission factors provided in [6], the estimated reduction in fossil-based heat generation at the pilot site corresponds to an annual savings of approximately 4.3 tons of CO_2, under the assumption that the electricity used to operate the heat pump is generated in a CO_2-neutral manner. The share of renewable energy increases from 32.6% before the nanoverbund concept to 89.2% with the nanoverbund concept, aligning closely with actual operational measurements from the 2023/24 heating season, which showed an increase from 33% to 91%. These findings validate the modelling approach and its applicability to estimating nanoverbund potential.

2.1.3 Adaptation and scaling to a national level

To assess the nationwide scalability of the nanoverbund concept, suitable clusters of buildings needed to be identified. These clusters were characterized by sufficient proximity, matching heating system types, and demand profiles. Initially, the pairwise distances between residential buildings were calculated, followed by linkage clustering with a maximum average inter-building distance of 30 meters. Clusters were retained only if they included at least one building with a heat pump and at least one with a fossil-fuelled heating system, based on data from the Swiss Register for Buildings and Dwellings (RBD) [4].

Matching heat demand profiles across buildings is essential to make use of heat pump overproduction. The ambient temperature at which surplus heat from the pump can compensate for fossil demand is a crucial design parameter. Lower threshold temperatures lead to higher fossil demand coverage but lower utilisation rates of the heat pump. Conversely, higher thresholds allow for higher utilisation, but lower fossil offset. For the buildings in the individual clusters, the yearly heat demand is calculated [5]. Heating curves for all buildings in the clusters were modelled using the same method as for the pilot site. Heat pump capacity curves were derived using specifications from a representative air-water heat pump by Ochsner [6], scaled to meet building demand at -5°C, in line with empirical data on standard sizing practices [7]. Fossil-heated buildings within the identified clusters were further filtered based on pairwise distances, retaining only those for which the heat pump's excess capacity was sufficient to offset the fossil heating demand at an ambient temperature of 4 °C.

2.2 Results

The analysis identified 82’870 building clusters across Switzerland where the nanoverbund concept is feasible. The aggregated replacement potential of fossil energy consumption was estimated at 1’024 GWh/year, corresponding to 239 Mt of CO_2 savings annually under the assumption of CO_2-neutral electricity [6]. The spatial distribution of these clusters is shown in Figure 4.

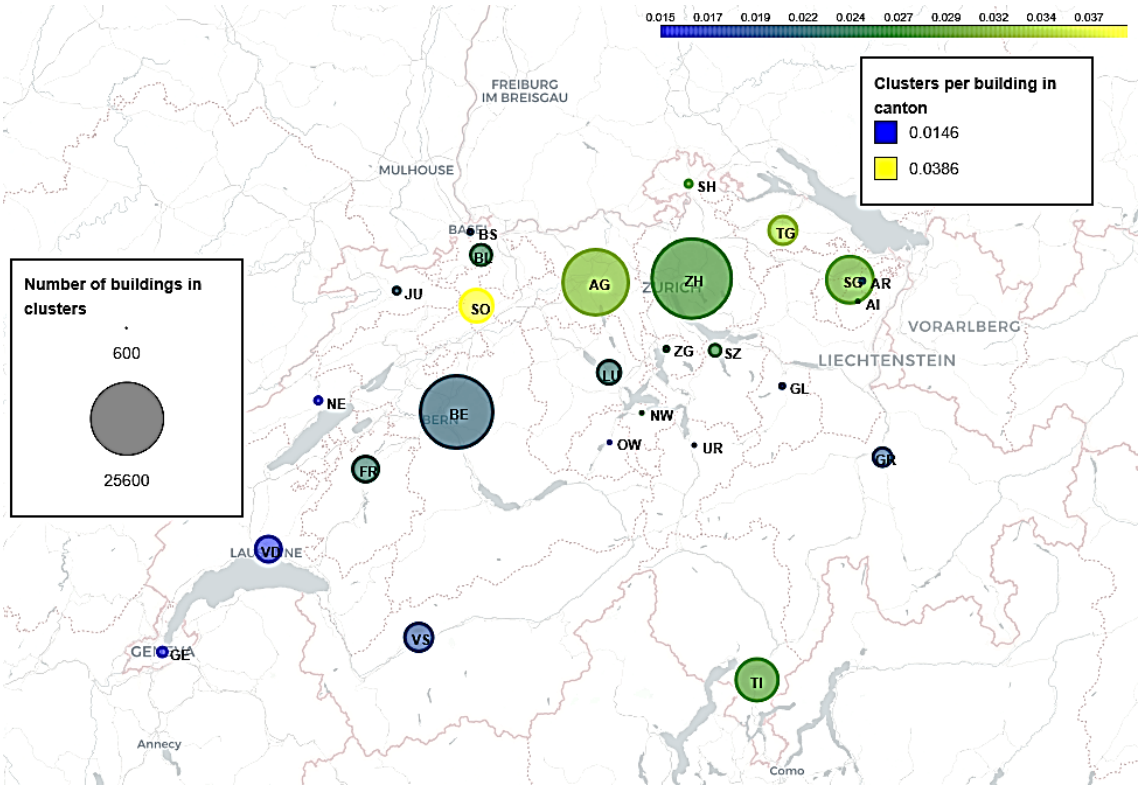


Figure 4. Number of thermal clusters per building, together with the number of buildings in thermal clusters for each canton in Switzerland.

As an illustrative example, Figure 5 presents the potential building clusters identified in the city of Basel. The left panel offers a city-wide overview of all detected clusters, while the right panel provides a detailed view of a selected neighbourhood. Especially promising are clusters located along the same street, where the short inter-building distances and comparable architectural characteristics closely resemble those observed at the demonstration site. These features suggest favourable conditions for implementing the nanoverbund concept, both in terms of technical feasibility and energy efficiency.

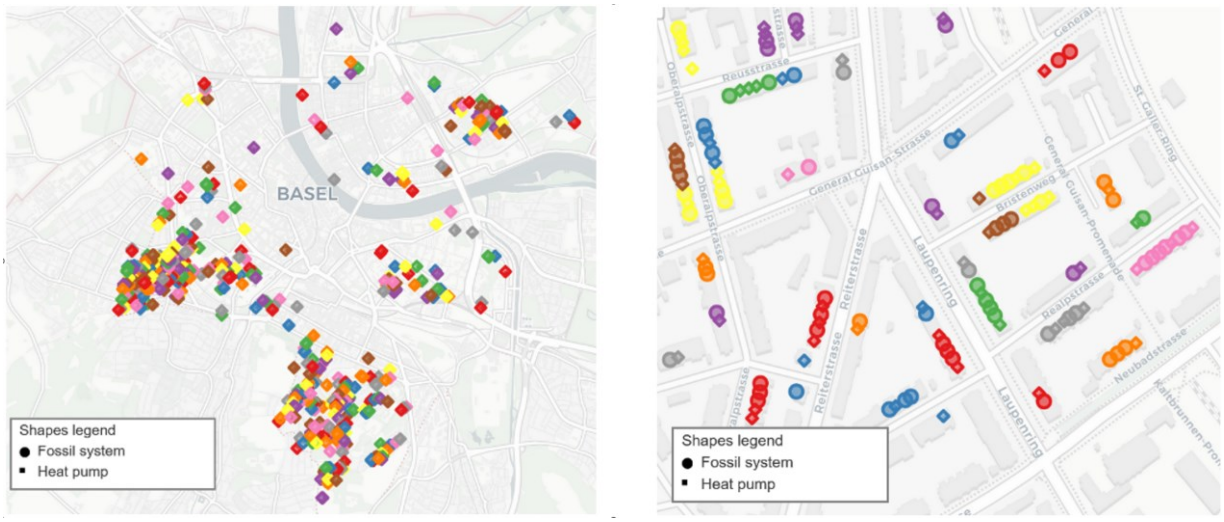


Figure 5. Overview of the clusters found in the city of Basel in the left panel and zoom on a quarter in the right panel. The individual colors represent different clusters. For the city of Basel, 446 potential nanoverbund clusters were found.

3 Flexible energy consumption

This section summarizes the work, aiming to unlock operational flexibility through the implementation of an optimal control framework, which enables more cost-effective system operation by minimizing electricity costs and CO_2 emissions.

3.1 Methodologies

The methodology is organized into three main layers: 1) physical Layer, 2) control layer, and 3) forecasting layer. In the upcoming sections, each layer is presented separately, followed by an explanation of how they work together to create the complete control framework.

At the physical layer, the nanoverbund system is a bidirectional thermal network connecting multiple units in parallel between two main pipes: cold water in one pipe and warm water in the other. Unlike traditional systems, it features direct hydraulic links, enabling units to act as heat producers or consumers. nanoverbund directly builds upon existing heat distribution systems within the house. Due to the lack of controllability of the gas boiler, we considered a static yet common scenario: the heat pump Unit (house 198) produces heat, and two gas boiler Units[2] (house 196 and house 200) serve as consumers. Each unit supports space heating (SH) and domestic hot water (DHW) modes, activated by schedules or temperature triggers. The heat pump has a separate TES to reduce cycling and enhance efficiency. Units have internal controls inaccessible for modification, with only pumps and valves being controllable. Operation is influenced indirectly through network control, limiting flexibility but aligning with a minimal intervention approach, allowing easy decoupling by closing a valve.

At the control layer, a hierarchical control framework was developed, consisting of a higher-level Energy Planner being executed every 15 minutes and a lower-level Power Tracker operating every 1 minute. Together, feedforward and feedback control form a robust control architecture, enabling effective thermal

[2] We use "unit" to refer to heating systems of houses in the pilot site.

power tracking within the limitations imposed by model uncertainty, non-minimum phase dynamics, and transport delays.

At the forecasting layer, the Domestic Hot Water (DHW) demand was forecasted using recurring weekly and daily usage patterns. However, Units 196 and 200 exhibited highly irregular behaviors, which limited the forecasting accuracy for these cases. The SH demand was predicted using a lookup table model based on ambient temperature and time of day. Both forecasting models were validated using data from winter 2023/2024. MeteoSwiss provided an ambient temperature forecast.

3.2 Results

3.2.1 Carbon footprint reduction contributed by heat pumps

The measurements from the pilot site are summarized in Table 1, which shows CO_2 savings due to heat pump-fed energy with a basic controller in two houses with gas boilers, assuming 200 g CO_2 per kWh.

Table 1. Statistics of renewable energy production, consumption, export, and carbon footprint reduction.

Period	Renew. Energy Produced (MWh)	Consumed at House 198 (MWh)	Fed to Grid (MWh)	CO_2 Saved (tons)
1.10.2023 - 1.1.2024	5.994	3.841	2.153	0.43
1.1.2024 - 1.4.2024	9.54	4.587	4.953	0.99
1.4.2024 - 1.7.2024	2.341	1.36	0.981	0.196
Total 2024	17.875	9.788	8.087	1.6
1.10.2024 - 1.1.2025	8.226	4.279	3.947	0.797
1.1.2025 - 1.4.2025	11.42	5.607	5.813	1.16
1.4.2025 - 1.7.2025	1.914	1.223	0.691	0.138
Total 2025	21.56	11.109	10.451	2.095

The monitoring system and actuation interface were established, bridging multiple communication protocols and metering systems from different vendors and the underlying hardware that can be controlled. The key message is that there are sufficient off-the-shelf resources to roll out the necessary solutions for monitoring and actuation to replicate the results in a scalable way. The scalability is achieved by reusing existing technologies and installations as much as possible, while the scale of adoption in real life is being explored by IWB. Moreover, Figure 6 gives an example energy cost calculation using the measurements, which highlights the cost saving (i.e., 605 CHF in 2024) with the nanoverbund.

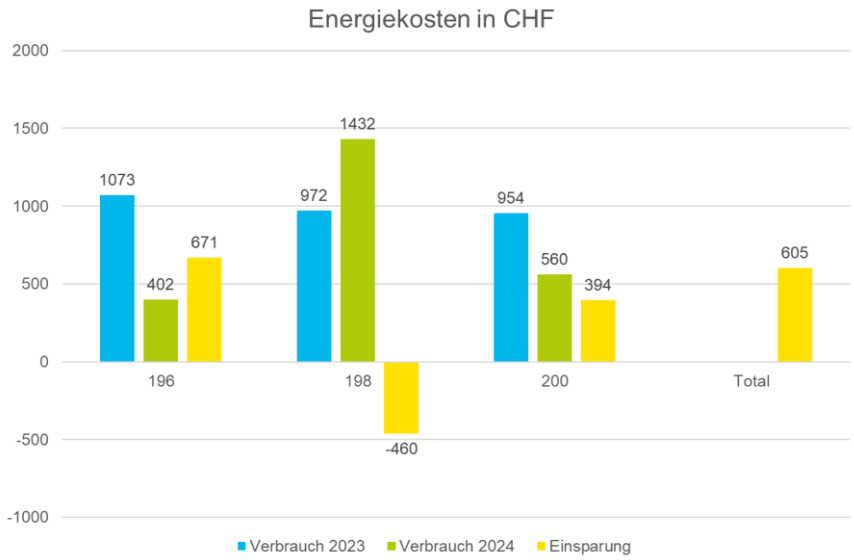


Figure 6. Energy cost calculation using measurements from 2024.

3.2.2 Daily operation patterns under optimal control

Both Figure 7 and Figure 8 illustrate the operational patterns of the consumer unit, with 196 and 200 units, during the evaluation periods. The cost signal represents either the electricity price or the CO_2 emission intensity, depending on the objective function used in the MPC formulation. The shaded band highlights the interquartile range (50% quantile band), capturing typical daily variability. The benchmark controller was developed by YUON and deployed in the winter of 2023 and 2024. Both units show increased sharing operations (Q_exch) during daytime, with a peak in the early morning. The reason for the significant drop in Q_exch from 21:00 to 22:30 in Unit 196 is an internal control policy that shuts off the circulation pump completely and closes the valves to the room, thereby preventing any energy transfer. For Unit 196, the gasboiler (Q_src) was mainly active in the early morning hours, primarily operating in DHW mode. For Unit 200, no clear pattern for Q_src can be identified.

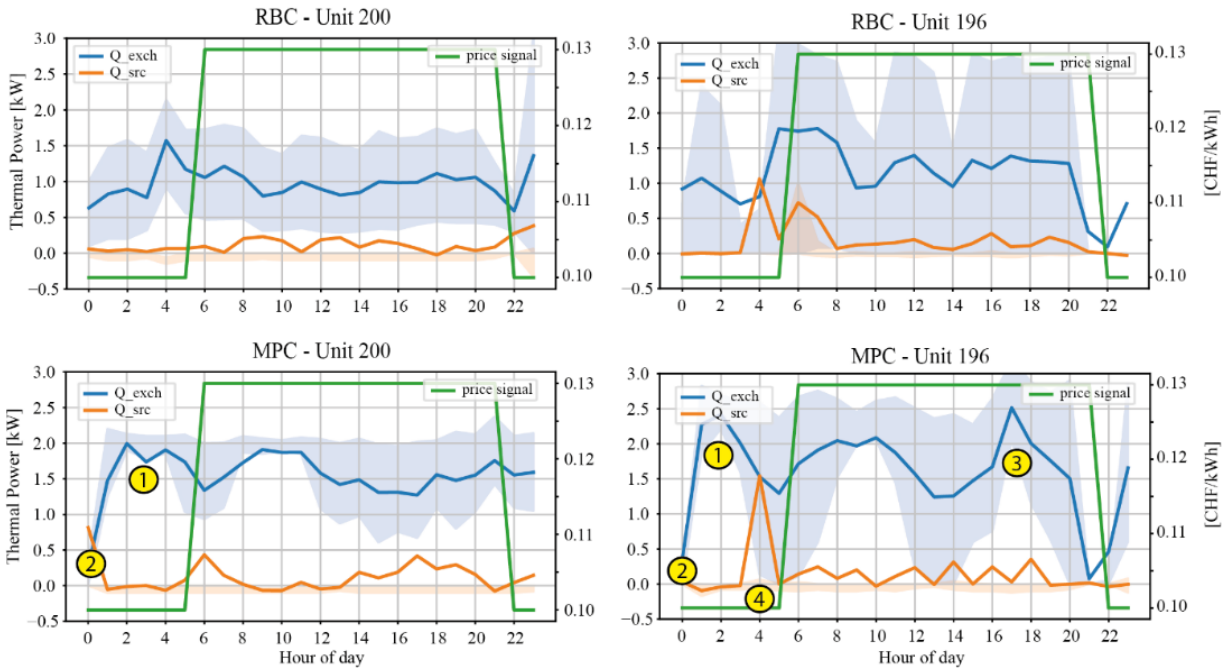


Figure 7. Daily operation patterns of consumer units 200 and 196 under RBC from 01.01.2024 to 01.04.2024 and under price-aware MPC from 01.02.2025 to 20.02.2025.

Figure 7 shows consistently increased operation between 01:00 and 04:00 (marked as Nr. 1) when prices are low, compared to the Rule-Based Control (RBC) approach. The sharp drop in operation around midnight (Nr. 2) is caused by a control constraint that disables thermal sharing when the heat pump unit (198) switches to DHW mode. This constraint was introduced to avoid instability observed in the controller during these periods, when supply temperatures are very high. In contrast, this rule was not enforced under RBC, which explains the absence of a corresponding drop. In retrospect, this design choice significantly limited the MPC's performance, as it prevented optimal use of flexibility during a low-price time window. The peak in Q_exch (Nr. 3) reflects preplanned compensation, triggered by the scheduled shutdown of Unit 196 between 21:00 and 22:30. The drop in operation around 4:00 (Nr. 4) is due to DHW operation in Unit 196, where it was decoupled from the network.

In Figure 8, the MPC results demonstrate increased operation in the morning (Nr. 1) when CO_2 emission intensity is low, and reduced operation during periods of high CO_2 emissions (Nr. 2), aligning with the controller's environmental objective. As observed in Figure 7, Q_exch drops consistently whenever Q_src is high (Nr. 3), indicating periods when the corresponding unit is operating in DHW mode and is temporarily decoupled from the network.

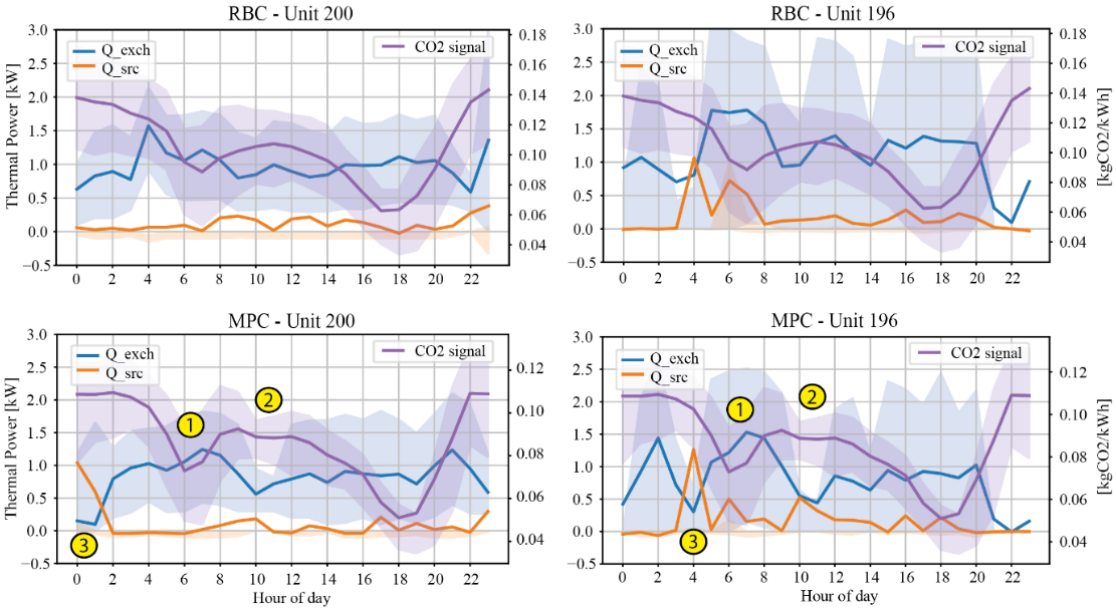


Figure 8. Daily operation patterns of consumer units 200 and 196 under RBC from 01.01.2024 to 01.04.2024 and under emission-aware MPC from 03.14.2025 to 04.04.2025.

4 Economic and ecological performance

This section summarizes the framework to investigate nanoverbund's optimal designs through multi-objective optimization systematically. According to the feedback from relevant stakeholders, the analysis considers nine scenario parameters to reflect the complexity observed in a real-world heat prosumer community, leading to 23 scenarios in total. We assess each scenario's economic and ecological performance, providing decision thresholds and final design recommendations.

4.1 Methodologies

The methodological workflow starts with preparing input data such as techno-economic parameters, demand profiles, and renewable potentials. Then, we formulate a multi-objective optimization using the energy hub modelling method to minimize costs and emissions, considering design and operational decisions for supply-demand balance within hubs and energy exchange among hubs via a small thermal network. Note that, we use hub to refer to house where energy system design can be optimized. Next, we create scenarios based on field observations for sensitivity analysis by combining the problem formulation with relevant data. For each scenario, we solve the optimization problem and assess costs, emissions, and technology sizing using EhubX[3] in collaboration with WP2 of PATHFNDR.

[3] EhubX is an energy system design tool developed at the Urban Energy Systems Lab of Empa.

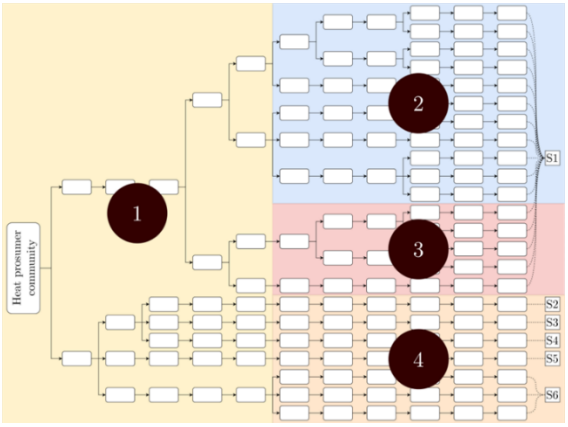


Figure 9. Overview of the decision tree linking various conditions of the heat prosumer community to specific design recommendations. Each branch of the tree corresponds to one situation a community can encounter and represents the solution to an objective optimization problem.

For brevity, the detailed mathematical formulations are summarized in Appendix 9.1. To ensure the representativeness of our study, we consider a comprehensive set of parameters to define scenarios that reflect a range of real-world situations, informed by feedback from community stakeholders and researchers. Specifically, the scenario parameters include several key aspects influencing decision-making, and they are summarized in Table 2.

The scenario parameters define the key factors that determine the configuration and performance of heat prosumer communities. Household behavior establishes whether cooperation among residents is possible, influencing the extent to which collective energy solutions can be developed. The selection of technology candidates indicates the level of coordination in choosing suitable renewable systems, which affects both technical compatibility and operational efficiency. Investment budgeting sets financial boundaries for household groups, determining the scale and ambition of achievable projects. At the same time, the network subsidy reflects the level of government financial support available for thermal network development. Construction complexity captures the variability in network cost and feasibility arising from local layout conditions and infrastructure requirements.

Within this framework, the design strategy specifies the guiding objective of the community—whether it aims for cost optimization, CO_2 reduction, or a balanced approach combining both. The heat pump types, including air-source and ground-source technologies, determine the system's technical characteristics and spatial adaptability. Decision key performance indicators (KPIs) identify the metrics used to evaluate design alternatives, typically focusing on cost or CO_2 performance. Finally, decision thresholds establish the limits and conditions—such as investment capacity or spatial distance—that influence which configurations are ultimately feasible and preferred within the community context.

Table 2. Key parameters used to model and split decision trees for realistic scenarios.

Scenario parameters	Description
Household behaviour	Whether house owners decide to cooperate
Technology candidates	Whether house owners coordinate for technologies of heating and coupling
Investment budgeting	Whether a particular household group has a budget limit
Network subsidy	Governmental financial support for the thermal network
Construction complexity	Cost variations of the thermal network

Design strategy	Preference for cost-optimal, emission-optimal, or a hybrid
HP types	Types of heat pumps (i.e., air-source, ground-source)
Decision KPI	Key performance indicators guiding the decisions
Decision thresholds	Thresholds or limits influencing the final decisions

4.2 Results

4.2.1 System design

The results of the system design depend on the scenario parameters listed in Table 2. To improve accessibility, their impacts on design recommendations are illustrated in a decision tree in Appendix 9.2. The main observations are summarized as follows, and quantitative results are illustrated in Figure 10.

For cost-optimal designs, compact neighborhoods (i.e., within approximately 15 meters for ground source heat pumps and 10 meters for air source heat pumps) support the formation of full prosumer communities. When these distance thresholds are exceeded, the design shifts toward business-as-usual configurations, resulting in an emission increase of about 204%. In contrast, CO_2-optimal designs using ground source or air source heat pumps can maintain full prosumer communities regardless of neighborhood size or additional investment costs. The additional network investment cost represents the extra expenses caused by construction challenges such as difficult terrain, extended connection distances, or the need for network reinforcement to prevent congestion. Cost-optimal designs with ground source heat pumps remain viable only when these additional costs stay below 50%; beyond this threshold, systems tend to revert to business-as-usual operation, resulting in an emission increase of about 204%. Under a balanced design approach, which accounts for both cost and emissions, different outcomes emerge. Full prosumer communities can be maintained when additional network investment costs remain below 100%, partial prosumer operation occurs when costs range between 100% and 300%, and business-as-usual configurations dominate once costs exceed 300%, resulting in an emission increase of about 204%.

For CO_2-optimal designs, with distances of up to 500 meters for ground source heat pump-based systems and 300 meters for air source heat pump-based systems, full prosumer communities can be formed that maintain baseline CO_2 emissions. Larger spatial layouts, however, result in business-as-usual configurations with emission increases of around 204%. When both cost and CO_2 performance are considered jointly, ground source heat pump systems consistently form full prosumer communities at baseline emission levels.

Under existing neighborhood conditions, where the distance between houses influences network feasibility, balanced designs using ground source heat pumps generally lead to partial prosumer communities. In these cases, neighborhood CO_2 emissions range from about +7% to +204% above the baseline. When economic factors such as budget limitations or differences in household coordination hinder cooperation, business-as-usual configurations dominate, resulting in emission increases of +204%. When there is no coordination within the neighborhood, cost-optimal designs under these conditions often favor fossil fuel–based systems, which cause a significant emission rise of approximately +327%. In contrast, CO_2-optimal designs using ground source heat pumps enable heat pump–based neighborhoods with a CO_2 reduction of around 9% compared to the baseline.

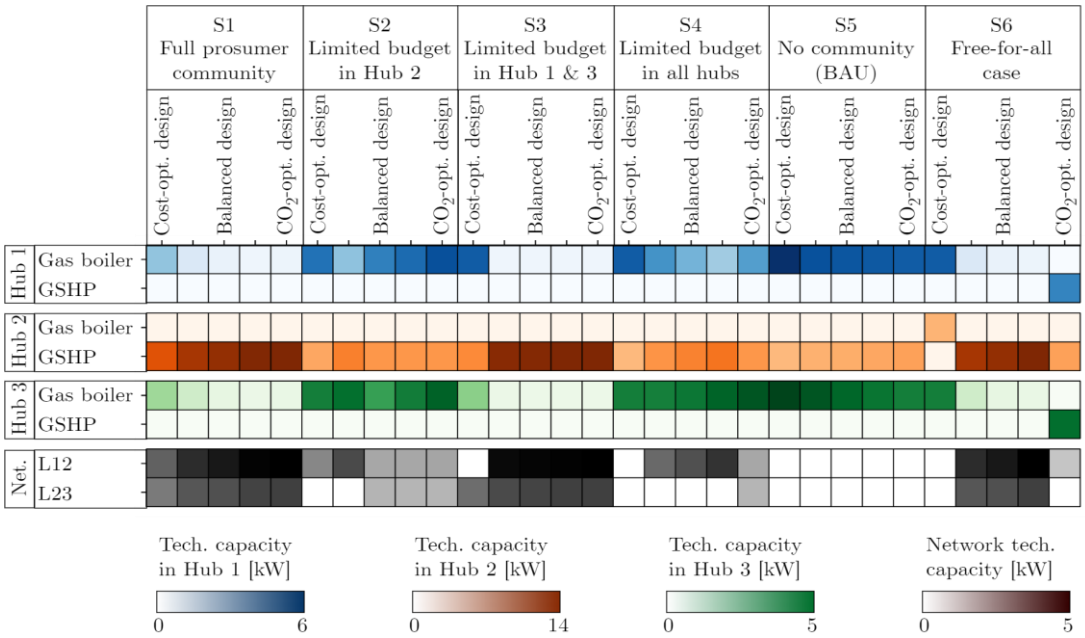


Figure 10. Summary of the main heating technology capacities in each hub and network capacities in the pilot site with the corresponding measured consumption for all optimal designs in scenarios S1 to S6. A higher capacity is represented with a darker color. Four color ranges correspond to technology capacities in Hub 1, Hub 2, Hub 3, and network capacities.

Figure 10 summarizes the main heating technology capacities in each hub and network capacities in the neighborhood for all optimal designs in scenarios S1 to S6. Generally, gas boilers are preferred in cost-optimal designs, while GSHP are preferred in the CO_2-optimal designs. Network sizes depend on the neighborhood's cooperation to produce energy at a particular hub. Larger capacities of gas boilers or GSHP correspond to larger network sizes to facilitate energy exchanges.

The results provide important insights for policymakers in two key areas. First, they indicate that coordinated electrification can enhance both economic and ecological performance at the community level, while current electrification efforts tend to be uncoordinated. However, there is a trade-off between the intrusive nature of intervening in individual homeowners' decisions and achieving efficient electrification from a societal standpoint. Second, the coordinated electrification framework, which incorporates the concept of a heat prosumer community, can help lower costs and reduce emissions. The resulting savings can be redirected to subsidize the heat network, thereby improving the viability of the heat prosumer community and creating a cycle of positive feedback.

4.2.2 Comparison with conventional systems

The economic and environmental impacts across six scenarios constructed using parameters listed in Table 2 are provided in Figure 11, in terms of total annualized emission and cost.

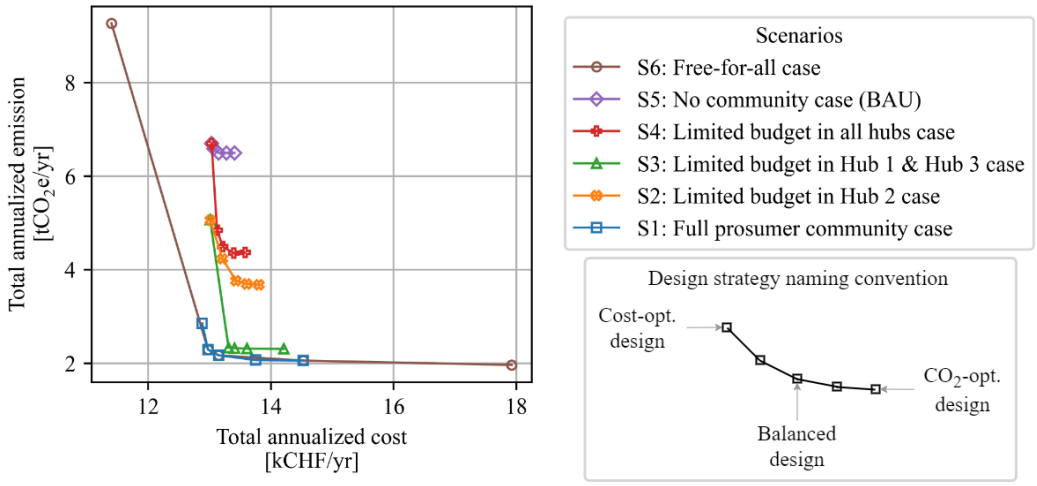


Figure 11. Economic and environmental impacts across six scenarios. Each Pareto front shows five optimal solutions, with three of them selected to present in this study: cost-optimal (minimum cost), balanced (intermediate), and CO2-optimal (minimum emission).

On the other hand, centralized district heating relies on large heat generation plants that supply multiple consumers through a shared network. In Switzerland, more than 1,000 such networks are in operation [8], using a broad range of generation technologies with different energy and emission characteristics. These include nuclear, oil, gas, wood, geothermal, biogas, and waste-to-energy plants, as well as heat pump systems utilizing wastewater, groundwater, or boreholes. The average carbon footprint of Swiss district heating networks is 0.066 kg CO_2-eq per kWh. According to [9], a 2024 survey reports annual heating costs between CHF 1878 and CHF 5267, with an average of CHF 3467 per year, equivalent to about 0.17 CHF per kWh. With total consumption of 33.4 MWh for the entire pilot, the total annual cost and emission with centralized district heating system are 5.7 kCHF and 2.2 tons of CO_2 respectively.

Comparing this national average with the analysis from this project as summarized in Figure 11, we can observe that large scale centralized district heating systems outperform decentralized district heating systems in terms of both cost and carbon footprint. Therefore, the nanoverbund concept is especially recommended for cases where large, centralized distribution systems are unavailable, or infeasible due to time and space.

5 Ecosystem alignment

This section sets out to analyze the ecosystem alignment of the nanoverbund. The work package specifically aimed to identify how previously independent residential heating systems across different houses can be interconnected to leverage the synergies of their interdependencies. The ecosystem alignment structure of the nanoverbund is displayed in Figure 12.

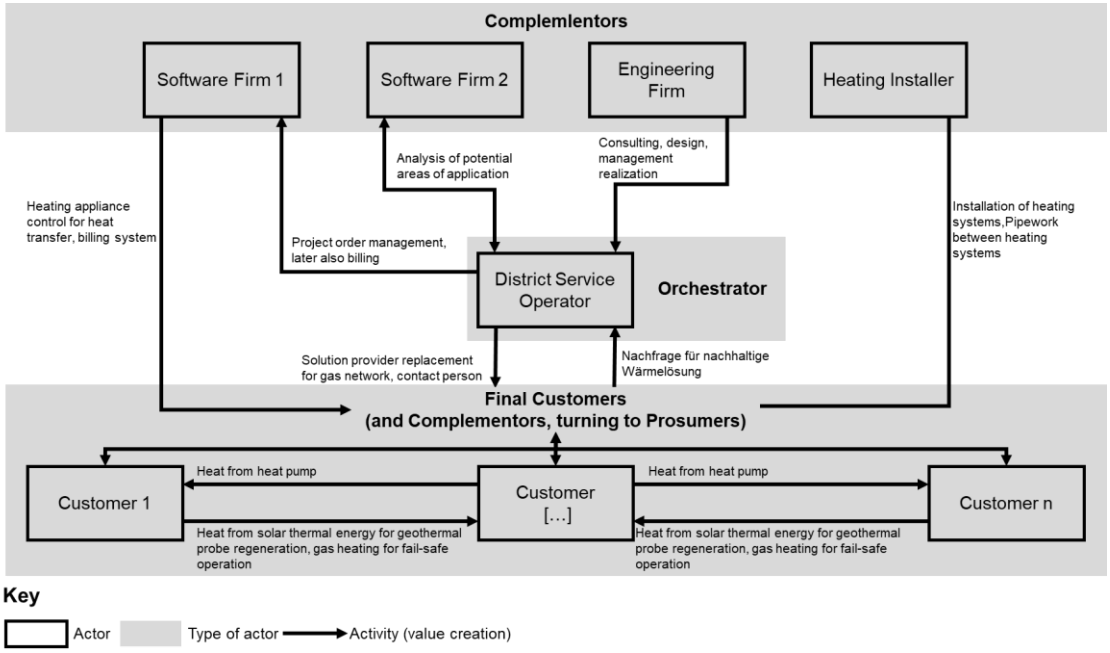


Figure 12. Sketch of the nanoverbund ecosystem alignment structure.

To detect synergy potential, it is essential to understand the interdependencies on both the customer and provider sides. The goal was to delineate these interdependencies and determine the prerequisites necessary for interdependent heating systems. We used a qualitative case study approach to analyze and map the nanoverbund ecosystem. We conducted interviews with 24 individuals between October 2023 and February 2024. One challenge was the limited number of directly involved stakeholders (e.g., IWB staff, customers, heating system installers). To address potential bias, we interviewed informants from other work packages to provide their understanding of the ecosystem. This approach enabled us to triangulate and validate the information provided by the directly involved members of the ecosystem.

The study revealed that the innovation of the nanoverbund emerged from the recombination and transfer of principles from the energy domain, "prosumer communities" (ZEV). A key insight is the transformation of the customer role into that of a “prosumer,” becoming a complementor providing heat to the ecosystem. As a heat producer, the prosumer must ensure delivery obligations to other heat consumers. This obligation can be fulfilled in different ways, such as through redundant heating units and fossil fuels during heat shortages (switching on gas heaters). It was also found that the installation and operation of the nanoverbund does not necessarily have to be orchestrated by its inventor, IWB. The solution could also be distributed and scaled as a white-label product by competing DSOs or complementary actors, such as heating system installers. IWB can retain ecosystem control through its control of the steering platform and patents.

To increase public visibility and practical impact within the energy sector, we published the ecosystem analysis in the industry magazine Bulletin VSE [10]. The outcomes of the publication are threefold: First, the ecosystem analysis unveils new market potential for DSOs. With the nanoverbund, DSOs can expand beyond their current market boundaries, which are currently constrained by large-scale infrastructure limitations, to provide heat-sharing and related services in new regions. Second, the nanoverbund concept leads to prosumer-driven market dynamics, enabling consumers to become prosumers by offering “heat as a service” to neighbours and fostering new local value exchanges. Third, from an innovation ecosystem perspective, the nanoverbund is regarded as a modular system.

This modularity enables the expansion or restriction of renewable energy components (e.g., integrating PV, scaling solar-thermal installations), allowing for flexible adaptation of further nanoverbund sistes. The data acquired from the nanoverbund case offers multiple opportunities for further research in the innovation literature. Examples worth exploring are the interaction between heating systems and digitalization as a cyber-physical platform, the collaboration between public research institutions and industry as a driver of innovation, and intrapreneurship within companies.

6 Upscaling case for energy system

This section evaluates the nanoverbund's flexibility in the electric distribution network (DN). It quantifies how buildings connected through a nanoverbund increase DN flexibility. The study also examines multiple nanoverbunds' impacts, showing how their flexibility can reduce stress, such as under-voltages and line capacity violations. The evaluation assumes DN operators are aware of nanoverbund flexibility and can request buildings to shift heating loads to less stressful periods. The system setup in this section is not restricted to be the same as the existing pilot site.

6.1 Methodologies

The nanoverbund flexibility is quantified through the energy envelope, shown as a heatmap in Figure 13, which indicates for each timestep how long the system can sustain the given power consumption level without violating the temperature boundaries set for user comfort. The nanoverbund is operated with a Model Predictive Controller (MPC), which is aware of the system's properties and fully leverages the building's potential to anticipate or defer power consumption. More details can be found in [11].

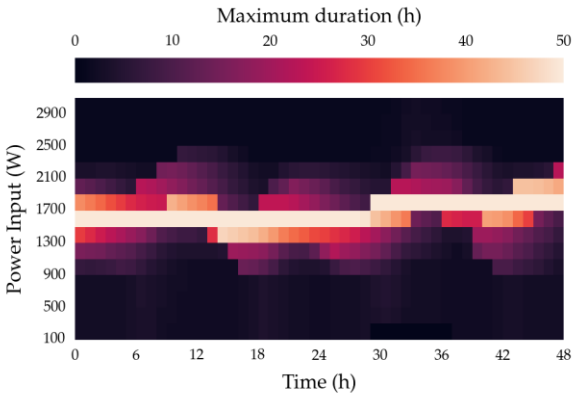


Figure 13. Energy envelope of a nanoverbund.

The energy envelope is calculated for two example cases, shown in Figure 14 and Figure 15. In the first case study, the nanoverbund consists of two buildings: one heated by a heat pump and the other by a gas boiler. In the second case study, both buildings are heated through heat pumps, and one of the buildings has a battery storage system.

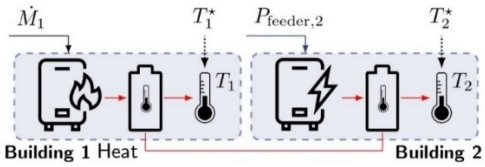


Figure 14. Case study 1 with one boiler and one heat pump.

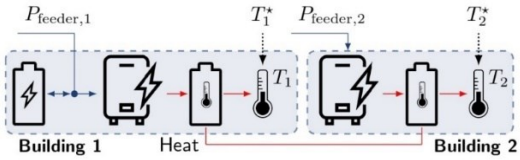


Figure 15. Case study 2 with two heat pumps and a battery in one of the buildings.

6.2 Results

The impact of the thermal connection on system flexibility is determined by the increase in the energy envelope, depending on the allowed heat exchange between the buildings. Figure 16 and Figure 17 present the results for the two case studies. The increase in flexibility (abstracted by the normalized time on y-axis) is significant for the gas boiler-heat pump case study, as the complete flexibility of the gas-heated building becomes available to the DN through the thermal connection. The improvement is more limited in the second case, where the thermal connection allows for sharing the battery flexibility between the buildings, but the impact is moderate.

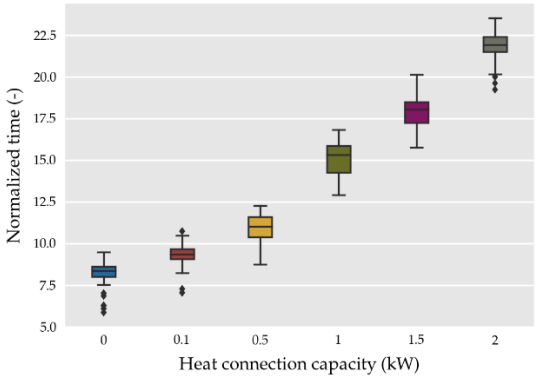


Figure 16. nanoverbund flexibility as a function of the heating connection capacity for case study 1.

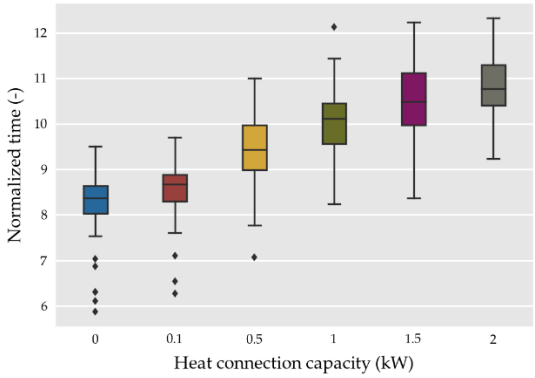


Figure 17. nanoverbund flexibility as a function of the heating connection capacity for case study 2.

The impact of the nanoverbund flexibility on DN is studied through power flow optimization with heating and PV curtailment. The heating load profile is optimized to minimize the heating costs and keep the temperature within the required bounds. In the event of a voltage or line current violation, the DN operator can partially or fully curtail power consumption for the time necessary. The buildings utilize their flexibility to adjust their power consumption while maintaining the users' comfort. The effect of nanoverbund is analyzed by comparing the system operation in cases with and without nanoverbund present in the network. The number and size of nanoverbund systems introduced in the distribution grid considered in the case study are the results in Section 2. The resulting operation is presented in Figure 18, which compares the hourly power profile and the heat pump curtailment for the case without nanoverbund (Base), with nanoverbund (NESS), and an additional case without nanoverbund but with increased electric heating consumption (Base+). While the base case, representative of today's condition, does not require curtailment, both the cases with increased consumption (nanoverbund and Base+) need curtailment to operate within the grid's limits.

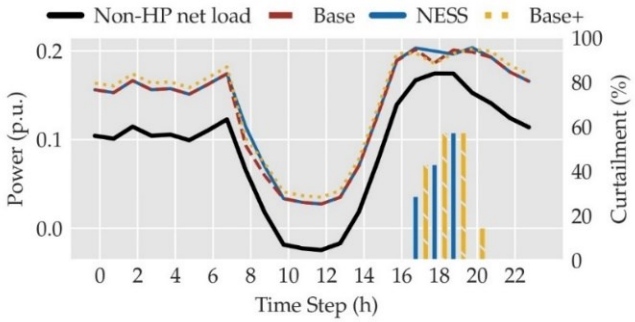


Figure 18. Daily power consumption and curtailment with and without nanoverbund.

The difference between the nanoverbund and Base+ is evident in the impact of the curtailment on the end users, shown in Table 3. While the nanoverbund curtailment leads to the activation of the gas boiler and no user discomfort, in Base+, the curtailment leads to the violation of the temperature bounds of the buildings.

Table 3. Impact on end users due to curtailment.

Scenario	Curtailment (%)	User discomfort (%)	Gas use (%)

Base	0	0	0
nanoverbund	0.31	0	0.018
Base+	0.12	0.0021	0

7 Conclusions and discussion

7.1 Concluding remarks

Throughout the project, we have investigated multiple aspects of the nanoverbund concept: candidate neigborhoods suitable for scaling across Switzerland, operation and advanced control of the nanoverbund, economic and ecological performance of the technology, alignment of stakeholders and new business model, and upscaling impacts on the electric distribution systems. The analysis of candidate neighborhoods across Switzerland supported project partner IWB in identifying suitable communities for engagement. The development of the smart controller provided valuable insights into system controllability, which is reflected in the next generation of the nanoverbund system design featuring higher controllability. The economic and ecological analyses offered IWB comprehensive recommendations for system optimization. Finally, the nanoverbund project was recognized with the Watt d'Or Award 2024. More specifically, the analyses so far have led us to five key insights below.

First, the nanoverbund concept demonstrates significant potential for reducing fossil energy consumption and greenhouse gas emissions across Switzerland. About 82,870 building clusters across the country have been identified as suitable for this approach, with the potential to cut 239 million tons of CO_2. By strategically connecting buildings with different heating systems, particularly linking those with oversized heat pumps to nearby buildings still using fossil-fuelled systems, a considerable increase in renewable energy and emission reductions can be achieved. The nanoverbund concept not only offers an immediately actionable strategy for CO_2 reduction in Switzerland's built environment but also lays the foundation for more flexible, efficient, and integrated heating solutions as part of a broader energy transition.

Second, analysis shows 84% to 90% of fossil heat demand in the connected buildings could be supplied by the shared heat pump. During the pilot site operation, the heat pump contributed to carbon footprint reduction of 2 tons in 2025. Optimal control's potential is limited in this specific site due to practical challenges limiting control effectiveness including system complexity, limited observability, and reduced controllability. Specifically, system complexity arises from the increased effort and uncertainty involved in modeling the thermal network and internal logic. Additionally, limited observability results from key states such as flow, pressure, and temperatures being unmeasured or drifting, which affects the reliability of the model. Furthermore, reduced controllability is due to control being exerted through shared components and inaccessible internal logic, which restricts responsiveness and flexibility. Together, these factors constrain the control framework, thereby reducing its ability to exploit flexibility and achieve cost and CO_2 savings. Considering these limitations, the next generation of the nanoverbund features higher observability and controllability by integrating additional sensors and actuators. Thus, the flexibility potential may be higher than that shown in this report.

Third, the results show that decentralized heat prosumer communities, in full or in part, are viable for 14 out of 23 scenarios with improved economic and ecological performance. Our analysis also indicates that individual households' budget limits may prevent community formation. In comparison, large-scale centralized district heating systems outperform decentralized ones in cost and carbon footprint. The nanoverbund concept is therefore recommended where centralized systems are unavailable or infeasible due to time or space constraints.

Four, the study revealed that the innovation of the nanoverbund emerged from the recombination and transfer of principles from the energy domain, "prosumer communities" (ZEV). A key insight is the

transformation of the customer role into that of a “prosumer” becoming a complementor providing heat to the ecosystem. As a heat producer, the prosumer must ensure delivery obligations to other heat consumers.

Lastly, the results show that the introduction of nanoverbund, that is, an effective increase in the electrification of the heating sector, leads to increased grid loading, and the DSO might need to take additional measures to prevent voltage violations. However, curtailing these loads is less impactful for the end-users, since they can rely on alternative heating sources. nanoverbund can be a useful measure to progress the decarbonization of the residential sector, providing flexibility in the energy transition while limiting the users' discomfort.

7.2 Limitations and outlooks

Looking ahead for screening suitable neighborhoods, several aspects warrant further investigation to harness the potential of thermal nanogrids fully. One critical factor is the inherent thermal inertia of buildings, which can provide flexibility in heat distribution and contribute to load balancing within a nanoverbund. Additionally, integrating complementary technologies such as photovoltaic (PV) systems and thermal energy storage (TES) could further enhance system performance and self-sufficiency, introducing new operational scenarios and optimization challenges. Long-term projections should consider climate change-induced shifts in heating demand, impacting seasonal and annual heat loads. Infrastructure constraints, like avoiding public ground during pipeline installation, must be accounted for. The spatial setup of buildings, including their distance and alignment, affects the feasibility and thermal losses of the infrastructure. Lastly, the identification of clusters composed solely of fossil-fuelled systems highlights further decarbonization opportunities. Such clusters may contain aging heating systems that are due for replacement and could serve as promising candidates for introducing shared heat pump solutions. Office buildings, due to their larger and more stable demand profiles, may also emerge as anchor points for future nanoverbund implementations, expanding the range of applicable use cases beyond residential buildings.

Several limitations of economic and ecological performance analyses must also be noted. First, the existing framework does not capture the remaining value of existing heating systems in the buildings, which can strongly impact the house owners’ decisions. Second, the current case study focuses on one community consisting of single-family houses and communities with a more diverse building composition that needs to be investigated to enhance the robustness of the conclusion. Third, the current case study is based on the size of an existing community, and the optimal size of such communities can be investigated in future studies.

Ecosystem alignment study can be further extended by exploring the interaction between heating systems and digitalization as a cyber-physical platform, the collaboration between public research institutions and industry as a driver of innovation, and intrapreneurship within companies.

Finally, in this project, we did not have legal experts on the team[4]. Therefore, the legal aspect was not investigated, but the question was raised throughout the project through interaction with external stakeholders. For example. when constructing the heating network, which potentially runs through public land, public law may apply. In the specific case of the pilot site, house owners own the technologies, so private law applies. This may change depending on the realized setup. Additionally, it is unclear whether nanoverbund is eligible for relevant decarbonization subsidies. While the request has been submitted to the authority, decisions remain unclear at the time of writing. Lastly, the investigation specific to Basel may not be transferred to other cantons immediately. Harmonizing legislation through MuKEn could be a viable path to upscale the solution nationwide.

[4] We thank SWEET-DeCarbCH consortium member Reto Müller, Madeleine Camprubi and her team for discussion.

8 Outputs and outreach to date

Publications (peer-reviewed or others)

Description: author(s), title, journal or type of publication, year of publication, doi
Miehé, L. (2025). Ökosystem-Ansatz für flexiblere Energiesysteme. Bulletin Electrosuisse, 116(3), 40-43. **https://doi.org/10.3929/ethz-b-000733534**

Public oral and visual presentations (scientific or broad audience)

Description: author(s), title, name of the event and location, year of presentation
Born, Dominik; 2024-03-06; Dialogveranstaltung Mausacker; Weihermatthalle Reinach, Gemeinde Reinach BL
Born, Dominik; 2024-03-21; Infoveranstaltung Gemeinde Bettingen; Gemeindesaal; Gemeinde Bettingen
Born, Dominik; nanoverbund - Wärme smart und flexibel teilen, Info- und Diskussionsveranstaltung "Heizdialog Mausacker", Rainach BL, 06.03.2024, ***https://www.reinach-bl.ch/de/aktuell/news/meldungen-projekte/stadtentwicklung/Mausacker.php***
SRF Audio, radio broadcast, IWB-Lösung: Verbünde statt Fernwärme, 11.03.2024, ***https://www.srf.ch/audio/regionaljournal-basel-baselland/iwb-loesung-verbuende-statt-fernwaerme?id=12553085***
Born, Dominik, 2025 Watt d'Or ceremony
Hanmin Cai, 03.04.2025 SWEET-DeCarbCH conference
Hanmin Cai, Plenary session: What do buildings and electromobility contribute? Energy Week at ETH 2024
Hanmin Cai, 09.10.2024 Expert meeting at International Energy Agency Energy in Buildings and Communities Annex 82, Copenhagen
Student Thesis, Bernadino, B. (master student at ETH supervised by Hanmin Cai, Philipp Schuetz and Binod Koirala) (2024) Economic and Environmental Assessment of Heat Prosumer Communities
Student Thesis, Luca Krebs (master student at ETH supervised by Hanmin Cai) (2024) Game-theoretic design of heat prosumer communities
Student Thesis, Andres Decormis (master student at ETH supervised by Hanmin Cai and Binod Koirala) (2024) Optimal Agent-Based Coordination of Energy Communities
Bernadino Bernadino, 11.09.2024, Economic and Environmental Assessment of Heat Prosumer Communities, 19th SDEWES Conference 2024
Matthias Brandes, 11th International Conference on Smart Energy Systems, Copenhagen, 16.09.2025

9 Appendix

9.1 Mathematical formulation

A multi-objective optimisation is written with Python using the Pyomo open-source optimisation modelling language and solved using the Gurobi solver. The model time horizon is set to one year with hourly time steps. The community is assumed to be designed from scratch, that is the investments in technologies are assumed to occur at the beginning of the year without prior existing technologies.

$$\min_{x,y,p,q,r,b_x,b_p,b_q} \quad (c_I^T + c_O^T) \cdot x + c_S^T \cdot y \tag{1a}$$

$$g_S^T \cdot y \tag{1b}$$

$$\text{s.t.} \quad Ky + Mp + Nq - d = 0 \tag{2}$$

$$x \leq V_x \cdot b_x \tag{3}$$

$$y \leq v_y \tag{4}$$

$$\begin{bmatrix} Ky \\ r \\ q \end{bmatrix} \leq x \cdot \Delta t \tag{5}$$

$$r_{t+1} - (1 - \Lambda) \cdot r_t + Mp_t = 0, \qquad \forall t \in \mathcal{T} \tag{6}$$

$$r_{t=1} - r_{t=t_{max}} = 0 \tag{7}$$

$$q - A_q q = 0 \tag{8}$$

$$A_m \cdot \begin{bmatrix} p \\ q \end{bmatrix} \leq BM \cdot \begin{bmatrix} b_p \\ b_q \end{bmatrix} \tag{9}$$

$$(I - A_m) \cdot \begin{bmatrix} p \\ q \end{bmatrix} \leq BM \cdot \left(1 - \begin{bmatrix} b_p \\ b_q \end{bmatrix}\right) \tag{10}$$

$$x, y, p, q, r \in \mathbb{R}^+, b_x, b_p, b_q \in \mathbb{B} \tag{11}$$

Equation 1 presents the two objective functions for this study optimization, which are total annualized cost $(1a)$ and total annualized emission $(1b)$ for the whole community. The cost parameters are annualised investment costs c_I, operating costs c_O, and import prices c_S. For emissions, energy import emission g_S is used. The multi-objective optimisation is solved using an epsilon ϵ-constraint method. The decision variables are technology capacity x, energy import y, storage energy flow p, network energy flow q, storage state-of-charge (SoC) r, installation binary variable b_x, storage and network modal binary variables b_p, b_q. The number of optimal designs that form the Pareto front is set at four solutions to capture a cost-efficient solution, an emission-efficient solution, and two intermediary solutions.

The optimization problem is subjected to several constraints. The energy balance of the community is ensured by Equation 2 with K, M, N as efficiency matrices and d as the demand vector of all hubs. Equation 3 decides on the installation of technology through the installation binary variable and limits that technology capacity at the upper limit matrix V_x. The availability of energy imports is constrained in Equation 4 with the import limit vector v_y. The operations of conversion technologies, the storage SoC, and the energy flow through the networks are bound in Equation 5 by the installed capacities over time interval Δt, which in this study is one hour. Equation 6 shows the SoC balance in a storage technology

between consecutive time steps considering a standby loss matrix Λ. The continuity of SoC at the beginning and the end of the time horizon is ensured in Equation 7. The network flow consistency, that is an energy outflow from one hub to other equals to the energy inflow of that other hub, is enforced in Equation 8 with a reflection matrix A_q. Both storage and network technologies are assumed to operate in one mode at-a-time, that is either charging or discharging for the former and either sending or receiving for the latter. Equations 9 and 10 formulate these modal constraints using the big M method and with a modal matrix A_m and the modal binary variables. Equation 11 summarises the numerical domains of all decision variables.

9.2 Design recommendation with decision trees

With Figure 19 to Figure 22, we can have the full set of scenarios with recommendations of the communities, and the impacts on neighborhood emissions are provided at the end of each branch (readers are advised to follow the branch from left to right to access the results of each scenario). It can be observed that the final recommendations are strongly dependent on the parameters shown in Table 2.

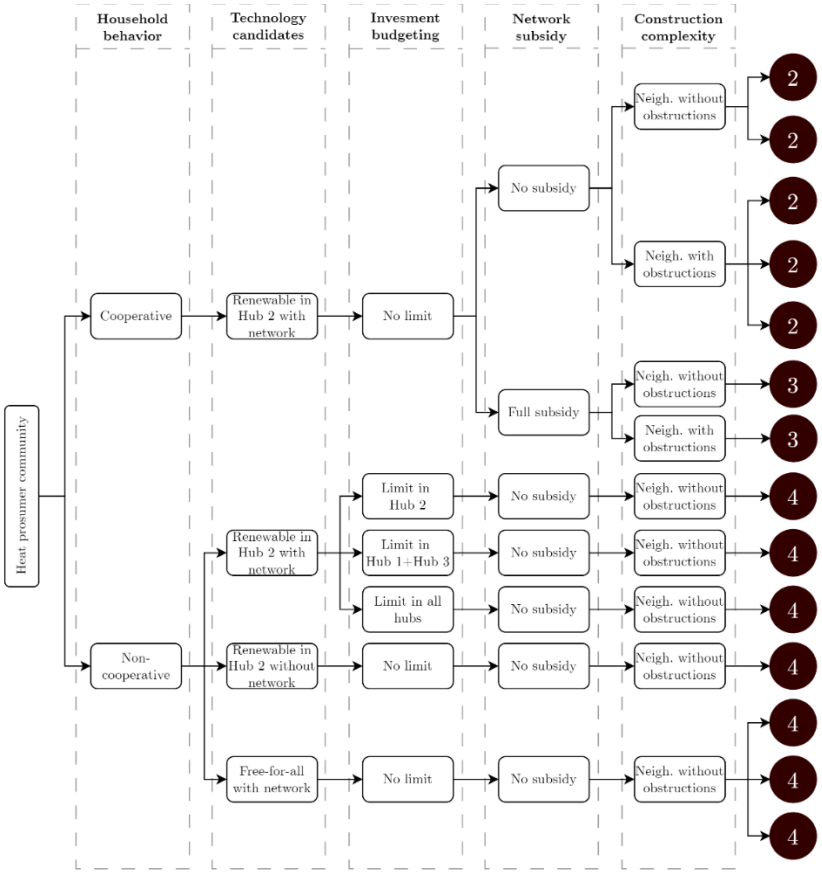


Figure 19. Segment 1 of the decision tree shown in Figure 9.

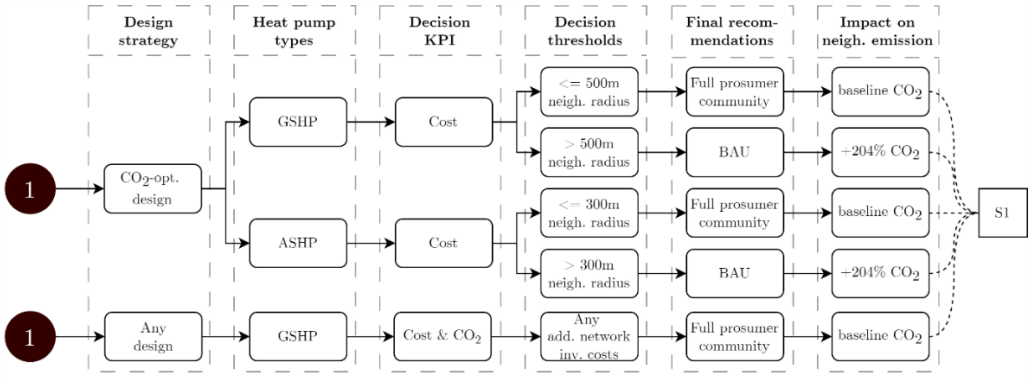


Figure 20. Segment 3 of the decision tree shown in Figure 9.

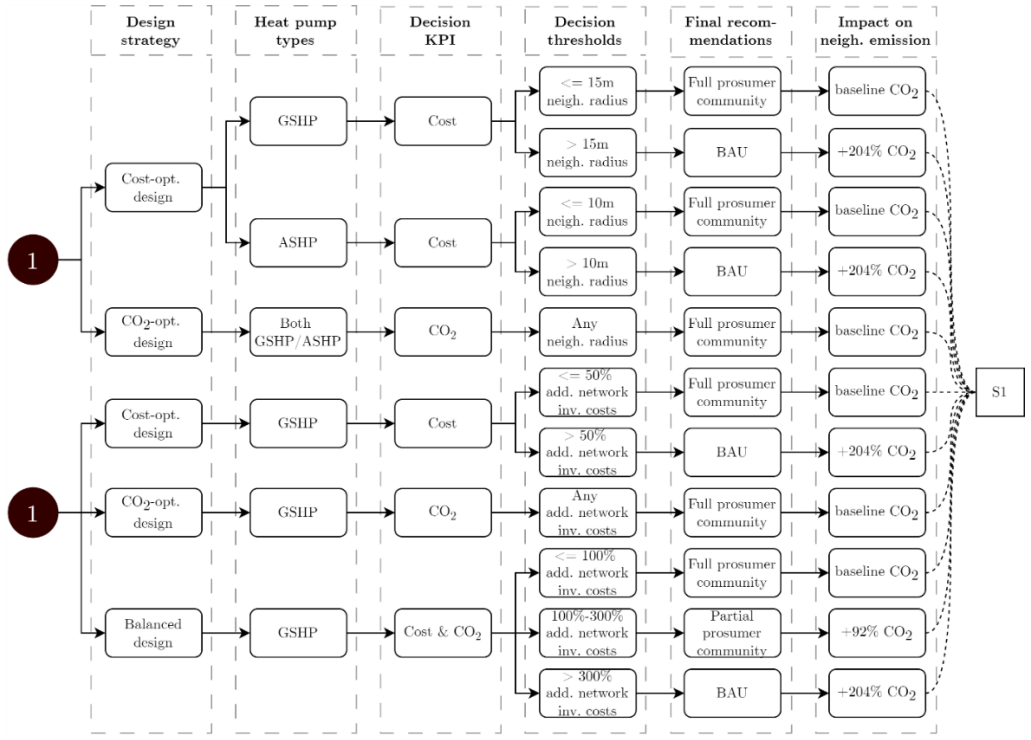


Figure 21. Segment 2 of the decision tree shown in Figure 9.

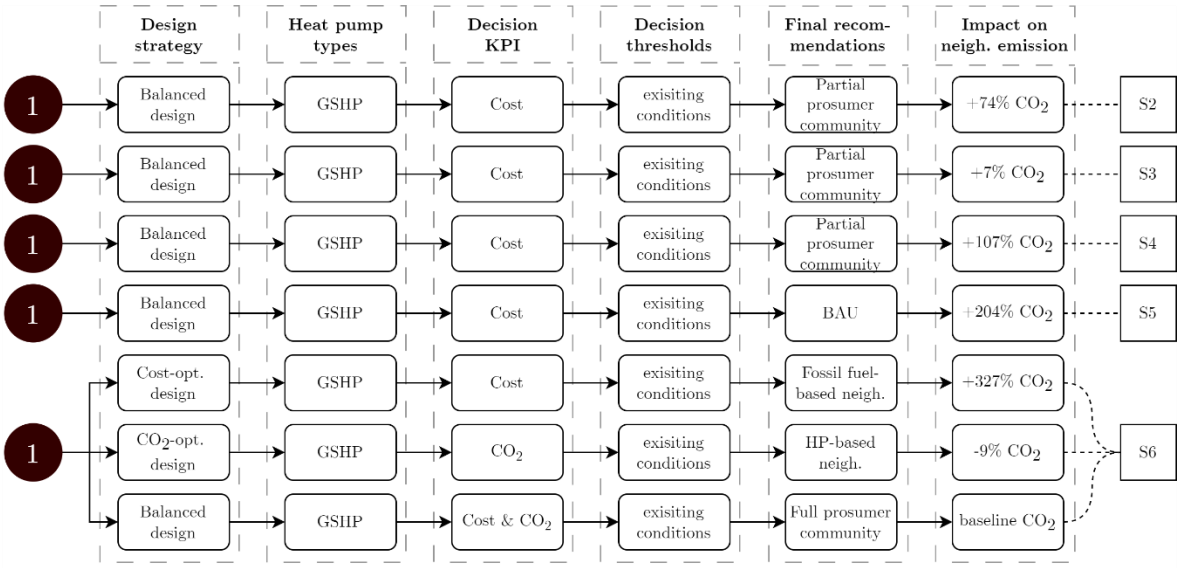


Figure 22. Segment 4 of the decision tree shown in Figure 9.

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