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FOSTER_DHN

Facilitate Overall and Systemic Transition to Efficient and Renewable District Heating Networks

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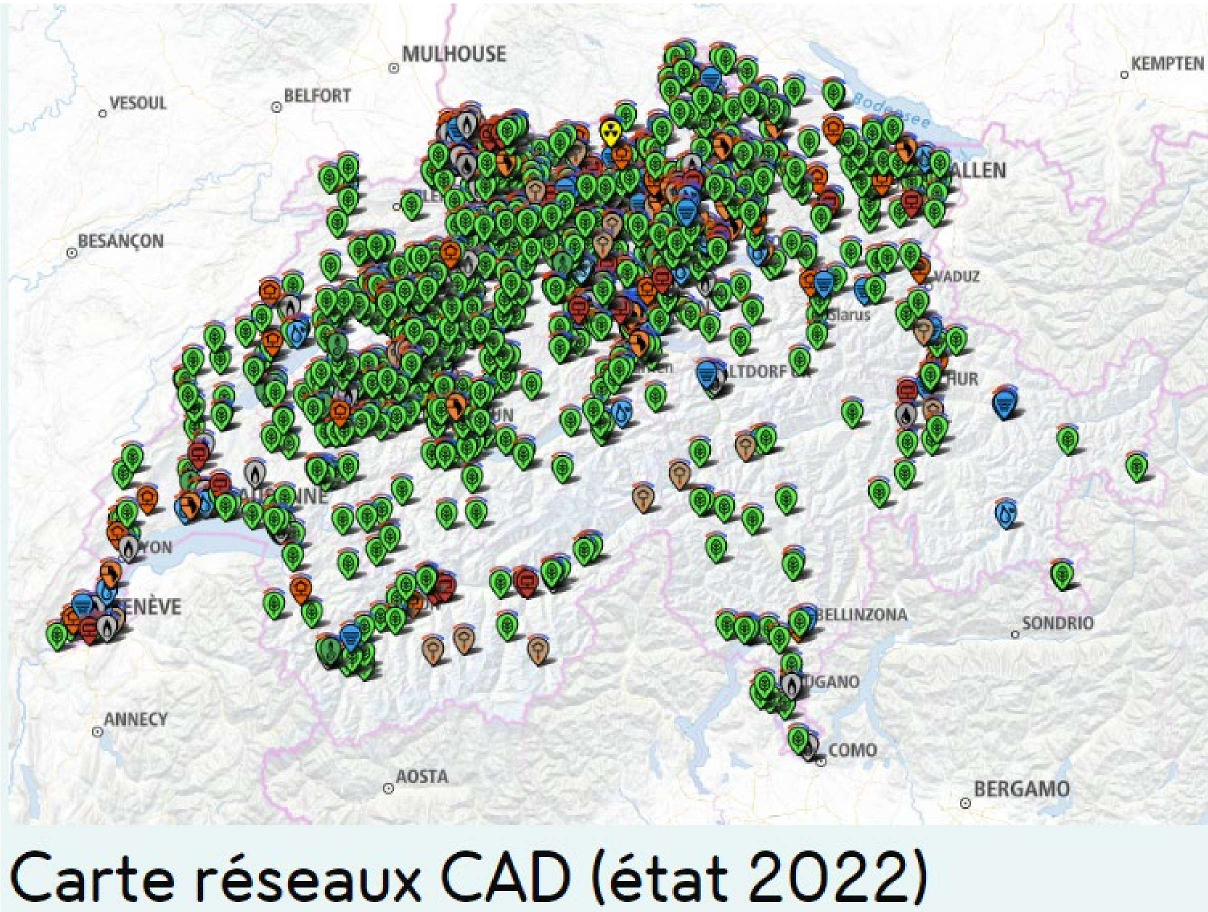

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Yverdon Énergies (SEY)
Rue de l'Ancien Stand 2, 1400 Yverdon-les-Bains (VD)
https://www.yverdon-energies.ch/

Direction de l'énergie du Canton de Vaud (DGE-DIREN)
Avenue de Valmont 30b, 1014 Lausanne (VD)
http://www.vd.ch

Subsidy recipients:
HEIG-VD – Institut des Energies
Route de Cheseaux 1
1401 Yverdon-les-Bains (VD)
http://energies.heig-vd.ch

HES-SO Valais-Wallis
Rue de l'Industrie 23
1950 Sion (VS)
http://www.hevs.ch

Authors:
Marten Fesefeldt, HEIG-VD, marten.fesefeldt@heig-vd.ch
Massimiliano Capezzali, HEIG-VD, massimiliano.capezzali@heig-vd.ch
Jessen Page, HES-SO Valais-Wallis, jessen.page@hevs.ch
Atefeh Behzadiforough, HES-SO Valais-Wallis, atefeh.behzadiforough@hevs.ch
Alexis Duret, HEIG-VD, alexis.duret@heig-vd.ch
Stefano Pauletta, HEIG-VD, stefano.pauletta@heig-vd.ch

SFOE project coordinators:
Andreas Eckmanns, andreas.eckmanns@bfe.admin.ch
Nadège Vetterli, nadege.vetterli@anex.ch

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Summary

The four fundamental research questions underpinning all FOSTER_DHN project activities are as follows:

1) To what extent is it possible to integrate a higher proportion of renewable or low-carbon energy sources into the supply of district heating networks?
2) Is it feasible to lower distribution temperature levels in district heating networks in order to integrate low-carbon supply points and aim for greater energy efficiency?
3) Is it possible to develop a fully open-source simulation environment for district heating networks, integrating multiple supply points right down to the detailed level of substations (exchangers) supplying buildings? Does it give us access to physical verification of scenarios and crucial operational parameters such as temperature levels and flow velocities?
4) Is it possible to identify synergies between district heating networks of different sizes, supplied by energy sources with different availability and environmental impact characteristics?

The research questions were tackled scientifically and systematically along four axes:

1) Detailed analysis of low-carbon energy sources that could be used to power district heating networks, from the point of view of overall potential and limitations. Two important distinctions served as study niches, namely the on-site availability (situationality) of a given source on the one hand and, on the other, its use to cover baseload demand as opposed to peak demand.
2) Building energy consumption model to assess the effects of energy retrofits and, subsequently, to study the possibility of lowering distribution temperatures at primary level.
3) Development of a simulation environment based on the pandapipes open-source framework for district heating networks. It includes a hydraulic and thermal model, as well as a module for identifying synergies between sub-networks, including anergy networks. Numerical simulation ensures the technical feasibility of scenarios and balances between demand and supply.
4) Calculation of relevant indicators for scenario comparison and decision-making, coupled with detailed mapping of relevant parameters.

The four axes were implemented in two distinct test-cases, to be seen in situations involving existing and future networks in the cities of Yverdon-les-Bains(YLB) and Lausanne. The studies on urban projects enabled us to test and validate the simulations, on the one hand, but also to compare scenarios co-constructed with the implementation partners. The simulation environment thus proposed is able to compute fluid mechanics parameters (such as flow velocities and temperatures) at any network point, along with relevant KPIs (such as GHG emissions) for an entire urban territory comprising several hundreds of buildings, as well as for smaller neighborhoods in a fully geo-localized fashion.

The six most important result horizons obtained within the framework of this multi-partner project are as follows:

1) A simulation environment for separate or connected district heating networks, of all topologies, multi-temperature and multi-injection sources, has been developed and used on complex urban territories comprising from a few dozen to a thousand buildings. This environment makes it possible to verify the physical feasibility of heat distribution in the studied areas, and to calculate a whole series of KPIs that are crucial for energy companies such as renewable energy share in the heat supply and CO_2 emissions related to selected heat generation scenarios.
2) On one hand, within the YLB test case, it has been demonstrated that the proposed district heating networks can reduce greenhouse gas emissions compared with the current situation by several tens of percents, depending on the considered scenario. On the other hand, the implementation of DHN in YLB can allow reaching up to 80% supply by renewable energies such as medium-depth geothermal energy and wood. However, it must be noted the usage of wood for

space heating and DHW preparation is not contemplated by SFOE heat strategy and restricted at cantonal level. Finally, lowering the distribution temperature from 80°C to 70°C is shown to have a significant impact on reducing emissions and network losses.

3) Still in the Yverdon-les-Bains test case, but also for the Neuchâtel DHN studied in a parallel project, a comprehensive methodology for identifying and exploiting synergies between DHN networks has been developed. It has been demonstrated that these synergies can improve energy and environmental indicators – for example, the share of renewable energy supply - and partly resolve issues linked to the local unavailability of certain renewable sources. Although a precise evaluation of potential CAPEX reduction thanks to synergies was out of scope within FOSTER_DHN and represents a research perspective, the obtained results on CAD STEP subnetwork clearly indicate that oversizing of installed capacities can be avoided by exploiting smart connections between subnetworks.

4) A simulation framework for a micro-DHN in Lausanne using waste heat from a data center was developed, considering demand modelling, network topology, and operational strategies. The simulations explored four scenarios with different temperature levels, in order to notably assess how changes in temperature affect system design and operation. Key results include a significant reduction in heat losses, from 873 MWh/year to 201 MWh/year in the low-temperature scenario. However, the reduction in temperature led to higher electricity consumption for decentralized heat pumps, increasing by up to 3890 MWh/year due to lower Coefficient of Performance at lower temperatures. The analysis also revealed that the first scenario (high-temperature DHN) had minimal heat power deficit (86 kW), while the third scenario (low-temperature DHN) faced higher heat power shortages (190 kW).

5) A second part of the Lausanne test-case study focused on integrating the waste heat from the Dufour micro-DHN into the existing Lausanne DHN. The study examined how Swisscom's data center waste heat (ranging from 1.5 MW to 3 MW) could be utilized in the broader district heating system of Lausanne. The integration was evaluated across several scenarios, with temperature reductions to optimize heat recovery and improve overall efficiency. Key findings included a 1.5% increase in renewable energy usage and a 9.3% reduction in natural gas consumption in Lausanne's DHN due to the integration. These changes demonstrated how the incorporation of waste heat can significantly improve the sustainability of the DHN, particularly in reducing dependency fossil heating sources. The smaller-scale Southwest Lausanne DHN saw even more impactful results, with a 2.3% rise in renewable resources and a 24.4% reduction in natural gas consumption.

6) The project further analyzed how reducing the distribution temperatures within the Dufour micro-DHN affects the overall efficiency of the system. In one scenario, the secondary side temperature was reduced from 65°C/40°C to 55°C/35°C, leading to a 21% decrease in electricity consumption for the central heat pump. However, while reducing temperatures lowered the heat losses from 872.8 MWh/year to 718.8 MWh/year, it also resulted in a heat power shortfall whereby the heat pump produced less heat. Additionally, in the scenario with decentralized heat pumps, the temperature reduction improved their COP, while the increased heat demand led to a higher required flow, increasing pump electricity consumption. This scenario hence highlighted the importance of balancing temperature reductions with operational adjustments (e.g., mass flow rate), as excessive temperature reductions can lead to challenges in meeting heating demands, even though energy efficiency improves.

Zusammenfassung

Die vier grundlegenden Forschungsfragen, die allen Aktivitäten des Projekts FOSTER_DHN zugrunde liegen, lauten wie folgt:

1) Inwieweit ist es möglich, einen höheren Anteil an erneuerbaren oder kohlenstoffarmen Energiequellen in die Versorgung der Fernwärmenetze zu integrieren?
2) Ist es denkbar, das Temperaturniveau der Verteilung in Fernwärmenetzen zu senken, um kohlenstoffarme Versorgungspunkte integrieren zu können und eine höhere Energieeffizienz anzustreben?
3) Ist es möglich, eine vollständig Open-Source-Umgebung für die Simulation von Fernwärmenetzen zu entwickeln, die mehrere Versorgungspunkte integriert und bis auf die Detailebene der Unterstationen (Wärmetauscher), die die Gebäude versorgen, reicht? Ermöglicht sie uns den Zugang zu einer physikalischen Überprüfung der Szenarien und zu entscheidenden Betriebsparametern wie Temperaturniveaus und Strömungsgeschwindigkeiten?
4) Ist es möglich, Synergien zwischen Fernwärmenetzen unterschiedlicher Größe zu identifizieren, die von Energiequellen mit unterschiedlichen Verfügbarkeitsmerkmalen und Umweltauswirkungen versorgt werden?

Die Forschungsfragen wurden wissenschaftlich und systematisch in vier Richtungen angegangen:

1) Detaillierte Analyse von kohlenstoffarmen Energiequellen, die für Fernwärmenetze in Frage kommen, im Hinblick auf das Gesamtpotenzial und die Beschränkungen. Zwei wichtige Unterscheidungen dienten als Untersuchungsfenster, nämlich die Verfügbarkeit einer bestimmten Quelle vor Ort (Lageabhängigkeit) einerseits und die Nutzung zur Deckung einer Bandnachfrage im Gegensatz zur Spitzennachfrage andererseits.
2) Modell des Energieverbrauchs von Gebäuden, um die Auswirkungen von energetischen Sanierungen zu bewerten und anschließend die Möglichkeit einer Senkung der Verteilungstemperatur auf Primärebene zu untersuchen.
3) Entwicklung einer Simulationsumgebung für Fernwärmenetze, die auf dem Open-Source-Framework pandapipes basiert. Sie beinhaltet ein hydraulisches und thermisches Modell sowie ein Modul zur Identifizierung von Synergien zwischen Teilnetzen, einschließlich Anergienetzen. Die numerische Simulation ermöglicht es, die technische Machbarkeit der Szenarien und das Gleichgewicht zwischen Nachfrage und Versorgung zu gewährleisten.
4) Berechnung von Indikatoren, die für den Vergleich von Szenarien und die Entscheidungsfindung relevant sind, verbunden mit der Erstellung detaillierter Karten für relevante Parameter.

Die vier Achsen wurden in zwei verschiedenen Testfällen umgesetzt, die sich auf bestehende und künftige Netze in den Städten Yverdon-les-Bains und Lausanne beziehen. Die Studien zu den städtischen Projekten ermöglichten es uns einerseits, die Simulationen zu testen und zu validieren, andererseits aber auch, die mit den Umsetzungspartnern gemeinsam erarbeiteten Szenarien zu vergleichen. Die vorgeschlagene Simulationsumgebung ist in der Lage, strömungsmechanische Parameter (wie Strömungsgeschwindigkeiten und Temperaturen) an jedem beliebigen Netzpunkt sowie relevante KPIs (wie Treibhausgasemissionen) für ein gesamtes Stadtgebiet mit mehreren hundert Gebäuden sowie für kleinere Stadtteile in einer vollständig geolokalisierten Weise zu berechnen.

Die sechs wichtigsten Ergebnishorizonte, die im Rahmen dieses Multi-Partner-Projekts erzielt wurden, sind die folgenden:

1) Es wurde eine Simulationsumgebung für getrennte oder verbundene Fernwärmenetze aller Topologien, mit mehreren Temperatur- und Einspeisequellen entwickelt und in komplexen städtischen Gebieten mit einigen Dutzend bis tausend Gebäuden eingesetzt. Diese Umgebung ermöglicht es, die physikalische Machbarkeit der Wärmeverteilung in den untersuchten Gebieten zu überprüfen und eine ganze Reihe von Kennzahlen zu berechnen, die für Energieunternehmen von entscheidender Bedeutung sind, wie z. B. der Anteil erneuerbarer Energien an der Wärmeversorgung und die CO_2-Emissionen im Zusammenhang mit ausgewählten Wärmeerzeugungsszenarien.
2) Einerseits hat der Testfall YLB gezeigt, dass die vorgeschlagenen Fernwärmenetze die Treibhausgasemissionen im Vergleich zur derzeitigen Situation um mehrere zehn Prozent

reduzieren können, je nach dem betrachteten Szenario. Andererseits kann die Einführung von FWN in YLB eine Versorgung von bis zu 80 % durch erneuerbare Energien wie Geothermie und Holz ermöglichen. Es ist jedoch zu beachten, dass die Verwendung von Holz für die Raumheizung und die Warmwasserbereitung in der BFE-Wärmestrategie nicht vorgesehen ist und auf kantonaler Ebene eingeschränkt wird. Schliesslich zeigt sich, dass die Senkung der Verteilungstemperatur von 80°C auf 70°C einen erheblichen Einfluss auf die Reduktion von Emissionen und Netzverlusten hat.

3) Ebenfalls im Testfall Yverdon-les-Bains, aber auch für das in einem Parallelprojekt untersuchte FWN von Neuchâtel, wurde eine umfassende Methodik zur Identifizierung und Nutzung von Synergien zwischen FW-Netzen entwickelt. Es wurde nachgewiesen, dass diese Synergien zu einer Verbesserung der Energie- und Umweltindikatoren führen und teilweise die Probleme lösen, die sich aus der lokalen Nichtverfügbarkeit bestimmter erneuerbarer Quellen ergeben. Die Vorteile im Hinblick auf die Senkung der Investitionskosten bei der Planung neuer Netze sind ebenfalls von entscheidender Bedeutung und bieten neue Forschungsperspektiven für FOSTER_DHN.

4) Es wurde ein Simulationsrahmen für ein Mikro-FWN in Lausanne entwickelt, das die Abwärme eines Rechenzentrums nutzt, und zwar unter Berücksichtigung von Bedarfsmodellierung, Netztopologie und Betriebsstrategien. Die Simulationen untersuchten vier Szenarien mit unterschiedlichen Temperaturniveaus, um insbesondere zu bewerten, wie sich Temperaturänderungen auf die Systemauslegung und den Betrieb auswirken. Zu den wichtigsten Ergebnissen gehört eine erhebliche Reduzierung der Wärmeverluste von 873 MWh/Jahr auf 201 MWh/Jahr im Niedrigtemperaturszenario. Allerdings führte die Temperatursenkung zu einem höheren Stromverbrauch für dezentrale Wärmepumpen, der aufgrund der niedrigeren Leistungszahl bei niedrigeren Temperaturen um bis zu 3890 MWh/Jahr anstieg. Die Analyse ergab auch, dass das erste Szenario (Hochtemperatur-FWN) ein minimales Wärmeleistungsdefizit (86 kW) aufwies, während das dritte Szenario (Niedertemperatur-FWN) mit einem höheren Wärmeleistungsdefizit (190 kW) zu kämpfen hatte.

5) Ein zweiter Teil der Lausanner Testfallstudie konzentrierte sich auf die Integration der Abwärme des Dufour Mikro-FWN in das bestehende Lausanner FWN. Die Studie untersuchte, wie die Abwärme der Swisscom-Rechenzentren (zwischen 1,5 MW und 3 MW) im breiteren Fernwärmesystem von Lausanne genutzt werden kann. Die Integration wurde in mehreren Szenarien mit Temperaturabsenkungen zur Optimierung der Wärmerückgewinnung und Verbesserung der Gesamteffizienz bewertet. Zu den wichtigsten Ergebnissen gehören eine Steigerung des Einsatzes erneuerbarer Energien um 1,5 % und eine Senkung des Erdgasverbrauchs im Lausanner FWN um 9,3 % aufgrund der Integration. Diese Veränderungen zeigen, wie die Einbindung von Abwärme die Nachhaltigkeit des FWN erheblich verbessern kann, insbesondere durch die Verringerung der Abhängigkeit von fossilen Heizquellen. Das kleinere FWN im Südwesten von Lausanne erzielte mit einem Anstieg der erneuerbaren Energien um 2,3 % und einer Verringerung des Erdgasverbrauchs um 24,4 % sogar noch bessere Ergebnisse.

6) Im Rahmen des Projekts wurde weiter analysiert, wie sich die Senkung der Verteilungstemperaturen innerhalb des Dufour micro-FWN auf die Gesamteffizienz des Systems auswirkt. In einem Szenario wurde die sekundärseitige Temperatur von 65°C/40°C auf 55°C/35°C gesenkt, was zu einem Rückgang des Stromverbrauchs für die zentrale Wärmepumpe um 21 % führte. Durch die Senkung der Temperaturen verringerte sich zwar der Wärmeverlust von 872,8 MWh/Jahr auf 718,8 MWh/Jahr, doch führte dies auch zu einem Mangel an Wärmeleistung, wodurch die Wärmepumpe weniger Wärme produzierte. Im Szenario mit dezentralen Wärmepumpen verbesserte die Temperatursenkung außerdem deren COP, während der höhere Wärmebedarf zu einem höheren erforderlichen Durchfluss führte, was den Stromverbrauch der Pumpen erhöhte. Dieses Szenario verdeutlicht, wie wichtig es ist, Temperatursenkungen durch betriebliche Anpassungen (z. B. des Massenstroms) auszugleichen, da übermäßige Temperatursenkungen zu Problemen bei der Deckung des Wärmebedarfs führen können, obwohl die Energieeffizienz verbessert wird.

Résumé

Les quatre questions de recherche fondamentales qui ont sous-tendu l'ensemble des activités du projet FOSTER_DHN sont les suivantes :

1) Dans quelle mesure est-il possible d'intégrer une proportion plus importante de sources d'énergie renouvelables ou bas-carbone dans l'approvisionnement des réseaux de chauffage à distance ?
2) Est-il envisageable de diminuer les niveaux de température de distribution dans les réseaux de chauffage à distance afin de pouvoir intégrer des points d'approvisionnement bas-carbone et de viser une plus grande efficacité énergétique ?
3) Est-il possible de développer un environnement de simulation des réseaux de chauffage à distance entièrement open-source et intégrant plusieurs points d'approvisionnement et allant jusqu'au niveau de détail des sous-stations (échangeurs) alimentant les bâtiments ? Nous donne-t-il accès à une vérification physique des scénarios et à des paramètres opérationnels cruciaux comme les niveaux de température et les vitesses d'écoulement ?
4) Est-il possible d'identifier des synergies entre réseaux de chauffage à distance de tailles différentes et qui sont approvisionnés par des sources d'énergie ayant des caractéristiques de disponibilité et d'impact environnemental de plusieurs natures ?

Les questions de recherche ont été affrontées scientifiquement et systématiquement selon quatre axes :

1) Analyse détaillée des sources d'énergie bas-carbone pouvant servir à alimenter les réseaux de chauffage à distance du point de vue du potentiel global et des limitations. Deux distinctions importantes ont servi de créneau d'étude, à savoir la disponibilité sur site (situationnalité) d'une source donnée d'une part et, d'autre part, l'utilisation pour couvrir une demande en ruban par opposition à la demande de pointe.
2) Modèle de consommation énergétique des bâtiments pour évaluer les effets des rénovations énergétiques et, successivement, d'étudier la possibilité de diminution de température de distribution au niveau du primaire.
3) Développement d'un environnement de simulation basé sur le framework open source pandapipes pour les réseaux de chauffage à distance. Il inclut un modèle hydraulique et thermique, ainsi qu'un module permettant d'identifier les synergies entre sous-réseaux, y inclus des réseaux anergie. La simulation numérique permet d'assurer la faisabilité technique des scénarios et des équilibres entre demande et approvisionnement.
4) Calcul d'indicateurs pertinents pour la comparaison des scénarios et la prise de décisions, couplé à l'établissement de cartes détaillées pour les paramètres pertinents.

Les quatre axes ont été mis en œuvre dans deux cas-tests distincts, à savoir des situations de réseaux existants et futurs dans les villes d'Yverdon-les-Bains et de Lausanne. Les études sur les projets urbains ont permis de tester et de valider les simulations, d'une part, mais aussi de comparer des scénarios co-construits avec les partenaires de mise en œuvre. L'environnement de simulation ainsi proposé est capable de calculer les paramètres de la mécanique des fluides (tels que les vitesses d'écoulement et les températures) en tout point du réseau, ainsi que les KPIs pertinents (tels que les émissions de GES) pour l'ensemble d'un territoire urbain comprenant plusieurs centaines de bâtiments, ainsi que pour des quartiers plus petits de manière totalement géolocalisée.

Les six horizons de résultats les plus importants obtenus dans le cadre de ce projet multi-partenaires sont les suivants :

1) Un environnement de simulation pour des réseaux de chauffage urbain séparés ou connectés, de toutes topologies, multi-températures et multi-sources d'injection, a été développé et utilisé sur des territoires urbains complexes comprenant de quelques dizaines à un millier de bâtiments. Cet environnement permet de vérifier la faisabilité physique de la distribution de chaleur

dans les zones étudiées, et de calculer toute une série d'indicateurs-clé de performance cruciaux pour les entreprises énergétiques, tels que la part des énergies renouvelables dans l'approvisionnement en chaleur et les émissions de CO_2 liées aux scénarios de production de chaleur sélectionnés.

2) D'une part, il a été démontré que les réseaux de chauffage urbain proposés peuvent réduire les émissions de gaz à effet de serre par rapport à la situation actuelle de plusieurs dizaines de pourcentages, en fonction du scénario considéré. D'autre part, la mise en œuvre du DHN dans YLB peut permettre d'atteindre jusqu'à 80 % d'approvisionnement par des énergies renouvelables telles que l'énergie géothermique de moyenne profondeur et le bois. Cependant, il faut noter que l'utilisation du bois pour le chauffage des locaux et la préparation de l'eau chaude sanitaire n'est pas envisagée par la stratégie thermique de l'OFEN et est restreinte au niveau cantonal. Enfin, l'abaissement de la température de distribution de 80°C à 70°C a un impact significatif sur la réduction des émissions et des pertes de réseau.

3) Toujours dans le cas test d'Yverdon-les-Bains, mais aussi pour le CAD neuchâtelois étudié dans un projet parallèle, une méthodologie complète pour identifier et exploiter les synergies entre les réseaux CAD a été développée. Il a été démontré que ces synergies peuvent améliorer les indicateurs énergétiques et environnementaux - par exemple, la part de l'approvisionnement en énergie renouvelable - et résoudre en partie les problèmes liés à l'indisponibilité locale de certaines sources renouvelables. Bien qu'une évaluation précise de la réduction potentielle des dépenses d'investissement grâce aux synergies n'ait pas été possible dans le cadre de FOSTER_DHN et représente une perspective de recherche, les résultats obtenus sur le sous-réseau CAD STEP indiquent clairement que le surdimensionnement des capacités installées peut être évité en exploitant des connexions intelligentes entre les sous-réseaux.

4) Dans le cas-test de Lausanne, l'intégration de la chaleur fatale issue d'un centre de calcul dans un mini-réseau de chauffage à distance a été étudiée en détail, tant du point de vue technique qu'économique et environnemental. Différentes configurations ont été simulées et comparées, notamment en termes de performances de la pompe à chaleur centralisée. La diminution de la température de distribution au niveau primaire permet de réduire les pertes de chaleur ainsi que la consommation électrique de la PAC grâce à un COP amélioré. Une approche systémique par rapport à l'ajustement des paramètres opérationnels est cruciale afin de trouver un équilibre entre la demande énergétique des bâtiments et la consommation électrique liée au CAD.

5) Une deuxième partie de l'étude de cas-test de Lausanne s'est concentrée sur l'intégration de la chaleur résiduelle du micro-CAD Dufour dans le CAD existant de Lausanne. L'étude a examiné comment la chaleur résiduelle des centres de données de Swisscom (de 1,5 MW à 3 MW) pouvait être utilisée dans le système de chauffage urbain de Lausanne. L'intégration a été évaluée à travers plusieurs scénarios, avec des réductions de température pour optimiser la récupération de chaleur et améliorer l'efficacité globale. L'intégration a notamment permis d'augmenter de 1,5 % l'utilisation des énergies renouvelables et de réduire de 9,3 % la consommation de gaz naturel dans le réseau de chauffage urbain de Lausanne. Ces changements ont démontré comment l'incorporation de la chaleur perdue peut améliorer de manière significative la durabilité du DHN, en particulier en réduisant la dépendance aux sources de chauffage fossiles. Le CAD du sud-ouest de Lausanne, à plus petite échelle, a obtenu des résultats encore plus significatifs, avec une augmentation de 2,3 % des ressources renouvelables et une réduction de 24,4 % de la consommation de gaz naturel.

6) Le projet a également analysé comment la réduction des températures de distribution dans le Dufour micro-CAD affecte l'efficacité globale du système. Dans un scénario, la température du côté secondaire a été réduite de 65°C/40°C à 55°C/35°C, ce qui a entraîné une diminution de 21% de la consommation d'électricité pour la pompe à chaleur centrale. Cependant, si la réduction des températures a permis de diminuer les pertes de chaleur de 872,8 MWh/an à 718,8 MWh/an, elle a également entraîné un déficit de puissance thermique, avec la pompe à chaleur produisant moins de chaleur. En outre, dans le scénario avec des pompes à chaleur décentralisées, la réduction de la température a amélioré leur COP, tandis que la demande de chaleur

accrue a entraîné un débit requis plus élevé, augmentant la consommation d'électricité de la pompe. Ce scénario a donc mis en évidence l'importance d'équilibrer les réductions de température avec des ajustements opérationnels (par exemple, le débit massique), car des réductions de température excessives peuvent conduire à des difficultés pour répondre aux demandes de chauffage, même si l'efficacité énergétique s'améliore

Main findings («Take-Home Messages»)

1) While it was already known in the scientific literature that renewable and low-carbon energy resources can play a significant role in the supply of district heating networks, the project has studied detailed implementation of the former in two Western Switzerland cities. In particular, scenarios have been proposed that allow to reach renewable shares as high as 80%
2) Identifying and exploiting synergies among subnetworks by suitable connections allows a larger share of supply by renewable energy sources by approximately 10 to 15% in one of the studied cities. The crucial role of exploiting localized energy sources has been analyzed and identified as a possible constraint.
3) A detailed study of the integration of data center waste heat to supply a new micro-DHN has identified the operational constraints in realistic conditions and shown to lead to decreasing usage of natural gas (by approximately 10%) and reduced GHG emissions (by few percents).
4) Lowering the distribution temperatures in a studied micro-DHN reduces central heat pump electricity use by 21% through improved COP. Integrating waste heat into the Lausanne DHN shows that high-temperature operation (3 MW, COP 2.9) increases electricity use, while low-temperature (1.5 MW, COP 3.6) reduces it, cutting gas consumption by 9.3% overall and 24.4% in the southwest network. Lowering distribution temperatures on a larger urban DHN has been shown to allow decreasing GHG emissions by 10 to 20%.

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CAD : Chauffage à distance
COP : Coefficient of performance – Coefficient de performance
DHN : District Heating Network
DIREN : Direction de l'Energie (Canton de Vaud)
DHW : Domestic Hot Water
FSO : Federal Statistical Office
FWN : Fernwärme Netzwerk
HP : Heat Pump
MWIP : Municipal Solid Waste Incineration Plant
SEY : Services des Energies d'Yverdon-les-Bains (Yverdon Energies)
SFOE : Swiss Federal Office of Energy
SIL : Services Industriels de Lausanne
STEP : Station d'épuration des eaux
WWTP : Wastewater Treatment Plant
YLB : Yverdon-les-Bains

1 Introduction

1.1 Context and motivation

The overall purpose of the FOSTER_DHN project is to explore a selection of territorial solutions for DHN, leading to an increase in the implementation of renewable and fatal energy sources and to a decrease in the distribution temperature levels. Such an effort, aimed at both existing as well as new infrastructures, needs to be attained by a series of technical actions, such as the replacement of existing fossil-based boilers or the refurbishment of residential units, but also by a careful and thorough planning of the deployment in the neighbourhoods.

In order to attain these purposes and, most of all, to verify the physical feasibility of the proposed solutions, numerical tools have been either developed or adapted. The academic partners have also relied on existing tools, as well as on their direct experience in this field. They have extensively work with input urban data stemming from the two partner cities located in the Canton of Vaud, namely Yverdon-les-Bains and Lausanne, both at the demand, as well as the supply level.

Synergies between DH networks have been thoroughly investigated and exploited within an innovative approach. The integration of renewable energy sources, as well as waste heat potentials, such as those stemming from data centers have been at the core of the scientific investigations.

1.2 Project objectives

FOSTER_DHN project consists of a three-pronged approach aimed at addressing the following issues:

1. maximize the penetration of DH networks in urban areas
2. increase efficiency by lowering distribution temperatures, enabling the integration of new energy sources and reducing network losses
3. improve the environmental footprint of this technology, notably by making greater use of available renewable energies sources and waste heat

The project team has been working in close contact with two partner cities in order to develop data, scenarios and indicators, as well as with the Energy Directorate of Canton de Vaud (DIREN).

In addition, both research institutions involved in FOSTER_DHN are currently working witihin the SWEET DecarbCH program, which is exploring all possible ways of decarbonizing the Swiss heating sector and reducing its overall consumption, including the increased use of DHN systems. Interactions with and learnings gained from this program, as well as the ongoing SFOE-co-funded project T-DROP, led by HEIG-VD, are discussed in the chapters below.

The district heating networks managed and planned for the coming years by Yverdon Energies have been considered as the first test case for this project, in order to validate the FOSTER_DHN approach in an urban situation where most district heating networks are still in the planning and design phase, with commissioning scheduled within the next 5 to 10 years. The project's second test case has focused on the development of a new DHN network fed by thermal waste from a computing center in Lausanne. In addition to the study of this specific case relevant to the project's objectives, its integration into the historical broad DHN network operated by Services Industriels de Lausanne will also be addressed.

Finally, a third case study has been realized focusing on the DHN system of a town in the Canton of Neuchâtel, as part of a master's thesis carried out at HEIG-VD (see Appendix).

Hence, the project results cover both new DH network developments, as well as issues related to existing infrastructures, where questions related to renewable energies integration and decreasing distribution temperatures is particularly challenging.

2 Approach, method, results and discussion

2.1 Procedures and methodology

2.1.1. Overview of existing tools for DHN simulations

The numerical simulation tools of hydraulic systems generally represent a well-developed area, with powerful FEM fluid-simulation softwares both in the market, as well as in academic research centers. However, a heavily detailed orientated simulation is usually not recommended when simulating whole fluid networks, like urban water distribution grids. For example, softwares such as TRNSYS allow performing rather general simulations of large networks, focusing on fluid behaviour oat junction level.

TRNSYS was developed at the University of Wisconsin original for the simulation of solar thermal systems. It was fist established in 1975 and has created over the time a rather large user base. Today TRNSYS focuses on the simulations of whole heating systems with the integration of modular construction. It enables the simulation of district heating network by thermal and hydraulic simulations. It operates as a closed standalone program based on FORTRAN and C++, and a paid license is required for usage.

STANET is a hydraulic simulation tool developed by stafu for the simulation of gas, water, and electricity distribution grids. However, a “special version” has been developed for alternative grids like district heating, steam or CO_2, the focus is on the hydraulic aspect. STANET offers a wide range of compatible import structures to integrate STANET into your local simulation environment. The district heating association “Thermische Netze” recommend the use of STANET, but also estimate the effort to use it as “high”. A license can probably be acquired free of charge for research projects.

Neplan is an all-in-one energy distribution simulation tool, combining electricity, fluid, and heat distribution as well as asset management. Neplan is a standalone software focusing on their user interface and customer service. NEPLAN is already widely used in energy utilities to determine bottlenecks and actions against it.

DistrictLab is a French DHN simulation tool that has been adopted by a few Western Switzerland utilities. It can provide very detailed hydraulic calculations, including behaviour of single components, such as exchangers, valves. It requires highly skilled personnel to be used in conjunction with planning software.

Finally, TESSA is a Swiss tool, developed in collaboration with UNIGE and other Western Switzerland utilities. It provides a map-based interface facilitating user interactions (e.g. data, network topology) while fluid mechanical parameters remain somehow “backstage” and the basic time granularity appears to be far higher than hourly or even daily.

Other simulation tools are, among others: Dymola, THENA (Excel-based), Sophena, Urbio and Symphony. Like the former ones, all require some kind of paying license outside academic research projects and are thus to be considered as closed-source environments. An excellent review of physically-based simulation and optimization models for DHNs has been recently proposed by Boghetti et al[1] [1]. In the latter paper, the authors propose a novel python-based software library coupled with a dynamic model to simulate complex DHN networks and validate the approach on an existing DHN situated in Valais. A broad list of references of various simulation and optimization models used in the field of DHN has been compiled by I. Sarbu et al[2] [2], no more recent reviews being known to the authors of the present report.

Pandapipes is a network calculation program aimed at automation of analysis of district heating and gas systems developed by the Fraunhofer Institute. It is written in Python and based on the data analysis library pandas and is also closely related to the power systems calculation tool pandapower. In addition, pandapipes and pandapower can be used in combination to analyze multi-energy networks. Both tools are also open source and licence free and are supported by a relatively large user community.

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[1] R. Boghetti et al, Energy 290 (2024) 130169 [1]

[2] I. Sarbu et al, International Journal of Energy Research 43 (2019) 6572 [2]

At the beginning of the project FOSTER_DHN, different requirements were identified, in order to check if an existing tool can be used and integrated in the project. The simulation framework developed for the project must allow analyzing separated district heating networks by enabling mass or heat transfer between them at specific determined time periods and detecting synergies with other networks. It is therefore beneficial to rely on tools that are open source and operate in a system that enables changes and to add models. In this respect, pandapipes has been selected for the Yverdon-les-Bains test-case, also based on previous extensive experience of the HEIG-VD research team with a space granularity down to the building level and an hourly time resolution.

In parallel, a python-code has been developed within the Lausanne test-case, that allows to directly simulate the integration of waste heat in a small, local DHN in a very detailed, building-by-building and pipe-by-pipe basis. On the other hand, this python code is well-suited to analyze the connection of the local DHN to the citywide existing and high-temperature network managed by SIL and to explore various scenarios in terms of network operation.

2.1.2. Presentation of general approach and introduction to test-cases

The overall objective of the FOSTER_DHN project is to study how to integrate an increasing share of renewable energy sources – such as wood or stemming from underground and lakes – or waste heat sources – e.g. from data centers or wastewater treatment plants – into existing and new district heating networks. In this context, the project aims at exploring possible lowering of distribution temperatures on the primary side of the DH networks (i.e. before the heat exchangers at consumer's level) and at identifying synergies among networks or subnetworks as to reach maximal utilization of low-carbon heat sources first (merit-order operation).

The project is structured in three work packages overlapping each other within a global approach to DH networks planning, dimensioning and operation.

First, **WP1** has allowed exploring a variety of renewable and low-carbon energy sources that can replace fossil energy sources in the heat production of DH supply systems. The analysis has been performed based on official documents from federal authorities and branch associations, as well as relying on a series of direct interviews performed within the project. A clear distinction has been drawn between baseload and peak operation, with the former giving way to far more options for substitution with renewable energies such as wood and heat harvested from the environment or a fatal energy source. WP1 lays down ground for the other WPs by identifying the low-carbon alternatives that are then considered.

In **WP2**, the possible decrease of distribution temperatures on the primary side of DHN has been explored, in connection with other ongoing projects. Indeed, second and, partly also third generation DH networks are operated at rather high forward temperatures ranging between 130°C and 80°C. This situation often stems for historical reasons (e.g. a DHN supplying an hospital including the heat demand required for sterilization) or for other contingent, local specificities. Among those, if preparation of DHW is provided by a DHN, distribution temperature usually is higher than 65°C or 70°C because of legionnellose generation prevention measures. Hence, FOSTER_DHN has studied some situations related to temperature decrease in the networks, notably in connection with the integration of renewable sources like heat stemming from a wastewaster treatment plant, geothermal energy and waste heat. The project, however, did not analyze possible impacts on the substations and on the secondary side, because these issues are out of scope and are being studied in the partner projects.

Finally, within **WP3**, two open-source python codes have been developed to tackle the planning of DH networks in urban zones. The first code has been specifically designed to study the integration of a waste heat resource for the development of a local subnetwork, including the connection to the return path of a larger, existing high-temperature network. The second code, based on pandapipes libraries, allow the full evaluation of energy balance and detailed hydraulic simulation of a complex citywide DH network, composed of four subnetworks, including an anergy loop fed by the local wastewater treatment plant. The latter code allows to consider multiple heat injection points, as well as multiple temperature levels of operation. Results stemming from the codes are then displayed on maps within GIS-based tools with a series of computed KPIs such as heat demand covering over time and space, renewable energy sources merit order and CO_2 emissions avoided.

All the elements developed in the three work packages have been used in synergy within two test-cases in real urban situations. The goals of the latter are indeed threefold:

1) Test the codes with real demand and supply data and large datasets
2) Validate code ability to compute meaningful results with reasonable computational power/ time
3) Elaborate and compare scenarios in close collaboration with local utilities

Hence, most of the results of the project have been produced within the two test-cases, with the possibility to reproduce the same approach to other urban territories in Switzerland.

Test-case Yverdon-les Bains

The city of Yverdon-les-Bains, an industrial town of approximately 30'000 inhabitants situated on the southern extremity of the Lake of Neuchâtel, is presently heavily dependent on natural gas for buildings heating. It ambitions to transition to renewable energy sources to cover heat demand by a proportion of at least 80% by 2050, mainly relying on four district heating networks, that may operate together as a single "big loop". Two of these networks (CAD STEP and Lotus) already partially exist today, as will be explained in more details below. Main supplies for the DHN in terms of energy should be geothermal energy – extensive campaign to evaluate geothermal potential is currently underway –, heat generated from local wastewater treatment plant and wood, complemented by limited amount of natural gas (to be used either in boilers or in large CHP systems). Hence, Yverdon-les-Bains test-case showcases two main aspects:

1) the thorough study of the deployment of new infrastructure over a given urban territory (including the effects of buildings refurbishment over time and construction of new estate) by taking into account the merit order imposed by renewable and low-carbon heat sources (with a granularity at the level of substations and hourly supply);
2) the possible synergies among the subnetworks in order to reach optimal generating capacities and maximal use of situational (localized) heat resources (e.g. geothermal), according to the new cantonal heat strategy for Vaud.

Test-case Lausanne

The city of Lausanne, a metropolitan center of more than 140'000 inhabitants, is situated on the shores of Lake Geneva and is one of the first cities in Switzerland, together with La Chaux-de-Fonds, to have built a large district heating network, originally intended to supply the local university hospital in the northern part of town. Hence, the distribution temperature of the DHN have historically been very high (> 150 °C), with the willingness to decrease them over time. The original DHN has then been operated together with other networks, in particular the one supplied by the Vidy wastewater treatment plant, located on the southwestern suburbs of Lausanne. The construction of a Swisscom data center close to the central railway station has opened up the possibility to create a small low-carbon heating subnetwork, potentially connected to the historical citywide DHN. The Lausanne test-case thus allows:

1) the designing and dimensioning of a relatively small DH network supplied by baseload waste heat provided at approximately 20°C in free-cooling mode and around 40°C in forced-cooling mode, based on different scenarios and detailed heat demand of the connected buildings (approximately 30);
2) the identification of possible operational modes that could lead to the connection of the small network to the large high-temperature DHN (albeit with possible lower distribution temperatures on the primary side).

2.2 Methodology for python code based on pandapipes

For large scale district heating network simulations, which give both overall system but also detailed operational results, a power flow simulation tool can be used. The purpose of the developed tool, is to simulate a district heating network which consists of more than one sub-grid, multiple heat sources and injected temperature levels.

The simulation tool used in this project for a city sized test case of a district heating network is based on the pipeline grid solver pandapipes[3] [3]. The simulation tools developed for the project FOSTER_DHN can be separated into three parts, as shown on Figure 1:

1) Input data
2) The hydraulic model
3) The thermal model

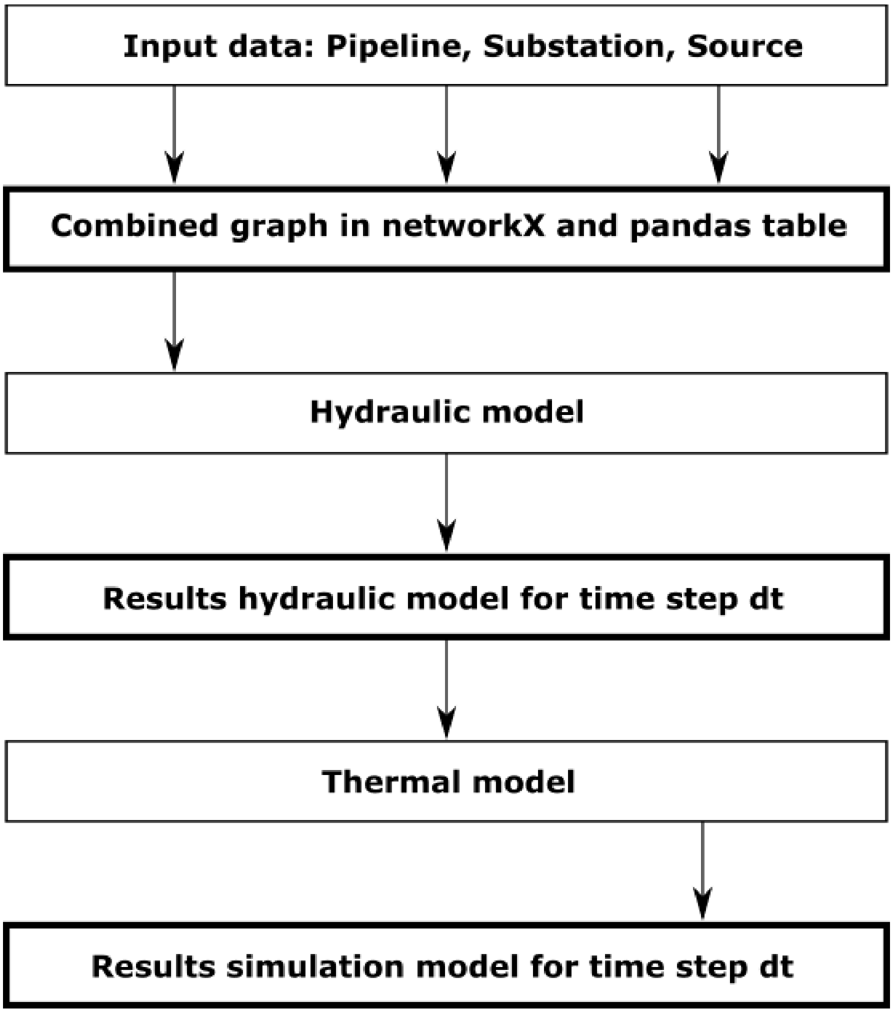

Figure 1 : Basic structure of the pandapipes based simulation tool

The first part is the provision and creation of input data, consisting of information about the pipeline grid, the substations and heat sources. The input data are transformed towards a structure which can easily be read by pandapipes. The generated pipeline graph is then firstly solved with a hydraulic model to

[3] D. Lohmeier et al, Sustainability 12 (2020) 9899

determine the mass flow and pressure level in the grid. If the hydraulic model gives a reasonable solution, the results of the hydraulic model are used as input data for the thermal model. In the thermal model the heat transfer is calculated based on the mass flow determined in the hydraulic model, the heat demand on the substation level and the temperature level at the heat sources.

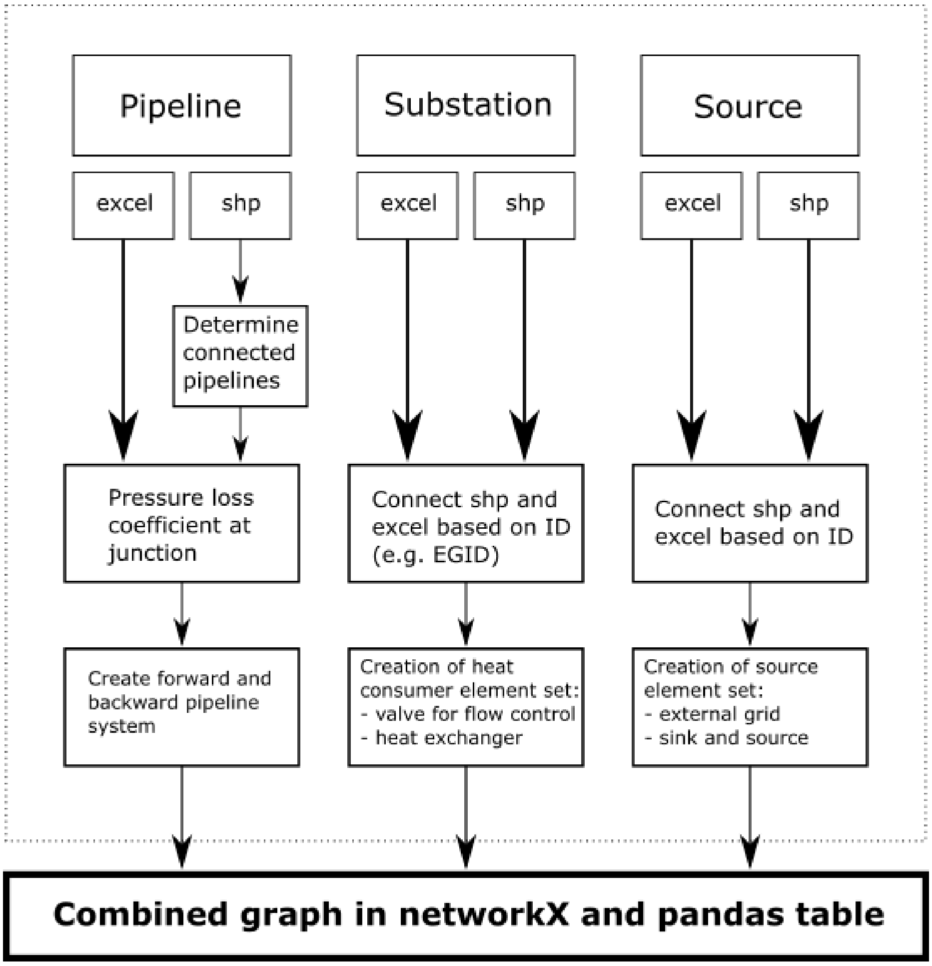

Figure 2 : Structure of the input data layers and modification

2.2.1. Methodology for python code based on pandapipes – Input data

The simulation tool requires three layers of input data considering of shapefile and excel format files (see Figure 2). The shapefile documents are generally used for their geographical coordinates which are used to determine the topology of the grid and connect the different input layers. In addition to coordinates, the shapefile needs to provide a unique id for each element, which can be used as a key to combine information from the excel file and the shapefile.

In the excel file, information about the grid is stored, which may either change during the development of the tool by becoming more precise, or parameter that change over time. This separation of data layer is chosen, since its more convenient to work on geographical information with a GIS software, while its easier to store and manipulate attributes in tables like excel files. The concept of input data with its three layers is illustrated in Figure 2 and defined in the following subchapters.

2.2.1.1. Pipeline layer

The first layer describes the topology and pipeline related information of the district heating network. In a shapefile the geographical location of the pipelines describes the topology of the grid, by assuming pipelines with similar geographical coordinates for their starting or ending nodes, are connected. Based on the angle of connected pipelines at each junction of the grid, an elbow loss coefficient is calculated to determine the behaviour of the flow at the junction. The shapefile also requires the information about the DN (*diamètre nominal)* of each separate pipeline, which is used as a key to the pipeline related parameters based on their DN, given in a separate excel file together with the elbow parameters. Different predefined insolation materials are implemented in the model for the pipelines, which can be selected by adding a key for each pipeline refereeing to each material in the shapefile.

When the general pipeline graph is created, the graph is duplicated in order to create a forward and a backward pipeline system.

2.2.1.2. Substation layer

In the substation layer, a shapefile gives the coordinates of the substations together with a unique id, which can be the EGID of the connected building. In the excel file substation related data are stored shown in Table 1, which are either fix or given for each time step separately.

Table 1 : Substation input parameter

Attribute	Type	Unit	Time dependant
Substation ID	Str/float/int	-	No
Heat exchanger diameter	Float	m	No
Installed Power	Float	W	No
Heat demand	Float	Wh	Yes
Mass-flow	Float	m^3/h	Yes
Temperature	Float/int	K	NO *
CAD name	str	-	No

The shapefile and excel files are connected via the substation id and based on the parameters of the excel file the required elements of a substation are created. For each substation a valve and a heat exchanger are modelized.

2.2.1.3. Station layer

The third layer gives the information of the heat sources for the heating network. As for the other layers, the shapefile only provides geographical coordinates and a unique id for each heat source.

Table 2 : Station input data

Attribute	Type	Unit	Time dependant
Source ID	Str/float/int	-	No
Installed Power	Float	W	No
Temperature	Float	K	No *
Pressure	Float	W	No *
Power	Float	Wh	Yes
Load Distribution	Float	%	Yes
CAD name	Str	-	No

The excel file stores the physical parameters given in Table 2, which are also either time-dependent or fixed. For each source an external grid is created to fix temperature and pressure at this point, in addition a source and a sink is modelized from where the heated water is entering the forward network and towards the water is leaving the network from the backward network. The attribute load distribution indicated the percentage each source power is responsible of the total heat demand of the grid.

The three layers are finally combined by connecting the forward and backward network with the heat exchanger of the substations and the sink of the source to the backward and the source to the forward network. The data is stored in pandas tables and as a networkX graph to make sure connectivity is given and as a straightforward way to use the pipe-flow simulation in the next step.

2.2.1.4. Merit Order

The load distribution and power parameter mentioned in the previous part have to be either indicated directly or be determined by conditions. In this project, a merit order-style control strategy was used to order the usage of the variety of heat sources in the thermal grid. In a first step, each heat source is ordered based on specific conditions like greenhouse gas emissions and availability of the primal energy resources. In general, these conditions can be time depending to create a different order based on the nature of the primary energy. The availability for wood might vary over the year, as does the GHG emission factor for electricity over even day and night. Based on a lack of data, the input data are assumed to be constant over the whole year. Then in a second step, the total heat demand of the interconnected network is calculated and the production of the heat is divided over the available heat capacity of each source based on the condition of the merit order. The last considered heat source, which is not operating in full load, will be used as variable source to cover inaccuracies in heat demand calculations and heat losses in the grid. It is therefore important to verify at the end if no source uses unreasonable heat capacities, since the condition of the heat capacity is not used for the variable source but only for the full load sources.

2.2.1.5. Synergy functionality

The synergy functionality requires a fourth layer in the input data: the connection layer. This layer represents connection points where the different sub-grids have a possible inter-connection. These connection points can either be a hydraulic connection with a valve or a heat exchanger where only heat is transmitted between the sub-grids. The only attributes required for this layer are the geographical coordinates, which have to match the coordinates of the connecting pipeline nodes of both sub-grids, the form of connection (hydraulic/heat exchanger) and a unique id.

As previous mentioned, the control strategy is either manually implemented or imposed by the merit order for each separate network as standalone district heating network. For each time step the heat balanced of each network is analysed and searched for missing heat capacities to supply the sub-grid internal heat demand. The missing heat is then covered with available heat capacities of a neighbouring sub-grid that shares a connection point. This form of synergy represents a rather important form to enforce a functioning grid operation and allow smaller grids to have lower heat capacities by not requiring to enforce the covering of each possible heat demand peak.

After the heat production is adapted to cover the heat demand in all sub-grids, the emission of the heat production in each sub-grid for each used and available heating technology is analysed (see a simplified concept in - Concept of synergy functionality in the large-scale district heating simulation frameworkFigure 3). Each technology is ranked based on the merit order for their emission and availability. If a technology is selected in a sub-grid that is ranked lower in the merit order than a technology in a neighbouring network with available free heat capacity. The available heat technology capacity is used until either the lower ranked technology is not used anymore or the higher ranked technology uses its full heat capacity. This process is repeated until no merit order difference exists anymore between technologies of possible connected sub-grid. With the help on this second form of synergy between sub-grids the emission and availability of the primary energy use can be improved for the network as a whole.

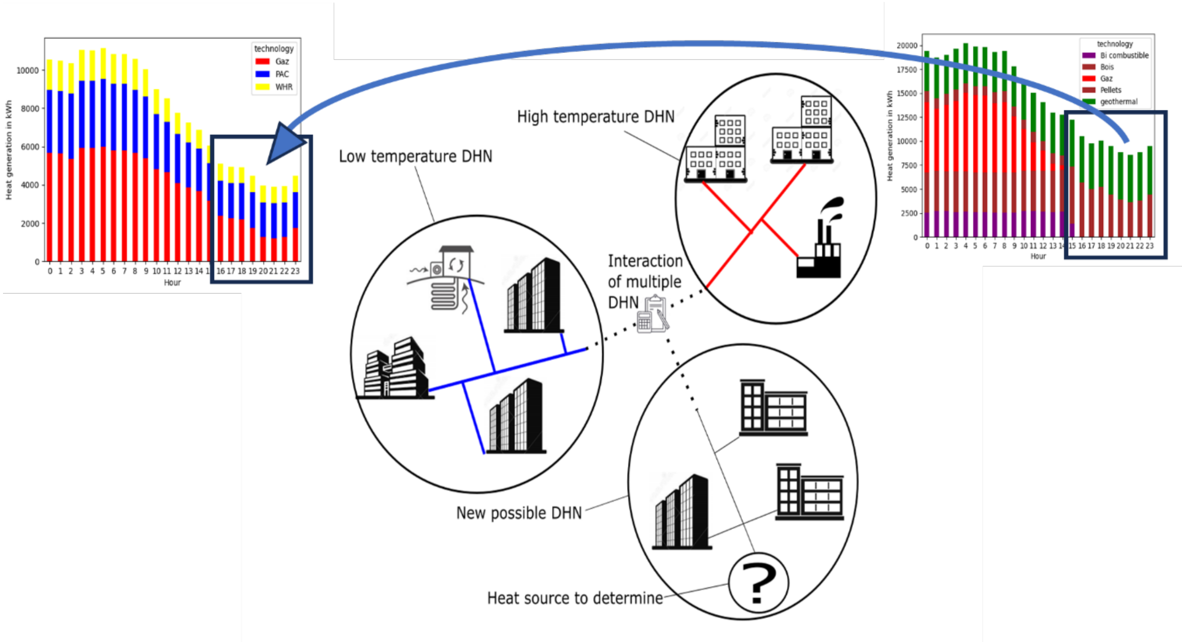

Figure 3 : Concept of synergy functionality in the large-scale district heating simulation framework

Whenever one of the two synergy forms are detected the valve in the connection point is opened and a heat transport between the two sub-grids is enabled. The above descripted functionality for synergy between different separate operating district heating sub-grids has been developed in the scope of a MSc thesis for a more detailed description see chapter 7.2.

2.2.1.6. Definition of pressure pump source

The pressure level in each heating network is set by a pressure pump. If only one source is available in a network, the pressure level can be determined by calculating the pressure drop to the least favourable point in the grid[4] [4]. However, if different heat sources are available in the grid, with different operational usage, the least favourable point varies in the grid. One source has to be selected to set up the operational pressure in the grid, all other sources injecting their heat via the determined mass-flow with the local pressure level into the grid.

2.2.2. Methodology for python code based on pandapipes – Hydraulic model

The created network tables are directly used for the hydraulic simulation, with the mass flow demand for each substation and the operational data for each source station, both also provided from the input data as shown in Figure 4. The mass flow at the source is determined with the sum of all substations and the load distribution parameter given for each source.

The hydraulic model is then simulated with the network data created in the previous step, and the pressure and mass flow data at the source. To ensure the mass flow at each substation (c), the pressure loss coefficient is manipulated by way of the valve connected to each substation. Whenever the simulation results in a wrong mass flow for a substation, the coefficient is iterative adapted for each substation (c) separately until an acceptable tolerance is reached. This process is repeated (after the thermal model) for every considered time step with changing mass flow at substation level and load distribution

[4] Handbook on Planning of District Heating Networks, Swiss Federal Office of Energy SFOE [4]

at source level. The pressure at the source is considered to stay constant over time, which may change in a future version.

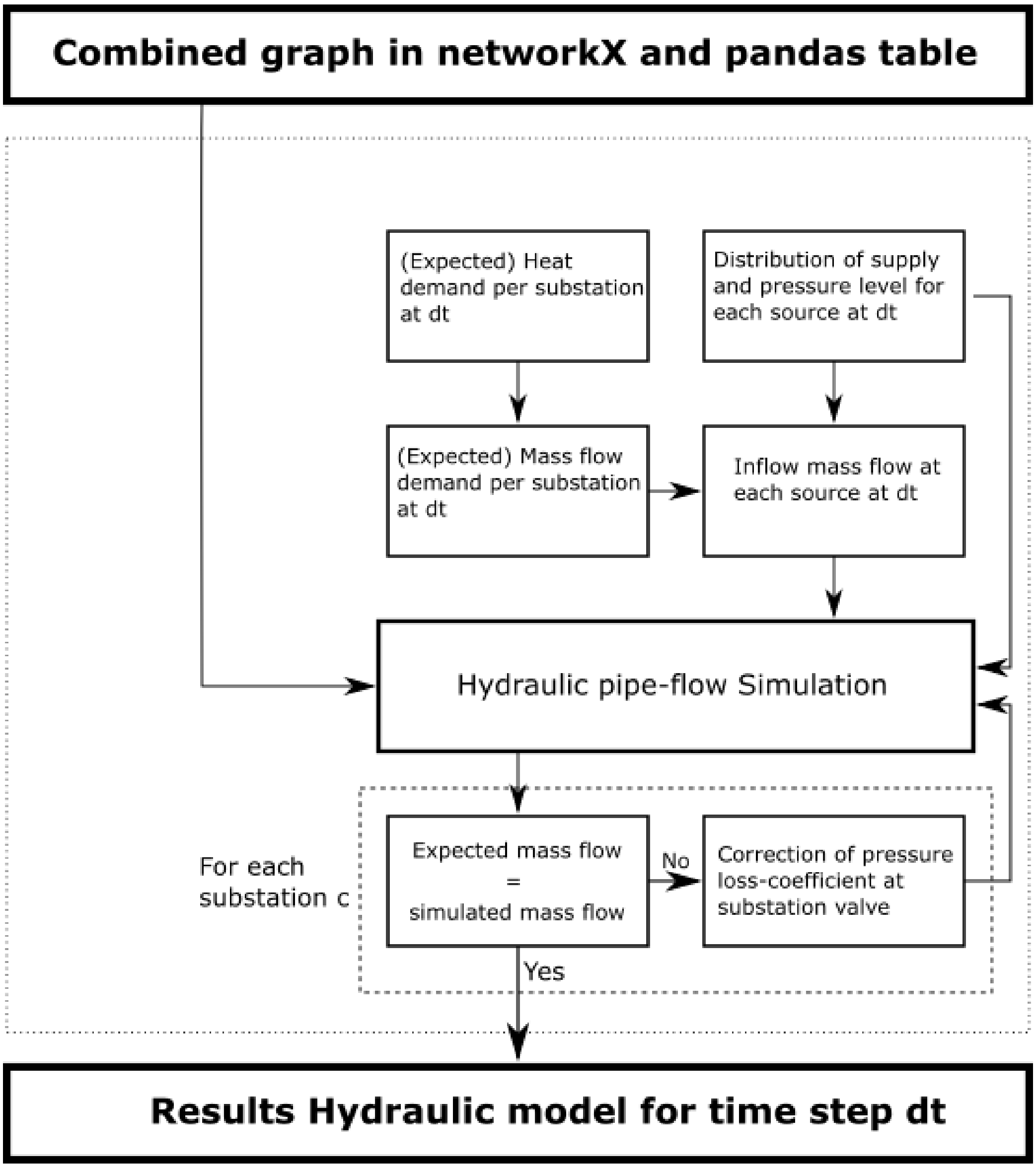

Figure 4 : General structure of the hydraulic model of the pandapipes based simulation tool

2.2.3. Methodology for python code based on pandapipes – Thermal model

The result of the hydraulic model provides a stable foundation to simulate the thermal model (see Figure 4). The heat exchanger at every substation is modelled to deduct the heat demand at each substation from the fluid passing through. It is important that the mass flow used in the hydraulic model was determined accurately, so the mass flow is able to deliver the required heat based on the temperature level in the section of the network. A combined thermal and hydraulic simulation is done with the heat demand at each substation, the corrected input data from the hydraulic model and the temperature level at the source. If the result of the thermal simulation gives heat exchangers with temperatures returning to the grid of below a specific temperature, the result is considered as faulty. The heat demand at this substation is updated iterative by using a temperature change $dT = T_{enter,c} - (T_{return,c} + T_{correction})$.

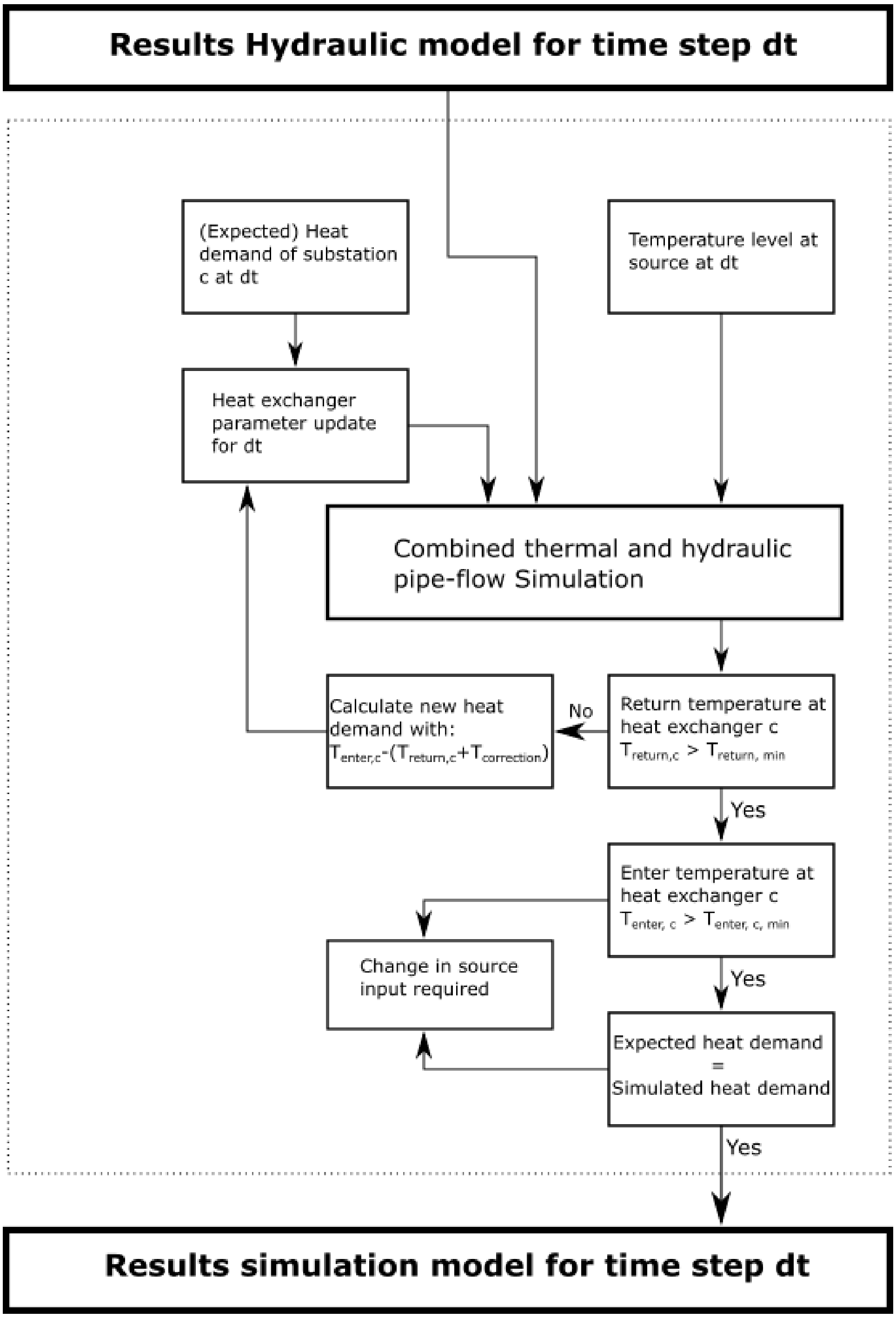

Figure 5 : General structure of the thermal model of the pandapipes based simulation tool

After ensuring that the return temperature of the heat exchange is physically correct, the enter temperature is evaluated at each substation to fit the desired temperature level. By choosing a $T_{correction}$ small enough, the tolerance in the change of heat supply might be acceptable. If the discrepancies between the expected and the simulated values for either the temperature level or the heat supply at any substation is continuous greater than the accepted tolerance, the network seems not to be capable to operate with the temperature and load distribution considered for the network heat sources. Otherwise, the results of the simulation provide a valid solution for the network and gives insights on many physical data and behavior of the network over time and changing operation.

2.3 Methodology for code used in Lausanne test-case

2.3.1. Methodology for code used in Lausanne test-case – Overview

In this section, we aim to address the heating demand in a specific neighborhood of Lausanne – the Dufour neighborhood - which is currently not connected to the existing Lausanne District Heating Network (DHN). The main idea is to recover waste heat generated by a data center owned by Swisscom and to distribute it to the buildings of the neighborhood. A visual representation of the neighborhood is presented in Figure 6.

To achieve this, we developed a simulation framework for design and operation of a micro–District Heating Network (DHN) that will efficiently distribute the data center's excess heat to meet the heating requirements of buildings within the case study area. In addition, we introduced 4 different scenarios for assessing the impact of temperature reduction on the design and operation of micro-networks.

This approach not only reduces energy waste but also offers a cost-effective and environmentally friendly solution for meeting the heating demands of these buildings.

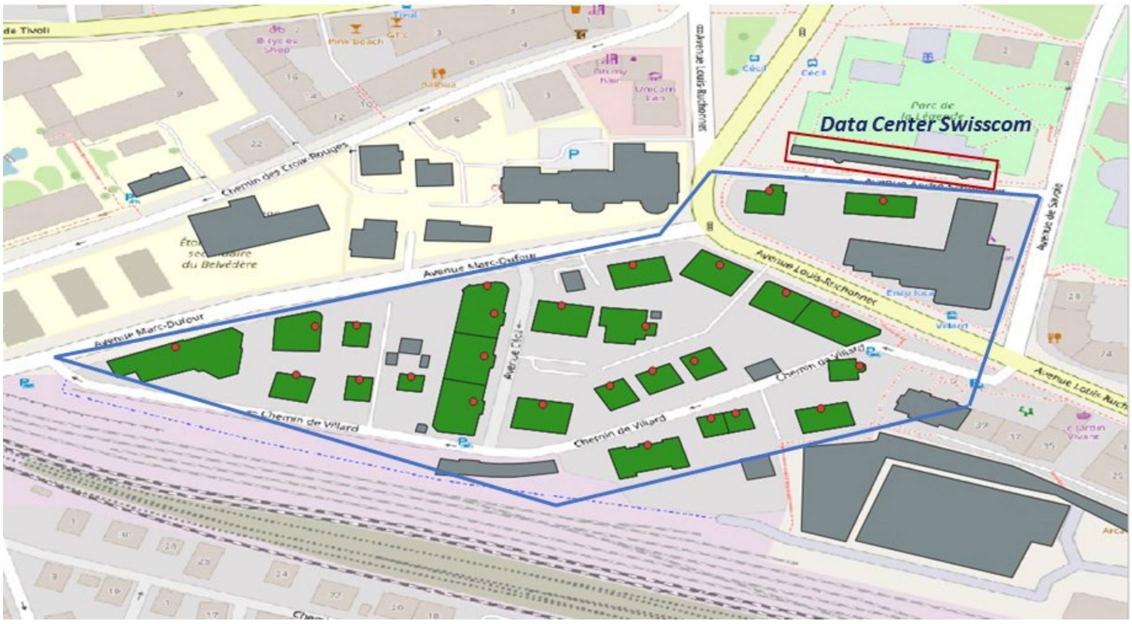

Figure 6 : Visual representation of buildings and resources in the neighbourhood of the case study.

The methodology developed for addressing the problem under study comprises three key steps, outlined as follows:

1) Demand Model
2) District Heating Network Topology Design
3) District Heating Network Simulation

The schematic of the proposed methodology is depicted in Figure 7, with each step detailed in the following subsections.

2.3.1.1. Demand model

In the first step, the total heating demand of buildings has been determined, taking into account both space heating and domestic hot water requirements. To achieve this, the required building data are provided by the local multi-energy utility, namely Service Industriels de Lausanne (SIL); they include: EGID, building usage, construction year, measured annual energy consumption and calculated surface. It is worth mentioning that most of the buildings in this considered area are old and that their specific energy consumptions are very similar. By using the data provided by SIL and the characteristics of each building, the hourly external temperature and using the SIA standard[5] [5], both space heating and domestic hot water hourly demand are calculated for one year for each building. More details on the applied method can be found in[6] [6]. Subsequently, the results are validated using data obtained from the SIL.

2.3.1.2. District Heating Network Topology Design

In the second step, a DHN topology model was developed to identify the most efficient piping routes for establishing a district heating network that connects resources to buildings. The model for optimizing the DHN topology and identifying the optimal piping routes was developed in Python using libraries such as GeoPandas[7] (geospatial data treatment), as well as network and graph theory concepts. A more detailed explanation of the model is provided in Section (2.3.3. Methodology for code used in Lausanne test-case – Code implementation).

To model the network, geospatial data for the case study neighbourhood - comprising building locations, heat resources (in this case, waste heat from a data center), and street network - were imported. Buildings and resources were connected to the DHN by linking them to the nearest network access points, allowing to construct a comprehensive graph representing the DHN.

This initial network included all potential routes across the neighbourhood's streets. The DHN was then refined by removing unfeasible piping routes based on civil engineering constraints, a process conducted in consultation with SIL. To determine the piping routes that minimize the length of the DHN piping, the Steiner tree method was applied to the initial network, facilitating the definition of the DHN topology.

2.3.1.3. District Heating Network Simulation

After identifying the buildings' demands and the DHN topology, the outputs of these two models are imported into the DHN simulation framework with the goal of determining the optimal dimensions and operation of the DHN. This model comprises two sequential sub-models: the design model and the operation model.

In the design model, the optimal diameters of each pipe are determined with the objective of minimizing the investment cost of the DHN. In this model, energy and mass balance constraints are applied to each node of the DHN, including intersection nodes. It is important to note that the maximum heat power demand of each building is considered in this model. The target pressure loss (TPL) for pipes is set at 200 Pa/m, and a sensitivity analysis is conducted to assess the impact of different TPL values.

Nominal pipe diameters, as an output of the design model, are then used in the operation model, which accounts for the dynamic demands of the buildings. In the operation model, four operational days (equivalent to 96 hours) representing the four seasons are considered to cover a variety of weather conditions. In similar fashion to the design model, energy and mass balance constraints are applied to each node but for each hourly time step. Furthermore, the dynamic pressure drops of each pipe and the energy loss for each pipe are calculated during the operating hours. Ultimately, the hourly profiles of heat power including heat loss and mass flow for each pipe are computed to minimize DHN electricity consumption.

[5] SIA 380/1 standard [5]

[6] M. Wenger, HES-SO Valais Wallis, 2022 [6]

[7] https://geopandas.org/

As a result, the total net present cost of the DHN is calculated, taking into account both investment and operating costs. Additionally, the final parameters are determined based on the outcomes of the simulation models.

As previously mentioned, we have introduced four scenarios in this phase of the project to evaluate the impact of reducing the DHN temperature on its performance. These scenarios are based on the status of Swisscom's data center cooling system and the configuration of both central and decentralized heat pumps. In consultation with Swisscom, it was confirmed that the company operates two separate cooling networks for its data center:

1) Direct Free Cooling (Ventilation): This is a cold distribution network that directly cools the data center by supplying water at 16°C and returning it at 22°C. The network maintains a stable temperature range of 16–22°C throughout the year, with a cooling capacity of 1800 kW.
2) Indirect Cooling System: This system includes two separate networks that adjust based on external temperatures. From November to June, indirect free cooling with air cooling operates between 20–14°C. From June to November, mechanical cooling operates at a temperature range between 45–39°C. It is worth mentioning that the temperatures of the mechanical cooling system are not fixed. Based on Swisscom's recommendation, we have considered 40°C as the hot side output temperature of the cooling system.

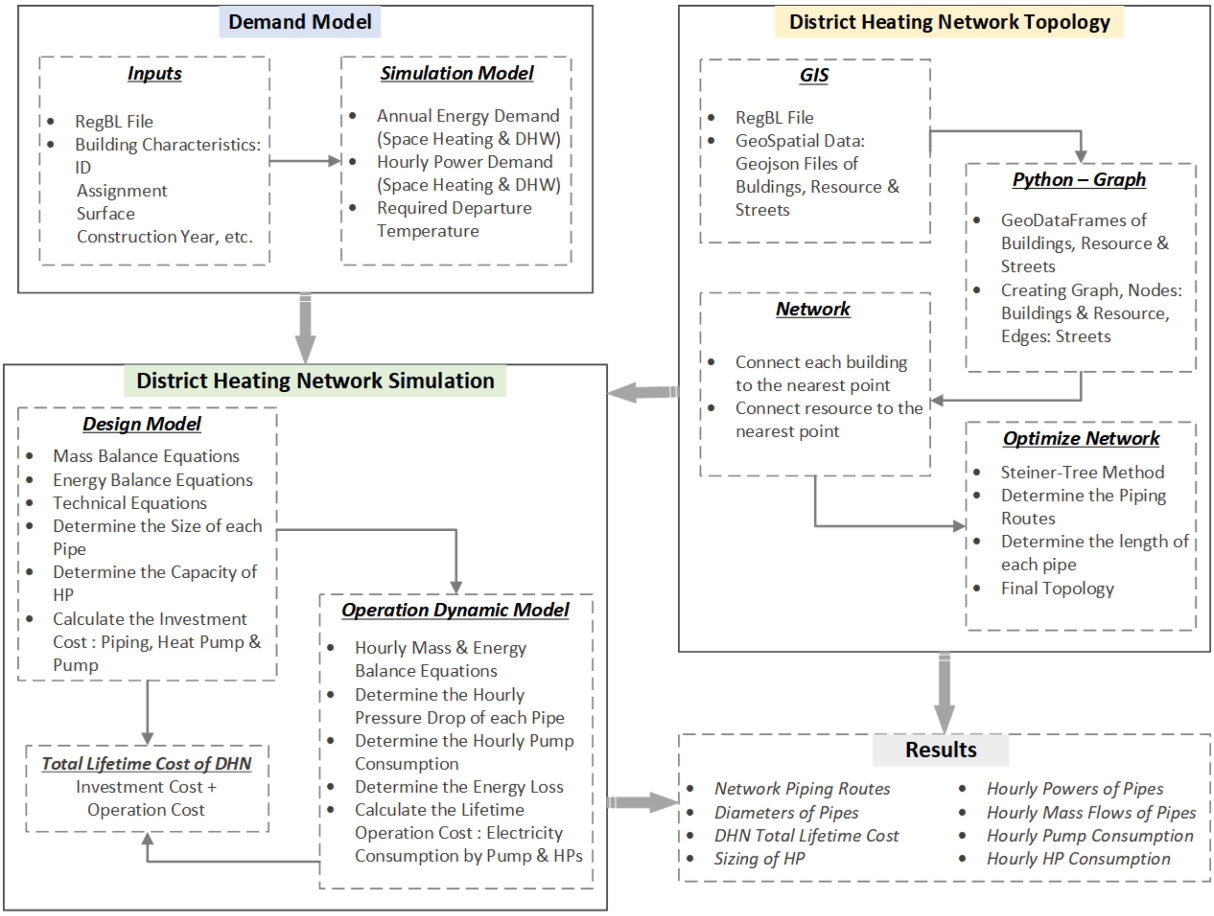

Figure 7 : Proposed methodology for step-by-step design of the District Heating Network

It is important to note that these cooling systems are currently in use and represent the existing situation. Swisscom has plans to retrofit and replace approximately two-thirds of these cooling systems by 2030, as they approach the end of their operational life. This retrofit is expected to increase the waste heat power generated by the mechanical cooling system to 3000 kW. Therefore, we consider this waste heat potential from their mechanical cooling system in introduced four scenarios. These four scenarios for developing the Dufour DHN using data center waste heat as a heat source were defined in consultation with SIL.

These scenarios are presented in the next subchapters.

2.3.1.4. Scenario 1: High-Temperature District Heating Network with Central HP

The configuration for integrating data center waste heat into the Dufour micro DHN is illustrated in Figure 8. The DHN design considers both free cooling (from November to June) and forced cooling (from June to November) based on Swisscom's data center cooling system. The waste heat power from forced cooling is 3000 kW, while from free cooling it is 2655 kW. It is important to note that the return temperature to the mechanical cooling machine at Swisscom is not clearly provided. This temperature difference can be controlled by adjusting the mass flow, as permitted by the system design.

- *Resource Side:* In forced cooling mode, waste heat is discharged at 40°C, and in free cooling mode at 20°C. This heat is then directed into a Central Heat Pump located near the data center to raise its temperature to the required DHN level.
- *Building Side:* A heat exchanger is integrated into each building to align the DHN supply parameters with the specific heating needs of each building.
- *DHN Temperature:* The network temperature is determined based on the highest departure temperature among the buildings, which has been set at 65°C, in consultation with SIL, as the buildings in the case study area are relatively old.

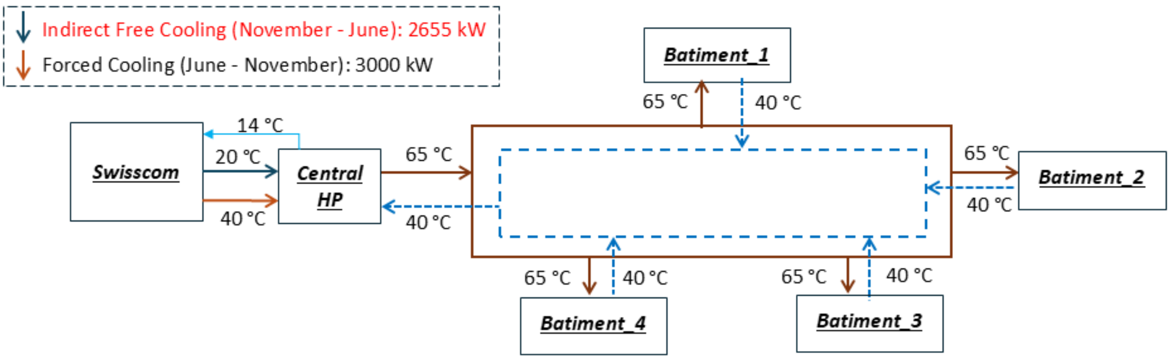

Figure 8 : The schematic configuration for integrating Swisscom's waste heat with the DHN in scenario 1

2.3.1.5. Scenario 2: Low-Temperature District Heating Network with Decentralized HPs

The configuration for integrating Swisscom's waste heat with the Dufour DHN and the corresponding temperatures in the second scenario is depicted in Figure 9. In this scenario, a mechanical cooling machine is utilized within the heat removal network of the data center. Therefore, in this scenario, the heat resource potential is 3000 kW.

It is worth mentioning that in the second, third, and fourth scenarios, where decentralized heat pumps (HPs) are installed in each building, the departure temperatures vary stochastically within a range of 10°C. This variation helps to better reflect the different COPs for each building, as suggested by SIL.

Resource Side: Waste heat is discharged at a temperature of 40°C and is then directed into the DHN.

Building Side: Distributed heat pumps have been integrated with each building to align the DHN supply characteristics with the specific needs of each building.

DHN Temperature: It is determined based on the temperature of the waste heat. In this case, the temperature level of network is set at 40°C/25°C.

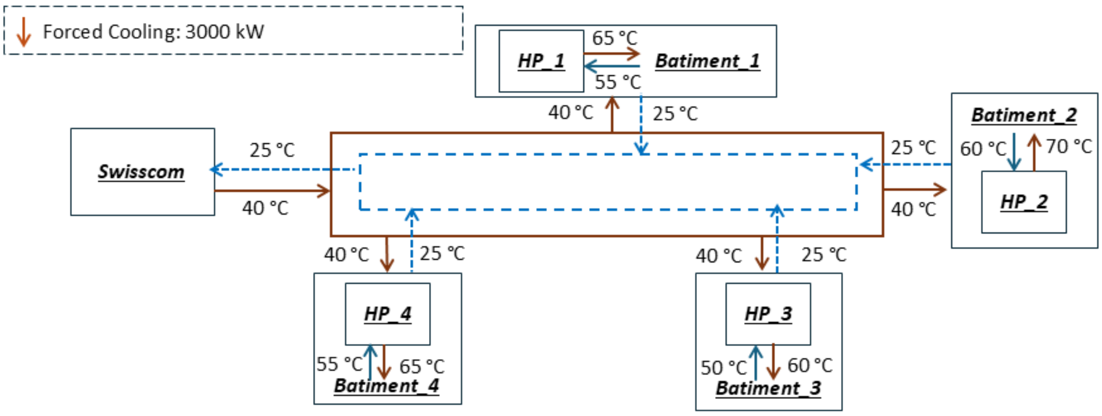

Figure 9 : The schematic configuration for integrating Swisscom's cooling system in scenario 2

2.3.1.6. Scenario 3: Cold District Heating Network with Decentralized HPs, Anergy Network

The configuration for integrating Swisscom's waste heat with the DHN and the corresponding temperatures in the third scenario is depicted in Figure 10. In this scenario, an indirect free cooling with air cooler is utilized within the heat removal network of data center. Hence, in this scenario, the heat resource potential is 2655 kW.

Resource Side: The waste heat is discharged at a temperature of 20°C and is then directed into the DHN at a temperature of 19°C.

Building Side: Distributed heat pumps have been integrated with each building to align the DHN supply characteristics with the specific needs of each building.

DHN Temperature: It is determined based on the temperature of waste heat, which in this case the temperature level of network is set at 19°C/14°C.

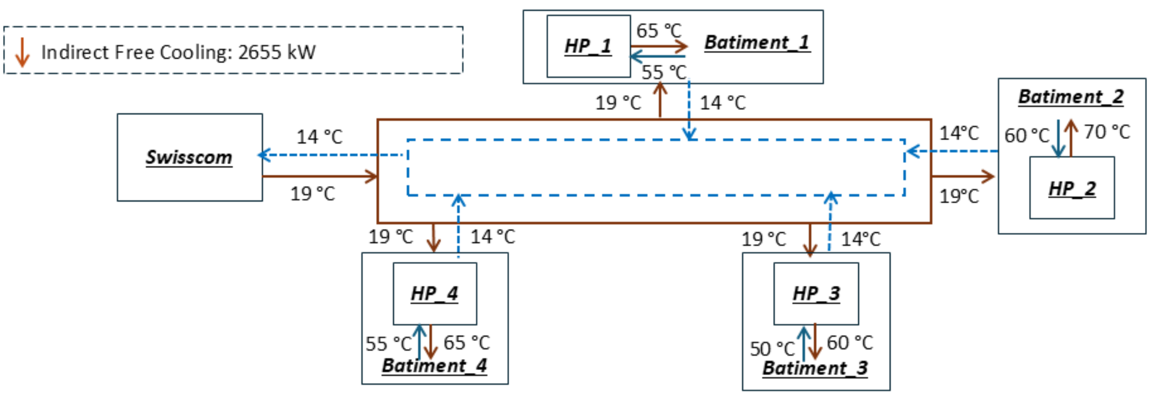

Figure 10 : The schematic configuration for integrating Swisscom's cooling system in scenario 3

2.3.1.7. Scenario 4 (Hybrid): District Heating Network with Central & Decentralized HPs

The configuration for integrating Swisscom's waste heat with the DHN and the corresponding temperatures in the fourth scenario is illustrated in Figure 11. In this scenario, the DHN design accounts for both free cooling (from November to June) and forced cooling (from June to November), based on Swisscom's data center cooling system. The waste heat power from forced cooling is 3000 kW, while from free cooling it is 2655 kW.

- *Resource Side:* From November to June, waste heat from free cooling is discharged at 20°C and directed into the central heat pump (HP) near the data center, where the temperature is raised to 40°C to supply the network. From June to November, waste heat from forced cooling is discharged at 40°C and directed into the DHN.
- *Building Side:* Distributed heat pumps are integrated into each building to align the DHN supply characteristics with the specific needs of each building.
- *DHN Temperature:* The DHN temperature is determined by the output heat temperature from the central HP, which in this case is set at 40°C/25°C.

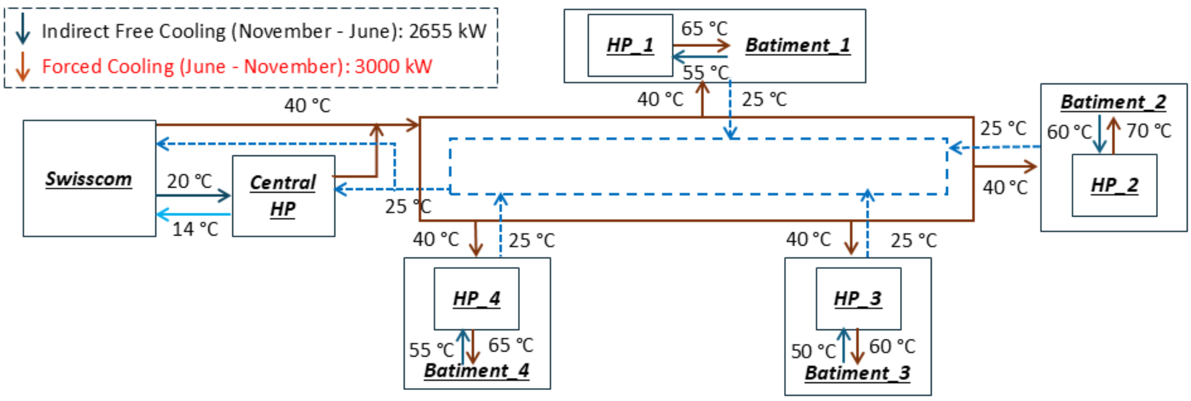

Figure 11 : The schematic configuration for integrating Swisscom's waste heat in scenario 4

2.3.2. Methodology for code used in Lausanne test-case – Input data

2.3.2.1. Demand model

SIL provides data on the characteristics of buildings within the case study area. As mentioned in section 2.3.1, this data includes building IDs, surface areas, building usages, construction years, number of floors, and annual energy consumption. The developed code utilizes this data, along with hourly external temperatures, to calculate the hourly heat demand for both space heating and hot water based on the SIA 380/1 standard. The code was written in Python using the Pandas and Numpy libraries. The results are stored in Excel files, capturing both annual and hourly heat demand. Regarding the departure temperature for the buildings, SIL has recommended the temperature for buildings in this area, as discussed in section 2.3.1.

2.3.2.2. District Heating Network Topology

The RegBL files containing building and resource geometries are provided by SIL. The building files have been carefully edited, validated, and updated through consultation with SIL. Furthermore, all the streets in this neighbourhood have been extracted using the QGIS software. All this prepared data is stored in GeoJSON files, making it accessible for use in Python.

2.3.2.3. District Heating Network Simulation

The calculated data from two demand and topology models are incorporated into the simulation model as constant input parameters. Demand data are imported as Excel files, while topology data is imported as a graph file representing the designed DHN. Most of the required data has been provided through consultations with SIL. Cost data related to the total cost of DHN, and the costs associated with central HP and decentralized HPs are presented in Table 3.

Additionally, SIL has prepared the heat transfer coefficient for pipe insulation and insulation thickness, which depend on the pipe inner diameters. For pipe nominal diameters ranging from 32 to 300 [mm], the conductive heat transfer coefficient of the pipe insulation ranges from 0.104 to 0.277 [W/mK].

Table 3 : Cost parameters for DHN and central & decentralized HPs in simulation model

Parameter	DHN cost	Central HP cost	Decentralized HPs cost	Discount rate	Electricity price
Value	4000	782.5	1066	5.5	0.31
Unit	CHF/m	CHF/kW	CHF/kW	%	CHF/kWh
Ref	Ref [8]	Ref [9] / Ref [10]	Ref [11] / Ref [12]	Ref [13]	Ref [14]

2.3.3. Methodology for code used in Lausanne test-case – Code implementation

In all the models within this phase of the project, we have generally utilized two software tools: QGIS and Python. Different Python libraries have been utilized to fulfil the specific requirements of each model, as detailed below.

2.3.3.1. Demand Model

In this model, the RegBL files of buildings are imported into Python, where the Pandas and NumPy libraries are employed to develop the code for processing the data and calculating final demand data.

2.3.3.2. District Heating Network Topology

In this model, QGIS was used initially to manage and extract GeoJSON files containing information about buildings, resources, and streets. Subsequently, these files were imported into Python. The visual depiction of the GeoJSON files for our case study can be seen in Figure 12. Within Python, these files were utilized to generate a network and a comprehensive graph of the DHN, including all buildings,

[8] Communication stemming from Services industriels de Lausanne (SIL)
[9] Communication streaming from Services industriels de Lausanne (SIL)
[10] J. Schnidrig et al, Frontiers in Energy Research 11 (2023) [7]
[11] Communication stemming from Services industriels de Lausanne (SIL)
[12] J. Schnidrig et al, Frontiers in Energy Research 11 (2023) [7]
[13] Communication stemming from Services industriels de Lausanne (SIL)
[14] https://www.lausanne.ch/vie-pratique/energies-et-eau/services-industriels/particuliers/je-choisis-mon-offre/electricite?tab=tarifs

resources, and connections. Key libraries such as GeoPandas and NetworkX, alongside others, were employed in Python for this purpose. In addition, the initial DHN network, featuring all possible connections, is illustrated on Figure 13.

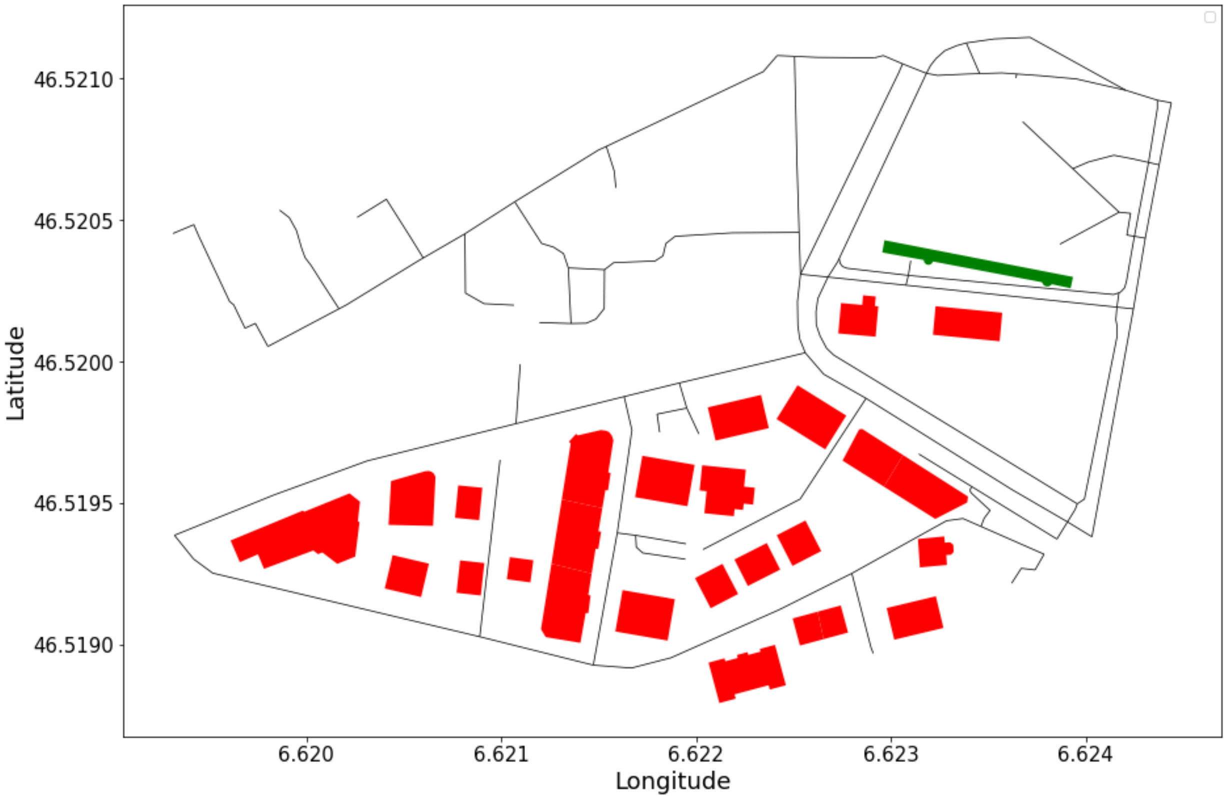

Figure 12 : Visualizing GeoJSON files depicting buildings (highlighted in red), resources (highlighted in green), and connections (represented by black lines).

2.3.3.3. District Heating Network Simulation

The main libraries utilized in the DHN simulation model include Pandas, gurobipy, and NumPy. In both design and operational models, the Gurobi optimization solver was applied through the gurobipy module. The developed simulation models were implemented in our case study, incorporating data from demand and topology models.

In the simulation module, the DHN technical and economic parameters are computed using developed code. Some of these parameters are explained as follows.

2.3.3.4. Pipe diameter

The determination of pipes diameters is an important outcome in the design model. The approach employed to calculate this variable is detailed in [8][15], and its general equation is presented as follows:

$$d_{ij} \geq \sqrt{\frac{4\dot{m}_{ij}}{\pi \cdot \rho \cdot v_{max}}} \quad (1)$$

[15] D. Wang et al, Energies 14 (2021) [8]

d_{ij} is pipe diameter, m_{ij} is mass flow of pipe, ρ is water density and V_{max} is the maximum velocity of water and it is determined based on the maximum pressure drop[16] [8].

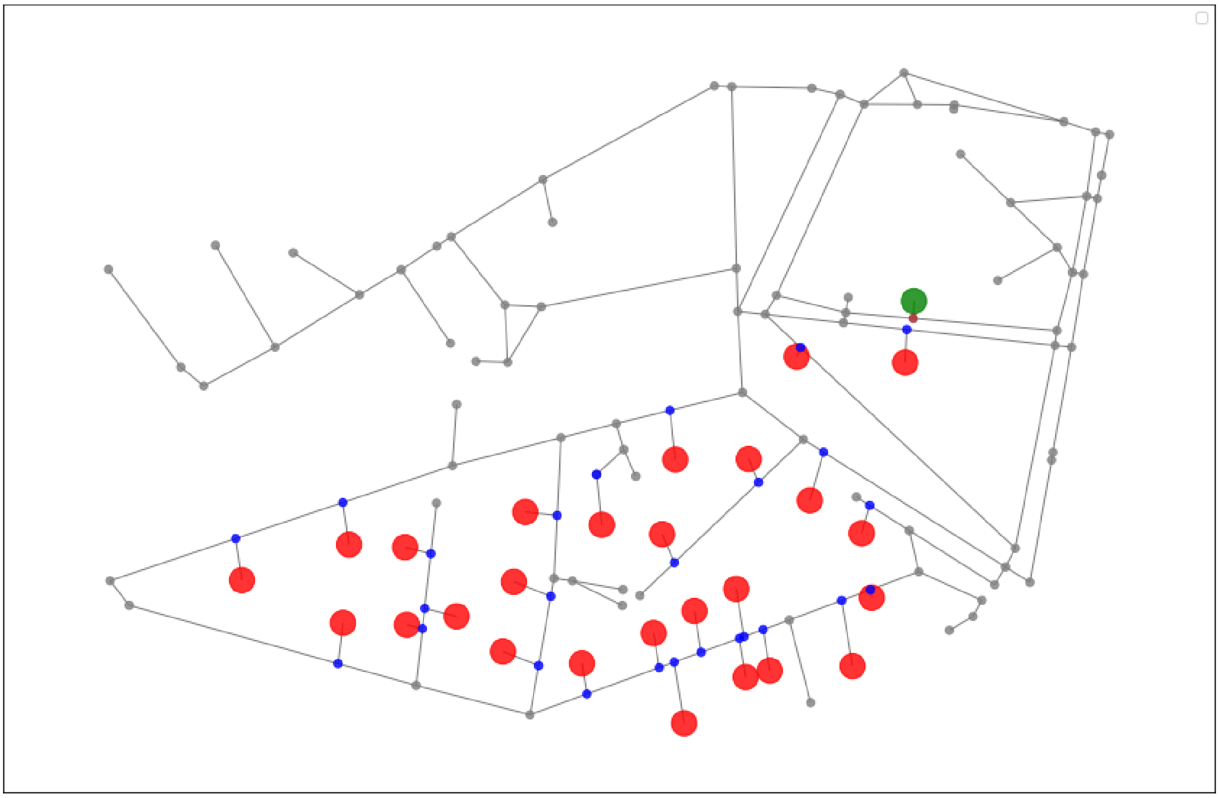

Figure 13 : The initial district heating network graph involves connecting all buildings and resources to the DHN.

2.3.3.5. Heat Losses

To calculate DHN heat losses for both supply and return lines, the methodology outlined in the "Handbook on Planning of District Heating Networks" for heat loss of underground pipes was employed [4]. In this context, three modes of conductive heat transfer through earth-laid pipes were considered. These modes include:

- ✓ Thermal conduction through the insulating material of the pipes.
- ✓ Thermal conduction through the soil.
- ✓ Interaction between the two pipelines, influencing each other's thermal characteristics.

The subsequent equation represents the heat loss flow in the supply and return lines of DHN[17] [4]:

$$\dot{Q}_L = U_P \, A_{S/R} \, \Delta T_{ELP} \tag{2}$$

In this equation, 'Up' represents the comprehensive heat transfer coefficient. It is computed by considering three modes of heat transfer and the physical attributes of both supply and return pipes. These

[16] D. Wang et al, Energies 14 (2021) [8]

[17] Handbook on Planning of District Heating Networks, Swiss Federal Office of Energy SFOE [4]

attributes encompass parameters such as pipe diameter, insulation thickness, thermal conductivity of insulation, thermal conductivity of the ground, and more[18] [4].

The temperature difference in earth-laid pipes is determined by the difference between the designed operating medium temperature (Top) and the mean soil temperature (Tgr):

$$\Delta T_{ELP} = T_{\overline{OP}} - T_{gr} = \frac{T_{SPLY} + T_{RTN}}{2} - T_{gr} \quad (3)$$

In this case, the T_{gr} is considered to be 10 °C. T_{SPLY} and T_{RTN} are the supply and return temperatures of heating networks that change in each scenario.

2.3.3.6. Pressure Drop

To compute the actual pressure losses in DHN pipes within the operational model of the simulation module, the methodology outlined in [8] [19] is employed. This approach involves calculating pressure losses based on the length and mass flow of each pipe, considering friction factors, and accounting for the diameter of the pipes.

2.3.3.7. Net Present Cost

In this project, the Net Present Cost (NPC) is calculated to assess the overall cost of the project. This economic criterion considers both Operating Expenditure (OPEX) and Capital Expenditure (CAPEX). It is defined as follows: "The total Net Present Cost (NPC) of a system is determined by calculating the present value of all expenses incurred by the system throughout its lifespan, subtracted from the present value of all revenues generated during the same period.

Costs include capital investments, replacement expenses, operation and maintenance costs, fuel expenditures, emissions penalties, and expenses associated with purchasing power from the grid. Revenues encompass salvage value and income generated from sales to the grid."

In this particular case, the analysis focuses solely on investment and operational costs, excluding any consideration of revenues. The total discount rate is set at 5.5%[20], and the anticipated lifespan of the DHN is 30 years[21], while the Heat Pump is expected to operate for 25 years[22].

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[18] Handbook on Planning of District Heating Networks, Swiss Federal Office of Energy SFOE [4]
[19] D. Wang et al, Energies 14 (2021) [8]
[20] Communication stemming from Services industriels de Lausanne (SIL)
[21] Communication stemming from Services industriels de Lausanne (SIL)
[22] Communication stemming from Services industriels de Lausanne (SIL)

2.4 Activities and results – Workpackage 1

2.4.1. DHN supply statistics

DHN cover approximately 4% of the heating demand for residential buildings in Switzerland, according to the FSO 2022 statistics published in 2023 and 3% of the energy demand devoted to domestic hot water (DHW) production (see tables below).

Table 4 : Heating technology for residential buildings by regions, FSO 2023[23]

Bâtiments selon le système de chauffage et la source d'énergie du chauffage, par type de commune et grande région — T 09.02.07.02

2022

	Bâtiments à usage d'habitation																	
	Total	Système de chauffage								Source d'énergie du chauffage								
		Pompe à chaleur	Installation solaire thermique	Chaudière	Poêle	Chauffage électrique	Echangeur de chaleur	Autres systèmes de chauffage	Aucun système de chauffage	Sources d'énergie pour les pompes à chaleur[1)]	Gaz	Mazout	Bois	Electricité	Solaire thermique	Chaleur à distance	Autres sources d'énergie	Aucune source d'énergie
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Suisse	**1 785 321**	**18,5**	**0,3**	**62,8**	**6,1**	**7,9**	**3,8**	**0,2**	**0,3**	**18,5**	**17,5**	**39,3**	**11,9**	**7,9**	**0,3**	**3,8**	**0,4**	**0,3**
Urbain	825 888	15,1	0,2	70,6	2,9	5,3	5,4	0,2	0,2	15,1	30,1	38,0	5,2	5,4	0,2	5,4	0,4	0,2
Intermédiaire (	471 028	22,9	0,3	59,1	5,7	8,8	2,7	0,2	0,3	22,9	9,3	43,2	12,2	8,8	0,3	2,7	0,3	0,3
Rural	488 405	20,1	0,4	53,2	12,0	11,4	2,1	0,2	0,6	20,1	4,3	37,7	23,0	11,5	0,4	2,1	0,3	0,6
Grandes régions																		
Région léman	301 772	14,1	0,3	61,9	6,3	14,6	2,2	0,3	0,3	14,1	23,9	34,2	10,0	14,8	0,3	2,1	0,3	0,3
Espace Mittell	438 526	18,7	0,3	66,5	5,4	5,7	2,9	0,2	0,2	18,7	13,9	43,8	14,1	5,7	0,3	3,0	0,3	0,2
Suisse du Nor	246 242	20,1	0,1	63,9	1,6	4,6	8,9	0,1	0,7	20,1	20,9	38,4	6,1	4,6	0,1	8,8	0,3	0,7
Zurich	227 835	20,2	0,1	66,9	3,8	3,6	4,8	0,5	0,1	20,2	23,4	40,8	6,4	3,6	0,1	4,8	0,6	0,1
Suisse orienta	310 242	18,8	0,6	61,1	10,7	5,9	2,6	0,2	0,2	18,8	17,6	36,6	17,3	5,9	0,6	2,6	0,4	0,2
Suisse central	146 665	23,5	0,2	59,5	5,2	7,1	4,1	0,1	0,3	23,5	8,4	39,9	16,0	7,1	0,2	4,0	0,6	0,3
Tessin	114 039	15,7	0,6	49,0	11,8	20,8	1,3	0,0	0,7	15,7	7,1	40,4	13,0	20,8	0,6	1,3	0,3	0,7

Etat au 31 décembre 2022

It represents a significant proportion of the heating sector, mainly in a certain number of large cities such as Basel, Zürich and Lausanne, but also in medium-size and small urban centers such as Köniz and La Chaux-de-Fonds.

Table 5 : Heating technology for residential buildings by cities, FSO 2023[3]

Bâtiments selon le système de chauffage et la source d'énergie du chauffage, par ville — T 09.02.07.01

2022

	Bâtiments à usage d'habitation																	
	Total	Système de chauffage								Source d'énergie du chauffage								
		Pompe à chaleur	Installation solaire thermique	Chaudière	Poêle	Chauffage électrique	Echangeur de chaleur	Autres systèmes de chauffage	Aucun système de chauffage	Sources d'énergie pour les pompes à chaleur[1)]	Gaz	Mazout	Bois	Electricité	Solaire thermique	Chaleur à distance	Autres sources d'énergie	Aucune source d'énergie
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Suisse	**1 785 321**	**18,5**	**0,3**	**62,8**	**6,1**	**7,9**	**3,8**	**0,2**	**0,3**	**18,5**	**17,5**	**39,3**	**11,9**	**7,9**	**0,3**	**3,8**	**0,4**	**0,3**
Zurich	37 390	9,6	0,0	74,5	0,9	0,1	14,7	0,2	0,0	9,6	50,5	23,6	1,1	0,1	0,0	14,7	0,4	0,0
Genève	7 482	3,0	0,0	93,4	0,5	1,0	2,1	0,0	0,0	3,0	45,7	46,4	1,5	1,0	0,0	2,0	0,5	0,0
Bâle	19 209	3,3	0,0	52,6	0,3	0,7	43,1	0,0	0,0	3,3	42,2	9,5	1,1	0,7	0,0	43,1	0,1	0,0
Berne	14 894	5,1	0,0	86,2	1,4	2,1	5,2	0,0	0,0	5,1	46,8	37,8	2,8	2,1	0,0	5,2	0,2	0,0
Lausanne	9 069	4,1	0,1	77,2	0,8	1,8	16,0	0,0	0,0	4,1	38,7	37,0	1,8	1,8	0,1	15,8	0,7	0,0
Winterthur	16 009	14,2	0,1	74,2	3,9	2,0	5,2	0,3	0,0	14,2	35,2	38,8	4,0	2,0	0,1	5,2	0,4	0,0
St-Gall	9 800	9,8	0,5	74,2	1,6	1,1	12,7	0,0	0,0	9,8	42,0	31,6	2,2	1,1	0,5	12,7	0,0	0,0
Lucerne	7 689	9,0	0,2	85,6	1,7	0,8	2,7	0,1	0,0	9,0	54,9	30,4	1,9	0,8	0,2	2,6	0,2	0,0
Lugano	10 451	12,3	0,2	67,3	6,7	12,1	0,5	0,0	0,9	12,3	19,8	48,0	6,0	12,1	0,2	0,5	0,2	0,9
Bienne	6 767	3,8	0,0	91,5	0,7	1,7	2,2	0,0	0,0	3,8	59,9	30,3	1,7	1,7	0,0	2,2	0,3	0,0
Thoune	7 571	8,5	0,1	85,9	1,5	3,3	0,7	0,0	0,1	8,5	43,1	41,2	3,0	3,3	0,1	0,6	0,2	0,1
La Chaux-de-l	4 498	6,0	1,2	70,2	4,1	4,7	13,6	0,2	0,0	6,0	25,2	43,5	5,5	4,7	1,2	13,6	0,4	0,0
Köniz	6 815	20,9	0,0	51,9	0,1	6,6	20,2	0,0	0,2	20,9	10,1	34,9	7,0	6,6	0,0	20,2	0,1	0,2
Schaffhouse	6 704	7,5	0,0	86,0	2,1	3,0	1,3	0,0	0,0	7,5	50,9	33,4	3,1	3,0	0,0	1,0	1,1	0,0
Fribourg	3 359	11,4	0,1	81,8	0,5	4,7	1,2	0,3	0,0	11,4	50,0	31,0	1,0	4,7	0,1	1,2	0,5	0,0
Neuchâtel	5 621	4,6	0,6	89,4	1,8	1,5	2,1	0,1	0,0	4,6	44,5	44,2	2,2	1,5	0,6	2,1	0,2	0,0
Coire	4 632	12,0	0,2	79,3	4,7	1,0	2,8	0,0	0,0	12,0	50,0	28,0	5,9	1,0	0,2	2,8	0,1	0,0

Etat au 31 décembre 2022

Always according to FSO [9], DHN systems supply heat to slightly less than 68'000 buildings with respect to a total of more than 1.7 Mio. However, the implementation proportion significantly increases with the size of the buildings, as well as with the inverse of the construction period.

This means that DHN systems are proportionally more present in newer dwellings, as well as in multi-family, large buildings located in urban/suburban areas. Hence, a more appropriate indicator in this respect would be represented by the total heated reference surface supplied by way of DHN, although

[23] FSO 2023, Buildings and Dwellings Statistics 2022 (not available in English) [9]

such a statistical information is not readily and publicly available for all the national territory, to the best of knowledge of FOSTER_DHN research team.

Table 6 : Heating technologies in buildings by construction year and building type, FSO 2023[24]

Bâtiments selon le système de chauffage, la source d'énergie du chauffage, l'époque de construction et la catégorie de bâtiment **T 09.02.07.03**

2022

	Bâtiments à usage d'habitation																	
	Total	Système de chauffage								Source d'énergie du chauffage								
		Pompe à chaleur	Installation solaire thermique	Chaudière	Poêle	Chauffage électrique	Echangeur de chaleur	Autres systèmes de chauffage	Aucun système de chauffage	Sources d'énergie pour les pompes à chaleur[1)]	Gaz	Mazout	Bois	Electricité	Solaire thermique	Chaleur à distance	Autres sources d'énergie	Aucune source d'énergie
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Total	**1 785 321**	**18,5**	**0,3**	**62,8**	**6,1**	**7,9**	**3,8**	**0,2**	**0,3**	**18,5**	**17,5**	**39,3**	**11,9**	**7,9**	**0,3**	**3,8**	**0,4**	**0,3**
Construits avant 1919	334 494	6,3	0,3	65,6	16,3	7,7	3,3	0,2	0,4	6,3	18,2	34,6	28,9	7,7	0,3	3,3	0,3	0,4
Construits entre 1919 et 1945	198 456	6,6	0,2	70,7	10,2	8,4	3,1	0,1	0,7	6,6	24,4	40,9	15,4	8,4	0,2	3,1	0,3	0,7
Construits entre 1946 et 1960	186 645	7,4	0,2	74,4	6,0	7,6	3,9	0,2	0,2	7,4	16,7	54,4	9,1	7,6	0,2	3,9	0,4	0,2
Construits entre 1961 et 1970	171 572	6,9	0,2	79,4	4,0	5,4	3,5	0,2	0,3	6,9	11,0	64,8	7,5	5,5	0,2	3,5	0,3	0,3
Construits entre 1971 et 1980	193 813	9,3	0,3	70,9	2,5	13,6	3,1	0,3	0,1	9,3	9,4	58,0	5,9	13,6	0,3	3,1	0,3	0,1
Construits entre 1981 et 1990	200 856	16,5	0,3	60,5	2,4	17,5	2,6	0,2	0,1	16,5	16,0	39,6	7,2	17,5	0,3	2,6	0,3	0,1
Construits entre 1991 et 2000	178 454	21,2	0,3	67,2	2,4	4,3	4,1	0,2	0,3	21,2	24,4	38,4	6,7	4,3	0,3	4,0	0,4	0,3
Construits entre 2001 et 2005	81 273	31,1	0,3	59,9	1,2	2,9	3,8	0,2	0,6	31,1	29,6	26,6	4,7	2,9	0,3	3,8	0,5	0,6
Construits entre 2006 et 2010	85 230	53,4	0,6	36,5	1,0	2,7	5,0	0,2	0,5	53,4	22,4	8,1	6,8	2,7	0,6	4,9	0,5	0,5
Construits entre 2011 et 2015	72 052	69,5	0,7	20,9	0,7	1,3	6,5	0,3	0,1	69,5	12,8	2,2	6,3	1,3	0,7	6,4	0,5	0,1
Construits entre 2016 et 2022	82 476	74,3	0,4	14,9	0,7	0,7	8,2	0,4	0,5	74,3	9,2	1,0	5,1	0,7	0,5	8,1	0,6	0,5
Catégorie de bâtiment																		
Maisons individuelles	1 012 237	22,7	0,4	57,2	6,9	10,0	2,4	0,1	0,4	22,7	15,6	37,5	10,9	10,0	0,4	2,4	0,3	0,4
Maisons à plusieurs logements (2 à 5 log.)	308 026	17,1	0,3	67,7	3,2	8,2	3,2	0,2	0,1	17,1	16,8	44,1	9,9	8,2	0,3	3,2	0,4	0,1
Maisons à plusieurs logements (6 à 10 log.)	130 081	15,0	0,1	73,3	0,3	1,4	9,0	0,6	0,2	15,0	27,7	43,3	2,3	1,4	0,1	8,9	1,1	0,2
Maisons à plusieurs logements (> 10 log.)	53 829	13,6	0,1	71,7	0,2	0,8	13,1	0,4	0,1	13,6	28,6	40,0	2,6	0,8	0,1	12,9	1,2	0,1
Autres catégories[2)]	281 148	7,8	0,2	70,9	10,3	4,6	5,4	0,2	0,6	7,8	18,5	38,4	24,2	4,6	0,2	5,4	0,3	0,6

On the other hand, the national FSO statistics on buildings and dwellings [3] also show that almost 10% of the Swiss population is supplied with district heating, further corroborating our argument above.

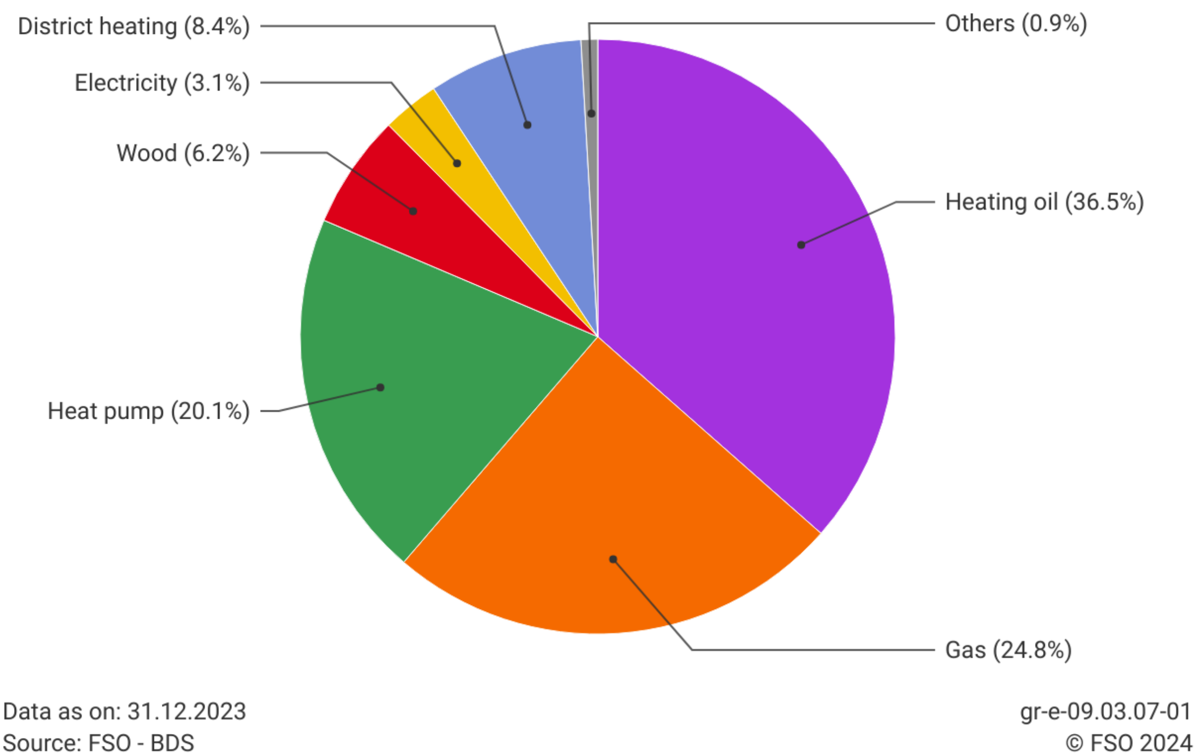


Figure 14 : Population by main heating source for year 2023, FSO 2024[25]

[24] FSO 2023, Buildings and Dwellings Statistics 2022 (not available in English) [9]
[25] https://www.bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees.assetdetail.32381461.html

In terms of historical evolution, penetration of DHN systems has been steady since the beginning of the 21st century, as shown in the table below. Such a trend is expected to continue in a sustained way, in particular because of the effect of strong political support for DHN nationwide.

Table 7 : Yearly evolution of energy consumption for various thermal applications, including heating and DHW, SFOE 2023[26]

Tabelle 4: Endenergieverbrauch für Wärme und Kälte
Entwicklung von 2000 bis 2022 nach Verwendungszwecken und Energieträgern, in PJ

Verwendungszweck / Energieträger	2000	2016	2017	2018	2019	2020	2021	2022	Δ '00 – '22
Raumwärme	265.8	258.2	249.0	226.5	230.6	214.2	252.2	200.5	-24.6%
Warmwasser	46.8	47.2	47.3	47.1	47.0	48.0	46.9	46.9	+0.1%
Prozesswärme	104.8	92.0	91.6	92.9	92.3	87.7	91.4	89.4	-14.7%
Prozesskälte	10.3	12.6	12.4	12.6	12.6	12.2	12.2	12.6	+21.6%
Klimakälte	4.2	5.6	5.9	6.0	6.0	5.7	5.3	6.2	+49.8%
Total Endenergie	**431.9**	**415.5**	**406.2**	**385.0**	**388.5**	**367.9**	**408.0**	**355.5**	**-17.7%**
Heizöl	206.2	136.6	127.1	113.6	110.2	98.9	107.5	85.8	-58.4%
Gase	90.3	117.7	117.3	111.0	113.0	107.5	119.5	100.6	+11.4%
Elektrizität	59.2	67.9	67.8	67.6	68.4	66.0	69.5	67.4	+13.9%
Holz	30.1	39.2	38.9	37.8	39.5	38.0	46.2	40.6	+34.8%
Kohle	5.8	4.4	4.3	4.0	3.6	3.4	3.5	3.8	-34.2%
Fernwärme	13.9	19.0	19.2	19.2	20.4	20.0	22.7	20.5	+47.5%
Umweltwärme / Solarthermie	4.2	17.8	18.4	18.4	20.1	20.8	25.5	22.8	+440.7%
sonstige	22.2	12.9	13.2	13.4	13.3	13.4	13.7	14.0	-37.1%

Gase: Erdgas, Biogas; sonstige: Müll, übrige fossile

Quelle: Prognos und TEP 2023

The role of natural gas as primary energy vector supply for DHN systems in Switzerland results relatively difficult to evaluate in detail. According to SFOE[27], the total heat delivered via DHN systems amounted to slightly less than 7 TWh in 2023. While the total quantity of natural gas used is known in heat generation is known, namely 1.6 TWh in 2023, important information is nonetheless missing. In particular, the number, size and distribution of gas boilers and CHP systems is unknown.

However - it might be said even more importantly - the concrete operation of these units is not explicitly given, in particular it is not known if the boilers are used for baseload heat generation or for peak cold periods (both in terms of power and functioning hours).

It must be noted that the statistics compiled by SFOE are not completely coherent with other existing figures compiled by national stakeholders. The difference is probably due to an incomplete inventory of all existing DHN systems, in particular the small ones.

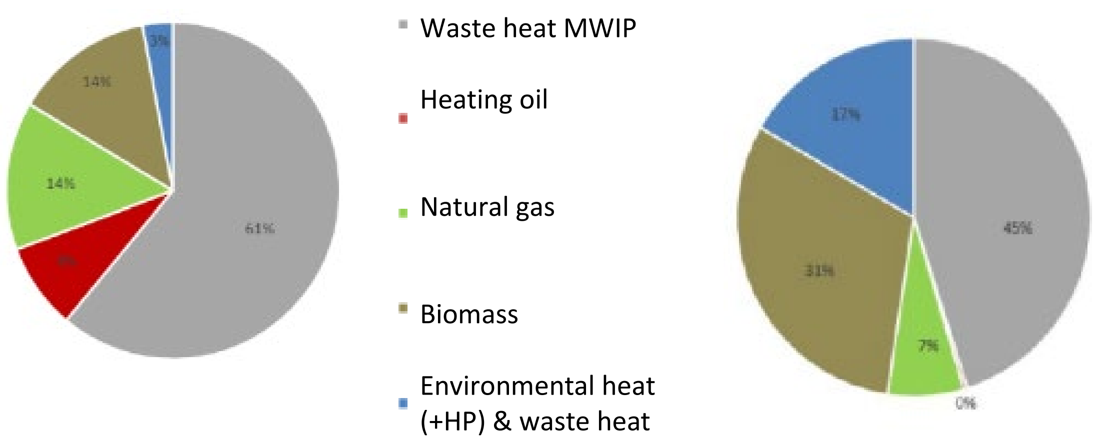
The statistics regarding the installed capacities is given below. It can be seen that the installed capacity in terms of natural gas boilers has been constant in the last ten years, while the usage of both renewable

[26] SFOE, Analyse des schweizerischen Energieverbrauchs 2000–2022 nach Verwendungszwecken (not available in English) [10]
[27] SFOE, Gesamtenergiestatistik 2023 (not available in English) [11]

and waste heat energy has increased dramatically Overall installed capacity has doubled over a little more than 10 years, further highlighting the increased role of DHN in terms of national heat supply.

Table 8 : Comparison of installed heat production capacities for DHN in 2010 and 202, Energieschweiz 2022[28]

2010 : Capacity 2.2 GW — **2021: Capacity 2.25 GW**



2010		2021	
1319 MW	Waste Heat MWIP	1916 MW	+45%
180 MW	Heating Oil	14 MW	-92%
207 MW	Gas	295 MW	-4%
292 MW	Biomass	1316 MW	+450%
63 MW	Environmental heat (+HP)	707 MW	+1122%
2161 MW	Total	4249 MW	+97%

From the table above, it seems logical to deduce that natural gas boilers are mostly used to cover peak operation. Nonetheless, when studying a given territory, the precise implementation of energy conversion technologies and vectors must be carefully quantified both spatially and temporally.

As it shall be highlighted in the section 2.4.3. below, the distinction between natural gas boilers operation (baseload vs peak production) will result as crucial, in order to be able to identify possible replacement with technologies based on renewable energy sources or more exergy efficient approaches (e.g. implementing CHP units).

2.4.2. Renewable and low-carbon energies potential

The SFOE statistics[29] displayed below show the evolution of all energy vectors supplying Swiss DHN systems, including renewable energy sources such as wood and environment heat (e.g. atmosphere and lakes). It must – alas – be underlined that, outside of wood and municipal waste, all renewable energy resources still are indeed « hidden » under the unspecified category « other », in SFOE statistics.

On the other hand, this situation means that the heat from waste incineration plants already represents, by far, the major supply of Swiss DHN systems and that the usage of wood has seen a 20-fold increase in slightly more than 20 years. In fact, the maximum envisaged supply of DHN by wood lies approximately slightly below 2 TWh/year, which is rather near the present-day usage of more than 1.2 TWh; it

[28] Energieschweiz, Liste «Thermische Netze», Auswertungsbericht 2021 (own translation) [12]
[29] SFOE, Gesamtenergiestatistik 2023 (not available in English) [11]

indicates that this resource probably has to be considered as «limited» in the future and that a prioritization will be needed by way of either local (municipal or cantonal) or national future policies.

Table 9 : Energy generation for DHN supply by energy vectors in Switzerland, SFOE 2024[30]

Jahr / Année	Energieeinsatz / Energie utilisée									Produktion / Production		Netzabgabe / Fourniture au réseau		Endverbrauch Fernwärme / Consommation finale de chaleur à distance
	Heizöl extra-leicht / Huile extra-légère	Heizöl mittel und schwer / Huile moyenne et lourde	Gas[1] / Gaz[1]	Kohle / Charbon	Müll[2] / Ordures[2]	Holz / Bois	Elektrizität / Electricité	Kernbrennstoffe[3] / Combustibles nucléaires[3]	Diverses[4] / Divers[4]	Wärme / Chaleur	Elektrizität / Electricité	Fernwärme / Chaleur à distance	Elektrizität / Electricité	
1980	–	–	–	–	6 400	–	–	120	–	–	–	8 920	–	7 920
1985	–	–	–	–	13 990	–	–	520	–	–	–	10 430	–	9 430
1990	710	480	4 270	380	16 490	–	–	890	–	–	–	11 470	–	10 420
1991	1 340	120	4 710	110	16 580	–	–	910	–	–	–	13 260	–	12 090
1992	1 500	50	4 670	100	16 270	–	–	970	–	–	–	13 070	–	11 970
1993	1 040	0	4 640	60	19 610	–	190	990	–	–	–	12 380	1 690	11 310
1994	290	0	4 730	80	21 080	–	0	1 010	–	–	–	12 440	2 170	11 280
1995	460	0	5 330	50	24 370	–	1 440	1 030	–	–	–	13 160	2 270	11 970
1996	720	0	6 600	0	24 570	–	250	1 020	–	15 600	3 730	14 020	2 920	12 480
1997	990	0	6 960	0	25 540	–	280	980	670	16 340	2 710	14 180	1 940	12 980
1998	780	0	6 810	0	27 340	–	290	1 100	770	19 290	4 030	14 480	2 680	13 250
1999	550	0	6 510	0	31 670	190	30	1 130	120	17 200	4 510	14 580	3 050	13 210
2000	320	0	5 630	0	34 210	190	20	1 100	120	15 380	4 970	14 290	3 490	13 180
2001	370	0	6 080	0	35 010	180	60	1 180	110	16 060	5 260	15 350	3 780	13 900
2002	310	0	5 830	0	37 000	230	40	1 070	40	15 890	5 430	14 970	3 900	14 020
2003	500	0	6 580	0	36 700	280	40	1 120	90	16 880	5 610	15 980	4 100	14 590
2004	310	0	6 540	0	37 190	320	30	1 150	100	17 200	5 900	16 520	4 340	14 770
2005	520	0	6 590	0	39 210	350	20	1 100	90	17 480	6 200	16 670	4 610	15 240
2006	540	0	5 480	0	42 840	340	40	1 290	80	17 810	6 800	16 960	5 070	15 720
2007	100	0	4 920	0	43 700	310	40	1 270	90	17 080	6 580	16 340	4 890	14 670
2008	90	0	5 710	0	42 540	400	40	1 290	50	17 750	6 940	16 870	5 230	15 260
2009	180	0	5 410	0	42 180	750	40	1 300	80	18 790	6 690	16 790	5 040	15 120
2010	220	0	6 100	0	43 570	940	50	1 300	70	21 000	7 120	18 700	5 420	17 030
2011	220	0	4 470	0	44 230	1 080	50	1 290	210	19 030	7 190	17 150	5 490	15 660
2012	630	0	5 670	0	45 350	1 570	40	1 370	300	20 620	7 670	18 140	5 910	16 650
2013	510	0	6 890	0	43 750	1 810	40	1 270	190	21 480	8 150	19 380	6 370	17 580
2014	650	0	4 560	0	44 640	1 840	40	1 190	210	19 590	8 300	17 530	6 500	15 980
2015	520	0	6 190	0	46 060	2 070	40	1 100	250	22 060	8 760	19 910	6 950	18 140
2016	290	0	7 490	0	47 750	2 160	50	1 330	250	23 240	9 720	21 170	7 880	19 350
2017	330	0	6 890	0	48 000	2 200	80	1 320	240	23 700	9 320	21 640	7 530	19 790
2018	250	0	6 550	0	48 630	2 130	70	1 350	20	23 370	9 270	21 290	7 450	19 360
2019	290	0	6 900	0	48 940	3 310	80	1 380	40	25 190	9 410	23 550	7 660	21 530
2020	220	0	6 820	0	49 130	3 300	80	1 420	50	24 820	9 450	23 260	7 690	21 050
2021	420	0	8 420	0	48 110	3 630	50	1 520	50	27 320	9 260	25 820	7 480	23 090
2022	420	0	6 460	0	46 170	3 710	20	1 390	150	25 480	8 740	23 710	7 020	21 360
2023	390	0	5 760	0	46 520	4 150	60	1 430	130	25 770	8 060	24 560	6 420	22 310

[1] unterer Heizwert
[2] inklusive Eigenverbrauch KVA; ab 2018 inkl. Klärschlamm
[3] nur Anteil für Fernwärme
[4] bis 2017 inkl. Klärschlamm

Quelle: BFE

[1] pouvoir calorifique inférieur
[2] y compris consommation des UIOM; dès 2018 y compris boues d'épuration
[3] seulement part pour chaleur à distance
[4] jusqu'à 2017 y compris boues d'épuration

Source: OFEN

In terms of energy potentials of renewable sources, the so-called « White book on DHN in Switzerland» [7], is usually referred to as the most accurate estimation of the development potential for DHN systems, both in terms of overall implementation, as well as of future energy supply sources. The global overview is given in the figure below.

According to [12], the overall installed DHN supply capacity fuelled by biomass could decrease at the 2050 time horizon (see table below), in parallel to the share from MWIPs. This is thereby signalling a possible future shift from this dominant energy source to the energy harvested in the environment, linked to an electrification of the heating sector, an issue that will be further discussed in the upcoming sections.

Indeed, the expected contribution stemming from energy harvested out of the environment is staggering, in parallel to an increased valorization of low- to medium-temperature heat from the waste water treatment plants. In both cases, if deep geothermal plants are excluded, the extracted enthalpy will need the implementation of power-driven heat pumps, in order to increase the distribution temperature as needed

[30] SFOE, Gesamtenergiestatistik 2023 (not available in English) [11]

for DHN systems. This would be the case both in direct DHN systems, maybe with the exception of very modern Minergie-type dwellings, as well as for so-called anergy networks. In order then to keep the renewable and low-carbon added value of these resources, the environmental impact of the necessary power supply will have to be carefully taken into account in any DHN territorial scenario (new grid, extension, densification or replacement). Moreover, due to the electricity production deficit during the winter period that is seriously handicapping the overall Swiss energy system in terms of supply security, **the availability of decarbonized power needs to be assessed in a robust manner**, also taking into account the power distribution capacities for a given territory/neighbourhood.

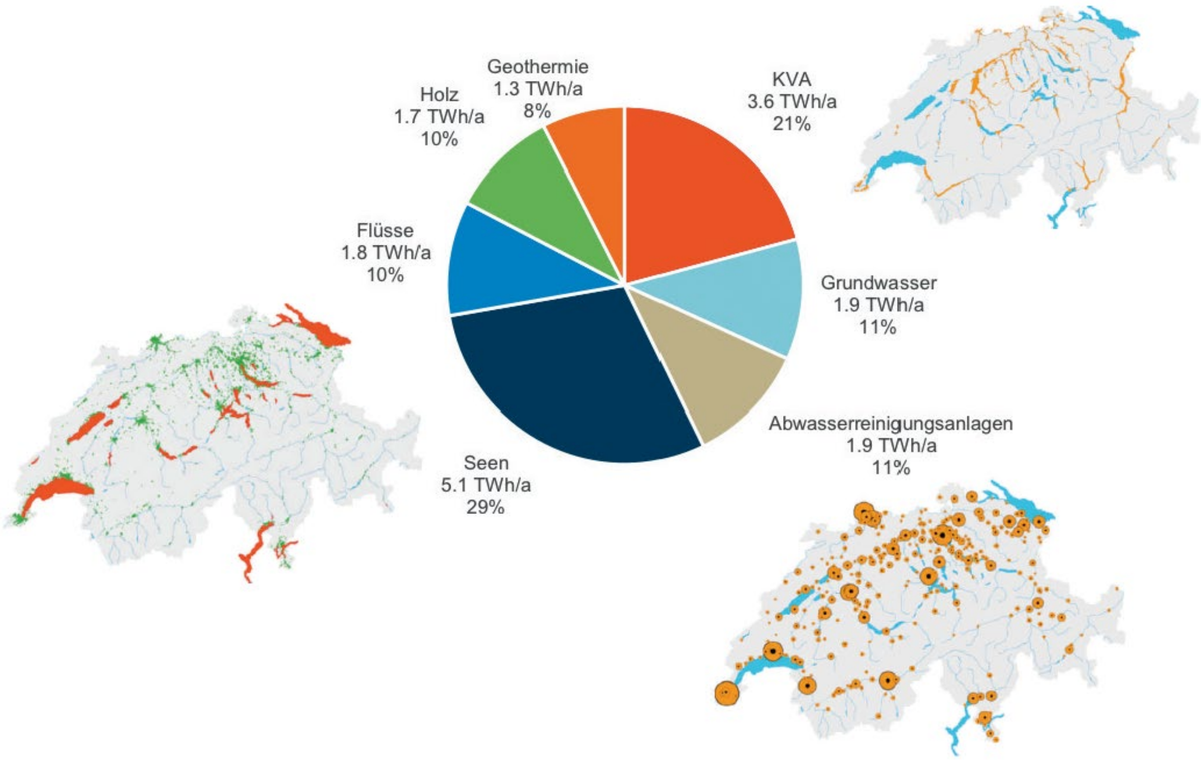


Figure 15 : Future evolution of the installed supply capacity by energy vectors for Swiss DHN systems at the time horizon 2050 (taken from [13])

The figure above and tables below also hint at another important aspect, on top of the electricity CO_2 footprint for heat pumps, namely the **localization of the renewable energy sources**. In particular, geothermal and waterborne resources are available on given territories and for given agglomerations, but not in other. At the same time, wood resources need to be transported by either rail or trucks, therefore potentially worsening the environmental footprint of an otherwise renewable energy. Hence, localization constitutes a limitation for the implementation of renewable resources.

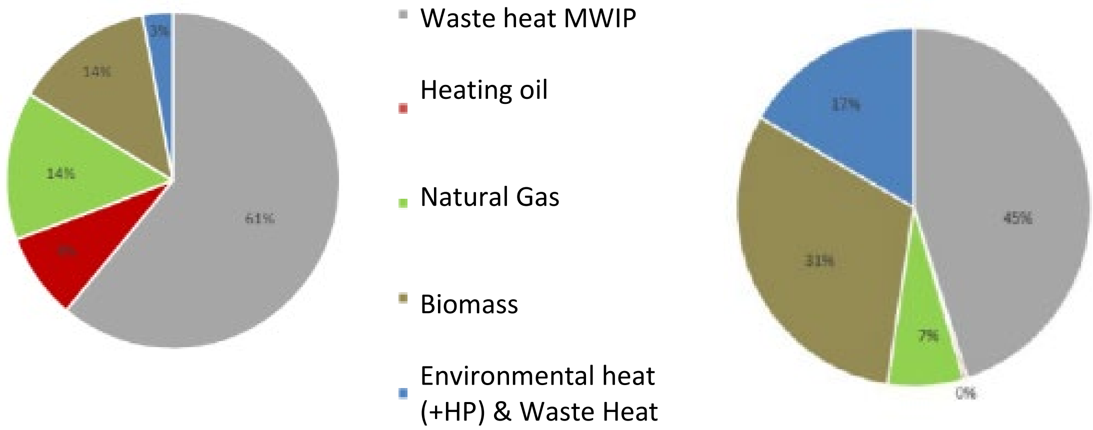
It must be noted that, among renewable energy sources, solar thermal is unfortunately not mentioned in the tables below, although recent projects have shown that it is not only a suitable option, but also technically already available from the components point of view [14].

The overall potential of renewable heat energy sources would thus be sufficient to cover the Swiss heat demand. It is however limited by various factors, ranging from logistical obstacles to physical availability (e.g. forests laying in hard-to-access mountainous regions) to the mismatch between location and correspondingly sufficient demand density, not to mention economic factors not addressed in this report.

Concomitantly, renewable resources would of course be sufficient to quantitatively replace current fossil energy supply for DHN systems, that is somewhat below 2 TWh/year. However, as already emphasized and discussed in more details below, not all renewable energy sources can provide peak power during the coldest periods and this situation must be taken into account.

Table 10 : Comparison of installed heat production capacities for DHN in 2010 and as prospected in 2050, Energieschweiz 2022[31]

2010 : Capacity 2.2 GW **2050: 17.3 TWh (8.65 GW)**



1917 MW	Waste Heat MWIP	1’800 MW	-6%
14 MW	Heating Oil	0 MW	-100%
295 MW	Gas	0 MW	-100%
1’316 MW	Biomass	850 MW	-35%
707 MW	Environmental heat (+HP) & Waste Heat	6’000 MW	+848%
4’250 MW	Total	8’650 MW	+204%

Table 11 : Comparison of installed heat production capacities for DHN in 2010 and as prospected in 2050 according to SFOE, Energieschweiz 2022[32]

Heat source	Technical thermal potential	Geographical affectation*	Possible share of future district heating
Waste-to-energy heat recovery	5,7 TWh/a	3,6 TWh/a	21%
Industrial waste heat	3,6 TWh/a	Not allocated	Not allocated
Waste heat WWTP	7,7 TWh/a	1,9 TWh/a	11%
Heat from groundwater	12,2 TWh/a	1,9 TWh/a	11%
Lakes	97 TWh/a	5,1 TWh/a	29%
Watercourses	21,3 TWh/a	1,8 TWh/a	10%
Wood	20,5 TWh/a	1,7 TWh/a	10%
Geothermal energy	70 TWh/a	1,3 TWh/a	8%
Total	238 TWh/a	17,3 TWh/a	100%
*Areas with a high local heat demand (sufficient connection density) have been allocated to the technical potential.			

[31] Energieschweiz, Liste «Thermische Netze», Auswertungsbericht 2021 (own translation) [12]

[32] Potentiel des installations de chauffage et de refroidissement à distance, Rapport du Conseil Fédéral en réponse au postulat 19.4051, BFE-042.16-127/5 (own translation) [15]

In 2020, AEE Suisse presented a thorough study on renewable and decarbonized heating [16] that displays interesting figures, made all the more quantitative by taking into account:

1. Localization and sustainable exploitation
2. Infrastructure needed to exploit certain resources
3. Operational mode (monovalent vs bivalent)

Table 12 : Overview of the heat-side potential of renewable energies. Please note: the potentials cannot simply be added together. REA : Räumliche Energieanalysen, (Spatial energy analyses) [33]

Type of potential	**Energy vector**	**Potential [TWh]**			**Source**
		Theoretical	**Sustainably exploitable**		
Site-related	Wood		14		Thees et al 2017
	Biogas		6		Thees et al 2017
Building- and demand-related	Solar energy (thermal)	10,8	8.2 (roof) 2.6 (facade)		Remund 2017
	Solar energy (PV)		50		Meteotest 2018
	Wind energy[1]		25-35 (dep. on scenario)		REA TEP
Site-related	Earth heat (near surface, without regeneration)		6		REA TEP
	Earth heat (near surface, with regeneration)		31-35 (dep. on scenario)		REA TEP
		Theoretical	**Monovalent (assignment)**	**Bivalent (assignment)[2]**	
Site-related, operation w/ infrastructure (thermal networks)	MWIP	7	2	5	REA TEP
	WWTP[1]	8	2	7	REA TEP
	Lakes, rivers[1]	160	1-21	1-17	REA TEP
	Groundwater[1]	14	1-5	1-9	REA TEP
	Medium-depth geoth. energy[1]	>140	8-31	4-22	Schädle (2020), Géothermie CH, REA TEP

[1]Including electricity for decentralized or centralized heat pumps
[2]Including approx. 30% of energy from point peak coverage systems, e.g. MWIP, wood or biogas

33 AEE SUISSE, Wärme Initiative Schweiz: “Erneuerbare- und CO_2-freie Wärmeversorgung Schweiz, Eine Studie zur Evaluation von Erfordernissen und Auswirkungen”, Schlussbericht vom 6. Juni 2020 [16] (own translation). References in the table can be found therein.

It can be highlighted that the uncertainties given in Table 12 are rather high, notably regarding geothermal or waterborne resources. This situation is notably determined by the state of knowledge of the Swiss underground hitherto, to the complex estimation of future heat demand densities (in particular in the case of low-temperature efficient buildings), but also to the difficult prognosis regarding the financial costs associated with some technologies.

These uncertainties must not represent an obstacle to consider these resources in a serious manner in the future planning of heat supply for urban and suburban zones. However, when a given canton or city includes them in the future DHN deployment planning, it ought to adopt a two-step approach. Namely, on one hand, the possible implementation timeline must be taken into account, since the latter might be rather long due to the necessary preliminary investigations, e.g. in the case of geothermal explorations.

Hence, in this case, in order to avoid fossil-to-fossil replacements for heat technologies, intermediary solutions for DHN connections should be proposed on the territory that are consistent with the future, renewable supply. Such temporary configurations could include CHP units in order to maximize exergetic efficiency and minimize implementation times. On the other hand, the DHN planning must include possible alternative solutions, in case the expected resource capacity lies underneath the estimations or is even unexploitable without unacceptably increasing final customer price per kWh.

2.4.3. Substitution of fossil energy sources as DHN supply – Decision tree

As has been discussed in the previous section, statistics are clearly missing even on the approximate distribution of fossil-based boilers (by far the vast majority being based on natural gas) supplying DHN networks in Switzerland. Therefore, evaluations regarding their future replacement by low-carbon alternatives result as very difficult and risky, not to mention utterly unprecise.

As a consequence of this obstacle, the project team decided to provide a form of decision-tree that:

1) on one hand, highlights the possible renewable and/or low-carbon alternatives to natural gas boilers;
2) on the other hand, provides additional information based on the present implementation (baseload vs peak operation), localization of resources (situational vs non-situational) and other possible limitations (e.g. availability of low-carbon electricity supply).

The decision-tree below contemplates first the specific base in which natural gas boilers are used to supply a district heating network as baseload heat.

As can be seen, there are solutions available for replacing natural gas boilers, when the latter are used as baseload supply. Nonetheless, caution must be brought to three aspects:

1) localization of the renewable energy resource, with the idea of giving priority to situational – i.e. available on-site - resources, such as lakes and geothermal wells;
2) the overall availability (capacity) of the renewable energy resource at the territorial level, especially in the case of wood;
3) the environmental impact of the electricity supply in case of both decentralized and centralized heat pumps implementation in terms of GHG emissions.

In the case of implementation of power-driven heat pumps, the combination with CHP units installed in the neighbourhood could turn out to give favourable results, since the power production out of the cogeneration schemes could be focused for the supply of the heat pumps, concomitantly decreasing the need to use - potentially grey and imported - electricity from the grid [17]. This combination is based on the time-phasing of heat demand and CHP heat-driven operation based on external meteorological conditions and temperature.

Table 13 : Replacement technologies for baseload DHN supply production by way of natural gas boilers

Type	**Alternative**	**Primary energy**	**Technologies**	**Advantages and dis-advantages**
NG baseload				
	RE = 100 %			
		Wood (chips)	Wood boiler or gasification + CHP	Non-situational, regional wood resources may be limited, direct wood combustion not recommended according to national heat strategy
		Biogas	Biogas boiler or biogas CHP	Non-situational, limited resource, direct biogas combustion not recommended according to national heat strategy
		Residual or fatal heat	Direct supply	Situational, risk in relation to the perennity of the re source (e.g. industrial relocation)
		Waste	MWIP	Situational, limited resource due to recycling policies
		Medium-depth geothermal energy	Direct supply	Situational, prospecting risk, completion time, direct GHG emissions at the well site
	RE < 100 %			
		Lake, river, waste heat, low/medium depth geothermal energy	Centralised heat pump	Environmental balance depends on electricity environmental evaluation for heat pumps
		Natural gas with biogas mix	CHP	Natural gas network on site availability, environmental balance depends on the use made of the electricity produced with CHP and the proportion of biogas in the mix

The next point consists in identifying alternative solutions to natural gas boilers used for peak heat production, namely operated only on the cold periods of the year. The set of technologies identified above can of course all be implemented also for peak operation, under the constraint that economic viability must be carefully taken into account. In that sense, technologies based on energy sources harvested from the environment seem to be less well suited, notably due to high CAPEX costs but OPEX might also become relevant, e.g. due to on-off operational constraints for some components. Technical limitations must also be considered, for example in the case of wood boilers, in terms of feasible power gradients and part load operation.

On top of the previous technologies for base-load operation, three more can be specifically considered for replacing gas boilers in terms peak heat production (see table below).

Table 14 : Replacement technologies for peak DHN supply production by way of natural gas boilers

Type	Alternative	Primary energy	Technologies	Advantages and disadvantages
NG peak load				
	RE = 100 %			
		Solar energy	Solar thermal installation (e.g. vacuum collectors on rooftop or beside the buildings themselves)	Situational, depending on weather conditions
	RE < 100 %			
		Synergy with neighbouring district heating	Physical connection via an exchanger or valve	Environmental balance depends on neighboring DHN environmental impact, optimization of CAPEX, utilization of existing assets
		Storage	Physical storage of hot water on site or distributed along a district heating network route	Presupposes the existence of a heat source for DHN, increases losses

Solar thermal represents a very interesting potential as a renewable resource for DHN systems, as shown in the SOLCAD project, for example [14]. It presents intrinsic limitations due to the connection with meteorological conditions avec with day-night cycle. However, the latter can be partially compensated by adequate integration of storage systems [18]. It can be further integrated in both centralized and decentralized heat producing schemes, thus providing flexibility with respect to potential territorial constraints and opportunities (e.g. pre-existing storage volumes).

Another solution is represented by implementing thermal storage systems in the design and operational modes of DHN systems [8]. It does not represent an additional source of heat power, but provides a very reactive flexibility leverage mean either to absorb excess production (e.g. in periods of lower heat demand) or to quickly inject power in case of peak consumption. On the negative side, thermal energy storage increases the overall losses of the DHN system, while requiring available facility space either above- or underground.

Finally, the implementation of a physical connection with a neighbouring DHN system also can provide peak power, thus leveraging on operational synergies. This approach represents one of the key research questions of FOSTER_DHN's work package 3, presented below. It is expected to indeed bring several advantages, among which an optimization of grid assets management, a reduction of CAPEX related to the acquisition of heat production systems and a possible increase in overall exergetic efficiency.

Using synergies can also lead to a more optimal utilization of situational renewable energy resources, as will be demonstrated in the case of Yverdon-les-Bains. The main limitation is given by the effective existence of a neighbouring DHN system, especially in territories where mature DHN grids have already been deployed over entire municipal areas.

Last but not least, it needs to be noted that natural gas boilers are also often implemented as backup boilers. In this particular function, their replacement seems to result particularly difficult due to the intrinsic characteristics of very quick availability and load flexibility. However, these situations go beyond the scope of the project. In case gas boilers cannot be easily replaced (e.g. because of unfinished amortization), utilization of biogas can be contemplated.

In summary, alternatives to fossil energy technologies exist and can be implemented in DHN networks for both baseload and peak heat generation from a technical point of view. The engineering considerations must then be completed by financial considerations on both CAPEX and OPEX, including amortization costs. In order to use the renewable resources in the most efficient way, situational on-site resources should be given priority, as to allow territories that do not have access to specific low-carbon sources (e.g. which are not located near a lake) to decarbonize the heat sector by using non-situational primary energies (e.g. wood or biogas).

2.4.4. Interviews with stakeholders in the field of DHN planning, design, deployment and operation

Four Western Switzerland companies involved in the development, extension and operation of DHN systems have been contacted for interviews. The latter are Viteos (Canton of Neuchâtel), Sinergy (City of Martigny, Wallis), Groupe E (Cantons of Fribourg, Vaud and Neuchâtel) and SATOM (Cantons of Vaud and Wallis). The interviewees are kept anonymous but the full content of the interviews can be made available, if requested by any of the project funding entities, provided the authorization of the contacted companies.

The conducted discussions have focused on the experiences acquired in the planning and operation of DHN systems, in particular regarding the possible decrease of distribution temperatures and increased usage of renewable energy sources.

The main outcomes are the following:

1) The limits for the exploitation of wood resources in terms of DHN supply are being reached for Cantons of Vaud and Fribourg.
2) One of the major drawbacks linked to the usage of wood boilers is linked to the limited modulation possibilities. This often leads to use natural gas boilers during the summer time, even if wood boilers are available, except for large DHN schemes. In the latter situation, only the time-phasing of successive boilers allows to implement the necessary modulation.
3) In many cases, wood originates from a regional basis, but it may as well stem from distant regions, a situation that, in turn, might hinder other territories to switch to wood as a renewable resource. In that case, grey energy linked to wood transport must be taken into account, since it often represents up to 5% of the energy content of the energy vector itself.
4) Long-term supply contracts are signed with specialized companies for wood supply.
5) Thermal storage based on solar heat collectors would allow increasing the renewable share substantially. It could cover 100% of the needs during summer time and partially cover demand during colder seasons.

6) As an alternative to solar thermal technologies, hydrogen production based on PV units should be considered, along with the conversion of natural gas boilers into hydrogen ones. Again, this solution would allow 100% coverage of heat demand by a renewable energy source during the warm months and partial coverage for the other seasons. Local and mutualized hydrogen storage solutions can also be put forward in this case although the costs are still rather high in comparison to other solutions and fewer market options exist.

7) Interviewed stakeholders see biogas as an important solution in order to increase the renewables share. For example, a direct connexion between the production sites and the DHN stations has been proposed, in order to avoid the purification steps necessary prior to grid injection for biogas. This type of technological scheme is very similar to the one that is usually implemented in waste water treatment plants. In addition, heat produced by biogas-based CHP systems should be used as baseload for DHN supply.

8) In some cantons (e.g. Ticino), the heat supplied by a CHP system is considered to be renewable or, more precisely, as waste heat with electricity being considered as the main "product". The non-renewable share is thus completely attributed to the power production. This legal provision could be envisaged in other parts of Switzerland as well.

9) In the future, artificial intelligence could be used to improve the heat demand forecast at residential level. Indeed, AI-based systems would allow a more efficient operation and optimization of DHN conversion systems.

10) DHN systems based on centralized heat pumps exploiting heat harvested from the environment, especially from lakes and rivers, are characterized by large CAPEX costs, due to construction of the necessary infrastructure. Yet, they present the advantage of: (i) allowing the utilization of a localized, on-site renewable energy source, and (b) not depleting the potential access to other low-carbon resources such as wood and biogas. However, the utilities should be legally allowed to distribute the high CAPEX costs on all the customers linked to DHN systems that they operate, in order not to disadvantage the customers linked to more expensive supply schemes and solve such a "paradox". However, a similar cost redistribution on DHN tariffs is presently not contemplated in the current (national and local) legislation and regulation. Political authorities should be made aware of this issue.

11) It is considered to be highly counterproductive that renewable electricity produced by a given energy utility in a given territory is thereafter not considered to be renewable when it is used to supply heat pumps connected to DHN systems operated by the same utility. From a legal standpoint, this is linked to the fact that the localization link between production and consumption is "lost". A legislative adaptation in this context is thus called for, in order to foster and valorize renewable power production more broadly for DHN heat pumps supply, even more by considering that the latter allow utilization of localized, on-site renewable resources (e.g. lake water or underground geothermal energy).

2.4.5. WP1 summary and key findings

The first work package of FOSTER_DHN focused on the possible increased usage of renewable and low-carbon energy sources for DHN supply, in order to decrease implementation of fossil energy vectors and associated GHG emissions.

While low-carbon energy sources can quantitatively replace natural gas and oil in terms of overall potential, attention must on one hand be taken with respect to the location of the resources (available on-site or not) in order to foster utilization of situational resources with highest priority. Prioritizing locally available low-carbon resources obviously leads to leaving access to non-situational resources for other regions which do not have access to local primary energy potential (e.g. a city which is not located on a lake or which does not own forests).

On the other hand, the specificities of each low-carbon energy resource must be taken into account in order to use it in a rational way with respect to band or peak operation at different time periods.

The conducted interviews bring additional elements brought in from the direct experience of energy companies with the planning, deployment and operation of DHN in Western Switzerland. In particular, the interviewees pointed out to the difficulties in replacing natural gas boilers for peak operation, which could open the way to a broader usage of thermal storage technologies in DHN (still relatively limited in Switzerland). The possible role of solar thermal has also been highlighted, along with renewable gases, although the latter are not contemplated by the SFOE heat strategy.

2.5 Activities and results – Workpackage 2

The second work package deals with the opportunities linked to decreasing the water distribution temperature on the primary side of district heating networks. The project has tackled this issue along two complementary routes. The first approach consists in considering the energy refurbishment of buildings which is supposed to lead to a decreased heat demand on the secondary side and, possibly, requires a lower temperature level on the primary DHN side. The second approach considers the integration of heat sources at lower temperatures in DHN, such as waste heat from data centers or industry, as well as geothermal energy. Both routes will be tested and analysed mainly in the two test-cases.

2.5.1. General model for buildings refurbishment and estimation of heat demand

To estimate heat demand within district heating networks (DHNs) under different refurbishment scenarios, a methodology was developed to model building energy consumption. These models reflect the energy efficiency standards outlined in SIA380-1:2016 [5], providing a foundation for evaluating the impact of upgrading existing buildings. By generating heat demand profiles for various building types and refurbishment conditions, it becomes possible to simulate and optimize DHN design. This approach helps investigate how future systems will need to adapt to meet the evolving energy needs of communities, aligning with sustainable energy practices and improving the overall system performance.

2.5.1.1. Building types and energy demand

The energy needs of a district serviced by a DHN is determined mainly by aggregating the energy demand of each building composing the district under investigation (i.e., excluding distribution losses). Except for high homogenous cases, as for residential-only districts, the buildings connected to the same DHN will feature differences in building material (i.e., overall type of envelope and insulation), in the energy production system, in the distribution system and in their type of use. This latter point is of particular interest, as the building use determines the overall space heating demand, since it is linked to the occupancy of the building.

The SIA380-1:2016 provides indications on the performance required from the thermal envelope of 12 building typologies, but in the framework of the current project, and for practical purposes, only the 9 categories shown in Table 15 have been investigated. The reader is referred to the Appendix A of SIA380/1:2016 to have further details for each type of building and its constructive elements.

Table 15 : Limit values of the annual heat demand for new construction and for an average annual temperature of 9.4°C, according to the SIA380-1:2016.

Building category	Use	Limit values	
		$Q_{H,li,o}$ in [kWh/m^2]	$\Delta Q_{H,li}$ in [kWh/m^2]
I	multi-family housing	13	15
II	individual housing	16	15
III	administration	13	15
IV	school	14	15
V	retail	7	14
VI	catering	16	15
VIII	hospital	18	17
IX	industry	10	14
XI	sports facility	16	14

For each building category considered, the limit and target performance values provided by the SIA380-1 are used to define two distinct refurbishment scenarios. The "limit value" scenario involves moderate improvements to the building envelope and a slight reduction in distribution temperatures, while the "target value" scenario represents more extensive renovations, including significant envelope upgrades and the lowest possible distribution temperatures achieved through underfloor heating, which requires a careful economic assessment to justify.

In fact, while the "limit value" corresponds to a feasible technical solution in line with the state of the art at a reasonable price, the "target value" corresponds to an overall system combining improvements to the energy system and thermal envelope, which can result in expensive modifications difficult to justify.

In order to derive the corresponding limit and target values for the building performance, the SIA 380 adopts the following computations, which depend on the different use category and on the overall building shape:

$$Q_{H,li} = \left[Q_{H,li\,0} + \Delta Q_{H,li} \frac{A_{th}}{A_E}\right] * f_{cor} \quad (4)$$

where $Q_{H,li}$ is the "limit value" of the building annual heating demand for new constructions; $Q_{H,li,0}$ and $\Delta Q_{H,li}$ are values provided by the SIA380/1 and shown in Table 15; A_{th} is the surface area of the building's thermal envelope, in [m^2]; A_E is the reference energy area, in [m^2]; f_{cor} , that is a temperature correction which takes into account the fact that calculation results are valid for an average outdoor temperature of 9.4°C, and that is computed as following:

$$f_{cor} = 1 + [(9.4°C - \theta_{e,avg}) * 0.06\ \mathrm{K}^{-1}] \quad (5)$$

where $\theta_{e,avg}$ is the mean outdoor temperature, in [°C]. According the SIA380-1, in order to derive the limit value for refurbished buildings, the limit computed for new building construction is multiplied by 150%. On the other hand, target values for building refurbishment corresponds to the limit values featured by newly constructed buildings.

Once computed, limit and target values can be adopted in reference to the building demand for space heating only. In order to include also the energy demand due to Domestic Hot Water (DHW) preparation, the specific energy needs reported in the SIA385/2 have been adopted [19].

An equivalence of 0.058 kWh/l of water at 60°C (from 10°C) allowed to compute the energy demand for DHW preparation as specific hot water consumption in [l/d/m^2] of reference energy area A_E.

Table 16 shows the values of the specific energy demand for DHW preparation for several categories of buildings that have been adopted.

Table 16 : specific energy demand for DHW preparation for several categories of buildings according to SIA385

Category	Building Use	Energy demand for DHW, in [kWh/m^2]
I	multi-family housing	21
II	individual housing	14
III	administration	7
IV	school	7
V	retail	7
VI	catering	56
VIII	hospital	28
IX	industry	7
XI	sports facility	83

2.5.1.2. Building statistics and archetypes

The method described in the SIA 380/1 to derive the energy demand of a building belonging to a particular category requires some of the geometrical features of the building under consideration, as the reference energy area (REA or A_E) and the surface of the thermal envelope (A_{th}). To develop an acceptable approximation over the extrapolation of energy demand profiles to buildings of different shape and height, the building portfolio included in the use case of the DHNs of Yverdon-les-Bains area has been statistically analysed in order to derive some insights on a typical building for each category, characterized in terms of number of floors and typical A_E. Table 17 shows the resulting typical number of floors and A_E considered in the following to create base models under Polysun, allowing to derive the energy demand and substation temperature hourly profiles for an "archetype building", not too dissimilar in its form factor from the rest of the building portfolio taken into account.

Table 17 : Number of floors and REA considered to model the typical buildings of the Yverdon-les-Bains user case and for each SIA category.

SIA Category	N. of floors	A_E, in [m^2]	Total A_E, in [m^2]
administration	2	1400	2656
retail	2	1400	30136
industry	2	1000	3470
sports facility	1	3500	3522
multi-family housing	2	2500	44635
individual housing	2	1000	4261
school	2	5000	162991

2.5.1.3. Building model development

The estimation of the building energy demand was carried out using Polysun software, by developing customized performance models for each of the nine building categories taken into account. Indeed, the modeling process followed a structured approach:

- Base model construction: a base model was created for each building category, featuring an envelope representative of buildings constructed prior to 1970. These models assumed heat distribution via high-temperature radiators with distribution temperatures set at 65°C. The purpose of the base model was to establish the "base building" energy demand, reflecting the performance of older, unrefurbished buildings. Figure 16 shows the typical base model built in Polysun.
- Scenario adaptation: after constructing the base model, the envelope and district heating (DH) substation designs were adapted to create two refurbishment scenarios:
    - a "limit scenario", involving moderate improvements to the building envelope and a slight reduction in distribution temperatures, designed to achieve specific energy demands in line with the "limit values" defined by the SIA 380-1:2016 standard;
    - a "target scenario", considering a more extensive refurbishment, incorporating significant upgrades to the building envelope and further reductions in distribution temperatures to meet the "target values" specified by the SIA 380-1:2016.
- Profile processing: for each of the three scenarios (base, limit, and target) and for each of the nine building categories, Polysun simulations generated hourly profiles for both building-specific energy demand and key temperatures at the substation level. Once normalized against the overall annual energy demand, these specific energy demand profiles were used to estimate the energy demand profile of each building included in the case studies.

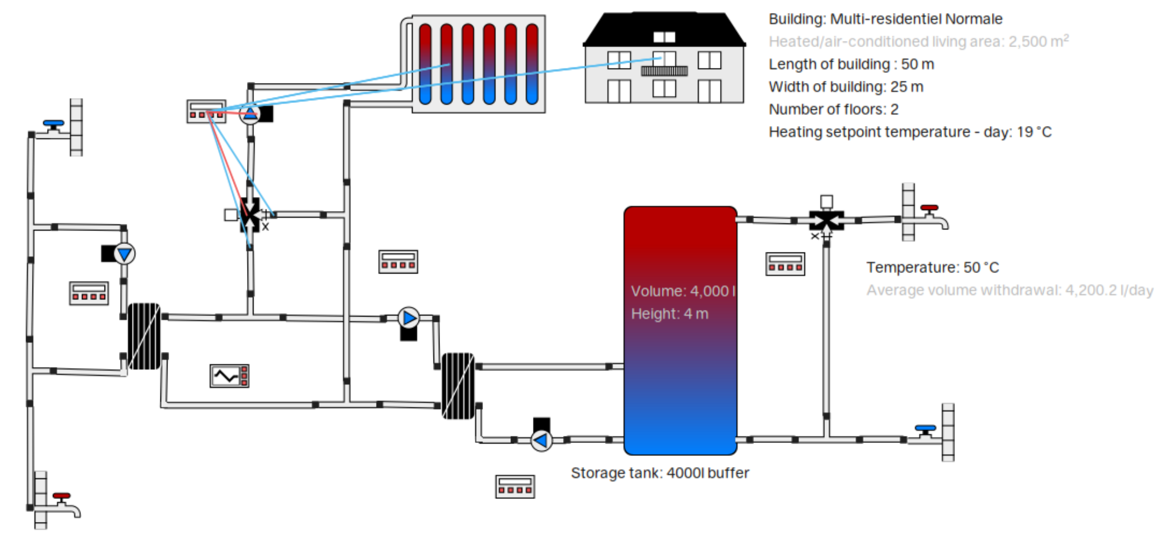


Figure 16 : Base model built in Polysun, depicting the DH substation composed by a main heat exchanger, the space heating distribution system and DHW preparation apparatus.

2.5.1.4. Impact of decentralized DHW production

In the two refurbishment scenarios taken into account (i.e., limit and target scenarios), the energy demand profile changes (both in shape and mean value) since the simulated building requires less energy due to the simulated intervention affecting the building envelope and the space heating distribution temperatures.

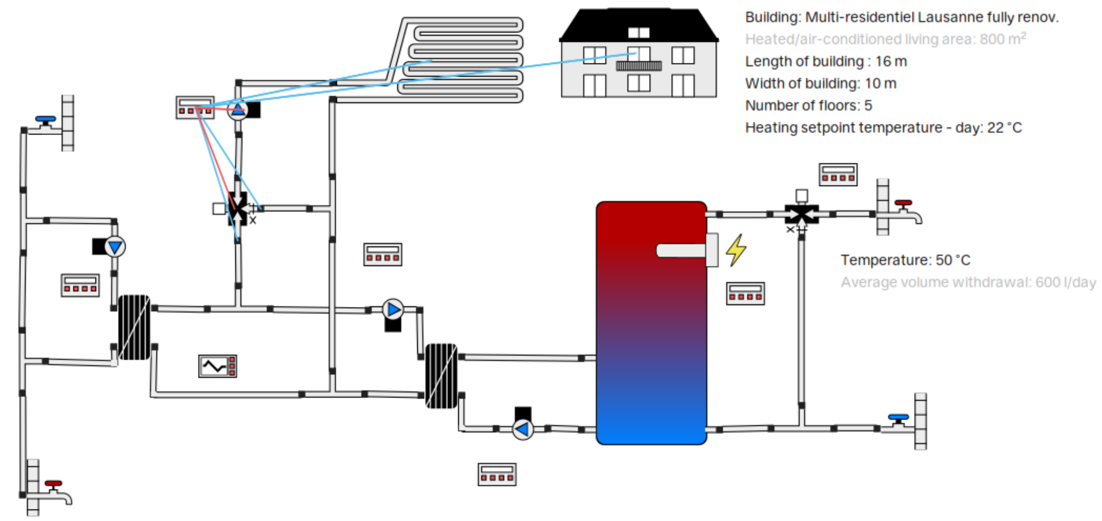


Figure 17 : A DHN building substation with decentralized DHW production equipped, as well as a dedicated auxiliary heater that is able to supply energy at temperatures lower than 70°C

By maintaining the same type of sub-station, though, the decrease in DHN supply temperature is limited to the temperature required on the secondary side for DHW production and from the heat exchanger pinch (i.e., DH forward temperatures can be lowered down to 70°C). Instead, if the DHW production is modified, distribution temperatures on the secondary side of the DH substation can lower even further, being limited only by space heating distribution temperatures. In the case of subfloor heating, these latter can be around 40 °C.

To account for this case, a variant of the 2nd refurbishment scenario, shown in Figure 17 has been adapted to include an auxiliary heat producer dedicated to DHW production only (e.g., an electric heater, an air source heat pump, solar thermal collectors, etc..), allowing the DH network forward temperature to be lowered in the range of 50-60°C.

2.5.1.5. Application of renovation scenario

To apply a renovation scenario to the building portfolio of the project, a simplified methodology has been adopted due to the lack of detailed construction information for each building. The buildings under investigation were first classified according to the energy performance categories outlined in Table 18, derived from [20]. Based on this classification, each building was assessed for its potential as a renovation candidate. If a building fell into a category below D in Table 18, it was considered eligible for renovation, with energy demand projections adjusted according to either the limit or target scenario. Conversely, buildings classified as category D or higher were assumed to remain unrenovated, with their energy demand corresponding to the base scenario used in the building model simulations.

Table 18 : Approximate reference values for building energy classification based on annual specific consumption for heating and domestic hot water, according to CECB certification [20]

	Annual energy consumption for SH and DHW, in [kWh/y/m^2]	Approximate CECB Class
Highly efficient buildings	40-50	B
Efficient buildings	60-100	D
Built before 1970	120-150	F

2.5.1.6. Energy demand profiles: an example

A Python class was developed to facilitate the retrieval of normalized profiles and corresponding temperatures for each building category relevant to the project, (*ChargeCurve.py*, see Appendix 7.1 for details).

To retrieve the typical load profile for the heat demand of a building in the “Administration” category, featuring an annual energy consumption of 100’000 kWh/y and a reference energy area of 1’000 m^2, the instruction is the following:

Office_Building_profiles=chargeCurve(affectation="Office",annual_consumption= 100000,SRE=1000)

The panda dataframe *“Office_Building_profiles.DB”* contains the following hourly profiles:

- ‘*Load1*’: the hourly profile of the specific energy demand of the building substation, in [kWh/m^2];
- ‘*Load2*’: the hourly profile of the specific energy demand of the building substation refurbished according the to “Limit” scenario, in [kWh/m^2];
- ‘*Load3*’: the hourly profile of the specific energy demand of the building substation refurbished according to the “Target” scenario, in [kWh/m^2];
- *Ts_i_1 or 2 or 3 and Ts_o_1 or 2 or 3* are the hourly profiles of the heat transfer fluid temperature on the secondary side at the inlet and at the outlet of the building substation for the base (1), the limit (2) and the target (3) scenarios respectively.

- *Tp_i_1 or 2 or 3 and Tp_o_1 or 2 or 3* are the hourly profiles of the heat transfer fluid temperature on the primary side at the inlet and at the outlet of the building substation for the base (1), the limit (2) and the target (3) scenarios respectively.

The hourly profile of the specific energy demand, as well as the temperature profiles for the 1000 m^2 Administration building taken as example are shown in Figure 18 and Figure 19, respectively.

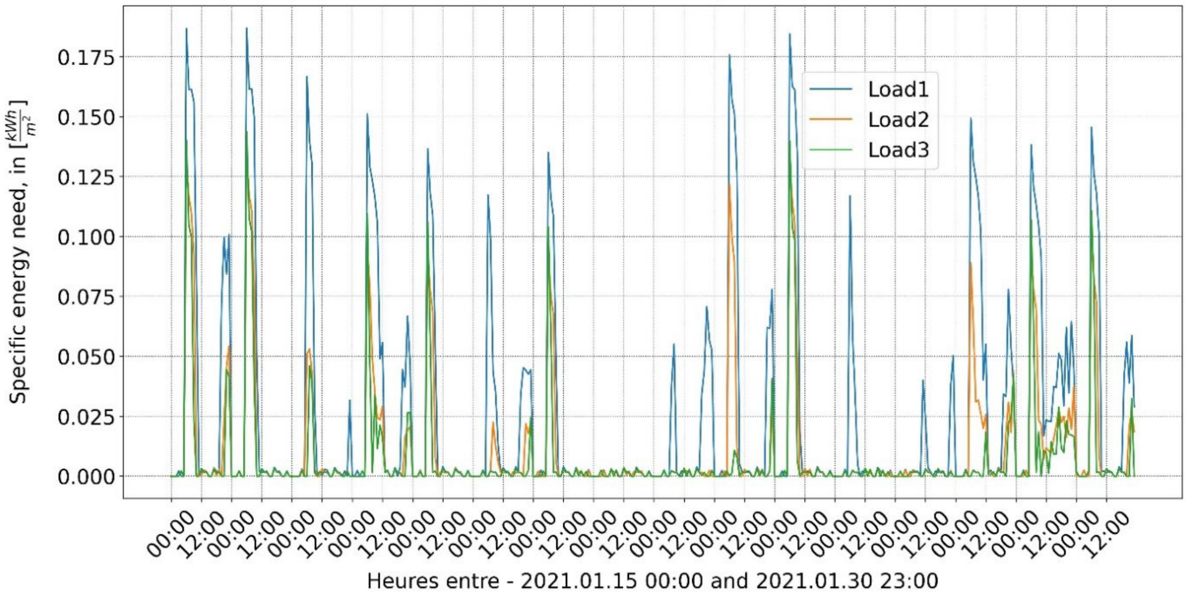


Figure 18 : Specific energy profiles (i.e., for Load1, Load2 and Load3) between the 15th and the 30th of January for an Administration building featuring 1000 m^2 of reference energy area and 100000 kWh heating demand.

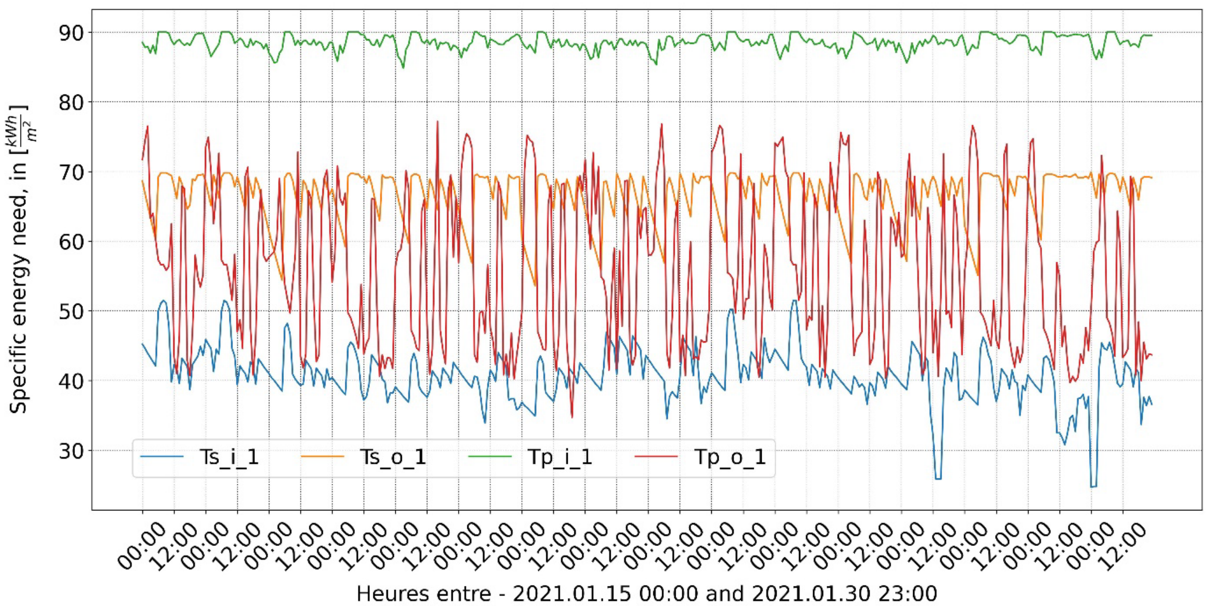


Figure 19 : Substation primary and secondary temperatures for the base scenario concerning an Administration building featuring 1000 m^2 of reference energy area and 100000 kWh/y of energy demand.

2.5.2. Inputs from DECARB.CH and T-Drop projects

This section presents a brief overview of two SFOE-funded projects, TDROP and DECARBCH, whose findings were leveraged within the FOSTERDHN project.

Key results and data from these projects are also highlighted.

2.5.2.1. TDROP Project:

One of the objectives of the TDROP (2023-25) project is to define and evaluate different strategies to reduce the temperature required to meet the heating DHW demand of existing multifamily building in urban area. A reduction of temperature level facilitates the decarbonization of heat production (better COP for HP and lower return temperature for DHN).

Due to planning incompatibility the transfer of results from the TDROP project was limited. Nevertheless, the strategies develop in TDROP mainly for sequential building retrofitting was used to estimate the required heating temperature level possible evolution as a function of retrofitting depth (see section 2.5.1). Due to time planning incompatibility, it was not possible to use more results from TDROP in FOSTER_DHN, as initially foreseen

2.5.2.2. DecarbCH project:

The result from the WP7 (Case studies Romandie: strategies and potentials of temperature reduction on existing district heating networks[34] [21] of DecarbCH project were also useful for the FOSTER_DHN project realization. DecarbCH is an ambitious SWEET project aiming at developing and evaluating strategies for the decarbonization of the heat sector in Switzerland. Domes-tic and industrial use of heat are both considered.

WP7 specifically investigated and compared various measures to decrease both the forward and return primary temperature levels in existing DHNs. Results indicate that DHW production is a primary constraint on temperature reduction. In most existing buildings, the maximum forward temperature is limited to 60°C to meet DHW requirements. Similarly, the DHN return temperature is often con-strained by DHW production.

Optimizing DHW production regulation and hydraulics is crucial. A substation configuration with two parallel heat exchangers, one for space heating and one for DHW production, offers a promising approach to limit both forward and re-turn temperatures. This kind architecture is commonly found in most Scandinavian DHN.

Furthermore, a literature review revealed that a significant portion of temperature errors and malfunctions in existing DHN substations are primarily caused by design flaws or regulation problems in the substation. By rectifying those issues, it is possible to efficiently lower primary return temperatures without intervention on the secondary side.

Two existing DHN were also studied and compared: one small rural DHN using a wood boiler and one large urban DHN located in Geneva. Inspection of DHN substation has shown that a large part of the substation is oversized (with an average oversizing of 55%). It might partly be explained by the fact that substation is often sized using the pre-existing boiler nominal power. And most of the fossil boiler in existing multi-family building are very commonly oversized. The excess flow method was also applied in this two DHN. This method allowed ranking the substations according to their negative impacts on the DHN forward/return temperature difference compared to a defined target. By optimizing a small portion of the existing substations, it is possible to increase substantially the DHN forward/return temperature difference. This is often much more difficult to apply to a large DHN with different substation architecture. Indeed, in the Geneva DHN, some substations are used to supply heat to a small local

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[34] S. Callegari, PhD Thesis, University of Geneva (2023)

thermal grid serving several buildings. It illustrates the importance of standardization of substation architecture and regulation to facilitate DHN operation and optimization.

Finally, two different substation architectures were compared (see Figure 20). The first architecture is very common in existing DHN in Switzerland. In this architecture, the heat is transferred to the secondary circuit via one plate heat exchanger. The DHW production is done on the secondary side with a second heat exchanger in cascade. The second architecture is less common. This architecture is used in the small rural DHN studied in DecarbCH WP7. It is composed of two heat exchangers: one is used for space heating and the other for DHW production. The primary return flow of the DHW heat exchanger is mixed with the primary forward flow before entering the space heating heat exchanger. In principle, this architecture allows reducing the return temperature especially during the heating season.

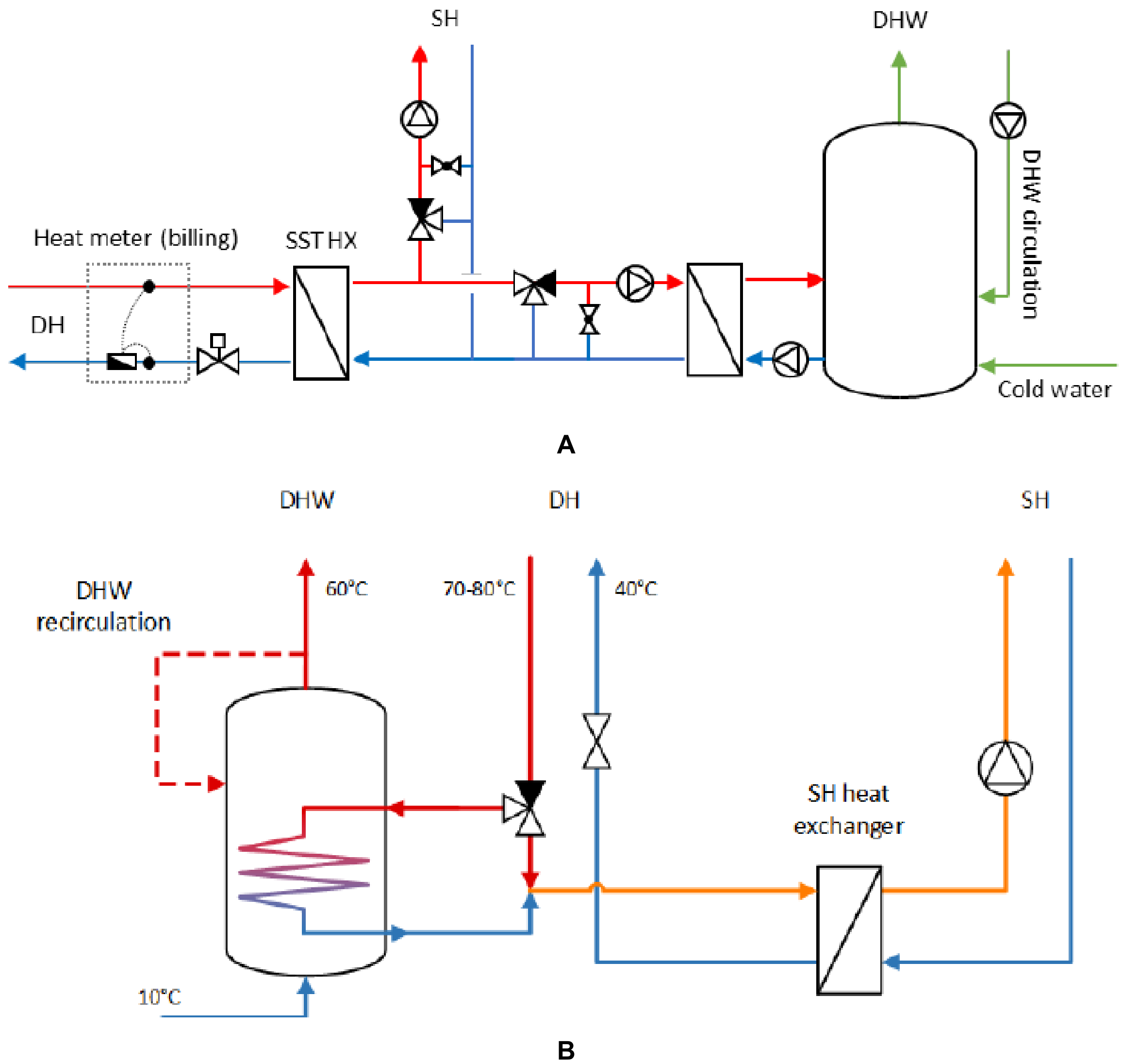

Figure 20 : Substation architecture compared in the WP7 of the DecarbCH project: A. common substation architecture (used in the Geneva DHN) and B. innovative substation architecture (used in the small rural DHN)[35] [21]

[35] S. Callegari, PhD Thesis, University of Geneva (2023)

This comparative analysis underscores the advantages of innovative substation to minimize the primary return temperature. The innovative architecture eliminates also on heat exchanger reducing the required forward temperature to respect the minimum DHW temperature.

2.5.3. WP2 summary and key findings

WP2 investigated the potential for lowering the distribution temperature in DHN. This was approached through two complementary routes: (1) energy refurbishment of buildings, aiming to reduce secondary-side heat demand and potentially requiring lower primary-side DHN temperatures, and (2) decentralized DHW production.

The research in WP2 addressed the following questions:

1. How can building energy consumption be modelled under different refurbishment scenarios to accurately estimate heat demand in DHNs?
2. How do specific building types and energy demand influence DHN design and optimization?
3. What is the impact of decentralized DHW production on lowering primary-side DHN temperatures?
4. What insights from ongoing and complementary projects like TDROP and DecarbCH can be applied to reduce DHN temperatures?

The WP2 key findings include:

1) **Building renovations, particularly those achieving "target scenario" standards, significantly impact DHN temperature requirements.** While the "limit scenario" yielded moderate improvements, the "target scenario" renovations, including substantial envelope upgrades and lower distribution temperatures (as low as 40°C with underfloor heating), showcased the potential to drastically reduce DHN temperature requirements.
2) **Decentralized DHW production is crucial for lowering DHN supply temperatures.** This strategy allows DHN forward temperatures to be lowered to 50-60°C, compared to the 70°C limit imposed by centralized DHW production.
3) **Older buildings (pre-1970) present the most significant opportunity for renovation and DHN temperature reduction.** Buildings classified below category D (consuming 120-150 kWh/y/m2) were identified as prime candidates for energy efficiency upgrades, directly impacting DHN optimization.
4) **Substation design optimization, including the use of two parallel heat exchangers (one for space heating and one for DHW) offers a promising approach to reduce both DHN forward and return temperatures.** This finding, supported by the DecarbCH project, highlights the impact of alternative substation architectures. Currently in Switzerland, a large majority of DHN uses substation with a unique heat exchanger to provide heat for space heating and DHW production.
5) **A significant portion of existing DHN substations is oversized (averaging 55% oversizing), hindering optimal temperature regulation.** Addressing this oversizing, often stemming from pre-existing oversized boilers, presents a key opportunity for improving DHN efficiency and temperature management. Standardizing substation architecture and regulation within district heating networks (DHNs) would facilitate more efficient operation, maintenance, and overall system optimization.

Overall, WP2 demonstrated the potential for reducing DHN temperatures through a combination of building refurbishment, decentralized DHW production strategy, and optimized system design, for example within the Lausanne text-case. There, it was analyzed how reducing the distribution temperatures within the Dufour DHN affects the overall efficiency of the system. In one scenario, high-temperature scenario, the secondary side temperature was reduced from 65°C/40°C to 55°C/35°C, leading to a 21% decrease in electricity consumption for the central heat pump. However, while reducing temperatures lowered the heat loss from 872.8 MWh/year to 718.8 MWh/year, it also resulted in a heat power shortfall as the heat pump produced less heat. In the meantime, pump electricity consumption increases from 37 MWh/year to 54.4 MWh/year due to the higher mass flow rate needed to compensate for the reduction in network temperature difference (ΔT).

Additionally, in the scenario with decentralized heat pumps of the Lausanne test-case, the so-called low-temperature scenario, the temperature reduction improved their COP and a 19% reduction in electricity consumption for decentralized HPs was observed. However, total Q_C that the network must supply increase from 2724 kW to 2917 kW for all buildings. Finally, pump electricity consumption increases from 122 MWh/year to 134 MWh/year due to the higher mass flow rate required to compensate for the increase in network heat power. This scenario highlighted the importance of balancing temperature reductions with operational adjustments (e.g., mass flow rate), as excessive temperature reductions can lead to challenges in meeting heating demands, even though energy efficiency improves.

The implications of primary distribution reduction strategies for the Yverdon-les-Bains test-case are explained in details in sections 2.6.2.6, 2.6.2.7 and 2.6.3.3.

2.6 Activites and results – Workpackage 3

2.6.1. Yverdon-les-Bains test-case – Simulations and synergies

The test case of Yverdon-les-Bains is applied to the simulation tool based on the pipe-flow solver pandapipes presented in 2.2. The test-case is based on the assumption that the energy utility of the city of Yverdon-les-Bains is planning to change the supply of heat in the coming years drastically from local gas and oil combustion towards district heating.

By using renewable and climate friendly heat sources the greenhouse gas emission for the heating sector is supposed to decrease by 90 % until 2050. Currently there are two district heating networks located in Yverdon-les-Bains:

1) a network connected to the local wastewater treatment plant (STEP);
2) a small heating network (Lotus) suppling the hospital and the thermal bath which is supplied by the co-generation plant located in the hospital, which ensures a secure and redundant electricity supply.

The expansion of the district heating network is illustrated in Figure 21 for 3 future stages proposed by Yverdon Énergies. In the first stage (îlot), the network will operate as three separate district heating networks with a fourth as an anergy network. The current existing low temperature network in the north (STEP - anergy) will supply a heat pump connected to the 70°C network of CAD STEP south of the anergy network.

A large network (Santal) will be installed in the south and west of the city, supplied by different sources as geothermal, heat pumps, the co-generation unit of the hospital as well as wood and gas combustion. The current existing network Lotus will be integrated into the new network Santal. To the east and centre is the fourth network located (Iris), covering among others a large part of the university and the city centre.

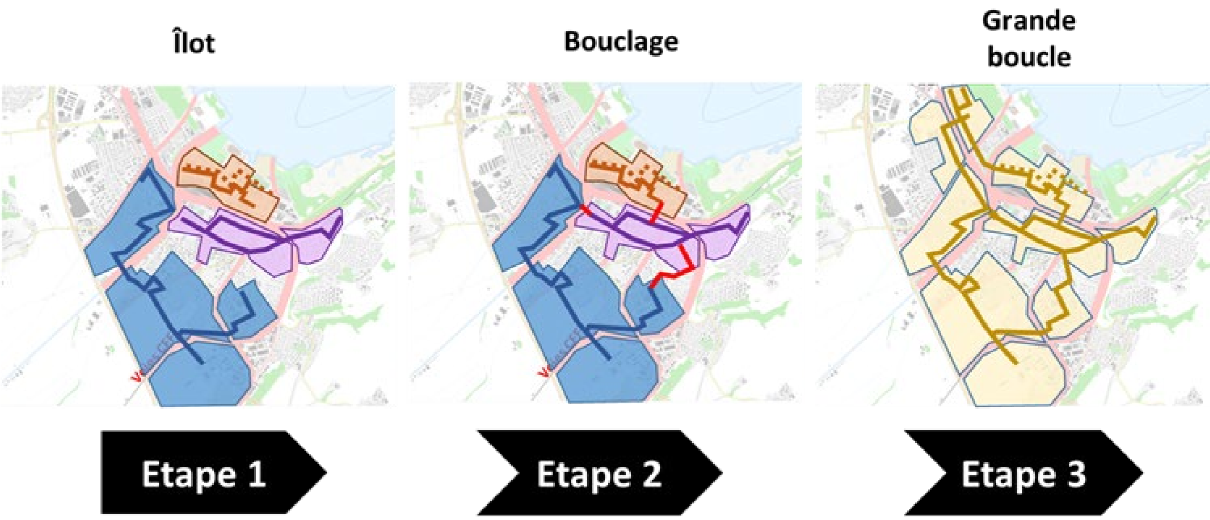

Figure 21 : Phases of the evolution of the district heating networks in the city of Yverdon-les-Bains (Source: SEY, not available in English)

In the second stage (Bouclage), the three separate district heating networks will be connected with each other with either valves where mass flow exchange between the networks take place, or with heat exchanger where only heat is transferred between the networks. The network Santal and Iris will be connected at two places with each other by valves which can be open and closed, whereas the STEP network will be connected to Iris at just one point.

In a last stage (Grande boucle) further in the future, the network will be further expanded in the north, which results in the STEP being connected to the Santal network. But it is foreseen to operate the network by then as a full interconnected network and not as sub-networks anymore.

The topology of the heating networks is shown in Figure 22 with the different heat sources in the grid. The connection between the heating networks is marked with a black dot between the networks. The heat sources are well distributed over the territorial of the heating network in both technology but also installed power (compare Table 19).

For both larger networks, CAD Iris and for CAD Santal the geothermal sources are expected to be used as base load source with wood and gas combustion to cover peak demand periods. Since there are two connection points between the CAD Iris and the CAD Santal, the southern one is named with the addition of “Lotus” in the following.

A valve as connection indicates a heat and mass-flow exchange, while a heat exchanger would only enable a transfer of heat between the networks. Stage 3 is not included in the figure and therefore also no direct connection between Santal and STEP exists.

Table 19 : Current and future heat sources in the DHN of Yverdon-les-Bains

Source id	Technology	CAD Name	Installed Power [MW]	Pressure [bar]	Temperature [°C]
1	Heat recovery	STEP (anergy)	variable	3	10-20
2	Heat Pump	STEP	1.8	8	70
3	Gas	STEP	3	8	80
4	Wood	Iris	5	8	80
5	Geothermal	Iris	5	8	80
6	Gas	Iris	10	8	80
7	Wood pellets	Iris	1	8	80
8	Bi-combustion	Iris	2.5	8	80
9	Gas	Iris	1	8	80
10	Gas	Iris	3	8	80
11	Co-Generation (Gas)	Santal (Lotus)	0.6	8	80
12	Wood	Santal	9	8	80
13	Gas	Santal	6	8	80
14	Geothermal	Santal	2.5	8	80
15	Gas	Santal	2.7	8	80
16	Geothermal	Santal	2.5	8	80

The anergy network of CAD STEP will be shortly discussed in the following, but will not be considered as part of the district heating network test case and therefore not included in the result diagrams of the network.

Moreover, the anergy network of CAD STEP is connected to the local sewage plant and uses the waste heat as heat source. The heat from the plant is depending on the external temperature and therefore time-depending in both day and night cycles, as in seasonality (see Figure 23). Each heat consumer connected to the anergy network is equipped with a local heat pump to raise the temperature (10-20°C) in the network to the required temperature (50-70°C).

The anergy network is considered in the following as source for the heat pump installed in one of the buildings of the university located in the 70°C part of CAD STEP. In order to ensure that the heat pump is able to operate in an efficient manner, the anergy network has to provide a sufficient temperature level of the transported mass-flow.

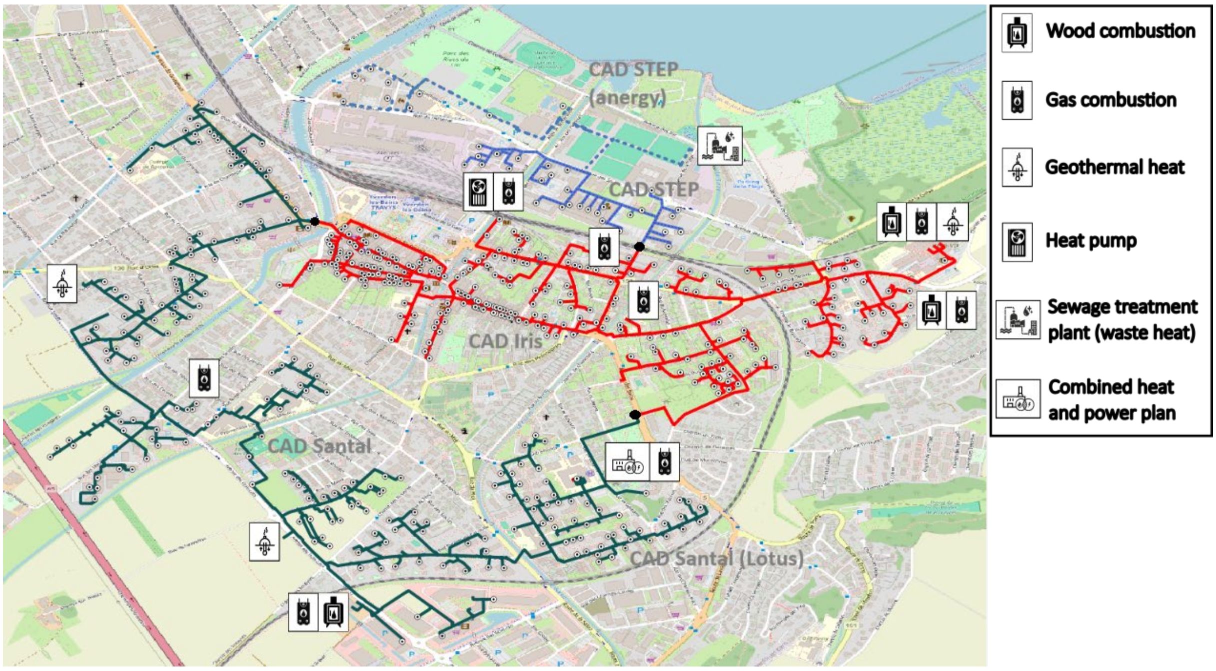

Figure 22 : Overview of the (expected) district heating network of the test case of Yverdon-les-Bains

Whereas gas and wood combustions are known and reliable technologies, a greater use of both is incompatible with the political goals of Switzerland, Canton Vaud and Yverdon-les-Bains based on reduction of greenhouse gas emissions and deforestation. These have thus to be understood as "exploratory" or transitional scenarios, not as long-term perspectives.

The geothermal sources are therefore playing a significant role in supplying the heat demand in the network. It is expected to find geothermal sources in the region of Yverdon-les-Bains that could operate at around 60°C. In order to reach the desired network operation temperature of 70°C or 80°C, the geothermal source have to be combined with an additional technology which can raise the temperature further (Figure 24).

Each geothermal source is therefore a combination of two technologies, with a combined emission parameter of both based on the temperature increase in each.

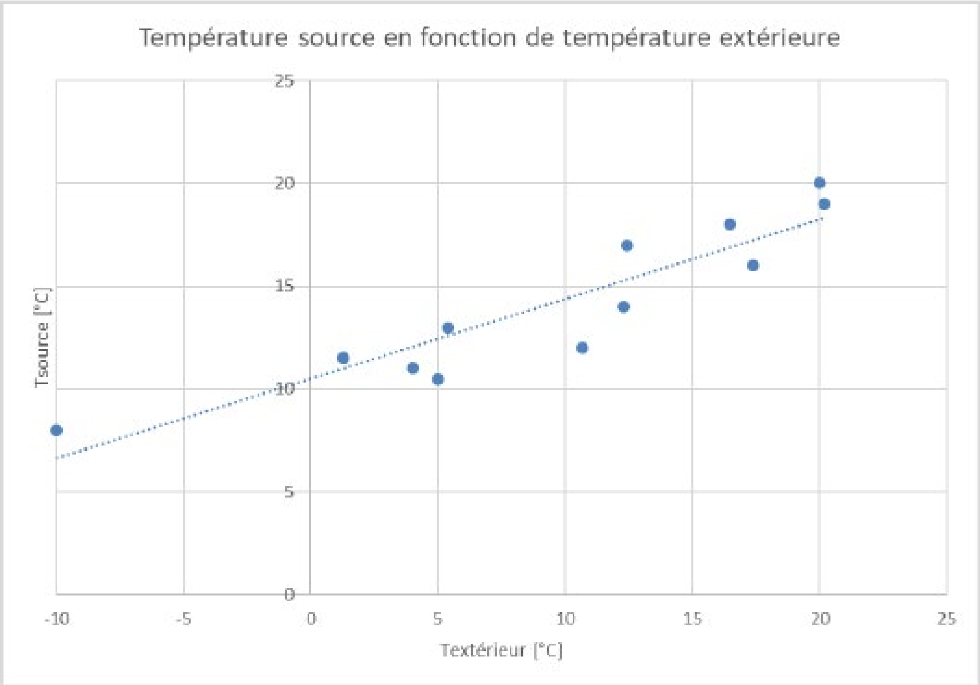

Figure 23 : Injection temperature of the sewage treatment plant (STEP) into the anergy network as function of the outside temperature[36]

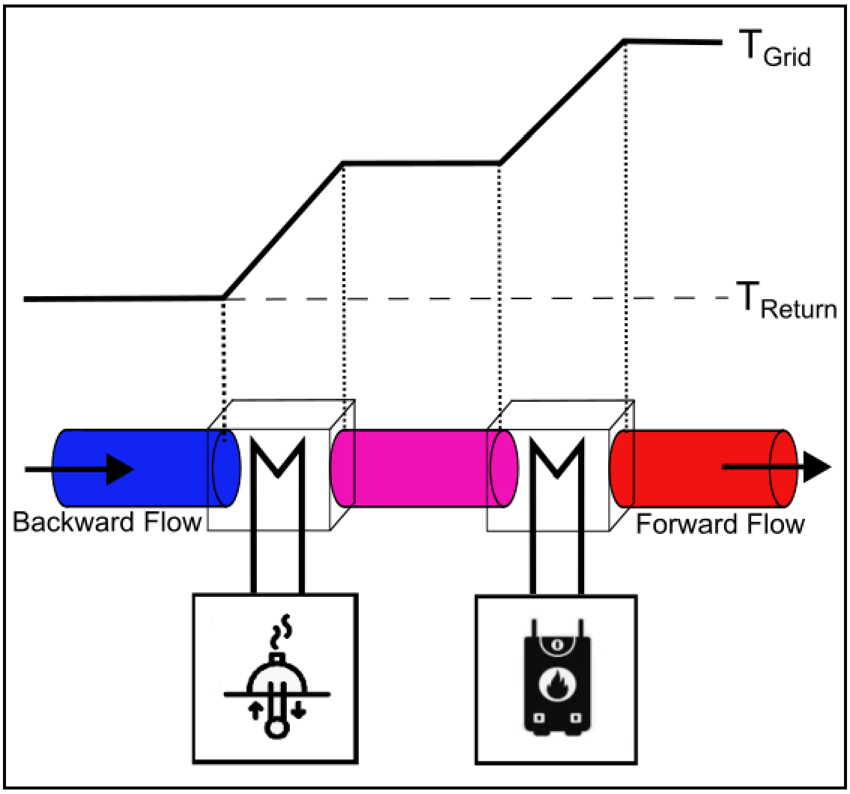

Figure 24 : Conceptional design of the geothermal sources with supplementary heating technology connected to the district heating network of Yverdon-les-Bains to raise the return temperature (T_{Return}) to the grid operational temperature (T_{Grid})

2.6.2. Yverdon-les-Bains test-case – General Results

In this project, we only consider and analyse stages 1 and 2 of the evolution plans of the heating network. Hereby, in a first step, the hourly based heat demand-supply balance for a whole year is determined based on two configurations representing "Etape 1" and "Etape 2". In a second step, the networks are simulated with both configurations for selected time periods and analysed in more details. The benefits of both ways of analyse is discussed further in Table 20.

Table 20 : Heat balance and simulation analyses: differences and benefits

	Heat balance	**Simulation**
Purpose	Strategical planning	Operational controlling
Analyse indicators	1. Primary energy 2. Emissions 3. General overview of usage of heat sources	1. Detailed distribution of physical parameters in the grid 2. Critical "breaking points" in the grid 3. Temperature and heat supply to the consumers
Time resolution	Long scale (annual or even over the whole project life time)	Instance of a time step (second, minute, hour)
Component level of details	Low – network as black box	High – detailed account of physical behaviour if the network
Efficiency evaluation	Simple assumption on energy converting technologies and losses	Detailed heat losses calculation based on physical parameters

The **general base scenario** that is considered in the following is the renovation scenario based on the recommended CECB strategy (scenario 1) with a heat injection temperature of 80°C (70°C for the heat pump) and gas combustion as supporting technology for the geothermal sources. All scenarios are based on these three configuration settings, unless its mentioned otherwise. All results are only considering the 70 and 80°C networks in the following and assuming the anergy network only as the cold source of the CAD STEP heat pump.

2.6.2.1. Heat demand and renovation

The results are separated into two parts. In a first step the general heat demand-supply balanced is analyzed based on different scenarios:

1) the renovation strategy
2) the impact of synergy vs separate networks
3) the source injection temperature and
4) different configuration for the geothermal heat sources.

The heat demand of the consumers in the heating network is calculated based on the mythology describted in 2.5.1 with one strategy where no renovation takes place (see Figure 25and Figure 26) and a renovation strategy where all buildings with a CECB classification lower than D are renovated (see Figure 28 and Figure 27). In the monthly bar chart, the renovation has especially an effect during the winter times and result in a relative increase of heat demand in the summer (even though the absolute heat demand also decrease in the summer).

The consumption per day charts show that the peak demands however decrease less than in the monthly overview. This phenomenon is even more significant on an hourly level.

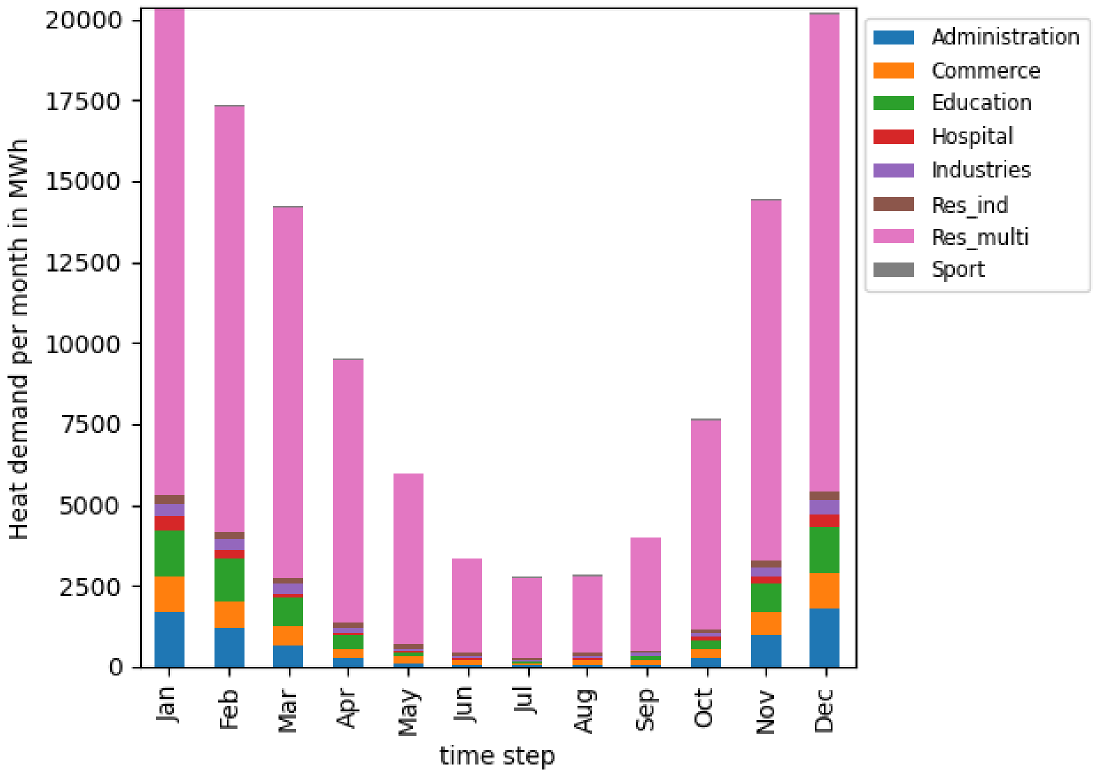

Figure 25 : Heat demand per month (DHN YLB) in renovation scenario 0 (No renovation)

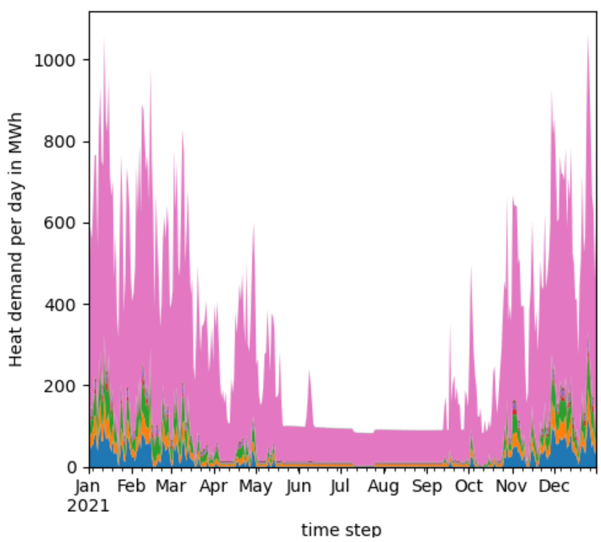

Figure 26 : Heat demand per day (DHN YLB) in renovation scenario 0 (No renovation)

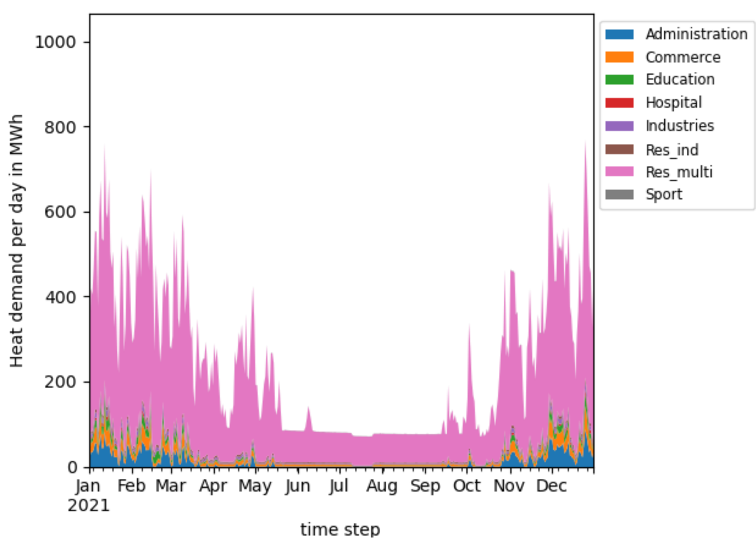

Figure 27 : Heat demand per day (DHN YLB) in renovation scenario 1 (CECB strategy)

2.6.2.2. Heat supply

The heat production is first calculated for each sub grid separately based on the merit order mythology described in 2.2.1. The heat production of the network with a separate configuration is shown on Figure 29.

A modified heat production of the separate heat distribution with applying the synergy methodology described in 2.2.1 is shown in Figure 30. By comparing both figures, especially an increase usage of the heat pump (PAC (+ STEP)) connected to the STEP anergy network can be seen.

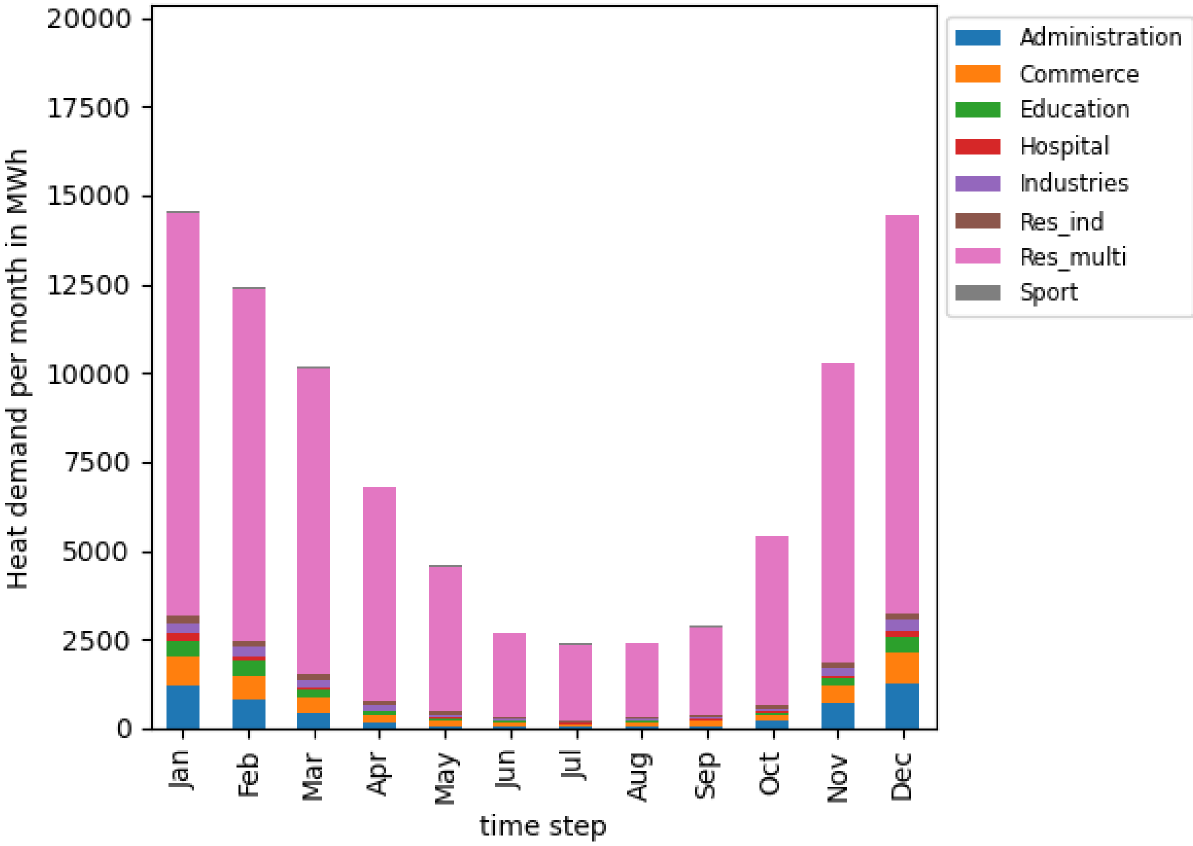

Figure 28 : Heat demand per month (DHN YLB) in renovation scenario 1 (CECB strategy)

2.6.2.3. Heat production per sub-grid

The heat sources of the district heating network are well distributed over the covered territory and the different sub-grids. On Figure 31 (CAD Iris), Figure 33 (CAD Santal) and Figure 35 (CAD STEP) the expected heat production is shown for a non-connected configuration of the DHN. Even though this represents the production in the sub-grids, since no connections are enabled, this also allows to compare the heat demand of each sub-grid.

It can be seen that CAD Santal has the largest heat demand, but relatively comparable to CAD Iris in magnitude. CAD STEP has a relatively small heat demand, which is also indicated by its relatively small heat source capacity.

For a grid configuration which allows interconnection (synergy) between the sub-grids, it can be seen on Figure 32 (CAD Iris) that production during low demand periods, as the summer month, the heat production drops significantly for CAD Iris.

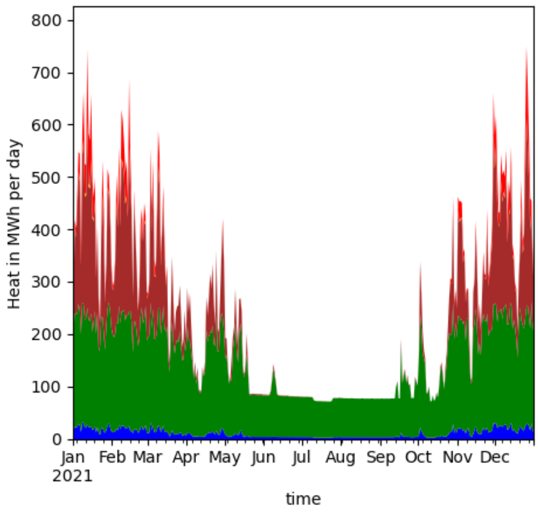

Figure 29 : Heat production of the district heating network of YLB without sub-grid connections (separate – “îlot”)

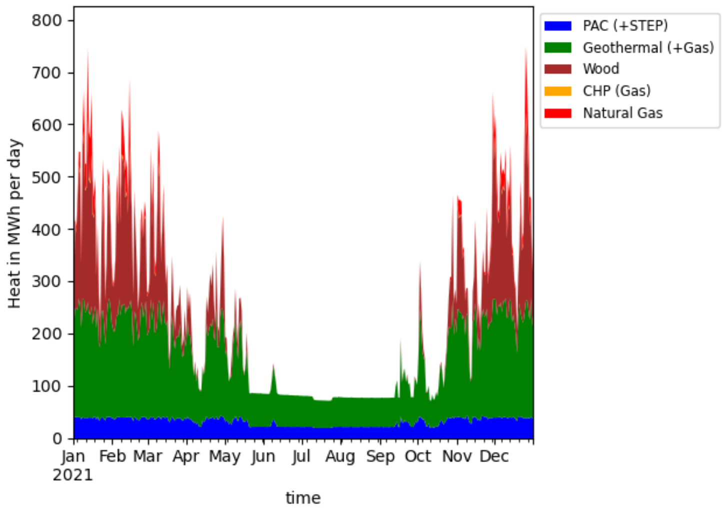

Figure 30 : Modified heat production of the district heating network of YLB with sub-grid connections (synergy – controlled “bouclage”)

The heat production in CAD STEP (Figure 38) however increases during these months and make up for the difference. The CAD Santal seems to operate relatively in autarky as little difference can be seen comparing Figure 33 and Figure 34.

By comparing the daily production inside the sub-grids (for CAD STEP: Figure 37 and Figure 38), it can be seen, that not only did the heat production increase in CAD STEP by using the synergy model, but also a more flattened production can be observed during the winter month with lower difference between upper and lower peaks.

2.6.2.4. Synergy between sub-grids

The synergy function calculates a frequent heat supply of the CAD STEP towards the CAD Iris (see Figure 39) for reasons of reducing emissions, since the merit order determine the heat pump connected to the anergy network as the best technology in the network.

The sub-grid CAD Iris is located between the two sub-grids CAD STEP and CAD Santal and is therefore able to supply both networks. During low heat demand time steps, CAD Iris receives heat from the CAD STEP in order to maximize the usage of the heat pump, during higher heat demand periods, On the other hand, CAD Iris supplies heat to both sub-grids CAD STEP (Figure 40 - top) and CAD Santal (Figure 40 – bottom).

CAD STEP having only two heat sources and one being a natural gas combustion unit, the more emission friendly heat sources in the CAD Iris are able to substitute the gas-based source during most time steps.

It can be seen that the sources in CAD STEP are also relatively often not able to supply its heat consumption during heat peak demand time steps and is required to receive heat from an equally merit order level technology from CAD Iris (Figure 41 - top).

The same cannot be observed for the CAD Santal, where the heat source capacity is at most times sufficient to cover its heat consumption (Figure 41 - bottom).

However, the sources in CAD STEP are also relatively often not able to supply its heat consumption during heat peak demand time steps and is required to receive heat from an equally merit order level technology from CAD Iris (Figure 41 - top). The same cannot be observed for the CAD Santal, where the heat source capacity is at most times sufficient to cover its heat consumption (Figure 41 - bottom).

Both sub-grids CAD Iris and CAD Santal are foreseen to be connected with similar heating technologies with geothermal as base load and wood and gas combustion for peak demand. A substantial synergy between CAD Iris and CAD Santal is therefore not unexpected.

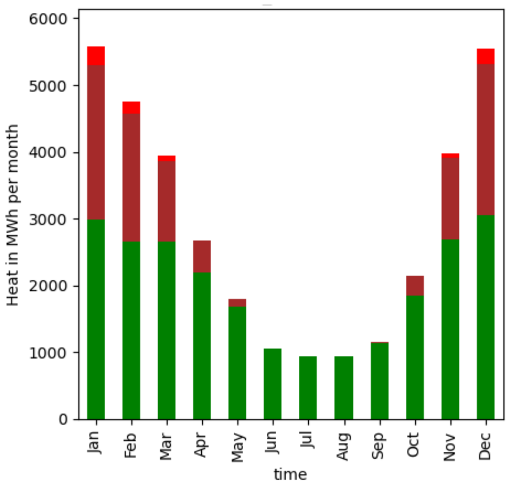

Figure 31 : Heat production of CAD Iris as separate district heating network

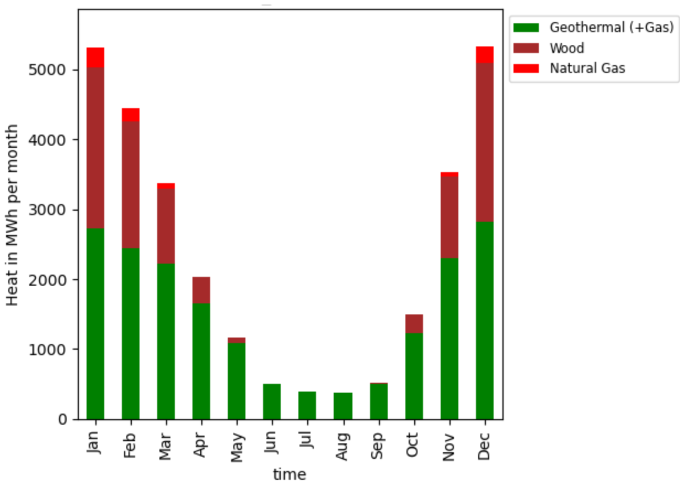

Figure 32 : Heat production of CAD Iris as synergy based connected district heating network

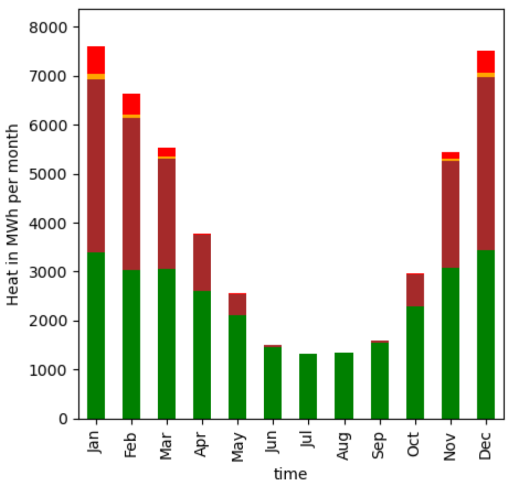

Figure 33 : Heat production of CAD Santal as separate district heating network

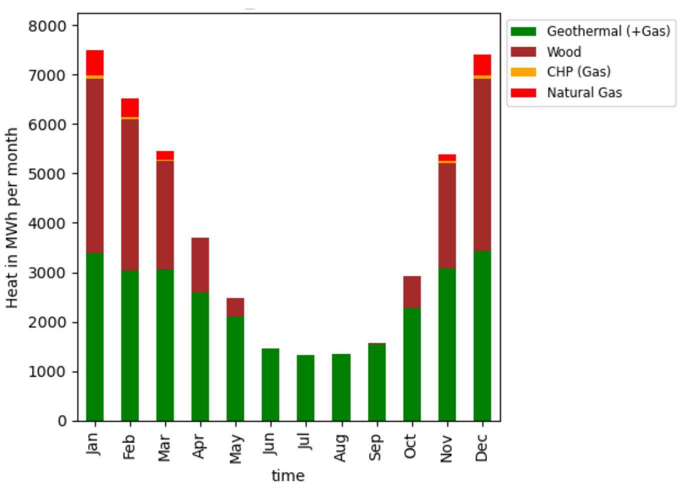

Figure 34 : Heat production of CAD Santal as synergy based connected district heating network

2.6.2.5. Emissions

The reduction of greenhouse gas emissions has been seen as an important reason to consider synergy between different sub-grids. However, the reduction of emissions is relative insignificant of less than 10% in the winter and around 20% during the summer (compare: Figure 42 and Figure 43).

As mentioned in the previous paragraph this can be easily explained by the similar in technologies and capacities of the heat sources in the two major sub-grids CAD Iris and CAD Santal.

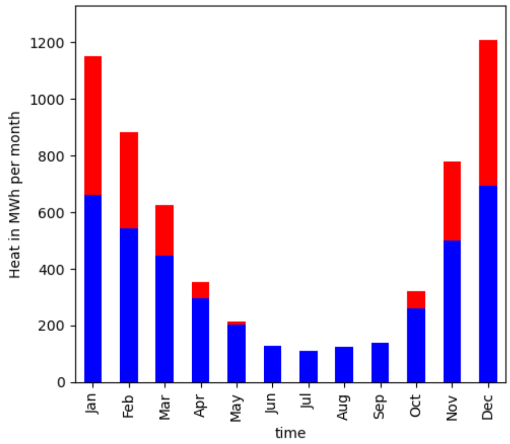

Figure 35 : Heat production of CAD STEP as separate district heating network

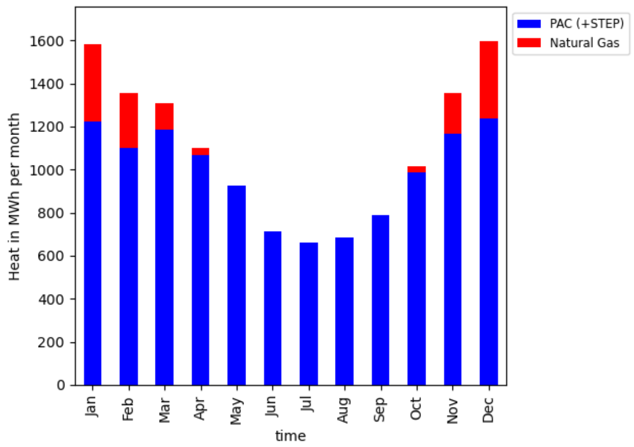

Figure 36 : Heat production of CAD STEP as synergy based connected district heating network

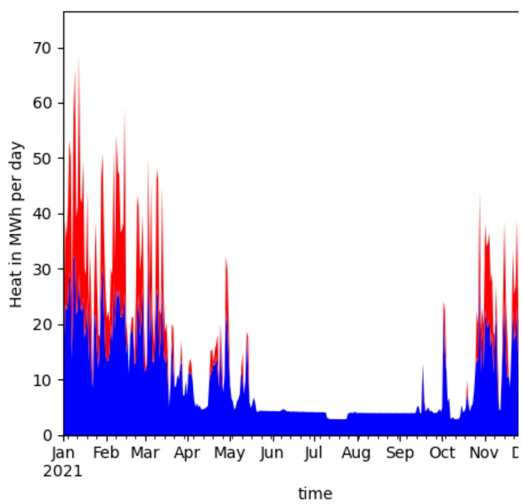

Figure 37 : Heat production per day of CAD STEP as separate district heating network

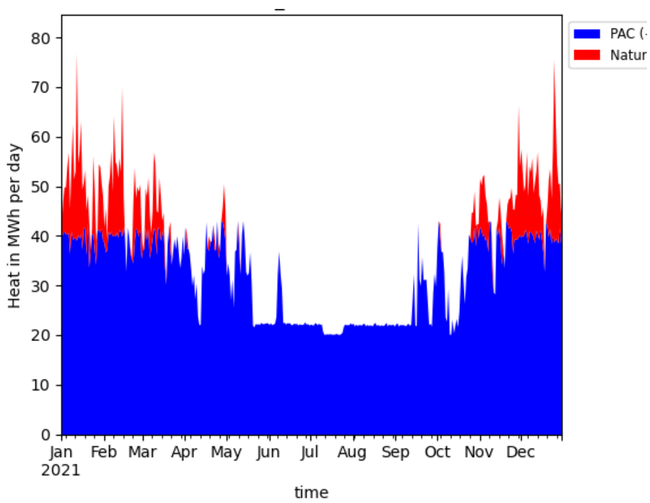

Figure 38 : Heat production per day of CAD STEP as synergy based connected district heating network

2.6.2.6. Geothermal source configuration

The geothermal sources are considered to be operating at around 60°C on the return flow at the source. The flow is then heated up towards the injecting temperature with a second heat source (80°C network temperature with supplementary gas combusting considered here as the base scenario). Different configurations are however thinkable for the geothermal heat sources.

The GHG annual emissions per month for the synergy base scenario is shown in Figure 44 as comparison towards the different geothermal configurations. By reducing the injection temperature, less gas combustion is required to reach the expected temperature and therefore the emission factor for geothermal source is reduced. This effect has an impact of around 20% reduced GHG emissions as seen in Figure 45.

Using an alternative for natural gas combustion as supplementary technology would results in the most significant reduction of GHG emissions. Different technologies and fuels are possible, in Figure 46 the emissions per month are shown for a scenario where the geothermal sources are supplied with wood combustion to reach the network temperature.

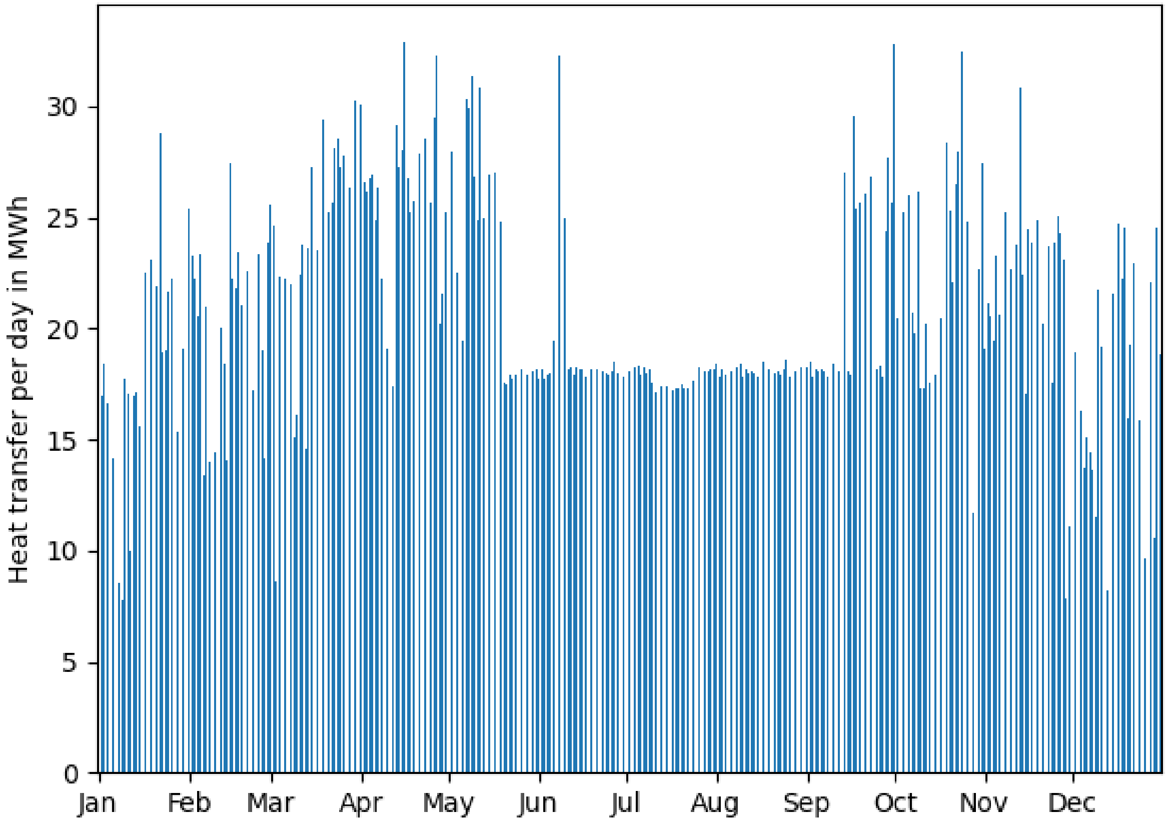

Figure 39 : Heat supply per day of CAD STEP towards CAD Iris

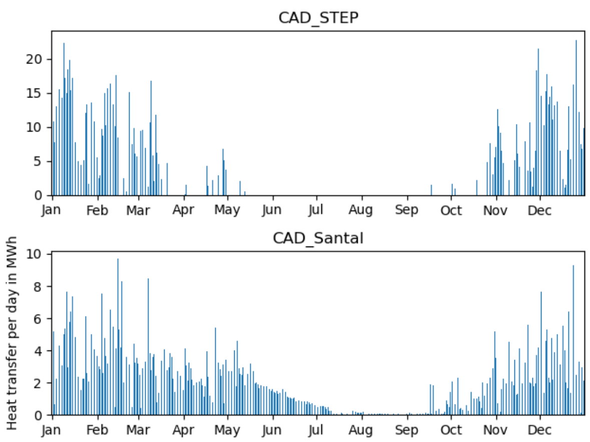

Figure 40 : Heat supply per day of CAD Iris towards CAD STEP (top) and CAD Santal (bottom)

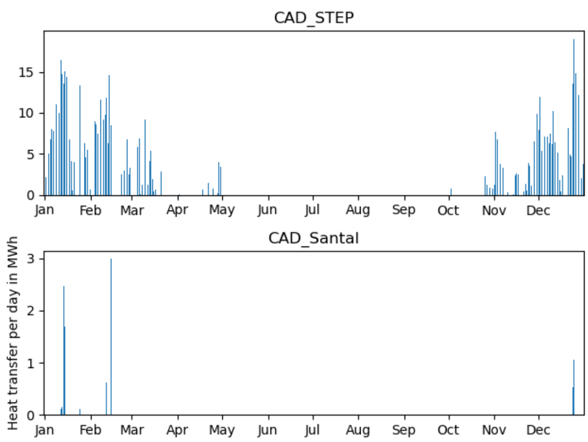

Figure 41 : Heat supply per day of CAD Iris towards CAD STEP (top) and CAD Santal (bottom) based on covering missing heat in the receiving network

A reduction of far over 50% in comparison towards the base synergy scenario is calculated. In a last scenario for the geothermal sources, a very pessimistic outlook is considered (Figure 47). If the exploration boreholes do not find sufficient temperature at the predicted locations, the geothermal sources would probably not be suitable as heat sources for the district heating networks, for this case the geothermal source capacities are exchanged with natural gas sources.

However, the emissions balance does indicate that this problem could be covered by using wood combustion for the baseload heat production instead of geothermal. Wood combustion does have a better GHG-coefficient than the geothermal + gas heat source used in this project. If no other indicators are considered to evaluate the heating network, this solution would not be considered as high as maybe expected and even a bit lower than the base scenario.

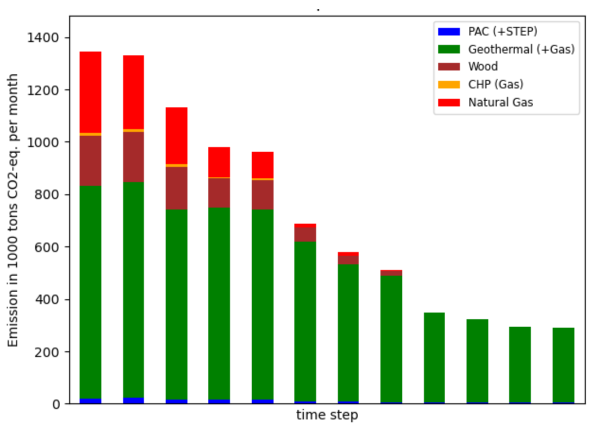

Figure 42 : GHG emissions of the district heating network without sub-grid connections (separate)

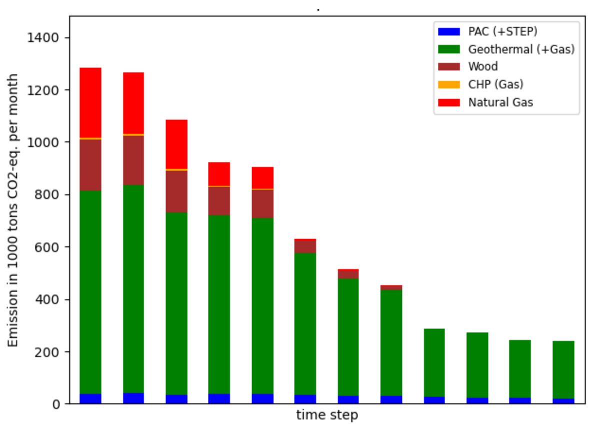

Figure 43 : GHG emissions of the district heating network with sub-grid connections (synergy)

As said above, the geothermal heat resource is expected to reach a temperature that does not allow for direct usage in a medium to high-temperature heating network. The temperature level needs to be increased by an additional heat generation technology before injection in the grid.

The total annual energy to increase the temperature level by standard natural gas boilers is computed to amount to:

1) 23468 MWh for the scenario with 80°C as primary distribution temperature
2) 15488 MWh for the scenario with 70°C as primary distribution temperature

According to the considerations of chapter 2.4.3, in order to further increase the renewable share in the DHN supply and decrease GHG emissions, one possibility is represented by the replacement of natural gas by biogas as fuel, to be supplied by the existing natural gas network.

Although biogas is not considered as situational according to cantonal regulations, it could be produced locally in the surrounding rural region of YLB. It is striking that 15 GWh corresponds to the biogas production that will be produced by the new biogas production plant “Agriteos” in La Chaux-de-Fonds (NE), a town only slightly larger than YLB (37’217 inhabitants). This points out to a concrete feasibility of such a fuel switch and on the positive effect of decreasing primary distribution temperature levels.

2.6.2.7. Renewable energy share

The strategy of the city of Yverdon-les-Bains includes a significant increase of the stare of renewable energy for its heating sector. The district heating network is supposed to take an important role in archiving this goal with the installation of geothermal heat as base load and wood and natural gas only for covering peak demand. The classification of renewable energy is not always straightforward, since heat source can have varying or mixed primary energy sources.

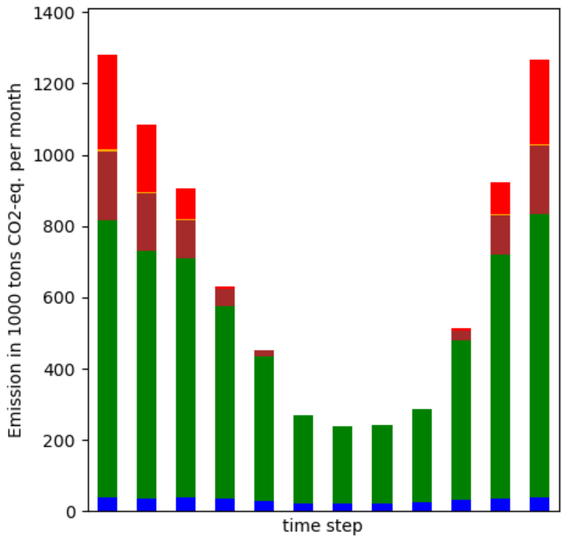

Figure 44 : GHG emissions for the base scenario (with synergy)

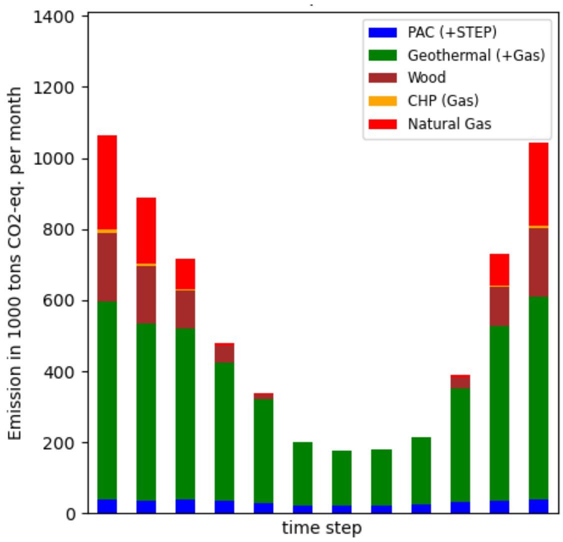

Figure 45 : GHG emissions with a reduction of the primary network temperature from 80°C to 70°C

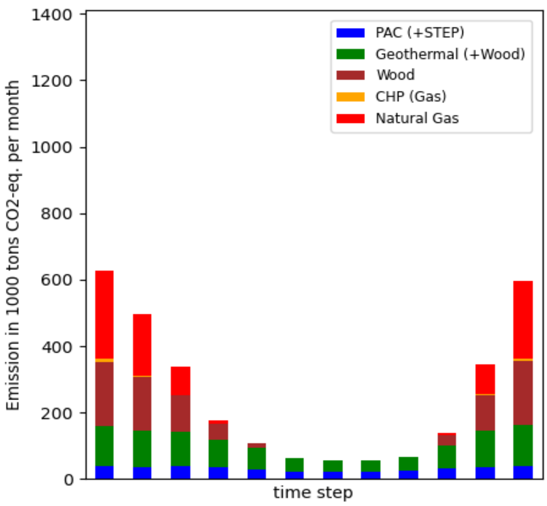

Figure 46 : GHG emissions with wood combustion as supplementary heat source for geothermal

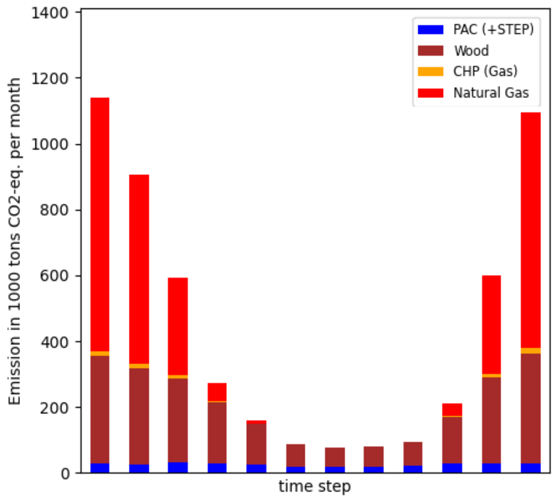

Figure 47 : GHG emissions without any geothermal heat source

The environmental balance of a heat pump, for example, is depending on the electricity mix used for operating. In the section about emissions the official emission coefficients were used, which are based on the year 2022, however, the district heating network of Yverdon-les-Bains in the considered state is planned to be ready after 2030. We assume that the heat pump connected to the anergy network is operated as full renewable, as is the combustion of wood. The geothermal sources are considered as renewable based on the share of heat injected by the geothermal source and the part of the supplementary source. The combustion of natural gas is considered as full non-renewable, it is however thinkable to replace natural gas with renewable fuels in the future.

The share of renewable energy for the heat production is heavy depending on the installed heat sources in the network but also on the operational plan. Based on the hypotheses given by the local energy utility (SEY) and the merit order model used for this test-case the share of renewable energy for the different sub-grids is shown in Figure 48 (CAD Iris), Figure 49 (CAD Santal) and Figure 50 (CAD STEP) for the connected base scenario with synergy between the networks. The CAD STEP network is producing during most time steps only with per heat pump, whereas missing heat is covered by geothermal or wood-based sources from the CAD Iris. Only during time periods, where all geothermal and wood capacities are operating on full load, the gas combustion source in CAD STEP is used. Whereas CAD STEP is capable of archiving far over 80% of renewable energy during most month, this cannot be seen for CAD Iris or CAD Santal. This is mostly because the usage of natural gas as supplementary technology to the geothermal source, which is considered as superior towards wood combustion in the merit order based on the situationally (availability) of wood.

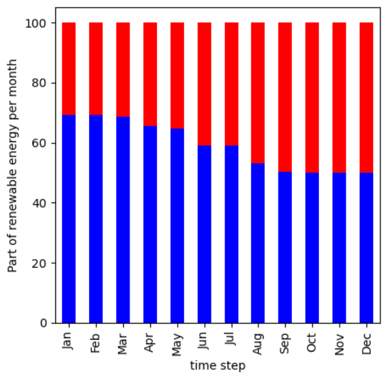

Figure 48 : Share of renewable energy of the heat sources in CAD Iris for the base scenario with synergy

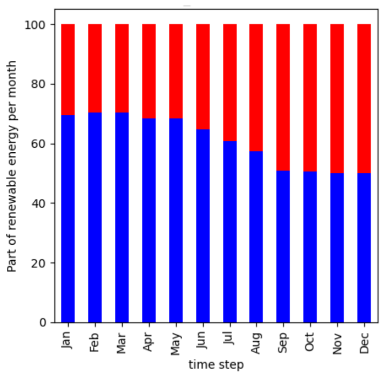

Figure 49 : Share of renewable energy of the heat sources in CAD Santal for the base scenario with synergy

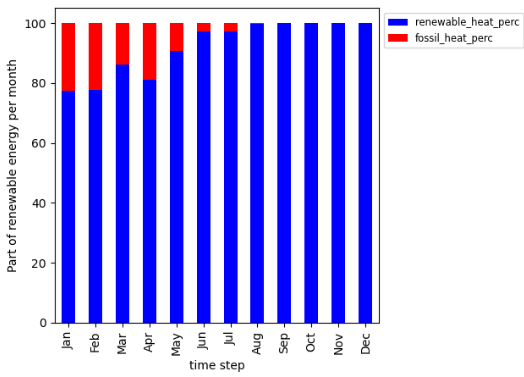

Figure 50 : Share of renewable energy of the heat sources in CAD STEP for the base scenario with synergy

By changing the configuration of the network operation or the primary energy of the heat source, the share of renewable energy can drastically change. In Figure 51, the share of renewable energy is plotted for different scenarios of the district heating network.

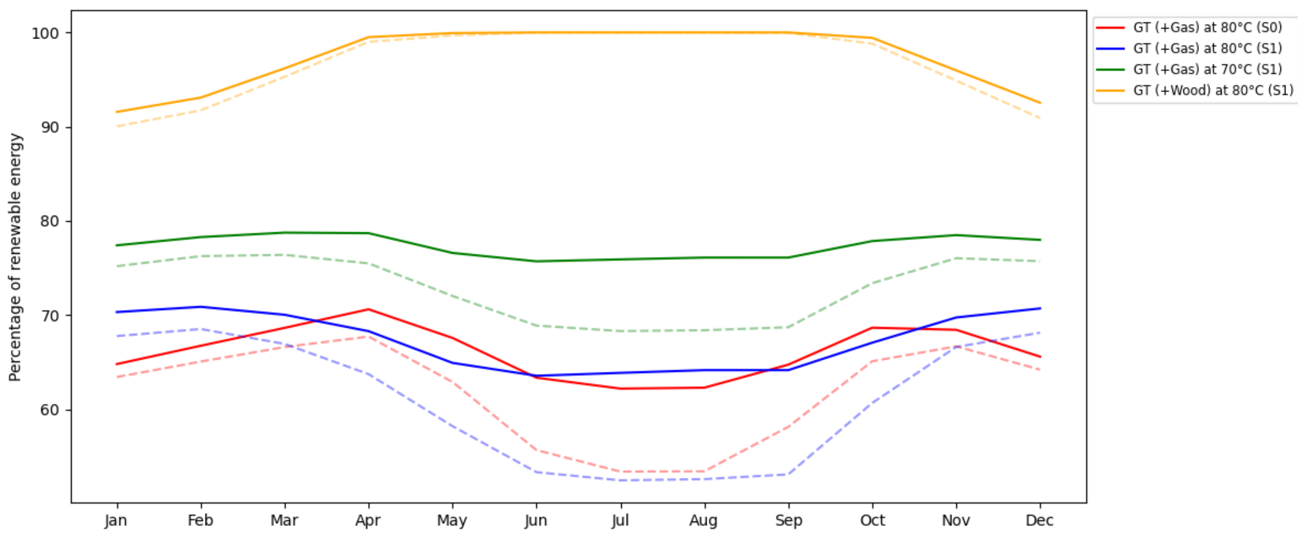

Figure 51 : Comparison of the share of renewable energy of the DHN of YIB for different scenarios (dashed lines: separate, continuous line: synergy)

The base scenario (continuous blue line) has a relatively constant renewable energy share of around 70% throughout the whole year when using the synergy configuration. Without synergy (dashed blue line) this share drops significant especially during the summer to close to 50%.

The impact of renovation of the buildings comes out as negligible for the share of renewable energy, for both operating the network with synergy or without (compare the two bottom line combinations).

A great impact on the renewable share is given by the reduction of the operation temperature, which results in a higher renewable share of the geothermal source. This can result, in combination with synergy renewable energy, in shares of close to 80% in the grid during the whole year. However, the largest effect is represented by far by the complete replacement by a renewable energy source as complementary to the geothermal source. In the scenario, it is assumed that wood combustion would be used instead of natural gas, but every renewable fuel or even heat pumps could be used instead. Direct combustion of both wood and renewable gases for heat generation is not in line with SFOE and cantonal recommendations.

2.6.2.8. Situational (wood) demand in the heating network

Despite its renewable nature, usage of wood for heating purposes is constrained by current federal and cantonal regulations. As shown above, substituting natural gas as supplementary technology to the geothermal source with wood, would result in a heating system with far over 90% renewable share over the whole year. This solution however contradicts the goal to limit the usage of wood. In Figure 52 the consumption per month of wood for different scenarios of the DHN is plotted. The heating value of wood is taken to be 4500 to 4770 Kcal/kg[37].

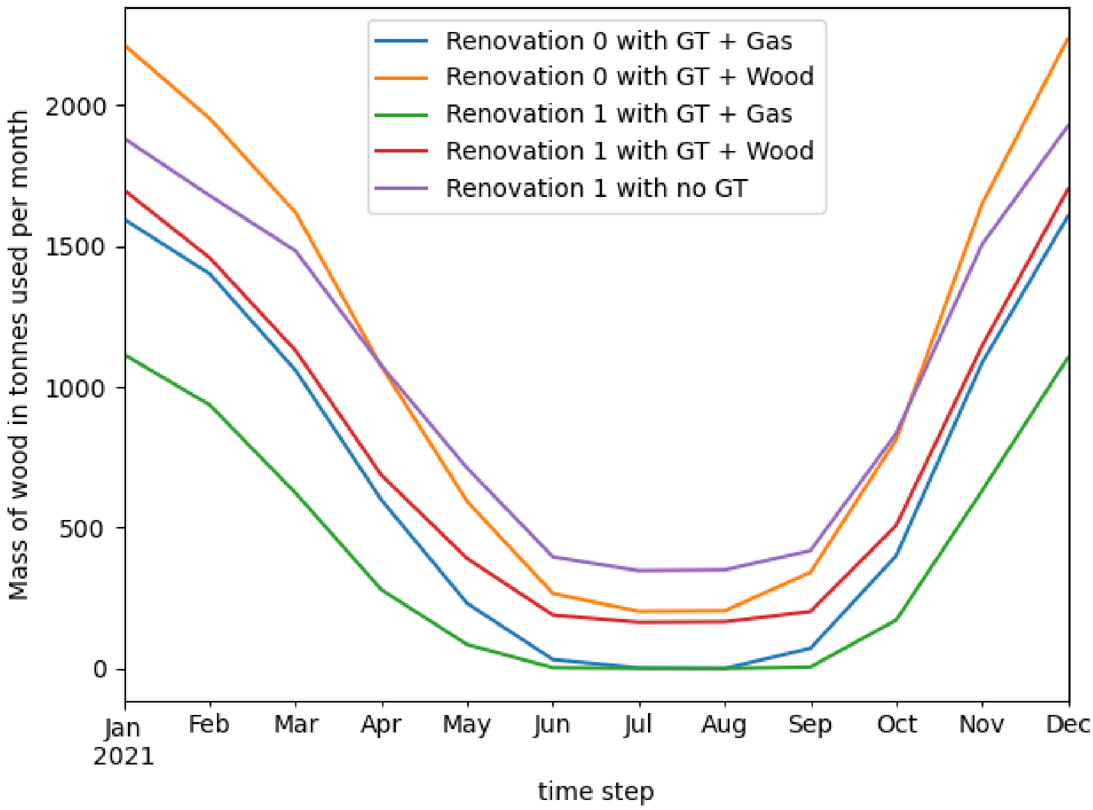

Figure 52 : Wood consumption for heating purpose in the DHN of Yverson-les-Bains for different scenarios

The scenario with no renovation and wood as supplementary fuel has a wood consumption of more than double of that of the scenario with reasonable renovated buildings and natural gas as supplementary

[37] Dried wood, https://www.fao.org/4/s4550e/s4550e09.htm

technology (base scenario). The solution that reaches over 90% renewable energy with wood and a reasonable renovation still uses over 50% more wood per month than the base scenario. The graph indicates that both configuration decisions of renovating and the use of supplementary fuel for the geothermal source have a similar impact on the usage of wood on the models used in this project. The pessimistic solution of no useful geothermal source available shows a large wood consumption over the whole year and even the largest during summer. These numbers have to be put in perspective with the estimated potential for available wood for energy purposes in Canton Vaud estimated at 285'000 tons /year.[38] Hence, a relatively limited share of this potential could be used, in order to foster the utilization of another renewable energy resource in DHN, namely geothermal energy, a complementary comment to the one made in 2.6.2.6 regarding biogas.

2.6.3. Yverdon-les-Bains test-case – Simulation results

The calculation of a heat balance enables a quick and comprehensive view of the heat system over a long period. However as already discussed in Table 20, if a more detailed view on the system is required, a detailed simulation of the hydraulic and thermal models of the heating network is necessary. Simulating the network gives insight into the distribution of important operational parameters and overall KPIs to evaluate system design and operation such as overall and seasonal heat losses or the length of critical pipelines. While the heat balance analysis focuses on the larger scale, the simulation focuses on instances in time. Heat demand and production model used in this project for the test-case of YLB was created on an hourly based time scale. Therefore, the simulation also is hourly based, even though a shorter time scale would give even more realistic results.

In the following, four different weeks are exemplary simulated for different configurations and operations of the network. It is not assumed that the simulations are representative of a full year, but each week is chosen at 3-month intervals to reflect a possible week in each season (winter/spring: 01.03 – 07.03, spring/summer 07.06 – 13.06, summer/autumn: 06.09 -12.09, winter: 06.12-12.12).Time steps with total heat demand lesser than 5 % of the total heat source capacity are not shown in the following heat loss diagrams. For once since these periods would probably be covered with private on-side heat storages and secondly might be unrealistic and are based on having only a limited amount of typical heat profiles resulting in low demand periods for all buildings at the same time.

The total heat losses shown for each simulated scenario include the distribution losses but also an indicator of the total losses, which represents the losses during the heat generation and the transportation of heat to the consumers. However, only the losses of primary energy due to gas and wood combustion are considered, whereas geothermal losses are neglected.

The operation of a district heating network can be analysed based on the geographical, as well as temporal distribution of important parameters in the network, such as temperature, mass flow, velocity, pressure or energy transfer. Below, a detailed view of the distribution of some important parameters in the network is presented for two time-steps for three different grid scenarios. The two-time steps were selected in order to find two different cases where full synergy of all three networks is active, one low-demand case for summer (June 12th at 17:00) and one high-demand case for winter (Dec. 12th at 12:00).

The anergy network part of the CAD STEP is not included in the following simulation results. But since the southern part of CAD STEP which operates at 70°C uses the anergy network as cold source for the heat pump connected to the district heating the simulation results are briefly discussed.

2.6.3.1. Simulation of separate networks

The district heating network in a non-connected configuration is simulated for four different weeks on an hourly base as mention before. The separate networks will be operating in the base scenario configuration but without connection between them and therefore no synergy.

[38] See e.g. Stratégie Bois-Energie du Canton de Vaud, September 2017

Simulation of separate networks – Heat losses

The heat losses of the non-connected configuration are discussed in Figure 53 in comparison to the total heat production in the whole network. The first block represents the first full week of March and shows a great variation in distribution losses in percentage between 3% and up to over 20%. The peaks shown for the distribution losses in MW, correlate to low production periods in the last plot of the Figure. This pattern can also be seen in the last simulated week for December. This behaviour of high heat losses during low demand periods is well known phenomena, as proposed in the guide book of energy schweiz to consider shutting down but not considered in the merit order-based control strategy used in this simulation [4]. While the heat losses are mostly in the range between 3 and 10% in the March and December month, they reach levels between 10 and 15% during the June and September months.

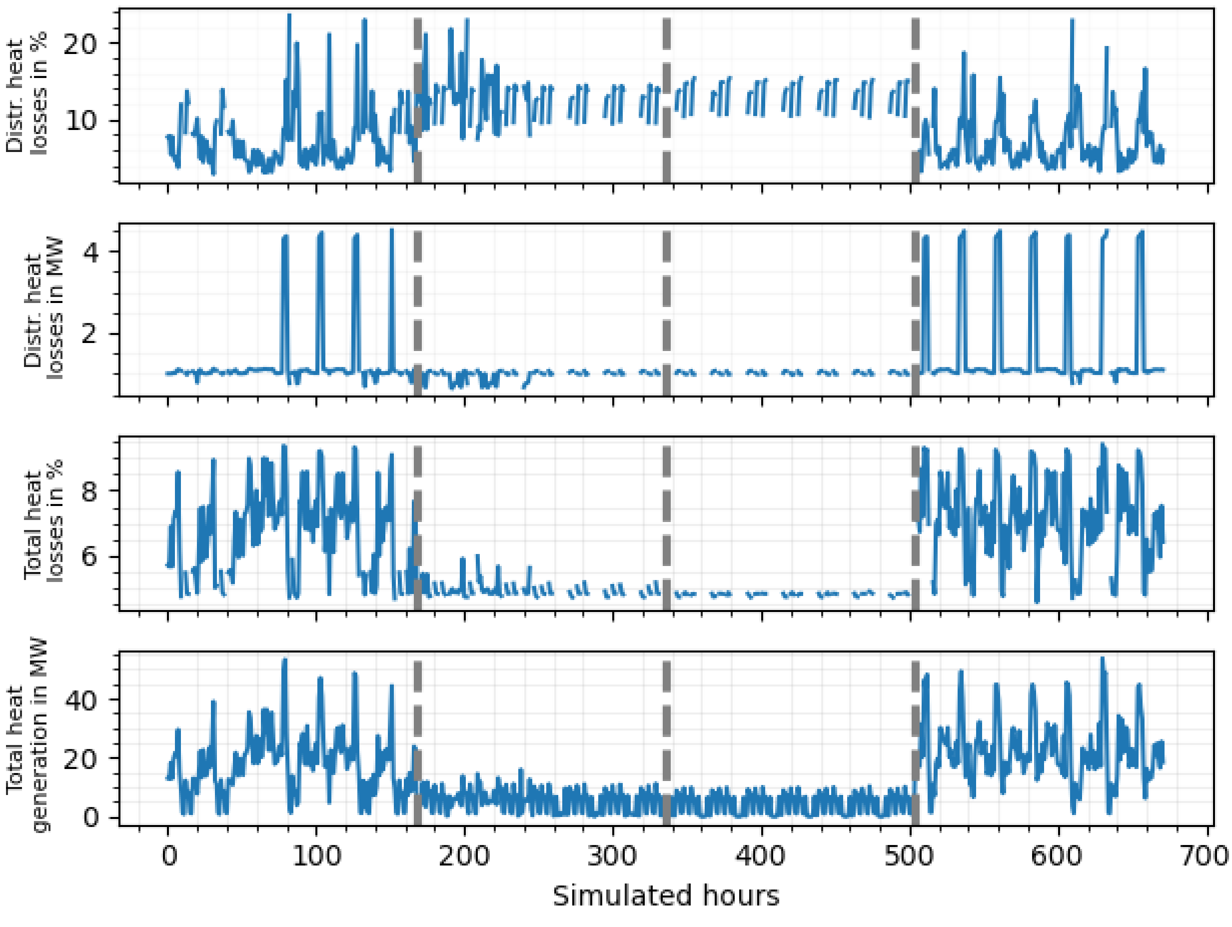

Figure 53 : Overview of heat losses during the four simulated weeks for the base scenario for all sub-grid combined but not connected in the district heating network of YLB

Simulation of separate networks – Temperature distribution

The temperature distribution of the non-connected base scenario networks for the two selected hours (summer and winter) are not showing great difference, despite their different in heat demand. It can be seen that the temperature in the summer hour (Figure 54) even reached a lower distribution temperature at one point of the grid in the CAD Iris than for the winter hour (Figure 55). This cannot be observed for the other two networks (see Figure 56 and Figure 57 for CAD Santal, and Figure 58 and Figure 59 for CAD STEP). The temperature distribution is however heavily influenced by the decision which heat source is selected. In general, both simulated time-step shows a similar temperature distribution reaching temperature levels at the consumer heat exchanger of at least 348°K (75°C) for CAD Iris and CAD Santal and 338°K (65°C) for CAD STEP.

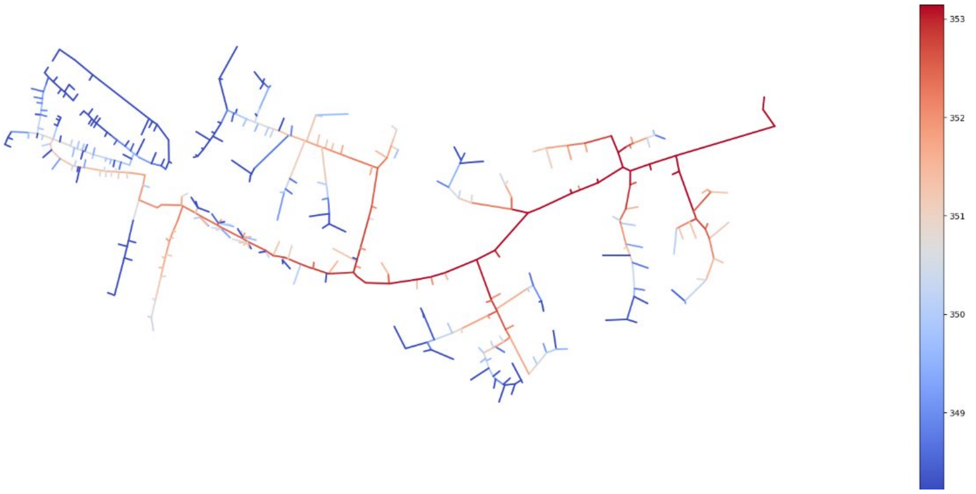

Figure 54 : Temperature distribution in °K of CAD Iris in summer with no connection between the sub-grids

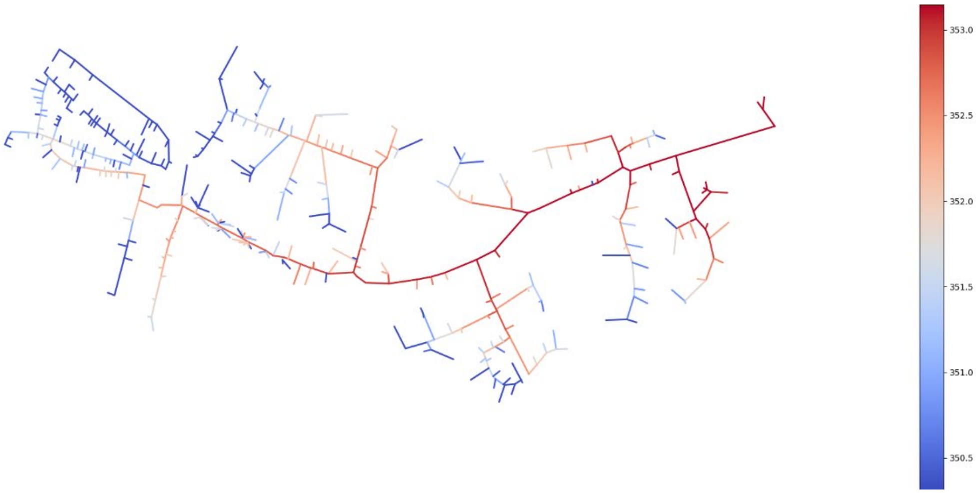

Figure 55 : Temperature distribution in °K of CAD Iris in winter with no connection between the sub-grids

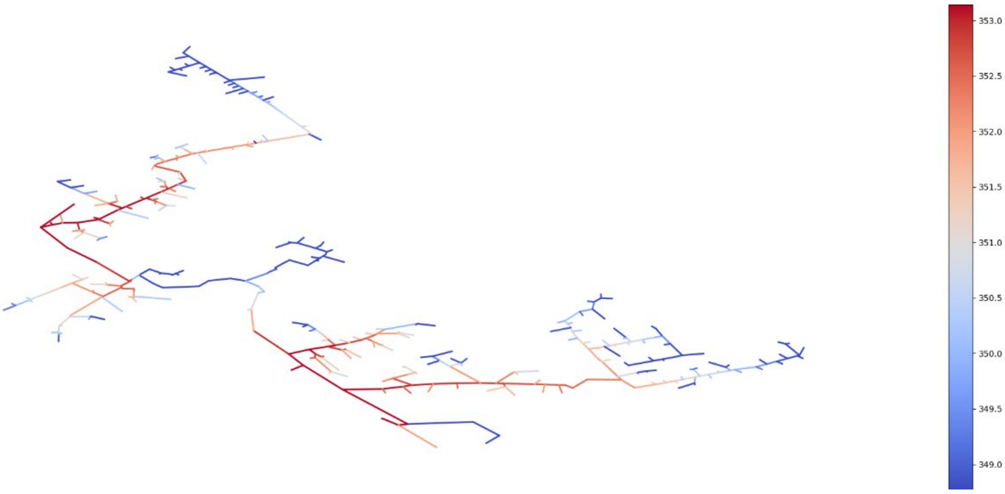

Figure 56 : Temperature distribution in °K of CAD Santal in summer with no connection between the sub-grids

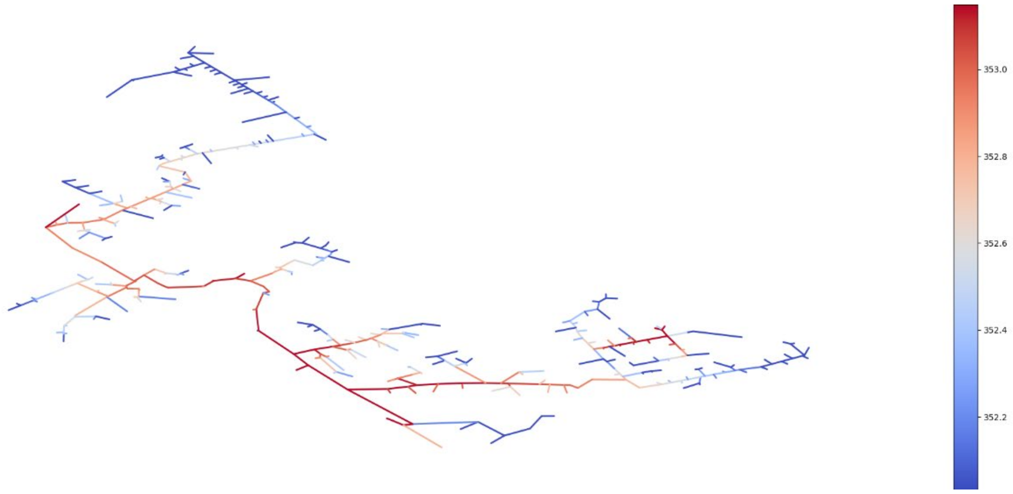

Figure 57 : Temperature distribution in °K of CAD Santal in winter with no connection between the sub-grids

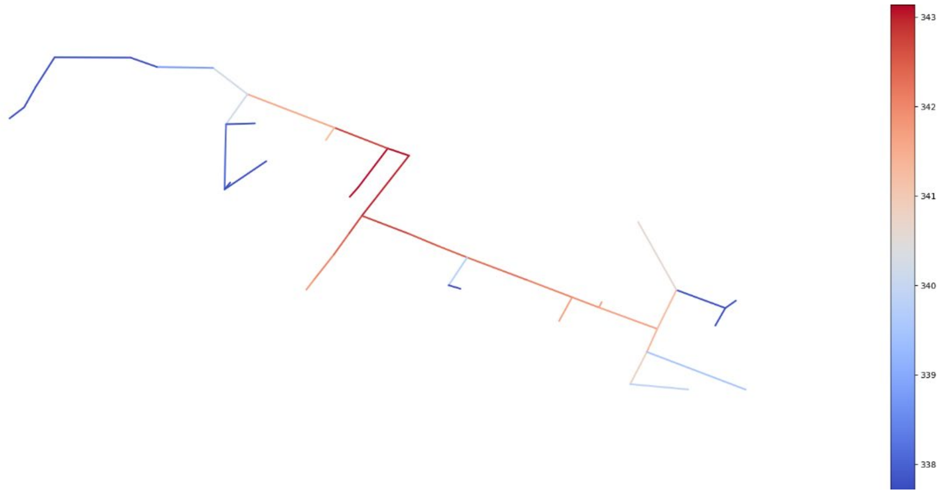

Figure 58 : Temperature distribution in °K of CAD STEP in summer with no connection between the sub-grids

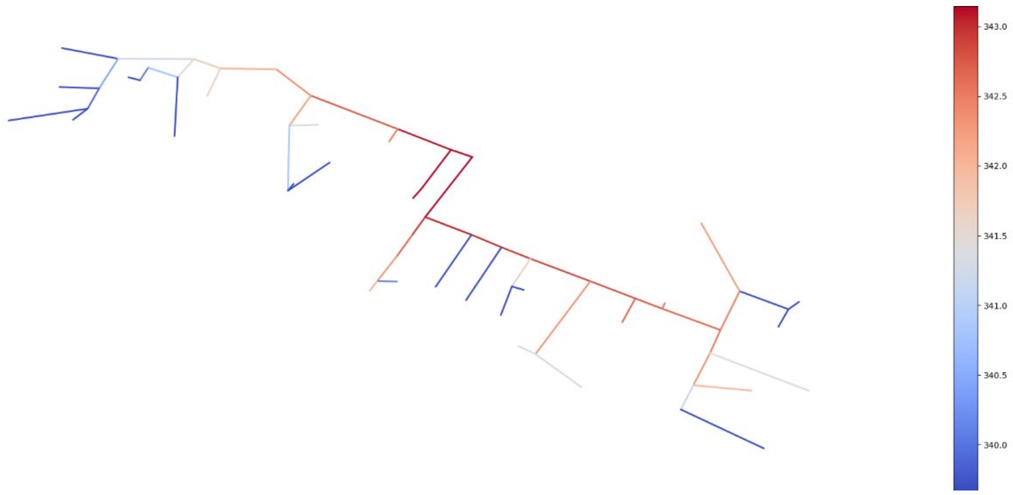

Figure 59 : Temperature distribution in °K of CAD STEP in winter with no connection between the sub-grids

Simulation of separate networks – Mass-flow distribution

The second parameter analysed is the mass-flow distribution in all networks for the two simulated hours. Similar to the temperature distribution, the position of the used heat source can be easily identified in the plot of mass-flow. In CAD Iris (Figure 60 and Figure 61) the heat sources in the east show the highest mass-flow of over 25 kg/s in summer and 80 m/s in winter.

The mass-flow distribution indicates that these sources also supply the majority of the network though the main pipeline going through the whole network to the west.

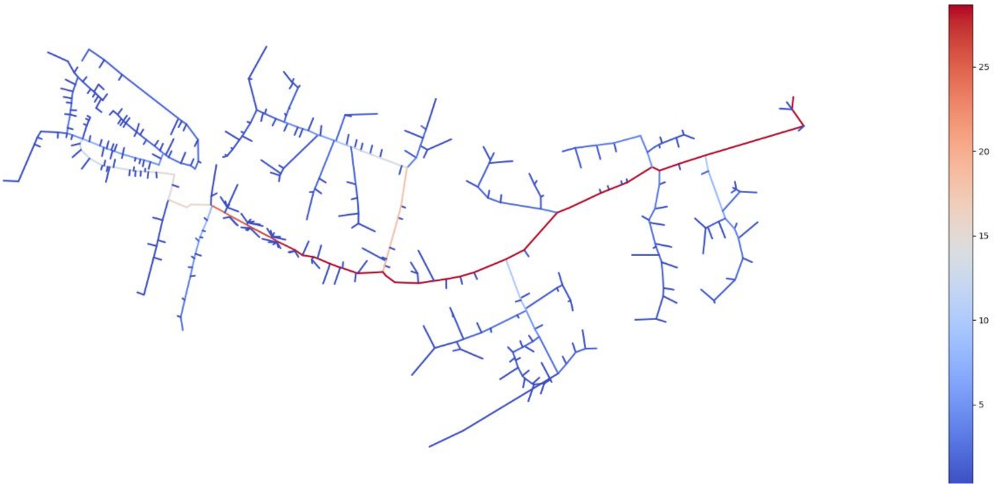

Figure 60 : Mass-flow distribution in kg/s of CAD Iris in summer with no connection between the sub-grids

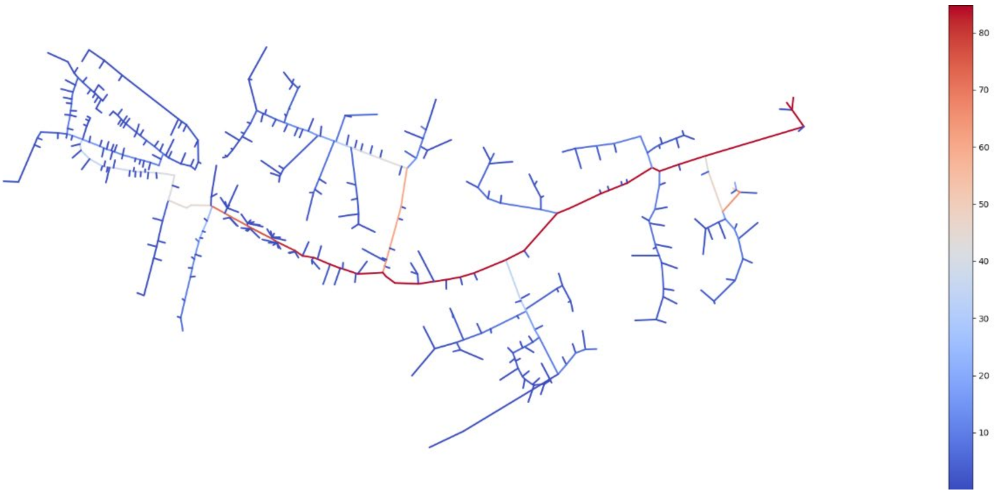

Figure 61 : Mass-flow distribution in kg/s of CAD Iris in winter with no connection between the sub-grids

The mass-flow distribution of CAD Santal (Figure 62 and Figure 63) shows that the grid indirectly separates into a western and an eastern part, especially during summer, when most heat demand is covered by the two different geothermal heat sources.

The mass-flow distribution of CAD STEP (Figure 64 and Figure 65) is relatively similar in both time-steps only varying in magnitude based in a different heat demand, which is no surprise, since only one heat source location exists.

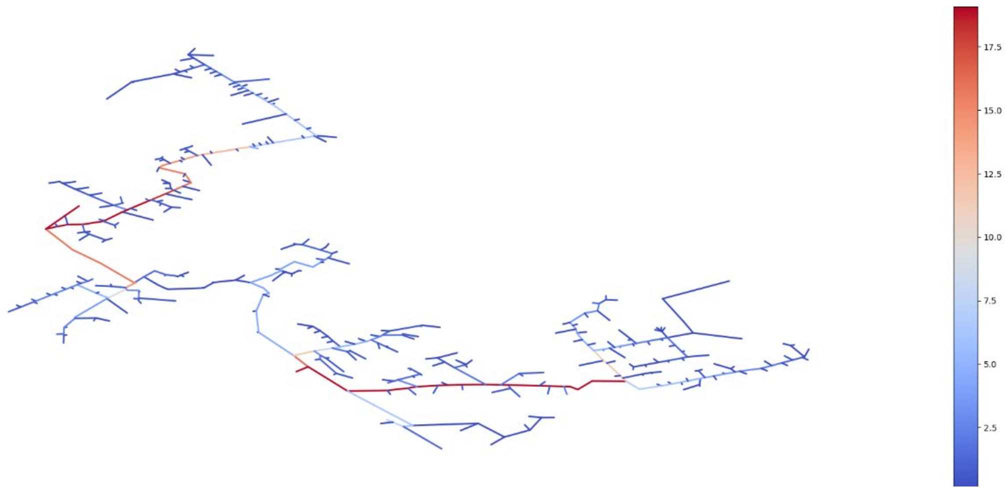

Figure 62 : Mass-flow distribution in kg/s of CAD Santal in summer with no connection between the sub-grids

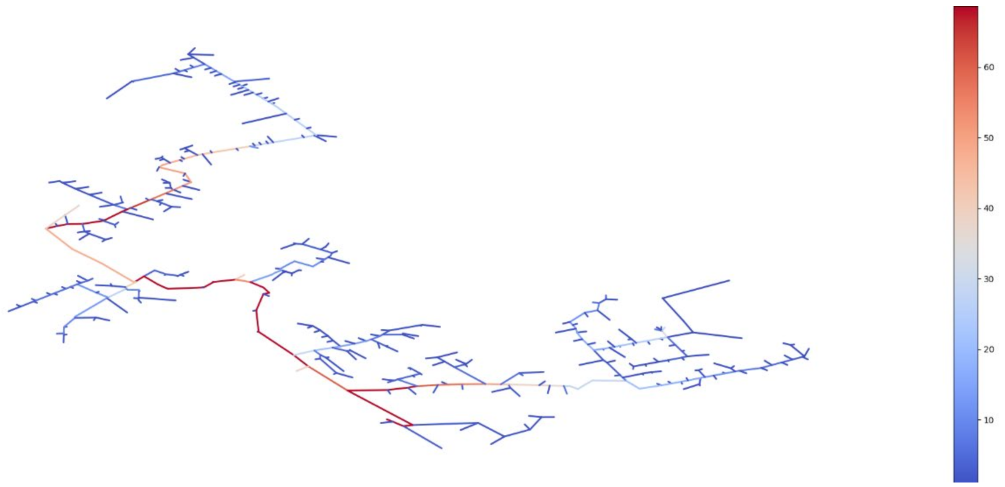

Figure 63 : Mass-flow distribution in kg/s of CAD Santal in winter with no connection between the sub-grids

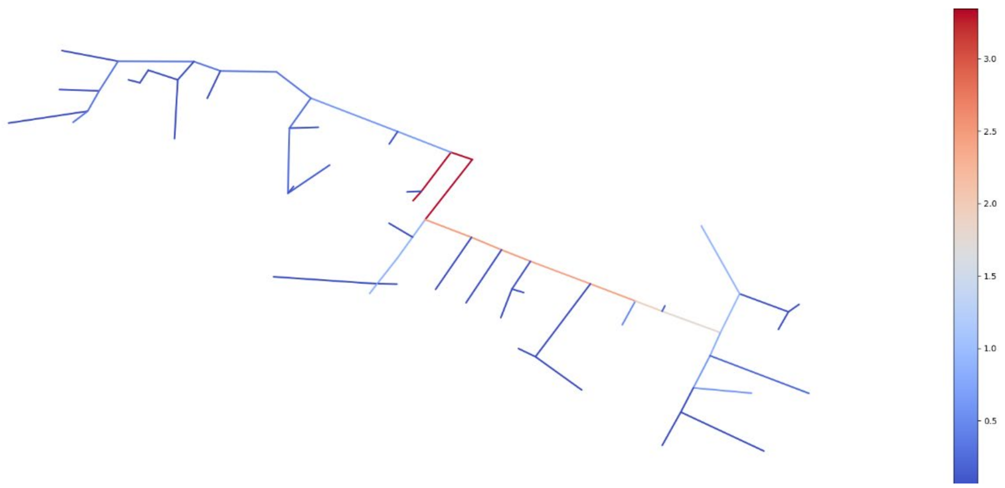

Figure 64 : Mass-flow distribution in kg/s of CAD STEP in summer with no connection between the sub-grids

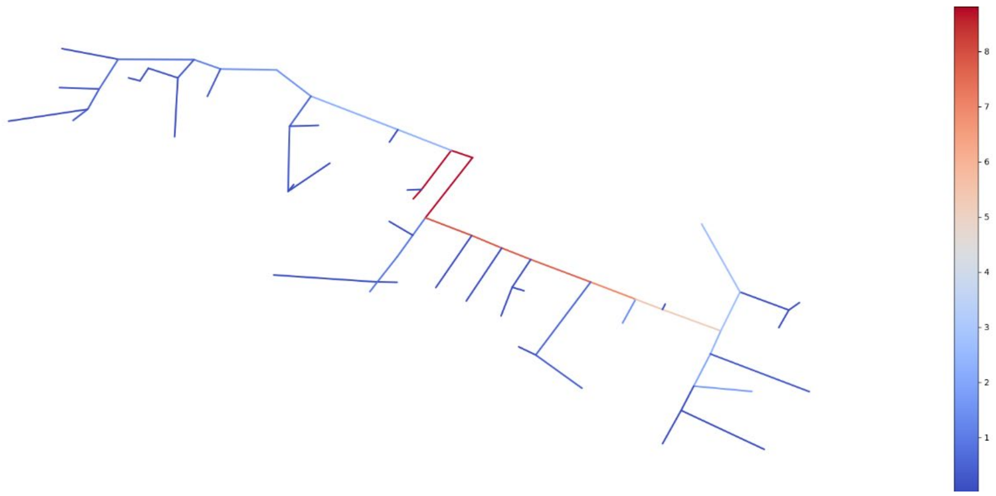

Figure 65 : Mass-flow distribution in kg/s of CAD STEP in winter with no connection between the sub-grids

Simulation of separate networks – Velocity distribution

The velocity of the water transporting the heat in the network is an important factor for the operation of the network and discussed therefore briefly in the following (see Figure 66 to Figure 71).

In principle, velocity is a complex function dynamically combining DN, mass-flow and pressure; however, an analysis of these relations goes beyond the scope of the present project, although the simulation framework would in principle allow it and give interesting insights on the hydraulic behaviour of the fluid in the network. The velocity in the grid follows a very similar pattern as the mass-flow, with higher velocities in places with higher mass-flow.

The velocity is however also impacted by the diameter of the pipeline, which varies in the grid and is smaller close to consumers. High velocities can therefore also be seen at some places with a relatively low mass-flow. But no critical velocity level could be identified in any of the networks and time steps.

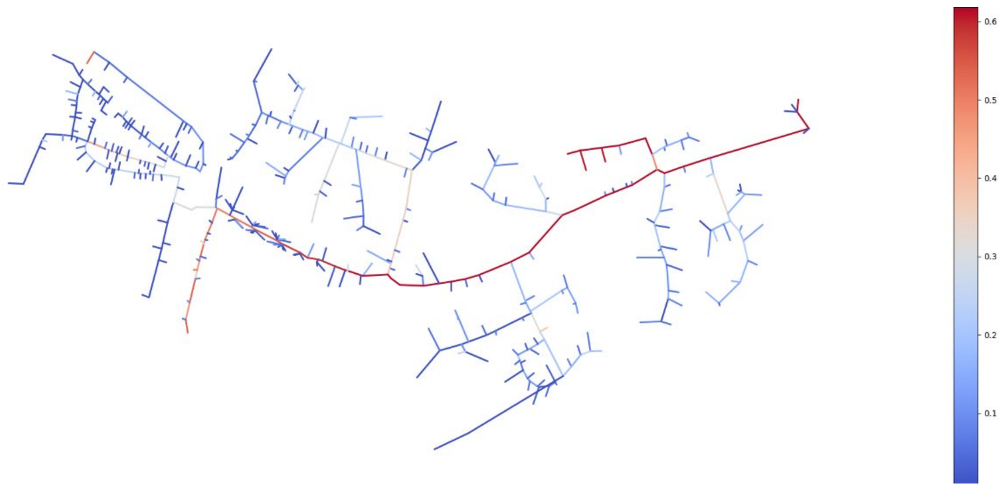

Figure 66 : Velocity distribution in m/s of CAD Iris in summer with no connection between the sub-grids

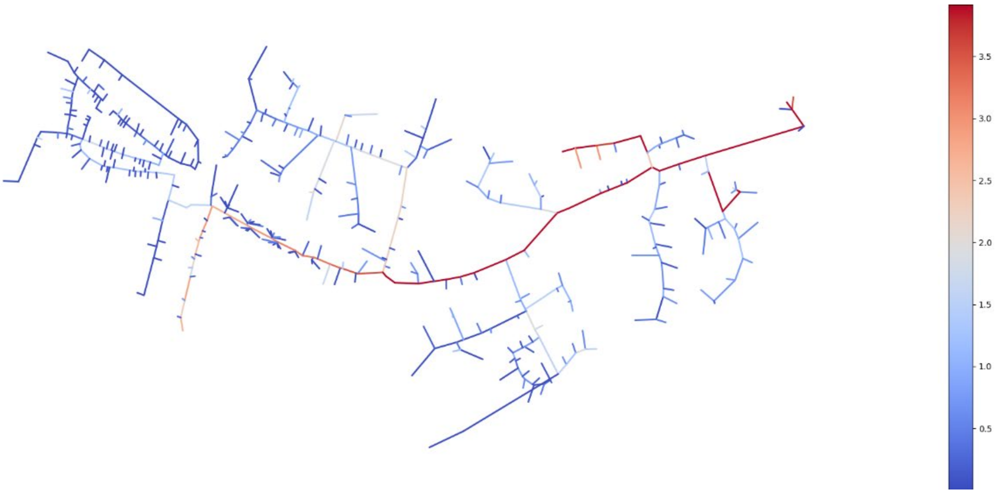

Figure 67 : Velocity distribution in m/s of CAD iris in winter with no connection between the sub-grids

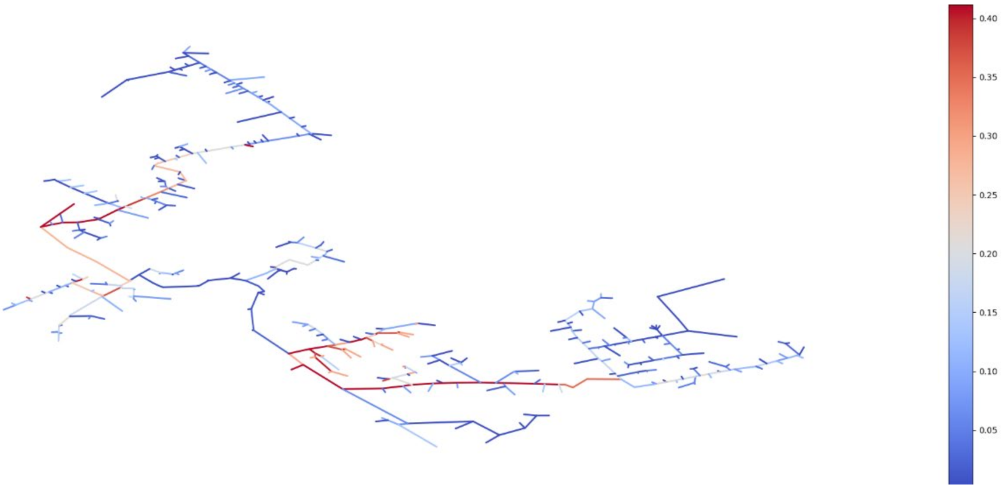

Figure 68 : Velocity distribution in m/s of CAD Santal in summer with no connection between the sub-grids

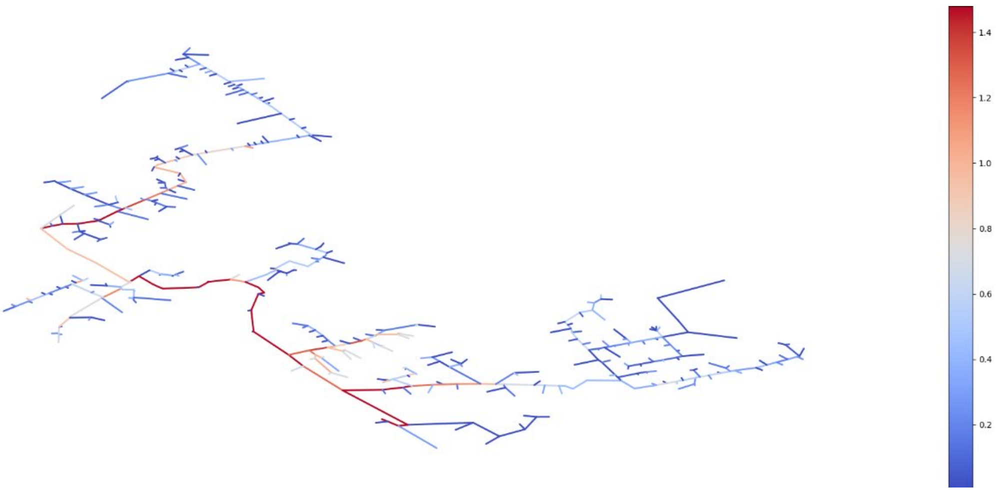

Figure 69 : Velocity distribution in m/s of CAD Santal in winter with no connection between the sub-grids

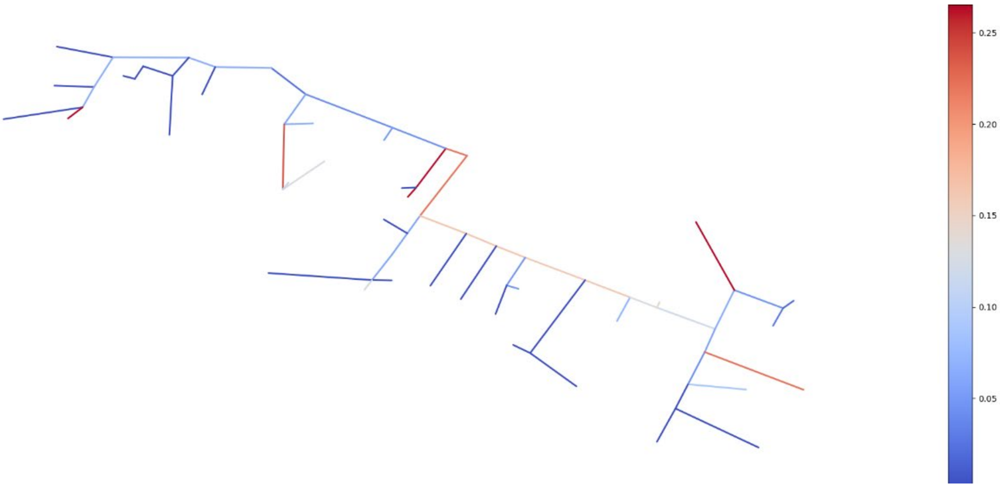

Figure 70 : Velocity distribution in m/s of CAD STEP in summer with no connection between the sub-grids

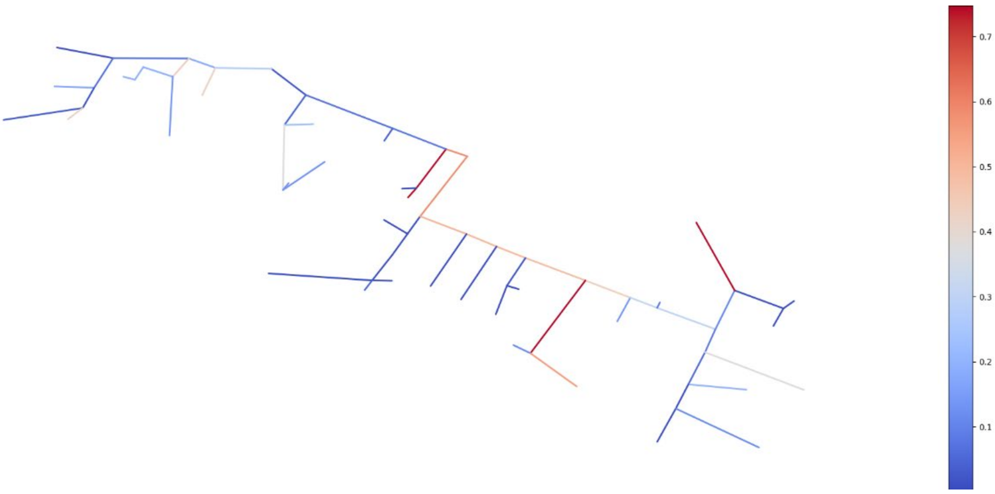

Figure 71 : Velocity distribution in m/s of CAD STEP in winter with no connection between the sub-grids

2.6.3.2. Simulation of connected (synergy) networks

For the second stage in the expansion of the district heating network of Yverdon-les-Bains, it is foreseen to enable a connection between the separate networks and thus constituting a “grande boucle” (big loop in French). In the following section the benefits and disadvantages are discussed in comparison to the separate network on an operational level.

Simulation of connected networks – Heat losses

The base scenario with a synergy configuration between the different networks shows a relatively similar pattern for the heat losses as the non-connected configuration. Large peaks can be identified during low heat demand periods. However, comparing Figure 53 and Figure 72 Figure 72two important differences can be seen. 1) The magnitude of the peak heat losses is far greater in the connected network of up to

30% (in comparison to around 20% for the non-connected configuration) and 2) there are far fewer significant heat loss peaks, in particular during the last simulated week of December.

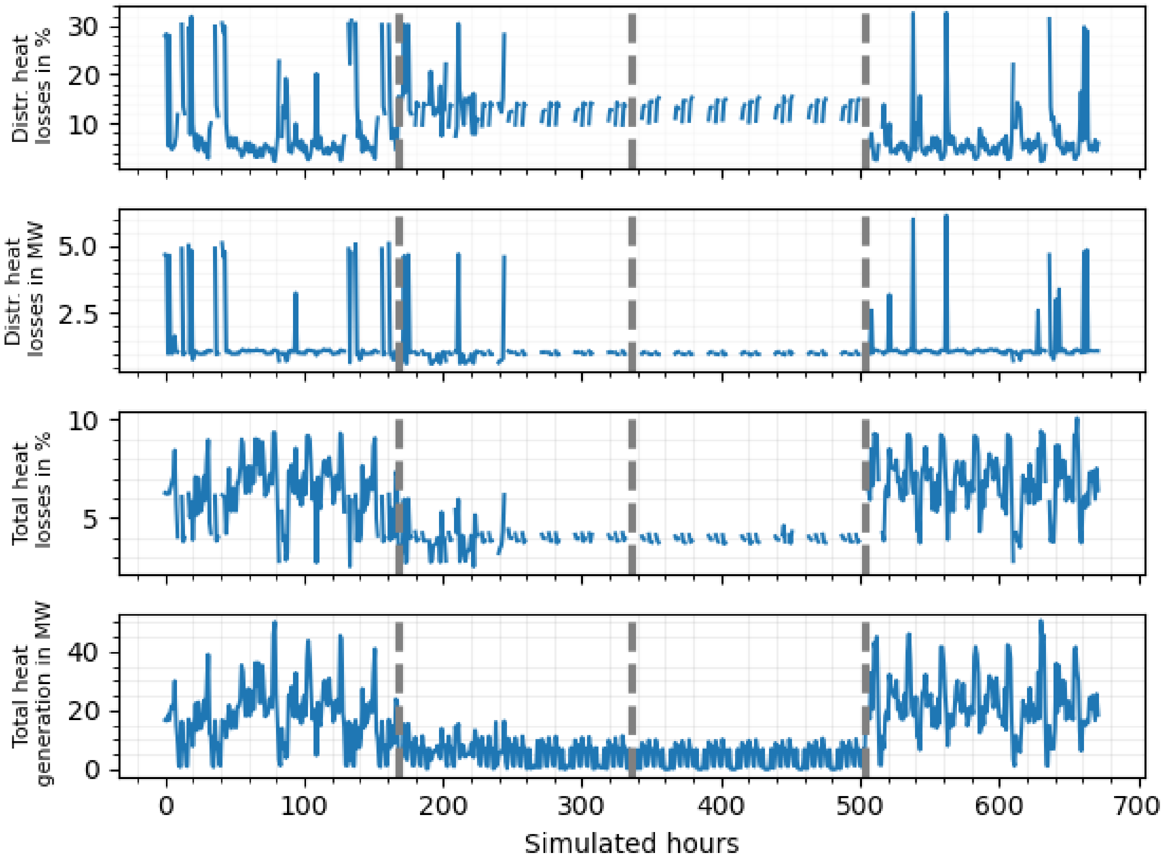

Figure 72 : Overview of heat losses during the four simulated weeks for the synergy base scenario for the district heating network of YIB

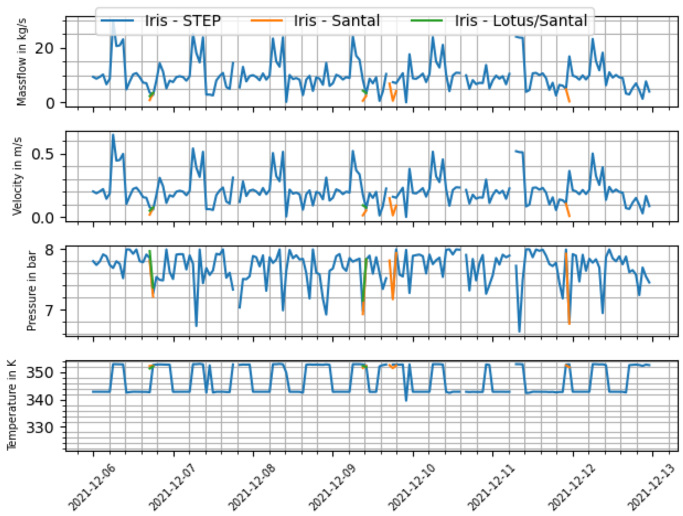

Figure 73 : Parameters in the connection points at forwards direction of the heating network of YLB between 06.12 and 13.12

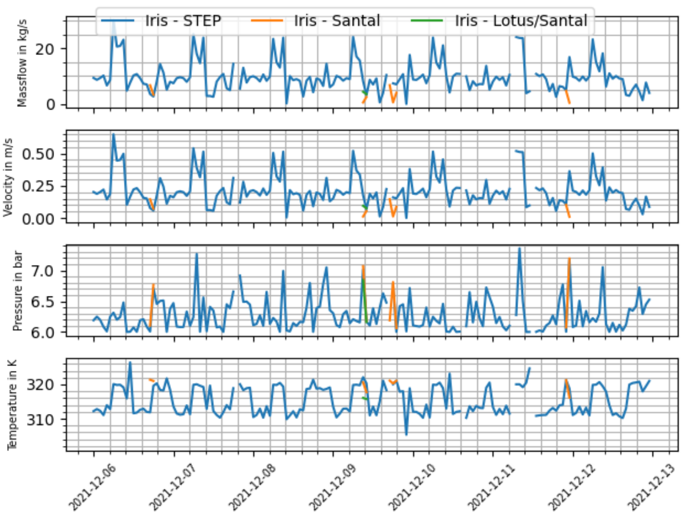

Figure 74 : Parameters in the connection points at backwards direction of the heating network of YLB between 06.12 and 13.12

Simulation of connected networks – Connection points

In addition to the heat losses, the connection points of the three sub grids are further discussed for the simulated week of December. The mass-flow, the velocity, the pressure and the temperature are plotted in Figure 73 for the forward pipeline and in Figure 74 for the backward pipeline. While the mass-flow and velocity follow a very similar pattern for the forward and backward pipeline, the temperature and pressure differ in both cases.

As already indicated in the heat balance analysis, the synergy between CAD STEP and CAD Iris is used far more often than the synergy between CAD Iris and CAD Santal.

Simulation of connected networks – Temperature distribution

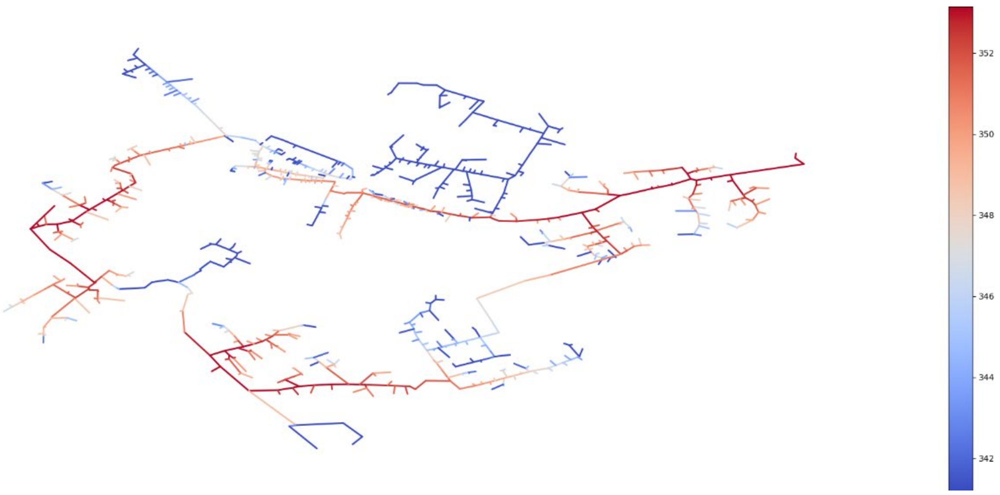

Figure 75 : Temperature distribution in °K in summer with synergy between the sub-grids

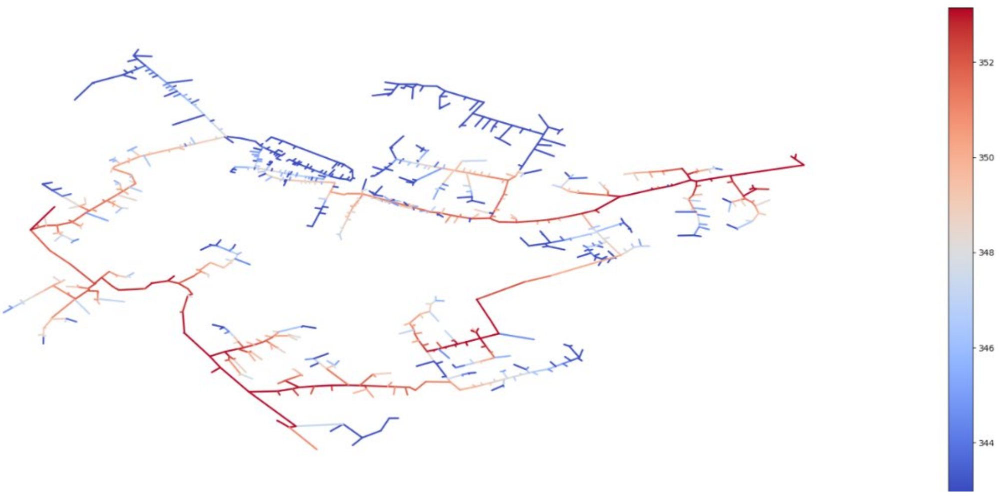

Figure 76 : Temperature distribution in °K in winter with synergy between the sub-grids

The different considered parameters in the grid are distributed similar for the synergy configuration than the non-connected configuration and no major difference can be identified. The region of CAD Iris which are directly south of CAD STEP are however delivered with a temperature level far lower in the synergy scenario (Figure 75) of around 342°K (69°C) in comparison to 350°K (77°C) in the separate configuration (Figure 54) during the summer time step, this is less significant in the winter time step (Figure 76).

Simulation of connected networks – Mass-flow distribution

The maximal values for mass-flow distribution are only slightly lower in the synergy case (see Figure 77 and Figure 78).

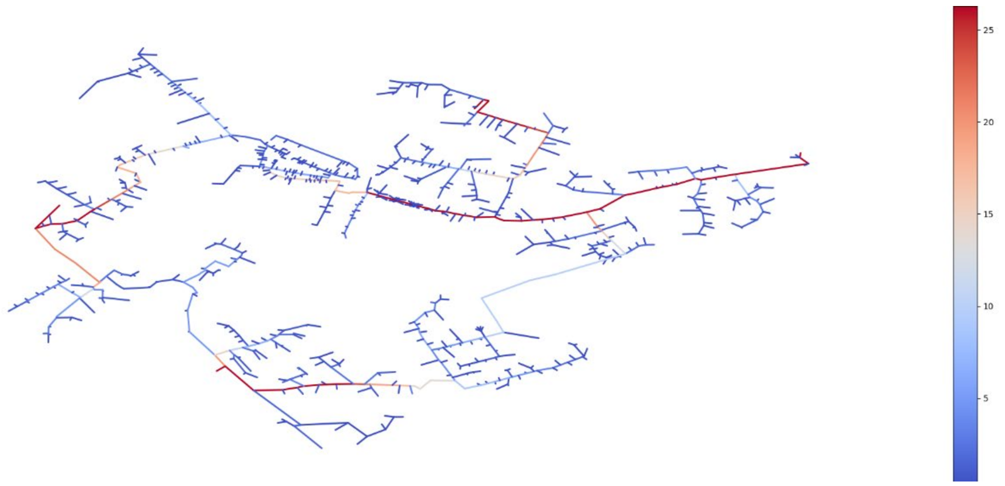

Figure 77 : Mass-flow distribution in kg/s in summer with synergy between the sub-grids

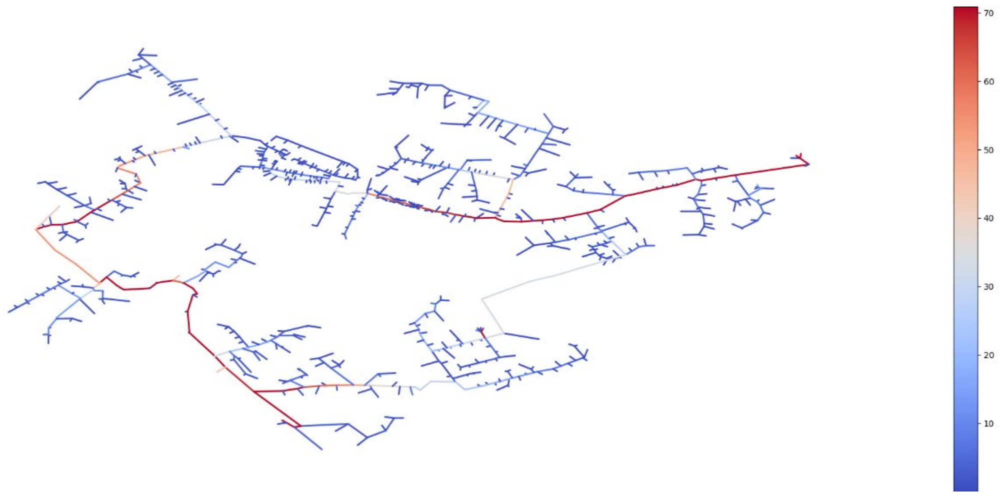

Figure 78 : Mass-flow distribution in kg/s in winter with synergy between the sub-grids

Simulation of connected networks – Velocity distribution

Similar to the maximal values for the mass-flow, the velocity values are also only slightly lower in the synergy case (see Figure 79 and Figure 80), but no critical operational point can be detected.

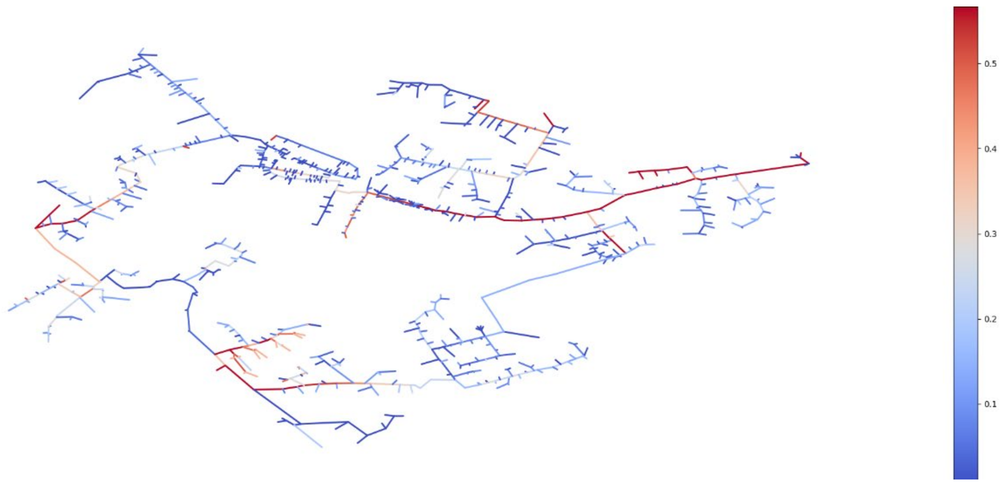

Figure 79 : Velocity distribution in m/s in summer with synergy between the sub-grids

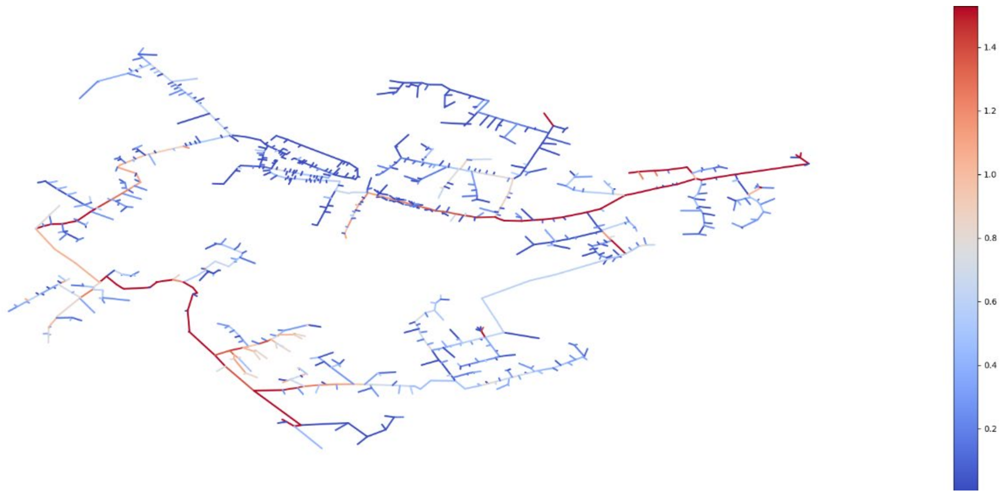

Figure 80 : Velocity distribution in m/s in winter with synergy between the sub-grids

2.6.3.3. Simulation of connected (synergy) networks at 70°C

In the heat balance analyse different scenarios has been analysed on reaching the political goals. The selection of the primary energy of the heat source has little impact on the distribution of the heat in the network if similar output parameters are assumed, therefore the variation is not further discussed here. The decision of the operational temperature in the grid however, has shown a great impact in the heat balance analyse and can also have a difference in the operation of the district heating network. By assuming the same heat demand of the consumers, a greater mass-flow is required to supply the heat demand in the heat exchanger with a lower temperature.

Simulation of connected 70°C networks - Heat losses

The heat losses shown in Figure 81 are very similar to the once shown in Figure 72 for the scenario with 80°C operational temperature. It was assumed that the reduction of the operational temperature would result in lower heat losses, which cannot be seen in the overview of the four simulated weeks, which focuses on the peaks and shows little about the difference of heat losses during non-peak time steps. It seems, that the impact of low production, has a greater impact on the heat losses than the distribution temperature.

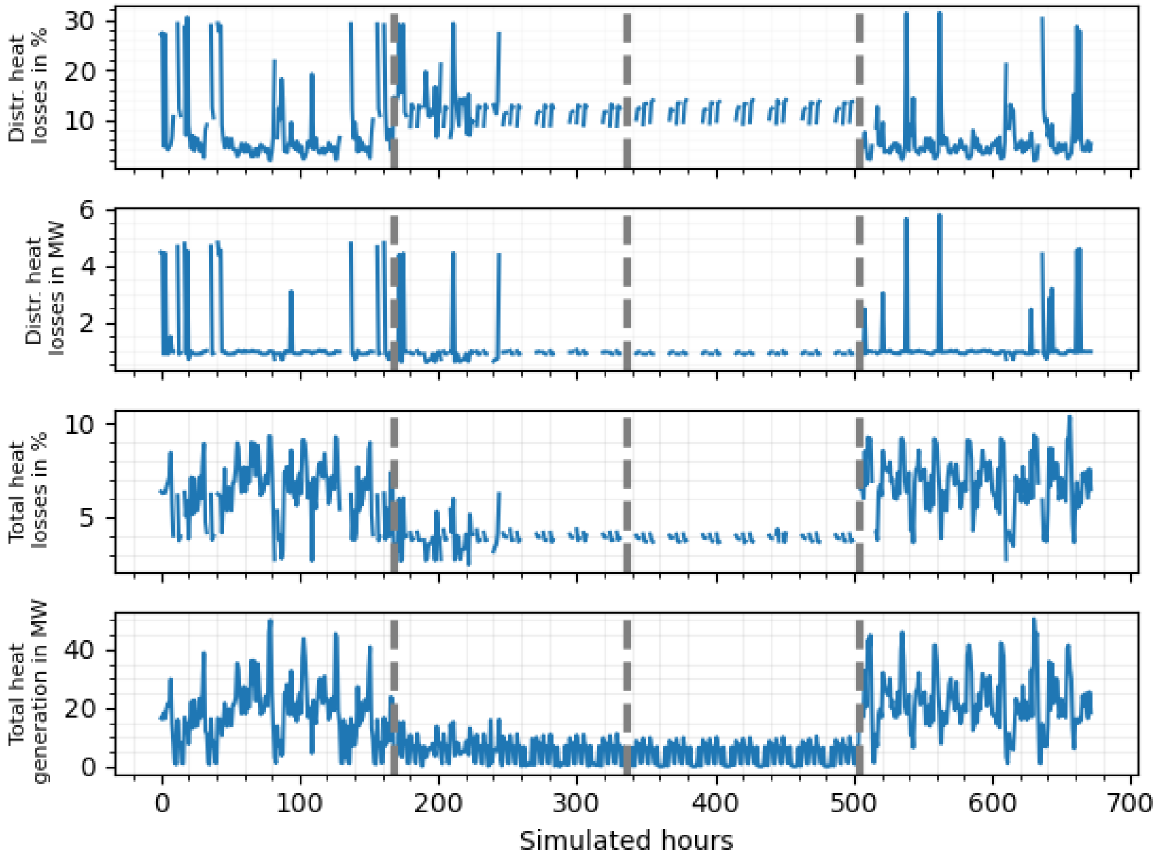

Figure 81 : Overview of heat losses during the four simulated weeks for the synergy scenario with a reduced network temperature of 70°C for the district heating network of YIB

Simulation of connected 70°C networks - Connection Points

The connection points between the sub-grids (Figure 82 for the forward network and Figure 83 for the backward network) also indicated little to no difference by changing the operational temperature by 10°C.

Only the temperature level is far more constant in the 70°C scenario, since both sub-grids are operating on 70°C, this indeed does not represent a surprising result.

Simulation of connected 70°C networks - temperature distribution

The temperature in the grid (Figure 84) varies between 343°K (70°C) to 340°C (67°C) in regions further away from selected heat sources. The simulation of the time-step in December shows a rather low temperature level in the centre of Yverdon-les-Bains, where mostly older buildings are located.

It would be necessary to determine if these buildings are suitable to be heated by temperature level far below 343°K (70°C) in order to evaluate this scenario. This is however outside the scope of this project.

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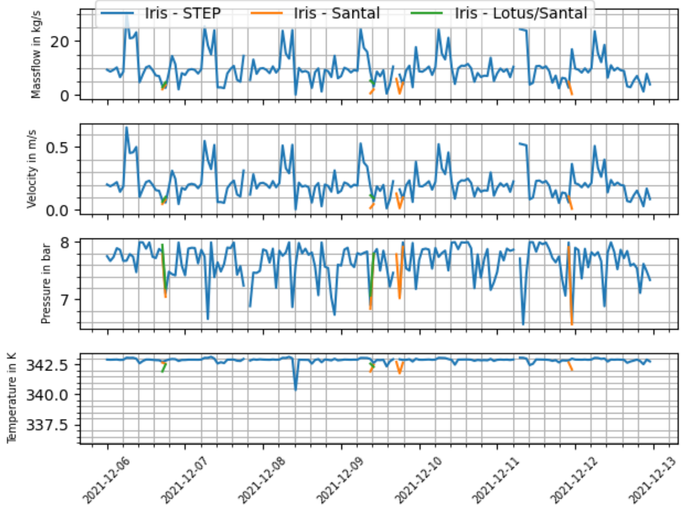


Figure 82 : Parameters in the connection points at forwards direction of the heating network of YLB for reduced network temperature of 70°C between 06.12 and 13.12

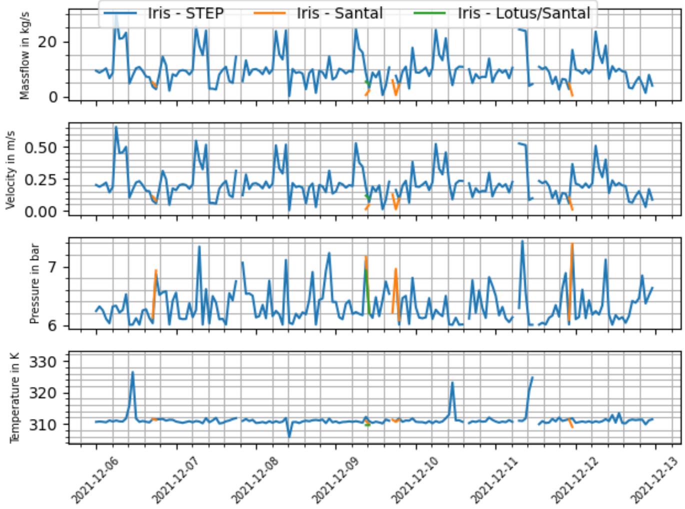


Figure 83 : Parameters in the connection points at backwards direction of the heating network of YLB for reduced network temperature of 70°C between 06.12 and 13.12

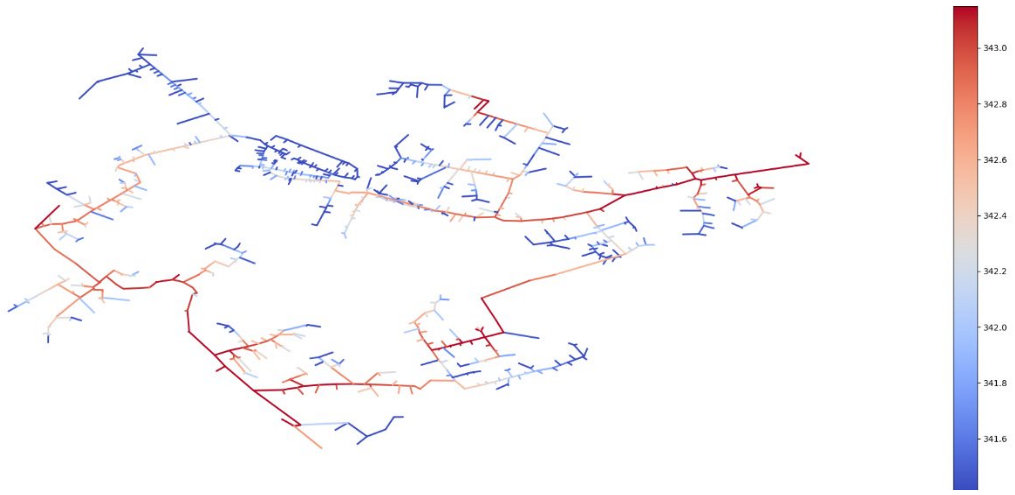


Figure 84 Temperature distribution in °K in winter with synergy between the sub-grids and an operational grid temperature of 343°K (70°C)

2.6.3.4. General heat losses discussion – Test- case Yverdon-les-Bains

Based on the four simulated weeks, the heat losses of 7.6% for the separate network, 7.4% for the 80°C scenario and 6.7% for the 70°C scenario are determined (Table 21). The heat losses of the 70°C network is lower for all simulated week as the 80°C network. The separated network however also has lower or similar heat losses during all but the last simulated week compared to the synergy network. Only during the week in December can a lower heat loss be identified for the synergy configuration. The overall losses during the whole simulated interval are also a bit lower in the synergy configuration. This can be interpretated that during low demand periods a non-connected configuration is beneficial for reducing the heat losses. The higher the heat demand the greater also the distribution of the heat sources, during low heat periods only a few heat sources are used, which result in long transportation routes of the heating medium.

Table 21 : Overview of heat losses for different simulated weeks and scenarios

Network configuration / Simulated week	Seperate at 80°C (“îlot”)		Synergy at 80°C (controlled “bouclage”)		Synergy at 70°C (controlled “bouclage”)	
	%	MWh	%	MWh	%	MWh
Week 1	6.3	189	7.2	217	6.4	193
Week 2	11.2	98	12.6	112	11.6	101
Week 3	12.1	79	12.1	78	10.9	69.7
Week 4	6.9	259	5.5	205	4.9	182
Total	**7.6**		**7.4**		**6.7**	

The heat losses of district heating network with comparable heat demand densities varies between 4 % and up to 35 %, whereas the stated interpolated curve in Figure 85 gives a distribution heat loss for a 1.3 MWh/(m*a) heat density network of around 17%. The blue cross represents the YLB DHN based on the 4 simulated weeks. The relatively low heat losses can be explained by using modern pipeline isolation material available in the current market, which are superior to isolations used in older heating networks. A second possible reason is the relatively low temperature level of 80°C in comparison to many existing district heating networks operating with 100 to 120°C. Also, simplifications in data assumption and the simulation cannot be excluded as reasons. Even though the four weeks are selected for the four annual seasons, no claim is made that they are representative for the full year. Also, the results here are based on a simulation with assumption of input data which might vary from the future real network.

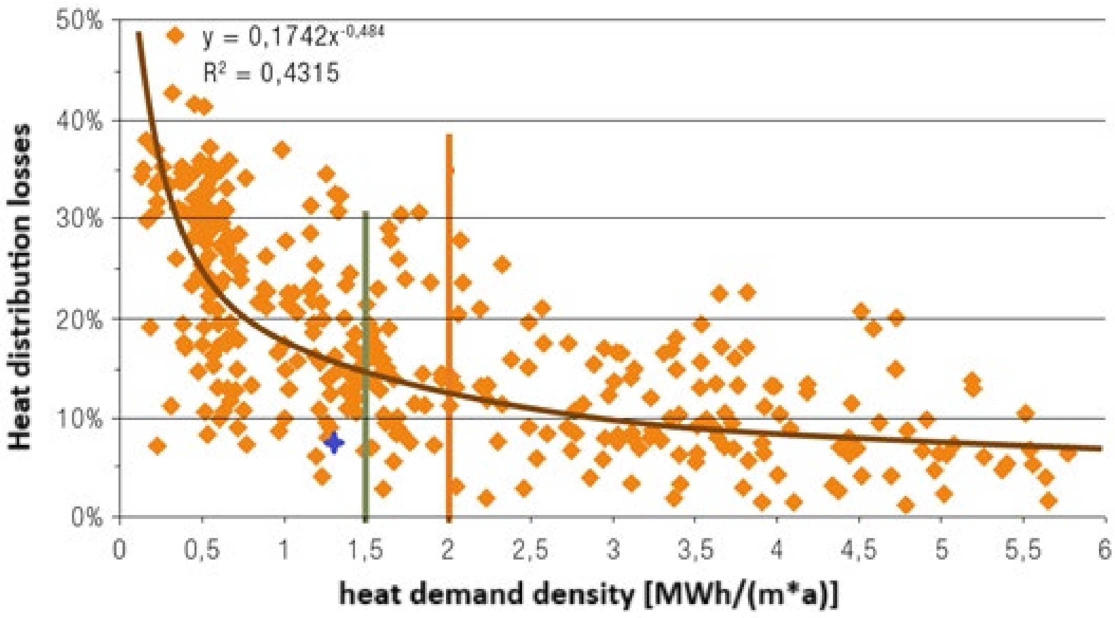


Figure 85 : Heat losses curve for different district heating networks based on heat demand density (taken from [4])

In the scope of the project a master thesis by Joris Ferroni analysing the district heating network of Neuchatel was carried out with a previous version of the simulation framework. The simulation framework was focusing on the forward network at that stage and neglected the controlling of the backward. By not enforcing the backward flow, the mass-flow returning to the heat source might be different to the mass-flow injected into the forward flow. This led to difficulties determining the total heat losses in the network. The work is further descripted in 7.2.

2.6.4. Yverdon-les-Bains test-case – Summary and key findings

The test-case of Yverdon-les-Bains includes two existing small-scale district heating networks which are presently envisioned to be extended in order to cover the whole city in the near future with three sub-networks. The three networks can either operate separately or as a connected entity.

The connected heat sources are operating based on their greenhouse gas emissions and a parameter describing the situational nature of the heat source primary energy. The main research questions for the test-case of YLB were:

1) to estimate the impact of a connected network in comparison to a separate operation of the three networks regarding the aimed goal of a share of renewable energy of 80%
2) to quantify the reduction of greenhouse gas emissions by exploiting synergies between the different networks.

The results show that the 80% renewable energy in the DHN can only be achieved if the geothermal heat source is combined with renewable heat sources to reach the expected temperature of 80°C for distribution in the network. A reduction of the operational temperature in the grid from 80°C to 70°C also shows a possibility to achieve the 80 % renewable share even when combined with natural gas, although this is not in line with SFOE and cantonal heat strategies. However, the temperature reduction scenario requires further and more in-depth analysis.

The benefit of connecting the sub-networks during some time steps showed a reduction of greenhouse gas emissions, since low-emission heat sources are able to be used on full load and substitute higher emission sources in other sub-networks. This can be seen as the heat pump connected to the waste water treatment facility (STEP) is operating 3 to 4 times more in the synergy scenario compared to the separate operation of all sub networks.

However, the benefits of synergy can only be seen if two sub-networks with very different heat sources and consumer configurations are available. The two sub-networks of CAD Iris and CAD Santal are both mainly connected to multi-family houses, with geothermal, natural gas and wood-based heat sources.

In a last step, the operation of different scenarios has been simulated and further analysed in detail, based on the distribution of important parameters and their heat losses. The considered network configuration showed few to none problematic zones based on temperature, mass-flow or velocity. The heat loss analyses showed high heat losses during time steps with little heat demand in the network.

By simulating four different weeks of the year, the annual heat losses have been approximated for the separate operation of the three networks, the synergy scenario and a lower temperature synergy scenario. The implementation of synergy results in lower heat losses, especially during winter; while a reduction of the operational temperature in the grid results in an even more significant heat loss reduction.

2.6.5. Lausanne test-case – Simulations of Dufour DHN using the data center waste heat

The phases of the evolution of the district heating networks in the city of Lausanne are illustrated in Figure 86 for the 2025-time horizon and Figure 87 for the 2050-time horizon.

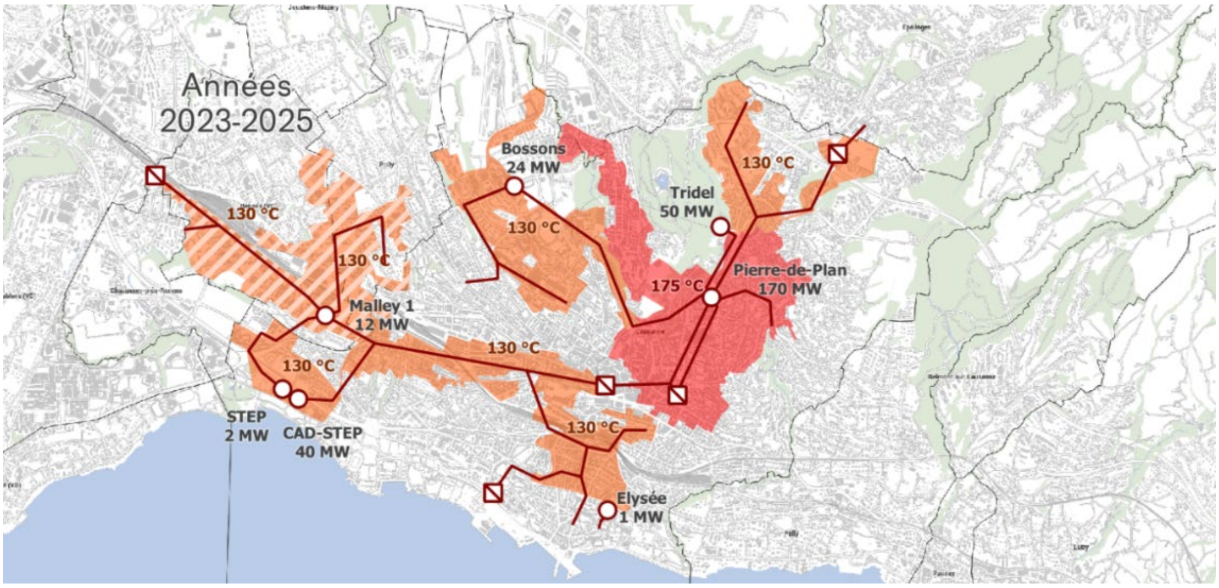


Figure 86 : Evolution phases of the district heating networks in the city of Lausanne with 2025 as time horizon

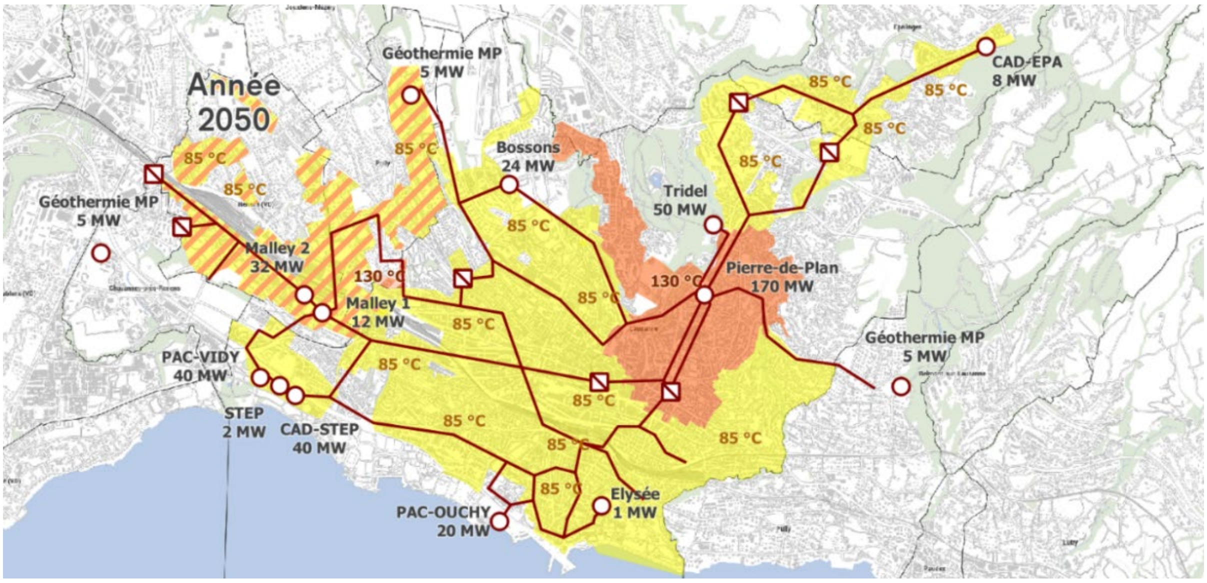


Figure 87 : Evolution phases of the district heating networks in the city of Lausanne with 2050 as time horizon

To achieve the objective of expanding the network in Lausanne, this project involves the development of a micro-district heating network to utilize waste heat potential and meet the demand of a specific area in Lausanne. Subsequently, an assessment of the potential of the designed network for integration into other networks, especially the existing network in Lausanne and its surrounding surburban region, has been conducted.

To design the mentioned network, the methodology outlined in Section 2.3, 'Methodology for Code Used in Lausanne Test-Case', is applied to the Dufour neighbourhood in Lausanne. The findings are presented and organized into three steps of the methodology: results from the demand model, topology design, and network operation simulation.

2.6.5.1. Demand Model

Results of the demand model are presented in Figure 88 (A, B, C). Figure 88-A represents the daily total heat energy demand of all buildings, Figure 88-B illustrates the annual heat energy demand for each building, and Figure 88-C displays the hourly heat power demand for one building with the highest annual energy demand.

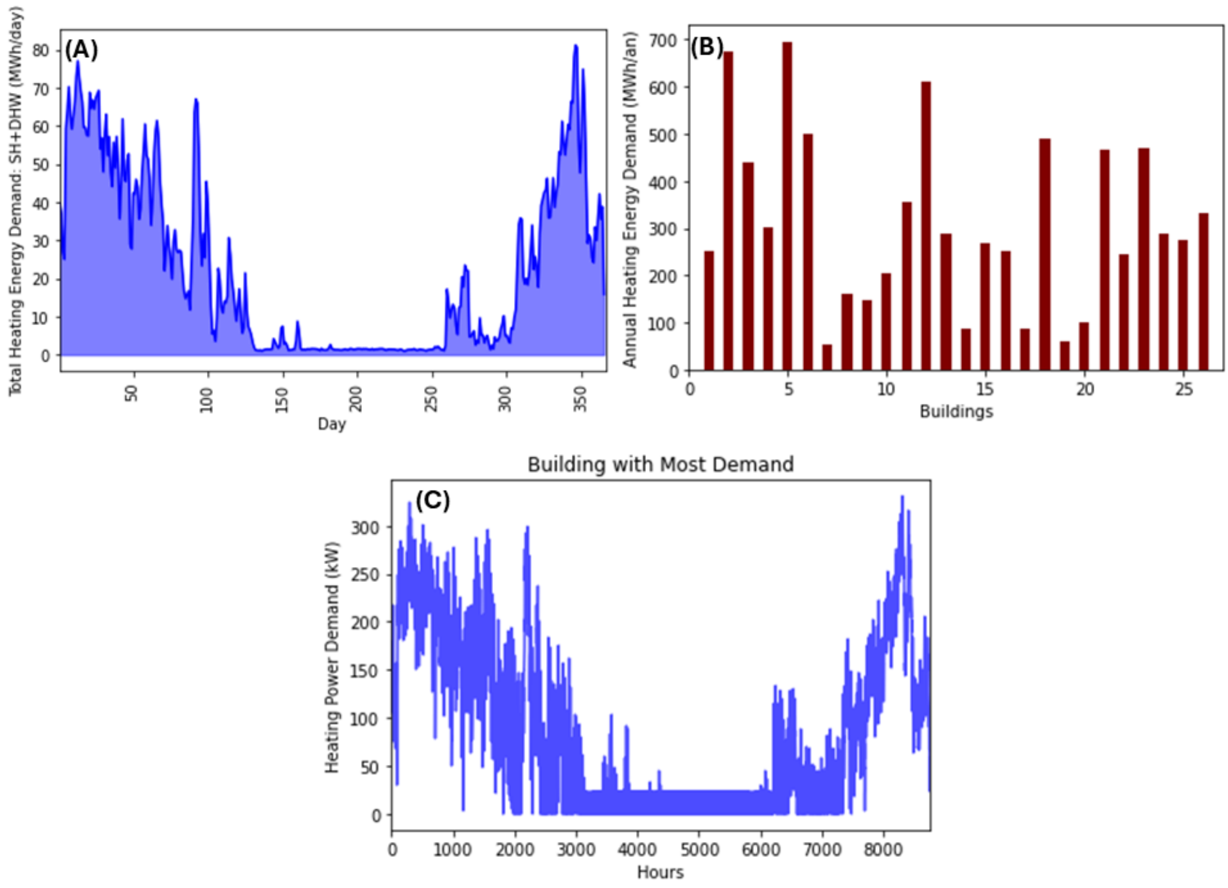


Figure 88 : Demand model results - (A) Daily total heat energy demand, (B) Annual heat energy demand for each building, and (C) Hourly heat power for the building with the highest demand.

2.6.5.2. District Heating Network Topology

By employing the topology model and refining the piping routes through consultations with SIL, as well as eliminating impractical connections based on civil constraints, Figure 89 presents the finalized graph of the designed DHN. This inclusive representation encompasses all nodes, including buildings, resources, intersections, and connections depicted by edges. Additionally, the lengths of each piping route are demonstrated in this figure.

Furthermore, through the integration of the topology results into QGIS, Figure 90 displays the visual representation of the DHN piping routes, buildings, and resource locations within the designated neighborhood.

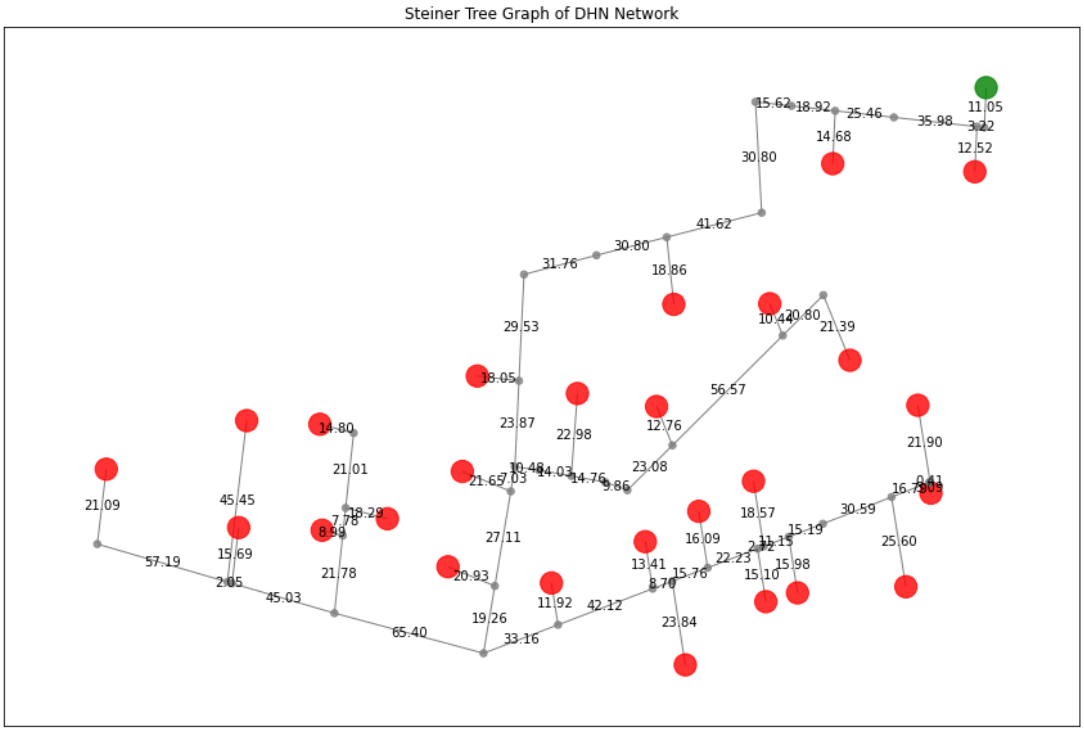


Figure 89 : Final DHN graph with nodes representing buildings, resources, and intersections, connected by connection edges.

Figure 90 : Visual representation of the designed District Heating Network (DHN) with connections

2.6.5.3. District Heating Network Simulation

In this section, simulation models are executed using the outputs from the demand and topology models. The results are organized into four introduced scenarios and comprehensive comparison among them. Additionally, an assessment of the potential integration of this designed network with other DHN in Lausanne is being conducted.

Scenario 1: High-Temperature District Heating Network with Central HP

In Figure 91, the calculated nominal diameter of each pipe is assigned to the visual representation of the designed micro DHN. These nominal diameters are one of the outputs from the design model in the first scenario.

Figure 91 : Nominal diameter integrated into each of the District Heating Network pipes in the first scenario

This section presents selected outputs from the operation model, which simulates the performance of the designed DHN over twelve operational days, spanning different months. It is worth mentioning that in the first and fourth scenarios, both free cooling and forced cooling operate depending on the month, with twelve operating days considered. Meanwhile, in the second and third scenarios, only four operating days have been simulated. Figure 92 shows the hourly heat power profile for each pipe (kW) and the corresponding mass flow (kg/hr) over the 288 operational hours.

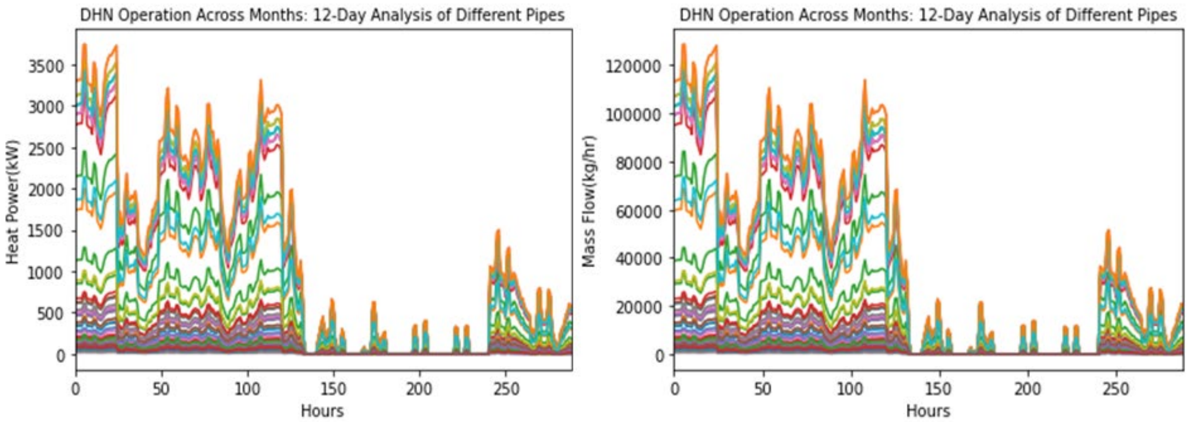


Figure 92 : Hourly heat power profile (left) and mass flow profile (right) for developed Dufour DHN pipes over 12 operation days, considering different months.

Figure 93 presents the simulated hourly electricity consumption of the DHN pump, accounting for the pressure drop across all pipes. Additionally, the right side of the figure displays the calculated energy loss for each DHN pipe during one hour of operation.

To assess the impact of the target pressure-drop (Pa/m) on simulation outcomes, the result of sensitivity analysis of the target pressure drop is depicted in Figure 94. The figure illustrates the net present cost of DHN (CHF), which encompasses both the investment cost of the DHN and the electricity consumption cost of the pump. This calculation spans 30 years of DHN operation, with the target pressure drop varied within the range of 50 to 500 (Pa/m). As mentioned earlier, a target pressure drop of 200 Pa/m was chosen for designing the DHN based on consultation with the partners. However, further analysis can be conducted by adjusting the pressure drop in the developed code to explore other options.

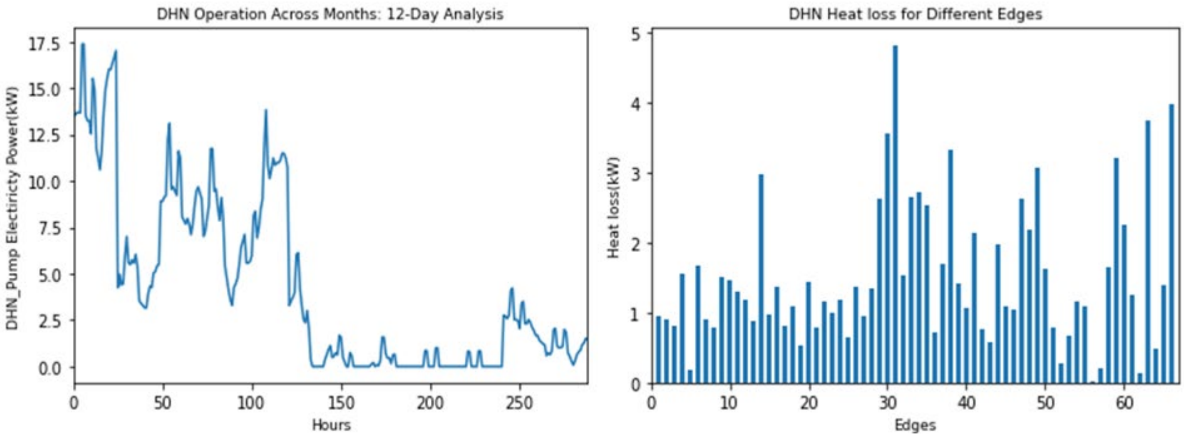


Figure 93 : DHN Electricity pump consumption (left) over 12 operation days in different months, along with the heat loss of each DHN pipe (right).

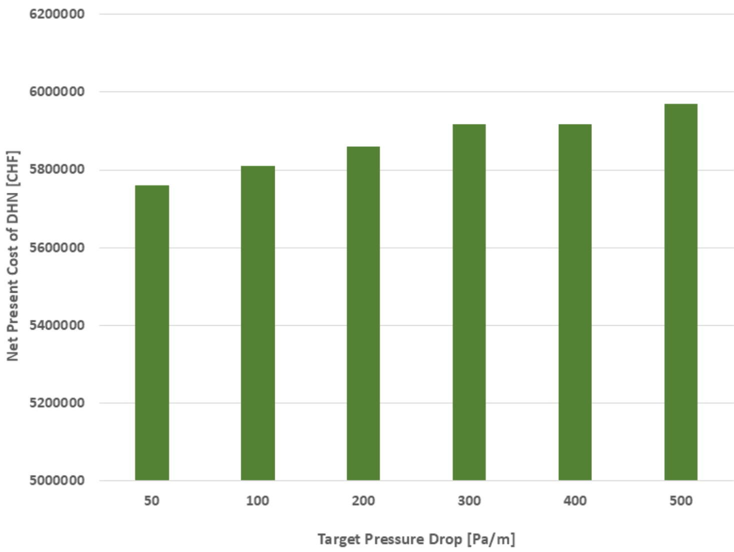


Figure 94 : Sensitivity analysis of the Net Present Cost of the District Heating Network, varying the target pressure loss and considering both the investment cost and the capitalized cost over 30 years of DHN operation.

The numerical results of the first scenario, including the heat pump COP (installed near the waste heat source), the maximum heat power demand of the DHN, and the assessment of resource potential, are presented in Table 22. A positive shortage of heat power indicates that the DHN requires additional resources to meet its demand, while a negative shortage of heat power means the resource's heat potential exceeds the DHN's demand, resulting in excess heat power. As shown in this table, from June to November, when the operation mode of the data center is “forced cooling”, the heat pump COP is higher than during the free cooling mode from November to June, due to the temperature differences between these two modes. Consequently, the heat power produced in forced cooling mode is greater than that produced in free cooling mode. Since the free cooling mode occurs in winter, the maximum DHN heat demand arises during this time, resulting in a shortage of heat power for supplying the DHN demand.

Table 22 : Numerical results of Heat Pump characteristics and resource sufficiency assessment in first scenario

Cooling System	COP of HP	Max Heat Power Demand of DHN [kW]	Heat Potential of Waste-heat [kW]	Shortage of Heat Power [kW]
Forced Cooling (June - November)	6.76 (40 to 65°C)	1071	3000	-1929
Free Cooling (November - June)	3.75 (20 to 65°C)	2741	2655	86

Using Figure 95, we can evaluate the resource sufficiency for supplying the entire demand of the considered Dufour network. The predicted waste heat power of the data center is 3000 kW in forced cooling mode from June to November and 2655 kW in free cooling mode from November to June. This figure allows us to assess the scheduling of heat power shortages or excess power during the 12 operational days of the DHN.

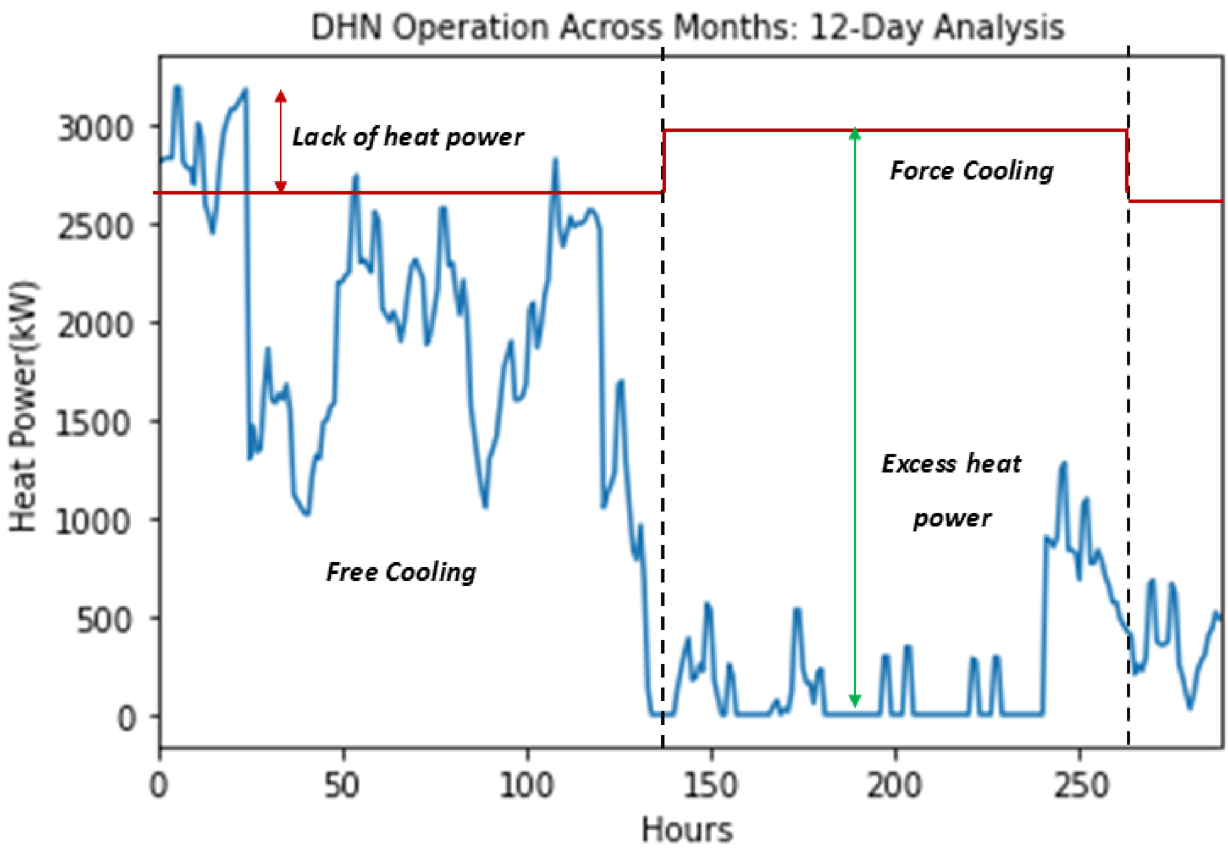


Figure 95 : Evaluation of resource sufficiency using the predicted waste heat potential of the data center in two modes: free cooling and forced cooling.

At the conclusion of this scenario, the total costs for two cases, DHN and DHN + Central HP, are evaluated and presented in Figure 96. These costs encompass the investment cost of the district heating network, the investment cost of the central heat pump, and the capitalized electricity consumption costs for both the DHN pump and the Heat Pump over a 30-year period. All CAPEX and OPEX are calculated based on the year 2023.

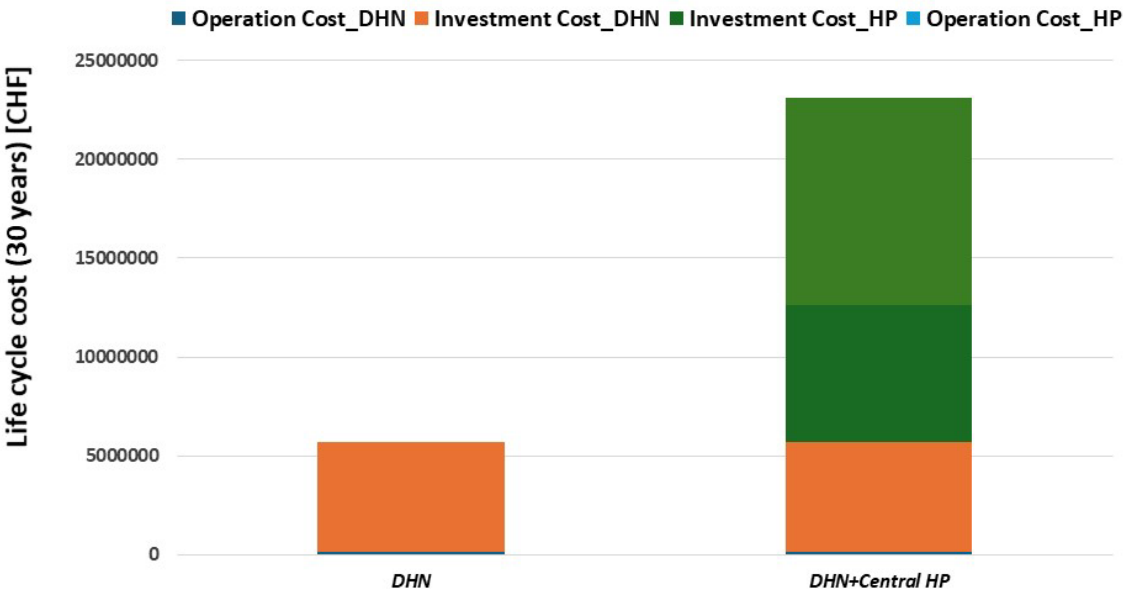


Figure 96 : Cost analysis of DHN and DHN+ HP considering both investment and operational costs.

Scenario 2: Low-Temperature District Heating Network with Decentralized HPs

The calculated nominal diameter for each pipe, an output of the design model in the second scenario, is incorporated into the visual representation of the designed district heating network in Figure 97. As shown, the pipe diameters in this scenario are greater than in the first scenario because the temperature difference (ΔT) is lower. This results in an increase in mass flow, which in turn leads to larger pipe diameters.

Figure 97 : Nominal diameter integrated into each of the District Heating Network pipes in the second scenario

The heat power capacities (kW) of each designed decentralized heat pump, situated near individual buildings in the considered neighbourhood, are depicted in Figure 98.

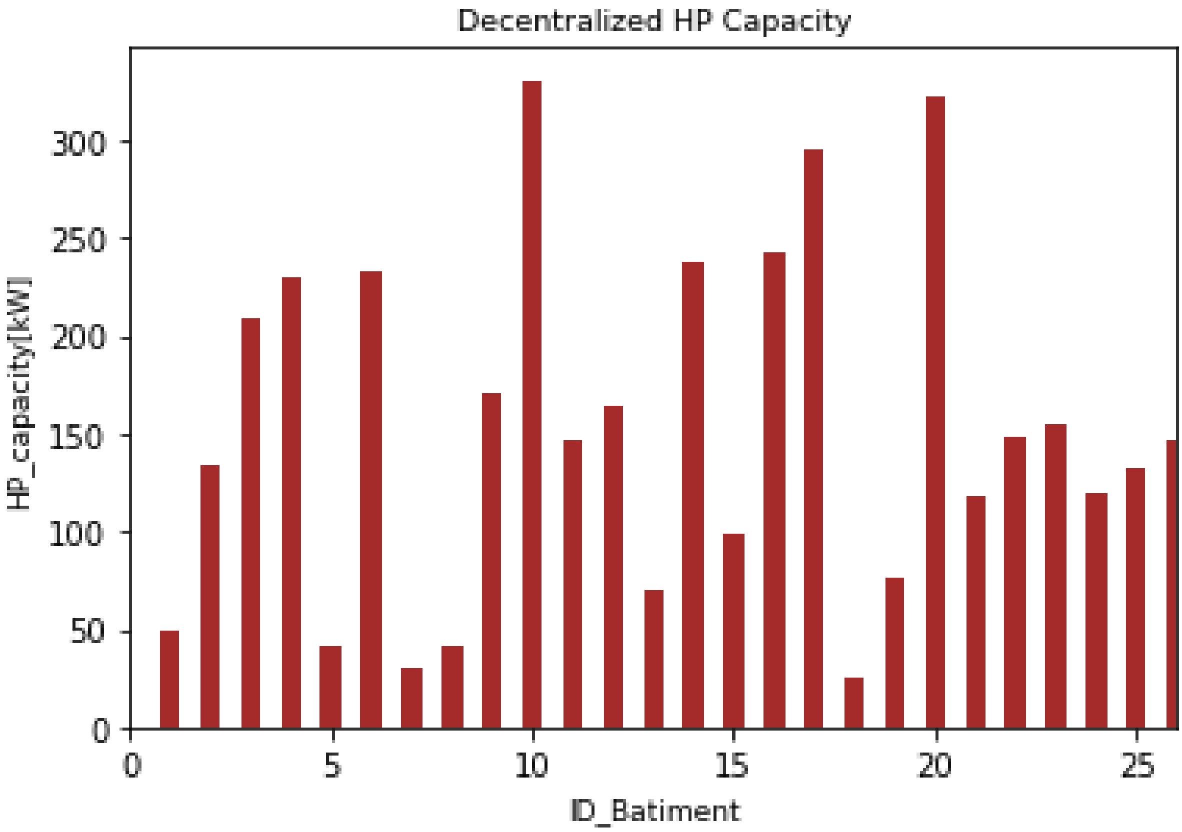


Figure 98 : Heat power capacities (Heat produced by HP) of decentralized Heat Pumps located in each building in second scenario.

The characteristics of the designed decentralized heat pumps in the second scenario, along with the results of resource sufficiency evaluation, are presented in Table 23. The coefficient of performance for each HP is calculated based on the required temperature of each building, and therefore, the average COP for decentralized HPs is presented.

Following that, the plot of hourly heat demand of the DHN, along with the predicted waste heat power (3000 kW), is depicted in Figure 99. Analyzing this figure provides a better understanding of heat power shortage of waste heat resource and excess heat energy of resource.

Table 23 : Decentralized heat pump characteristics and resource sufficiency assessment in the second scenario

Average COP of Decentralized HPs	Max Heat Power Demand of DHN [kW]	Heat Potential of Waste-heat [kW]	Shortage of Heat Power [kW]
6.76	3190	3000	190

Scenario 3: Cold District Heating Network with Decentralized HP

The calculated nominal diameter for each pipe, an output of the design model in the third scenario, is integrated into the visual representation of the designed district heating network in Figure 100. Similar to the previous scenarios, the pipe diameters in this scenario are greater than those in the first and second scenarios because the temperature difference (ΔT) is lower (5 degrees). This results in an increase in mass flow, which in turn leads to larger pipe diameters.

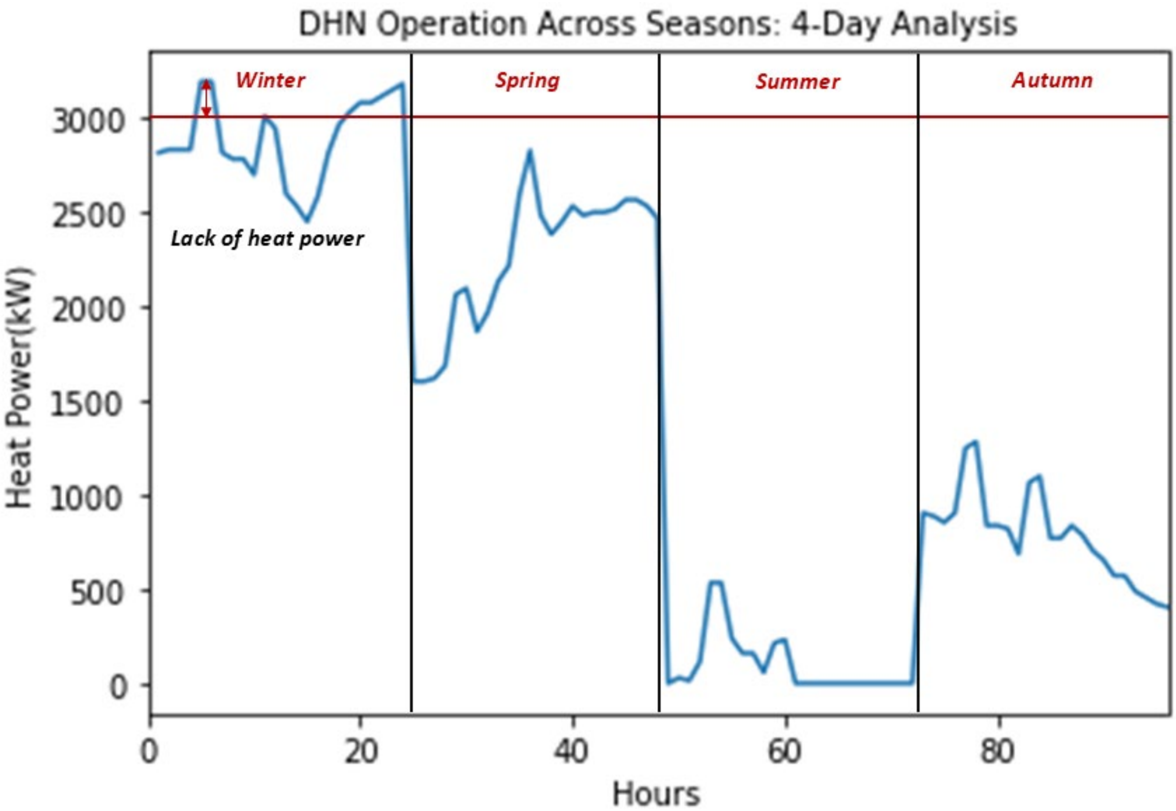


Figure 99 : Evaluation of resource sufficiency using the predicted waste heat potential of data center.

Figure 100 : Nominal diameter integrated into each of the DHN pipes in the third scenario

The characteristics of the designed decentralized HPs in the third scenario, along with the results of resource sufficiency evaluation, are presented in Table 24. Like the second scenario, the COP for each HP is calculated based on the required temperature of each building, and therefore, the average COP for decentralized HPs is presented. Since the temperature level of the DHN in this scenario (19ºC/14ºC) is lower than that of the second scenario (40ºC/25ºC), the COPs of the decentralized heat pumps in the buildings are lower than those in the second scenario.

Subsequently, the plot of hourly heat demand of DHN, along with the predicted waste heat power (2655 kW), is illustrated in Figure 101. In this scenario, the predicted waste heat power differs from the two previous scenarios, approximately amounting to 2655 kW, as the data center does not utilize the cooling machine in this instance. Indeed, analyzing this figure provides a better understanding of heat power shortages of DHN and excess heat power in data center.

Table 24 : Decentralized Heat Pumps characteristics and resource sufficiency assessment in the third scenario

Average COP of Decentralized HPs	Max Heat Power Demand of DHN [kW]	Heat Potential of Waste-heat [kW]	Shortage of Heat Power [kW]
3.67	2791	2655	136

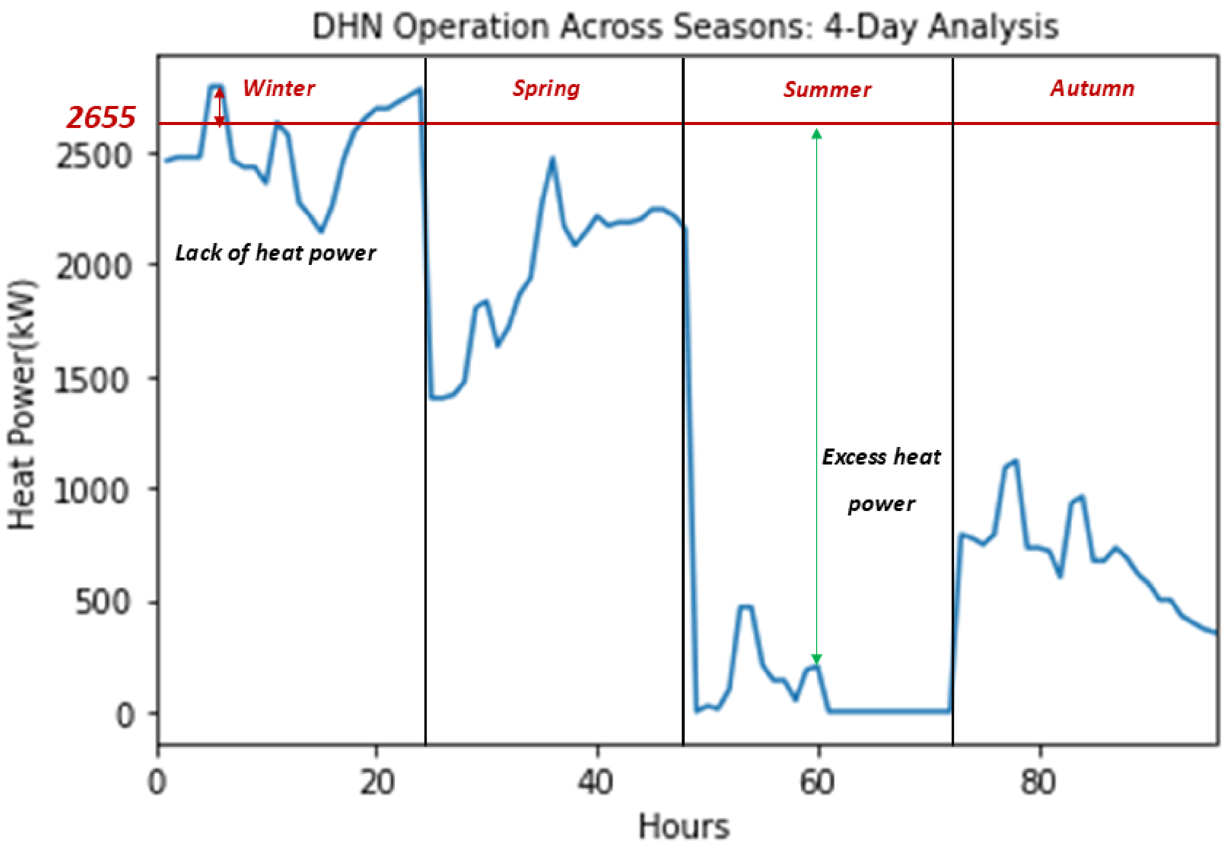


Figure 101 : Evaluation of resource sufficiency using the predicted waste heat potential of for third scenario.

Scenario 4/Hybrid scenario: District Heating Network with Central & Decentralized HPs

The calculated nominal diameter for each pipe, an output of the design model in the third scenario, is integrated into the visual representation of the designed district heating network in Figure 102. Since the temperature level of the network in this scenario (40ºC/25ºC) is the same as in the second scenario, the pipe diameters are similar.

Figure 102 : Nominal diameter integrated into each of the DHN pipes in the fourth scenario

The characteristics of the designed central and decentralized HPs in the fourth scenario, along with the results of resource sufficiency evaluation, are presented in Table 25. Similar to the second and third scenario, The COPs for decentralized HPs are calculated based on the required temperature of each building, and therefore, for decentralized HPs the average COP is presented.

Subsequently, the plot of hourly heat power demand of the DHN, along with the predicted waste heat power for the two different cooling modes, free cooling and forced cooling, is illustrated in Figure 103. In this scenario, the predicted waste heat power is 2655 kW in free cooling mode, as the data center does not utilize the cooling machine, and 3000 kW in forced cooling mode, as the data center uses the cooling machine. Analyzing this figure provides a better understanding of heat power shortages of DHN and excess heat power in the waste heat of data center.

Table 25 : Central & Decentralized HP characteristics and resource sufficiency assessment in fourth scenario

Cooling System of Date center	COP of HP		Max Heat Power Demand of DHN [kW]	Heat Potential of Waste-heat [kW]	Shortage of Heat Power [kW]
	Central HP	Decentralized HPs			
Forced Cooling (June - November)	-	6.9	1280	3000	-1720
Free Cooling (November - June)	7.8 (20 to 40°C)	6.9	2782	2655	127

2.6.5.4. Comparison of results across all scenarios

To summarize the numerical results of the simulation models for the four introduced scenarios, Table 26 is provided. In this table, the characteristics of the designed network for the four scenarios are compared. These characteristics include the network's temperature level, annual heating energy demand, heat power shortage to meet the network demand, annual heat loss, annual pump electricity consumption, and annual HPs electricity consumption.

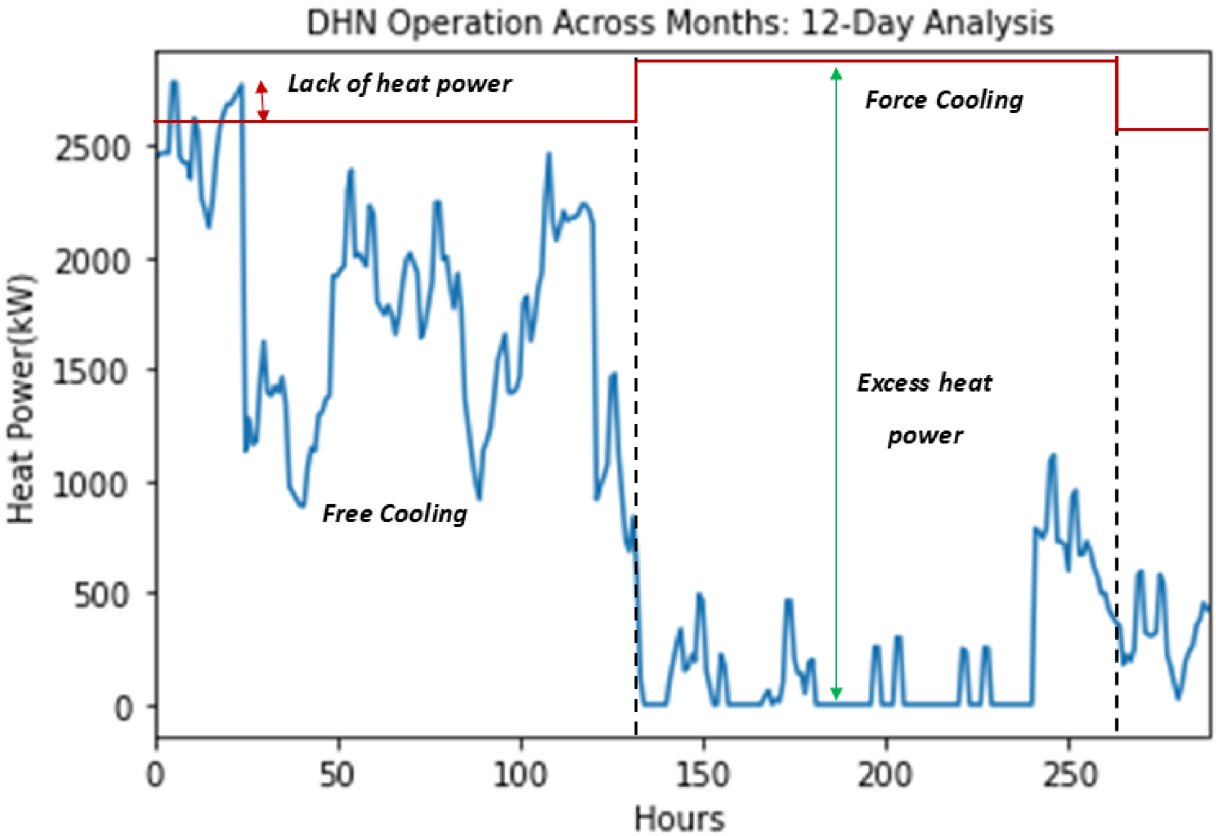


Figure 103 : Evaluation of resource sufficiency using the predicted waste heat potential of data center for fourth scenario.

Table 26 : Summarized the DHN characteristic results of the simulation model for four scenarios

Scenarios	Temperature level of network [°C]	DHN heat energy demand [MWh/an]	Shortage of heat power [kW]	Network Heat Loss [MWh/an]	Pump electricity consumption [MWh/an]	HP electricity consumption [MWh/an]
First	65/40	7959	86	873	38	2759
Second	40/25	13192	190	478	75	2253
Third	19/14	11416	136	201	157	3890
Fourth	40/25	8075	127	478	50	2516

Figure 104 presents a comprehensive cost analysis of the designed DHN, accounting for various investment and operational costs of both the DHN and Heat Pumps. The operational cost of the DHN includes the capitalized electricity consumption cost of the pump over 30 years, while the capitalized operational cost for the heat pumps over 30 years includes the electricity consumption for both central and decentralized units.

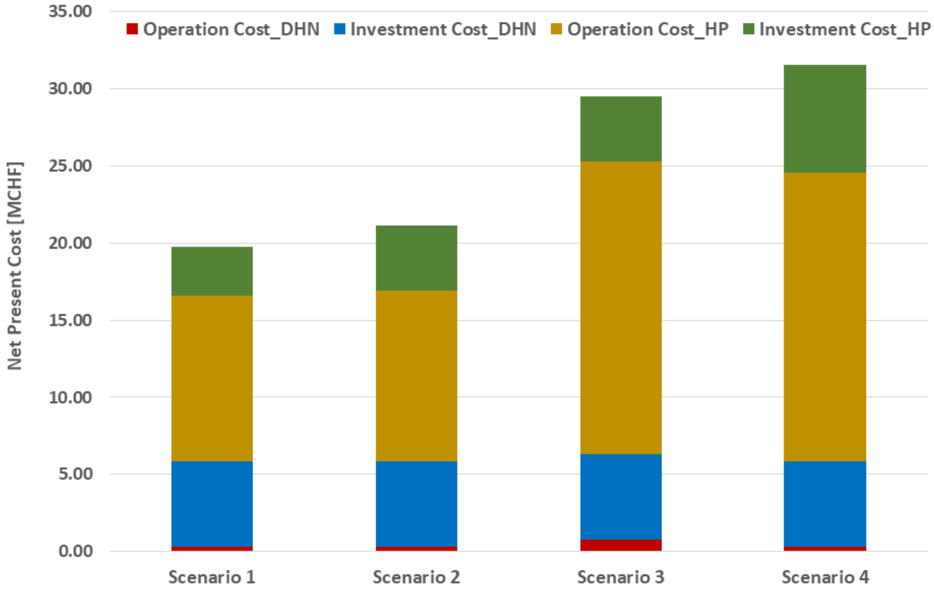


Figure 104 : Net Present Cost of the designed DHN considering investment and 30 years operational costs of DHN and HPs

2.6.5.5. Potential Integration with Other DHNs: Future Strategies

In this project phase, a micro-District Heating Network (micro-DHN) is designed for a specific neighborhood to meet its heat requirements using waste heat from the Swisscom data center. Four different scenarios were defined for designing the DHN, considering various temperature levels based on different states of Heat Pump integration. The designed DHNs exhibit varying levels of excess and shortage heat power across these scenarios.

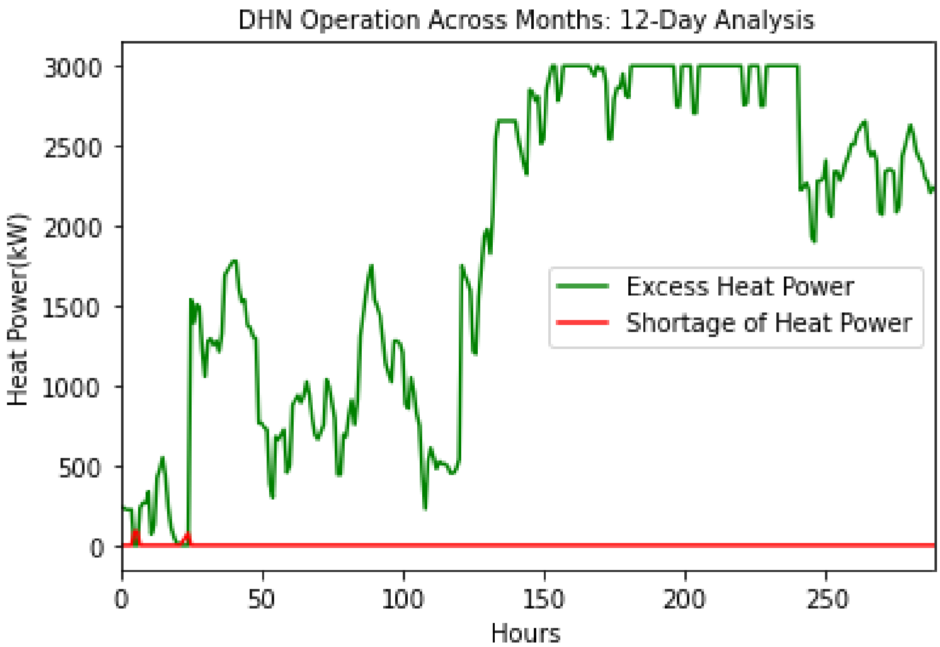


Figure 105 : Hourly profile of excess and shortage of heat power in the designed micro-DHN supplied by the data center waste heat

Figure 105 illustrates the hourly profile of excess and shortage heat power in the designed micro-DHN, allowing for a detailed analysis of the timing and magnitude of the required resources, as well as the timing and quantity of energy that can be transferred to other networks. The calculated excess and shortage heat power can be managed in subsequent phases by integrating this micro-DHN with other DHNs, including the existing network in Lausanne. This data serves as an assessment criterion for evaluating the potential integration of this DHN with others. It is worth noting that, beyond the magnitude, the timing of both excess and shortage power is critical for effectively integrating networks.

2.6.5.6. Simulations of Dufour DHN Using Data Center Waste Heat – Summary and key findings

1) Pipe Nominal Diameter: In the first scenario, characterized by high temperatures, the nominal diameter of the DHN pipes is at its minimum. This is due to the significant temperature difference of 25°C between the DHN supply and return lines, which is greater than in the other scenarios. Conversely, in the third scenario (cold DHN), the nominal pipe diameter is the largest, due to a temperature difference of only 5°C. At this stage, insulation thickness variation is not included in the calculated nominal diameter, although it has been considered in the heat loss calculation (section 2.3).
2) Heat Losses: For calculating heat losses, the insulation thickness was considered as explained in section 2.3. The third scenario shows the lowest heat losses, approximately 201 MWh/year, due to its DHN operating at the lowest temperature level (19/14°C) among the scenarios. In contrast, the first scenario has the highest heat losses, around 873 MWh/year, due to its DHN temperature level of 65/40°C.
3) HP Electricity Consumption: In the second scenario, the annual electricity consumption of decentralized HPs is lower (2253 MWh/year) due to a higher COP of the central HP, resulting from the operating temperature. In contrast, the third scenario has the highest electricity consumption (3890 MWh/year) due to the lowest COP of the decentralized HPs, which is caused by the largest temperature difference between the hot and cold sides and increased electricity consumption.
4) Total Cost of DHN Integrated with HP: The first scenario demonstrates the most favourable total cost, considering both the operation and investment costs of the DHN and HP. In contrast, the third scenario presents the highest total cost, approximately 33% higher than the first scenario. Two main factors contribute to this: firstly, the capital cost of the central HP is lower in the first scenario, as it uses one large central HP, whereas the other scenarios have decentralized HPs in each building. Secondly, the COP of the decentralized HPs in the third scenario is the lowest among all scenarios due to the significant temperature difference between the hot and cold sides, resulting in higher electricity consumption.
5) Shortage of Heat Power from the Heat Resource: The smallest heat power deficit occurs in the first scenario, with a shortage of 86 kW, due to the higher COP of the HP, which increases QH. In contrast, the second scenario shows the most significant heat power shortage, reaching 190 kW.

2.6.6. Lausanne test-case – Simulations for the integration of data center waste heat into the Lausanne DHN

In this part of the project, corresponding to WP3 and Lausanne test case, the potential for integrating Swisscom's waste heat into the existing district heating network (DHN) of Lausanne has been investigated.

- First, the potential for integrating the Dufour micro-DHN, which is supplied by waste heat from a data center, into the existing DHN is assessed. Various scenarios for reducing the DHN temperature and varying the potential amount of data center waste heat are also explored in this phase.

- Next, the impact of using the data center's waste heat within the existing DHN on the Lausanne monotone is evaluated. The merit order of data center waste heat, as a new heat source, is compared with other heat sources available in Lausanne.

It is important to note that all information and data related to scenario definitions, piping routes, diameters, and operational parameters (such as mass flows and temperatures in the existing DHN) were provided through consultation with SIL.

2.6.6.1. Integration of Dufour micro-DHN and existing Lausanne DHN

In the initial step, the integration of the Dufour micro thermal network (developed in section 2.3) with Lausanne's district heating network was studied. The geographical layout of both networks and the proposed connection points are shown in Figure 106.

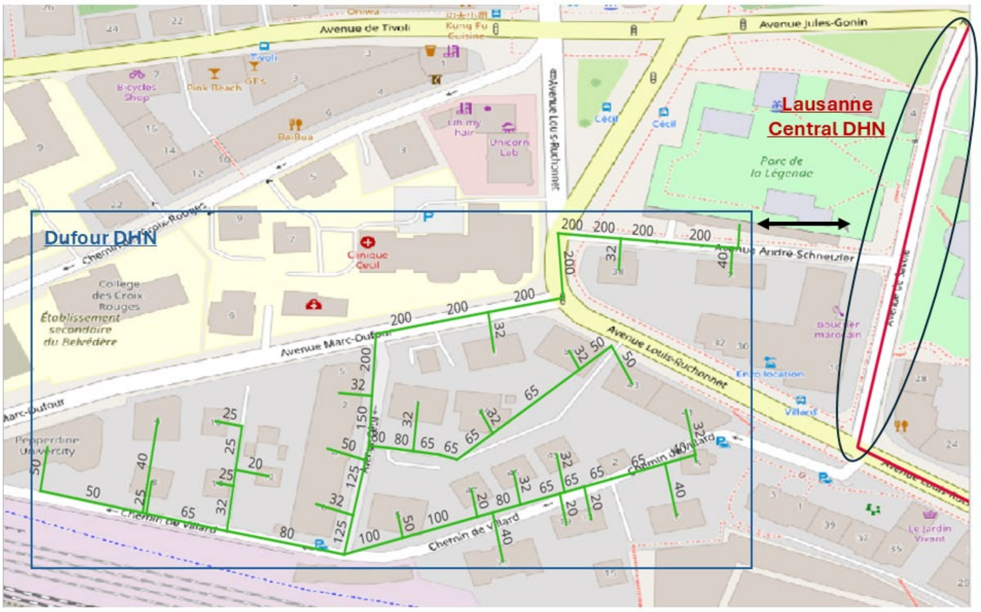


Figure 106 : The geographical schematic of integrating the Dufour mDHN into the existing Lausanne DHN.

As mentioned, various scenarios have been defined to evaluate the impact of temperature reduction and the waste heat potential of the Dufour m-DHN on the integrated networks. For this study (interaction between Dufour m-DHN and the main DHN of Lausanne), a hypothetic configuration of the data center is assumed: i) no cooling machines are installed at the Swisscom data center, so the heat is available at around 22°C in free cooling mode, ii) the available power might be of 1.5MW or 3MW to cover the future.

This leads to the elaboration of the scenarios presented in Table 27 along with the m-DHN temperature levels and the data center's waste heat potential.

To integrate the two networks, the installation of a heat exchanger is necessary. Interestingly, the direction of heat transfer is not always the same; it varies between summer and winter and depends on the heat demand of the Dufour m-DHN as well as the mass flow potential of the Lausanne DHN. Generally, based on the direction of the heat flow (from the Dufour DHN to the Lausanne DHN or vice versa), there are two modes of operation:

1) When the heat demand of the Dufour DHN exceeds the waste heat from the data center, heat transfers from the Lausanne DHN to the Dufour DHN through a heat exchanger. This typically occurs in winter.

2) When the heat demand of the Dufour DHN is lower than the waste heat from the data center, heat transfers from the Dufour m-DHN to the Lausanne DHN through a heat exchanger. This usually happens in summer.

Table 27 : Scenarios for Integrating the Dufour m-DHN with the Existing Lausanne DHN

Integrated Scenarios	First Scenario	Second Scenario	Third Scenario	Fourth Scenario	Fifth Scenario	Sixth Scenario
Dufour DHN Temp [C]	65/40	65/40	40/25	40/25	22/16	22/16
Data Center Waste Heat Potential [MW]	1.5	3	1.5	3	1.5	3

More details on the integration methods are discussed below for each scenario.

Scenario 1: In this scenario, the integration of the high-temperature Dufour network with the data center waste heat resource, which has a potential of 1.5 MW, with the Lausanne DHN is studied. Based on two different modes, the schematics of the proposed integrations are presented in Figure 107 and Figure 108 for the first and second modes (winter and summer modes).

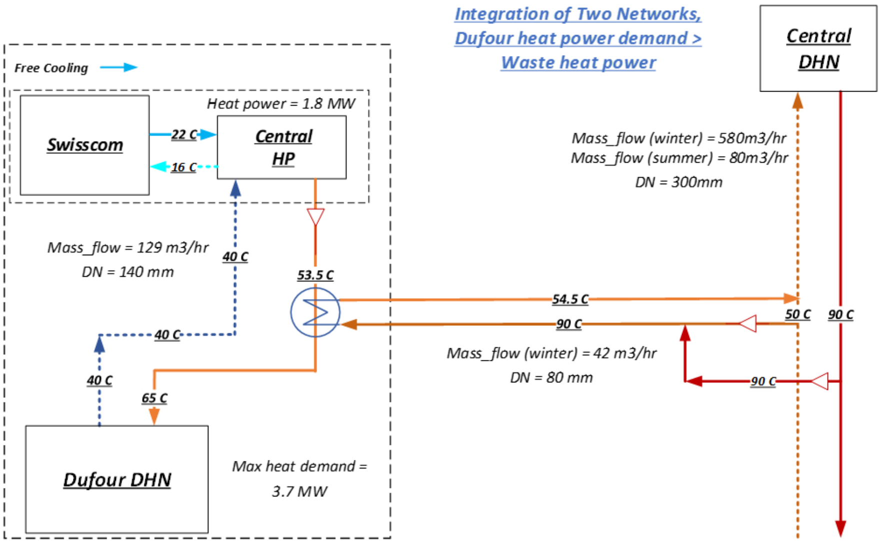


Figure 107 : Dufour DHN and Lausanne DHN: First scenario, first mode - winter mode

Figure 107, which corresponds to the first mode where the heat demand of the Dufour DHN exceeds the data center waste heat, a central heat pump raises the temperature of the waste heat.

- The DHN of Lausanne transfers heat to the Dufour m-DHN through a heat exchanger to compensate for the shortfall in the Dufour network.
- The temperature levels and maximum mass flow rates of the Lausanne DHN are 90ºC/50ºC and 580 m³/hr, respectively, with the Lausanne DHN injecting heat from its supply line at 90ºC.
- The input and output temperatures of the heat exchanger, as well as their mass flows, are determined based on the fixed supply line temperatures of 65ºC for the Dufour network and 90ºC for the Lausanne DHN, along with the heat balance and the constraint of maximum mass flows in both networks.

In Figure 108, which corresponds to the second mode where the heat demand of the Dufour DHN is lower than the data center waste heat, the heat pump must raise the temperature to 65ºC to meet the heat demand of the Dufour DHN or to 73ºC to send heat to the Lausanne DHN.

- The Dufour DHN transfers heat to the Lausanne DHN through a heat exchanger, providing Lausanne with a more reliable and renewable heat source. When the Dufour DHN has its own heat demand, it can self-consume the data center waste heat.
- The temperature levels and maximum mass flow rates of the Lausanne DHN are 90ºC/50ºC and 80 m³/hr, respectively. The Dufour DHN heats the return line of the Lausanne DHN, which enters the heat exchanger at 50ºC.
- The input and output temperatures of the heat exchanger, as well as their mass flows, are determined based on the fixed return line temperature of 50ºC for the Lausanne DHN, the heat balance, and the constraint of maximum mass flows in both networks.

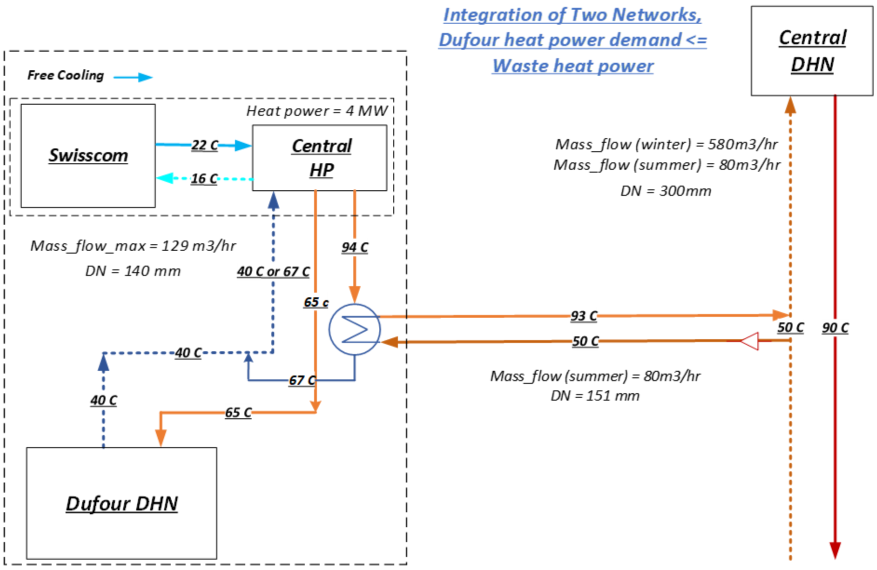


Figure 108 : Dufour DHN and Lausanne DHN: First scenario, second mode - Summer mode

Scenario 2: In this scenario, the integration of the High-Temperature Dufour network with the data center waste heat resource from Swisscom, which has double the potential of the first scenario at 3 MW (as part of a future plan), with the Lausanne DHN is studied. The schematics of the proposed integrations are presented in Figure (4) and Figure (5) for the first and second modes (winter and summer modes), respectively.

In Figure 109, which corresponds to the first mode (occurring in winter), unlike the first scenario, the peak heat demand of the Dufour network (3.7 MW) is lower than the heat potential of the heat pump (4 MW). Therefore, in this scenario, and in both modes, the direction of heat transfer is from the Dufour DHN to the Lausanne Central DHN. In the first mode, a central heat pump (HP) raises the temperature of the waste heat to 67ºC.

- The Dufour DHN transfers heat to the Lausanne DHN through a heat exchanger, providing Lausanne with a more reliable and renewable heat source.
- The temperature levels and maximum mass flow rates of the Lausanne DHN are 90ºC/50ºC and 580 m³/hr, respectively. The Dufour DHN heats the return line of the Lausanne DHN, which enters the heat exchanger at 50ºC.
- The input and output temperatures of the heat exchanger, as well as their mass flows, are determined based on the fixed supply line temperature of 65ºC for the Dufour network and the

fixed return temperature of 50ºC for the Lausanne DHN, along with the heat balance and the constraint of maximum mass flows in both networks.

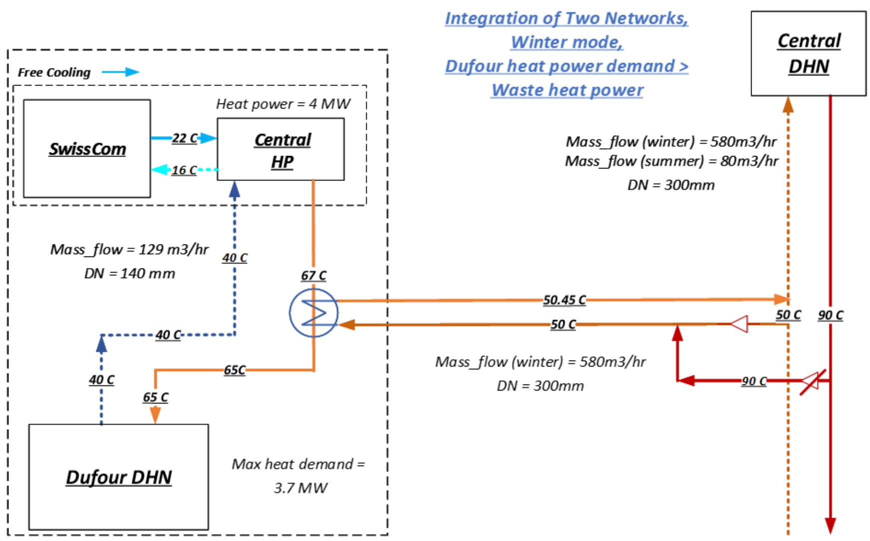


Figure 109 : Dufour m-DHN and Lausanne DHN: Second scenario, first mode - winter mode

In Figure 110, which corresponds to the second mode where the heat demand of the Dufour DHN is lower than the data center waste heat, the heat pump must raise the temperature to 65ºC to meet the heat demand of the Dufour DHN or to 94ºC to send heat to the Lausanne DHN.

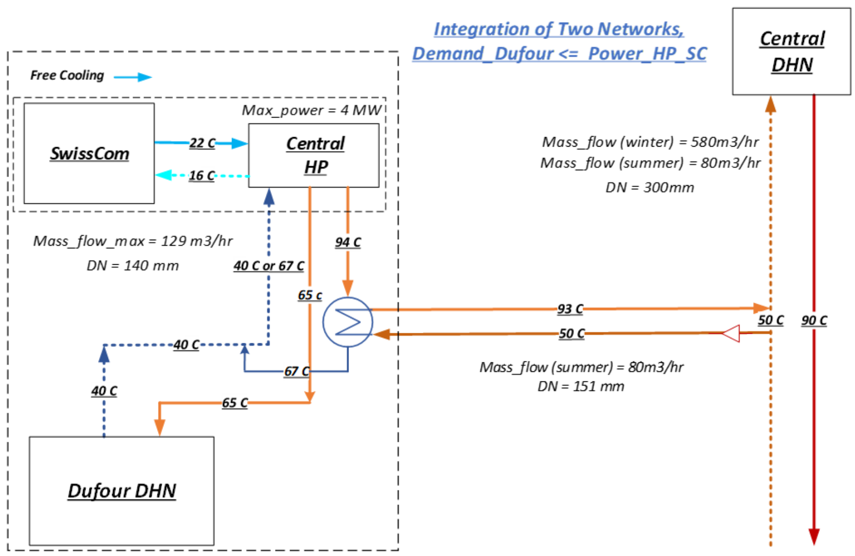


Figure 110 : Dufour DHN and Lausanne DHN: Second scenario, Second mode - Summer mode

- The Dufour DHN transfers heat to the Lausanne DHN through a heat exchanger, providing Lausanne with a more reliable and renewable heat source. When the Dufour DHN has its own heat demand, it can self-consume the data center waste heat.

- The temperature levels and maximum mass flow rates of the Lausanne DHN are 90ºC/50ºC and 80 m³/hr, respectively. The Dufour DHN heats the return line of the Lausanne DHN, which enters the heat exchanger at 50ºC.
- The input and output temperatures of the heat exchanger, as well as their mass flows, are determined based on the fixed return line temperature of 50ºC for the Lausanne DHN, the heat balance, and the constraint of maximum mass flows in both networks.

__Scenario 3:__ In this scenario, the integration of the Low-Temperature Dufour network (40ºC/25ºC) with the data center waste heat resource, which has a potential of 1.5 MW, with the Lausanne DHN is studied. Based on two different modes, the schematics of the proposed integrations are presented in Figure 111 and Figure 112 for the first and second modes (winter and summer modes).

In Figure 111, which corresponds to the first mode where the heat demand of the Dufour DHN exceeds the data center waste heat, a central heat pump raises the temperature of the waste heat to 33ºC by adjusting the mass flow.

- The main district heating network of Lausanne transfers heat to the Dufour m-DHN through a heat exchanger to compensate for the shortfall in the Dufour network.
- The temperature levels and maximum mass flow rates of the Lausanne DHN are 90ºC/50ºC and 580 m³/hr, respectively, with the Lausanne DHN injecting heat from its supply line at 90ºC.
- The input and output temperatures of the heat exchanger, as well as their mass flows, are determined based on the fixed supply line temperatures of 40ºC for the Dufour network and 90ºC for the Lausanne DHN, along with the heat balance and the constraint of maximum mass flows in both networks.

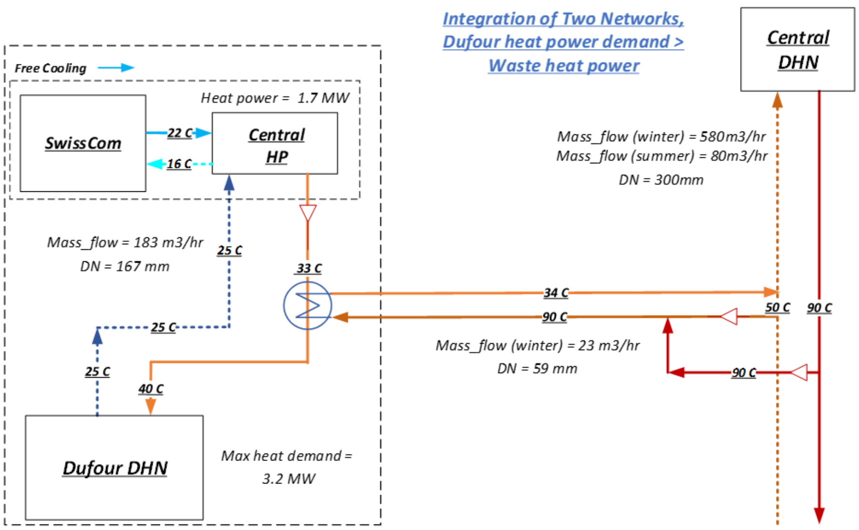


Figure 111 : Dufour m-DHN and Lausanne DHN: Third scenario, First mode - winter mode

In Figure 112, which corresponds to the second mode where the heat demand of the Dufour DHN is lower than the data center waste heat, the heat pump must raise the temperature to 65ºC to meet the heat demand of the Dufour DHN or to 73ºC to send heat to the Lausanne DHN.

- The Dufour DHN transfers heat to the Lausanne DHN through a heat exchanger, providing Lausanne with a more reliable and renewable heat source. When the Dufour DHN has its own heat demand, it can self-consume the data center waste heat.
- The temperature levels and maximum mass flow rates of the Lausanne DHN are 90ºC/50ºC and 80 m³/hr, respectively. The Dufour DHN heats the return line of the Lausanne DHN, which enters the heat exchanger at 50ºC.

➢ The input and output temperatures of the heat exchanger, as well as their mass flows, are determined based on the fixed return line temperature of 50ºC for the Lausanne DHN, the heat balance, and the constraint of maximum mass flows in both networks.

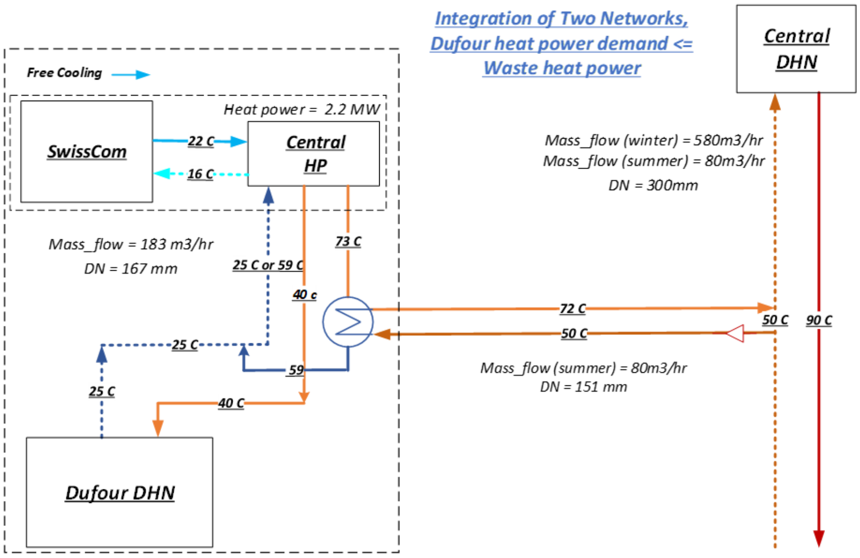


Figure 112 : Dufour m-DHN and Lausanne DHN: Third scenario, second mode - summer mode

Scenario 4: This scenario examines the integration of the low-temperature Dufour network (40ºC/25ºC) with the data center's waste heat resource, which has double the potential of the third scenario at 3 MW (as part of future planning), along with the Lausanne DHN. Like the second scenario, the heat demand of the Dufour DHN is lower than the data center's waste heat potential in both winter and summer modes. The peak heat demand of the Dufour DHN is 3.2 MW, while the heat pump produces 3.4 MW of heat power. In this scenario, the direction of heat transfer is consistently from the Dufour heat pump to the Lausanne DHN, as in the second scenario.

Scenario 5: In this scenario, there is no active cooling system in the data center, and only free cooling is considered. The integration of the low-temperature Dufour network (25/16) with the data center's waste heat, which has a potential of 1.5 MW, and the Lausanne DHN is studied. The schematics of the proposed integration are presented for two different modes: winter and summer, shown in Figure 113 and Figure 114, respectively.

In Figure 113, corresponds to the winter mode where the heat demand of the Dufour DHN exceeds the waste heat from the data center.

➢ The Lausanne DHN supplies heat to the Dufour m-DHN through a heat exchanger to compensate for the shortfall in the Dufour network.

➢ The temperature levels and maximum mass flow rates for the Lausanne DHN are 90ºC/50ºC and 580 m³/hr, respectively, with heat injected from its supply line at 90ºC.

➢ The input and output temperatures of the heat exchanger, along with the mass flows, are determined based on the fixed output flow temperature of 22ºC from the data center (which corresponds to the free cooling temperature levels of 16ºC/22ºC) for the Dufour network and 90ºC for the supply line of Lausanne DHN. These parameters are calculated considering heat balance and the maximum mass flow constraints in both networks.

In Figure 114, which corresponds to the second mode where the heat demand of the Dufour DHN is lower than the waste heat from the data center, the system operates differently. In this mode, free cooling with temperatures of 22ºC/16ºC is sufficient to meet the Dufour DHN's heat demand without the need for a heat pump.

Alternatively, the heat pump could raise the temperature to 73ºC to supply heat to the Lausanne DHN.

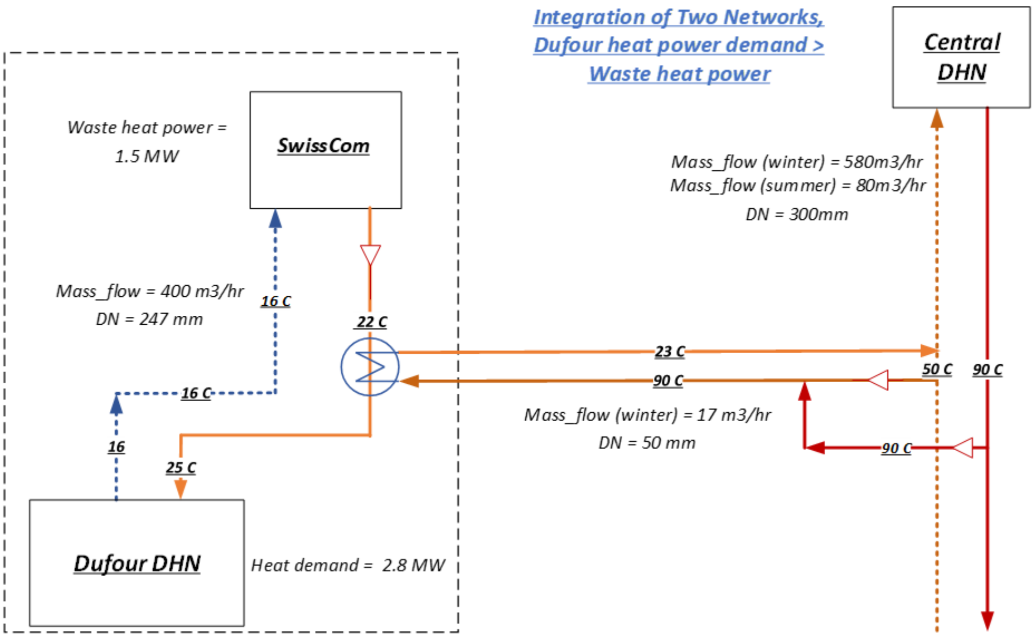


Figure 113 : Dufour m-DHN and Lausanne DHN: Fifth scenario, first mode - winter mode

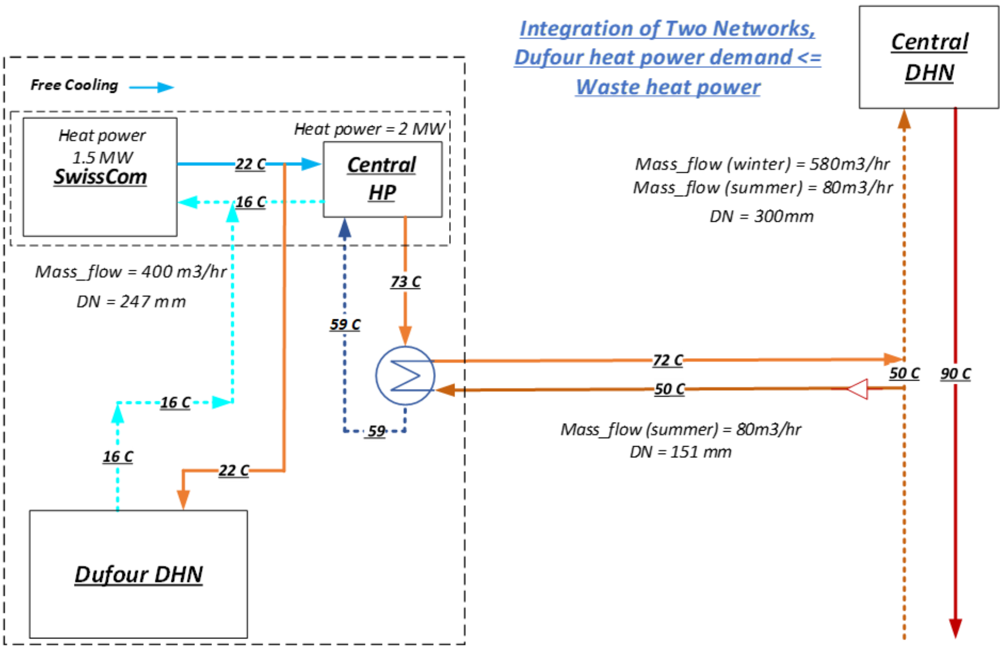


Figure 114 : Dufour m-DHN and Lausanne DHN: Fifth scenario, second mode - summer mode

- The heat pump of the Dufour DHN transfers heat to the Lausanne DHN via a heat exchanger, offering Lausanne a more reliable and renewable heat source. When the Dufour DHN has its own heat demand, it can directly consume the data center's waste heat.

- The temperature levels and maximum mass flow rates of the Lausanne DHN are 90ºC/50ºC and 80 m³/h, respectively. The data center waste heat heats the return line of the Lausanne DHN, which enters the heat exchanger at 50ºC.
- The input and output temperatures of the heat exchanger, along with the mass flows, are determined by the fixed return line temperature of 50ºC for the Lausanne DHN, the heat balance, and the constraints of maximum mass flow rates in both networks.

Scenario 6: This scenario examines the integration of the Low-Temperature Dufour network (22ºC/16ºC) with the data center's waste heat resource, which has double the potential of the third scenario at 3 MW (as part of future planning), along with the Lausanne DHN. Like the second scenario, the heat demand of the Dufour DHN is lower than the data center's waste heat potential in both winter and summer modes. The peak heat demand of the Dufour DHN is 3.2 MW, while the heat pump produces 3.4 MW of heat power. In this scenario, the direction of heat transfer is consistently from the Dufour heat pump to the Lausanne DHN, as in the second scenario.

The summary of the results for six scenarios integrating the Dufour DHN with the Lausanne DHN, including heat exchanger capacity, heat pump hot output temperature, COP, and heat pump capacity, is presented in Table 28. The COP of the heat pump is calculated ideally based on the average temperatures of the cold and hot sides, using an efficiency of 50%.

Table 28 : The summary of the integration results regarding 6 scenarios

	First Scenario [1.5 MW] 65°C/40°C	Second Scenario [3 MW] 65°C/40°C	Third Scenario [1.5MW] 40°C/25°C	Fourth Scenario [3 MW] 40°C/25°C	Fifth Scenario [1.5 MW] 22°C/16°C	Sixth Scenario [3 MW] 22°C/16°C
Heat Power of HEX [MW]	2.2	4.9	2.2	4.9	2.2	4.9
Output Temp of HP in hot side [C]	53 - 65 - 73	65 - 67 - 94	33 – 40 - 73	40 - 94	73	94
COP of HP	5.8 -4.8 - 3.6	4.9 - 4.7 - 2.9	15 - 11.3 - 3.6	11.3 – 2.9	3.6	2.9
Heat Power of HP [MW]	1.8 - 2- 2.2	4 – 4.9	1.6 - 1.7 - 2.2	1.7 – 4.9	2.2	4.9

2.6.6.2. *Integration of Swisscom Waste Heat and existing CAD_SIL*

A schematic illustrating this integration concept is shown in Figure 114. The waste heat temperature is increased using a heat pump, after which the heat is injected into the central Lausanne DHN via a heat exchanger. In consultation with SIL, the time horizon for this study is set to 2040, with the temperature levels of the Lausanne DHN considered at 85ºC/60ºC, and the waste heat potential at 2 MW.

To achieve a more accurate simulation of the integration of the data center's waste heat into the Lausanne DHN, the hourly mass flow of the Lausanne DHN is modelled based on the hourly heat demand projected by SIL for 2040. Using this mass flow, a return temperature of 60ºC for the central Lausanne DHN, and a heat pump input temperature (T_hp_in) of 62ºC (as shown in Figure 114), the performance of the heat exchanger is calculated. This approach allows for the determination of both the heat pump's hot outlet temperature (T_hp_out) and T_hex_cad. The resulting hourly mass flow of the Lausanne DHN and the heat pump's hot outlet temperature (T_hp_out) are shown in Figure 115.

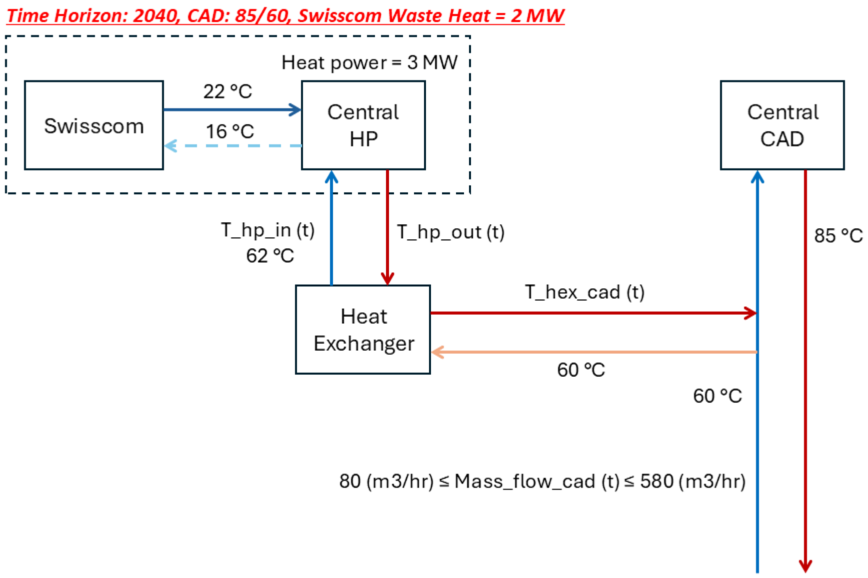


Figure 115 : Integration of data center waste heat into the central Lausanne DHN

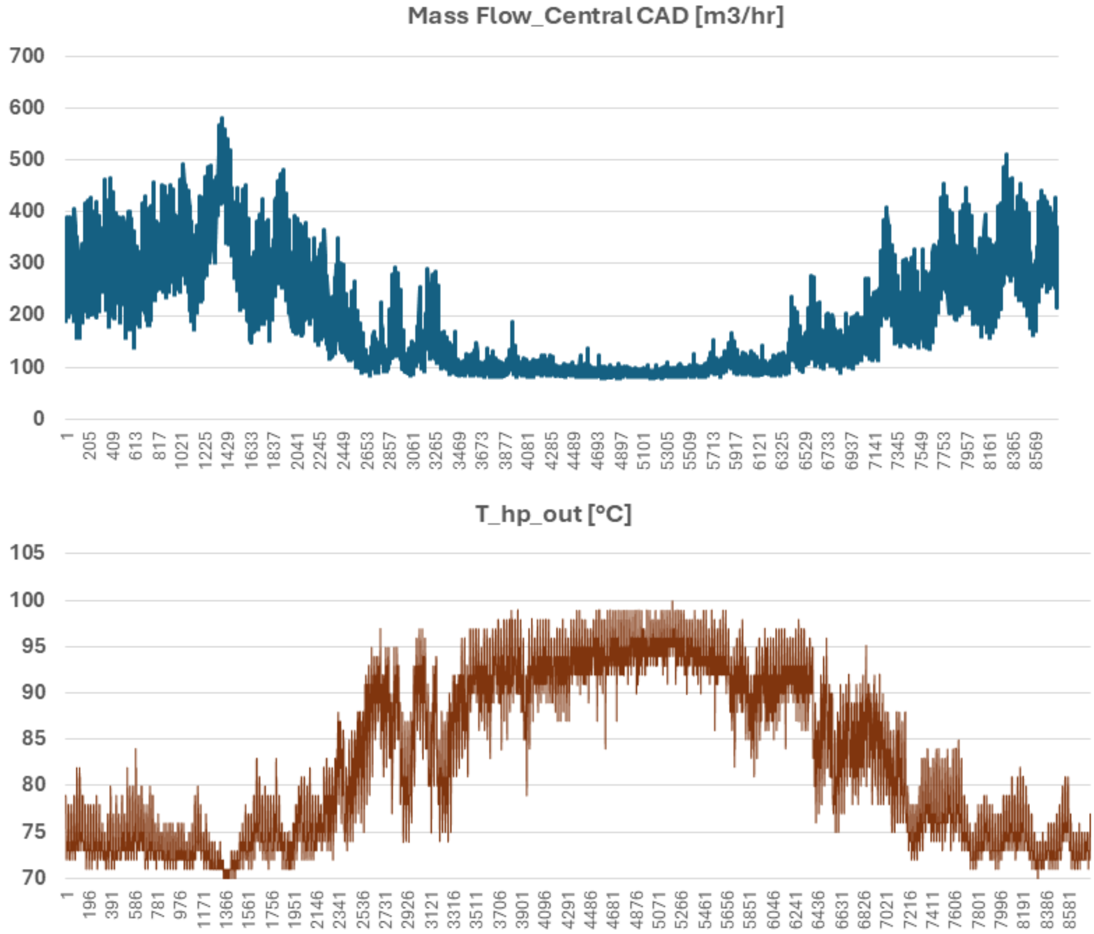


Figure 116 : Hourly mass flow of the Lausanne DHN and the heat pump's hourly hot outlet temperature (T_hp_out)

Therefore, based on the calculated hourly temperatures and mass flow, the hourly COP of the heat pump and the injected heat power into the Lausanne DHN are calculated and displayed in Figure 117.

The projected parameters of the Lausanne DHN for the 2040 horizon, covering both the total Lausanne DHN (CADSIL_ALL) and the southwest Lausanne network (CADSIL_SO), are presented in Table 29. Figure 118 illustrates the daily heat power exchanged through the heat exchanger alongside the daily COP of the heat pump.

Using the results from simulating the output power of the heat pump and the exchanged heat power of the heat exchanger, this section evaluates the impact of incorporating data center waste heat into the Lausanne monotone for the 2024 horizon. To achieve this, data regarding the Lausanne monotone, along with heat resources for the 2040 horizon, has been provided by SIL for both the total Lausanne District Heating Network (DHN) (CADSIL_ALL) and the southwest Lausanne network (CADSIL_SO).

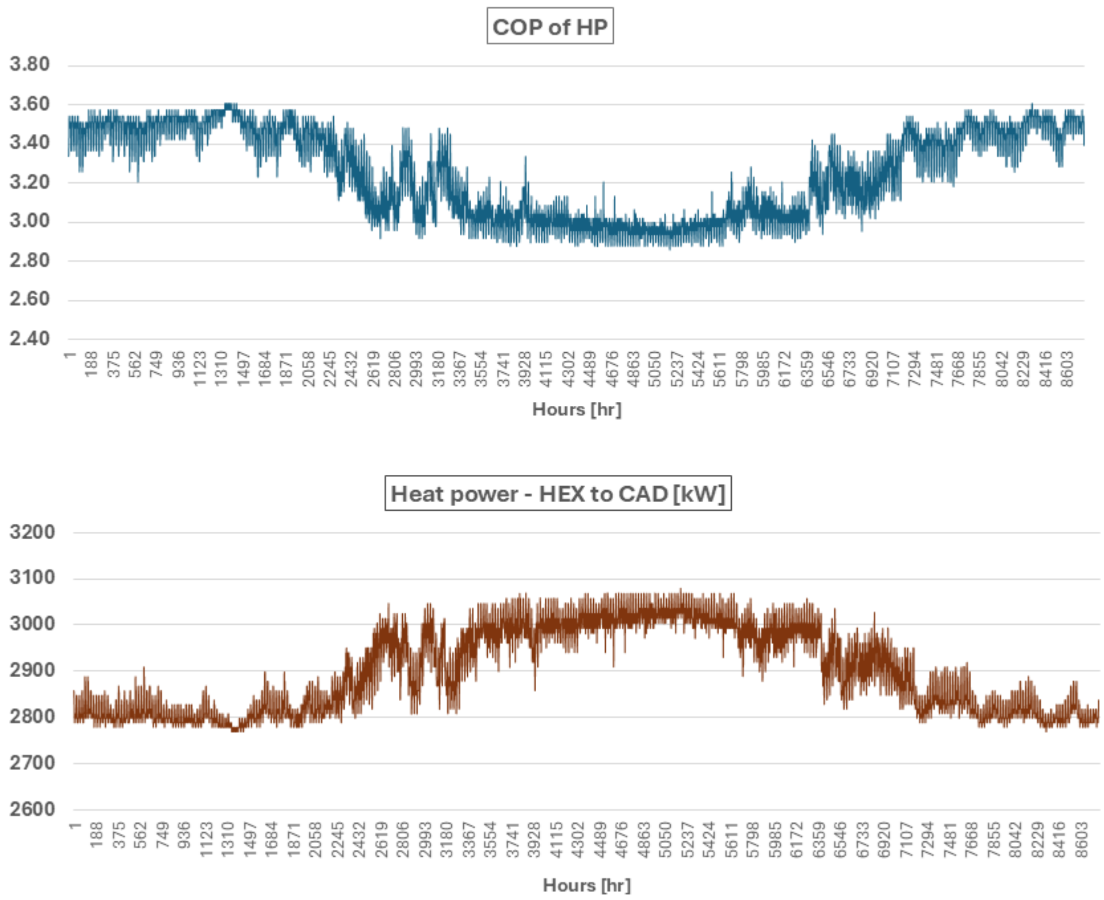


Figure 117 : Hourly COP of the heat pump and hourly exchanged heat power via the heat exchanger, the power represents the heat output power.

Table 29 : Projected Parameters of Lausanne DHN for the 2040 Horizon

Horizon 2040	Production CAD	CAD_Supply Temp	CAD_Return Temp	CAD_Mass flow_Max	CAD_Mass flow_Min
Unit	[GWh/an]	[°C]	[°C]	[m3/hr]	[m3/hr]
CADSIL_ALL	1015	85	60	580	80
CADSIL_SO	525				

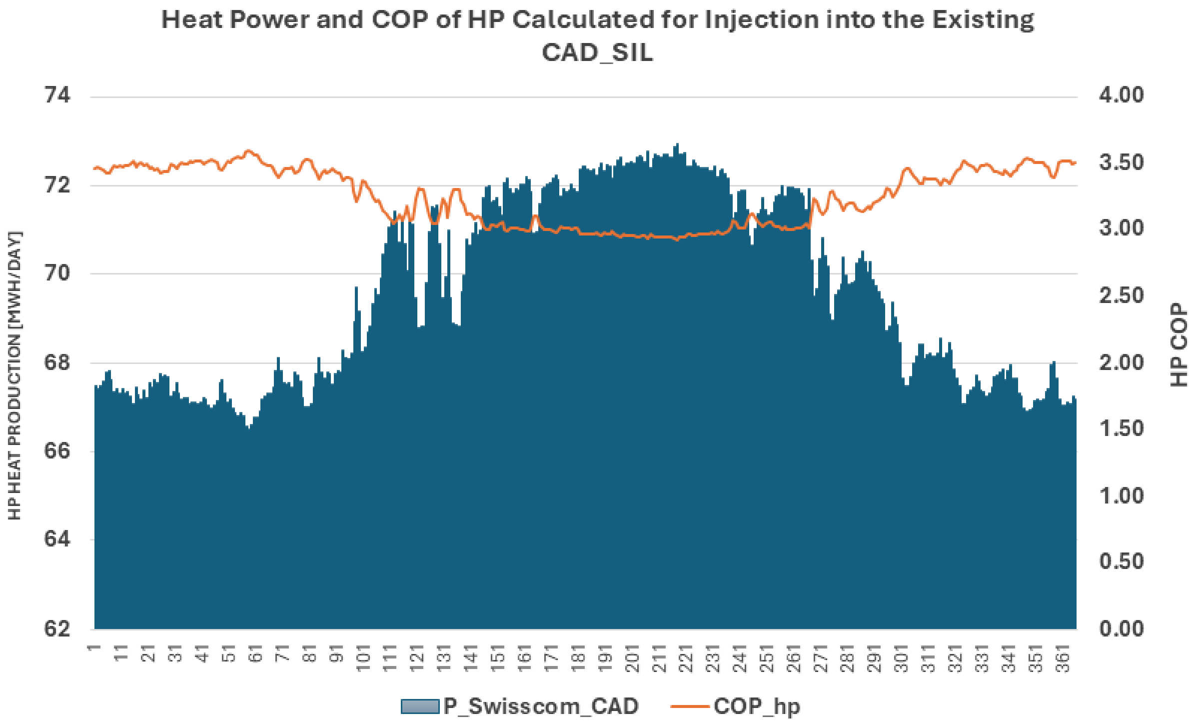


Figure 118: Daily COP of the heat pump and the daily heat power exchanged through the heat exchanger, the power represents the heat output power.

2.6.6.3. Total Lausanne DHN (CADSIL_ALL), Horizon 2040

The monotone for the total Lausanne DHN in the 2040 horizon is illustrated in Figure 119. This monotone depicts the predicted heat production from heat resources for 2040, based on the priorities established by SIL, which are intended to supply the Lausanne DHN. The total predicted heat demand for Lausanne is 1015 GWh/year, with a maximum heat power of 430 MW. This monotone was created using an Excel tool developed by SIL specifically for plotting the Lausanne DHN monotone.

By utilizing SIL's Excel tool and the results from the heat exchanger simulation, a new Lausanne monotone incorporating data center waste heat has been generated. This monotone, which corresponds to the total Lausanne DHN, evaluates the merit order of data center waste heat in comparison to other resources.

This updated monotone is illustrated in Figure 120 including data center waste heat. As seen in this figure, based on SIL's recommendation, the data center waste heat is the second priority, following the incineration plant (STEP), which holds the priority. Utilizing the data center's waste heat reduces the consumption of gas, which has the lowest priority.

The numerical results of injecting data center waste heat into the Lausanne DHN are presented in Table 30. This table shows the calculated indicators for the Lausanne DHN in two modes: with and without the data center waste heat. As shown, using the data center waste heat increases the share of renewable heat resources by 1.5%, and the gas resource is reduced by 9.3% as it is replaced by waste heat.

However, the ratio of electricity consumption to heat sold to the DHN increases by 0.8% due to the electricity consumption of the heat pump used to raise the waste heat temperature.

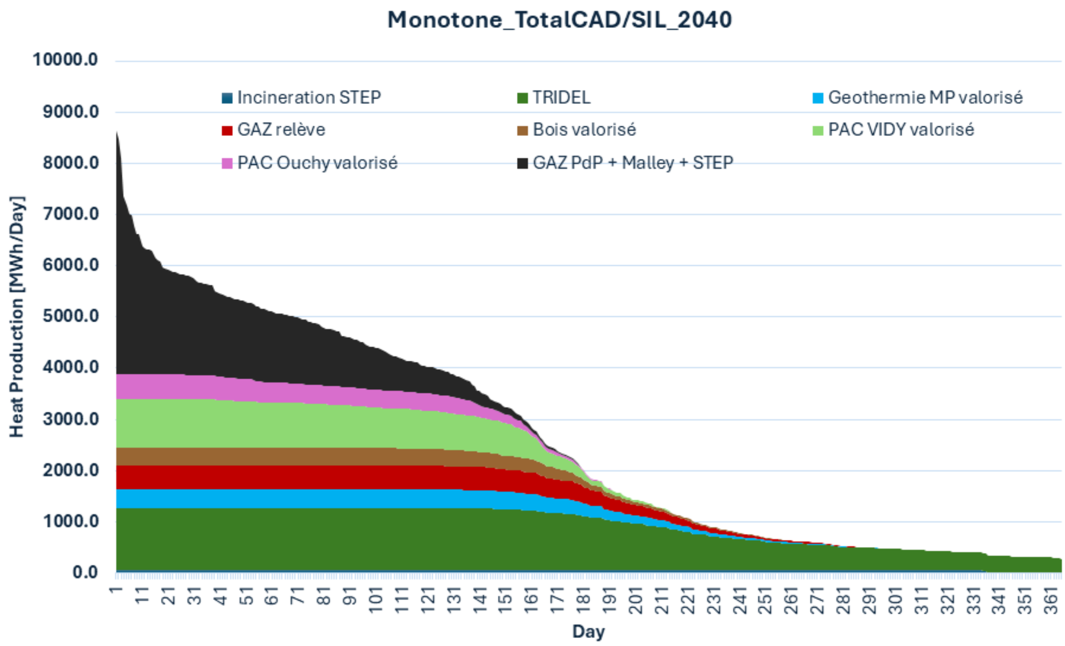


Figure 119 : Total Lausanne heat monotone for the 2040 horizon without data center waste heat.

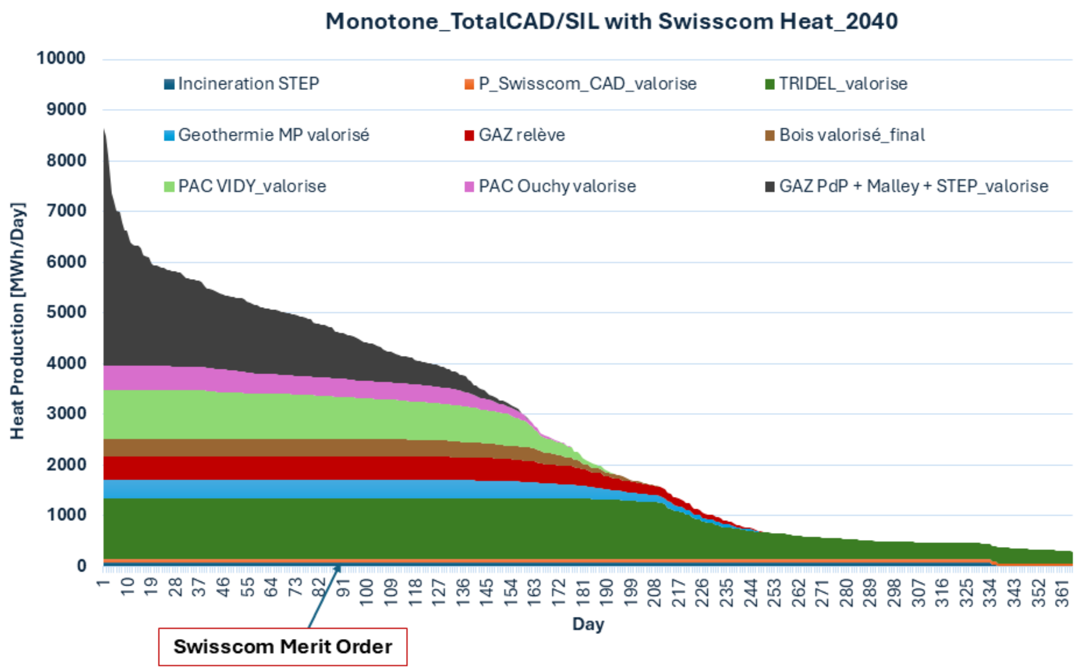


Figure 120 : Total Lausanne heat monotone for horizon 2024 with data center waste heat.

Table 30 : Indicators of the total Lausanne DHN in two modes: with and without data center waste heat.

INDICATORS: Without Swisscom	Value	Unit
Rate of EnR&R	71.5	%
CO2 Content (production)	104	gCO2/kWh
CO2 Content (sales)	118	gCO2/kWh
Geothermal Electricity	4	GWh/an
Electricity for the VIDY Heat Pump	47	GWh/an
Electricity for the LAC Heat Pump	20	GWh/an
Percentage of electricity consumption for the heat sold to SST	7.9	%
INDICATORS: With Swisscom	**Value**	**Unit**
Rate of EnR&R	73	%
CO2 Content (production)	91	gCO2/kWh
CO2 Content (sales)	104	gCO2/kWh
Geothermal Electricity	4	GWh/an
Electricity for the VIDY Heat Pump	46	GWh/an
Electricity for the LAC Heat Pump	20	GWh/an
Electricity for the Swisscom HP	8	GWh/an
Percentage of electricity consumption for the heat sold to SST	8.7	%
Amount of gas savings	25.7	GWh/an
Percentage of gas savings	9.3	%

2.6.6.4. Southwest Lausanne DHN (CADSIL_SO), Horizon 2040

The monotone for southwest Lausanne in the 2040 horizon is illustrated in Figure 121. This monotone shows the predicted heat production from various resources for 2040, based on the priorities established by SIL, which are intended to supply the southwest Lausanne DHN. The total predicted heat demand for southwest Lausanne is 525 GWh/year, with a maximum heat power of 222 MW. This monotone was created using an Excel tool developed by SIL specifically for plotting the southwest Lausanne DHN monotone.

Upon using SIL's Excel tool and the results from the heat exchanger simulation, a new southwest Lausanne monotone incorporating data center waste heat has been generated. This updated monotone, which includes data center waste heat, is illustrated in Figure 122. As shown, the share of data center waste heat in southwest Lausanne is larger than in the total Lausanne network, due to the smaller scale of the southwest Lausanne DHN. Therefore, in this network, data center waste heat can save more gas consumption compared to the total Lausanne network.

The numerical results of injecting data center waste heat into the southwest Lausanne DHN are presented in Table 31. This table displays the calculated indicators for the southwest Lausanne DHN in two scenarios: with and without data center waste heat. As shown, using data center waste heat increases the share of renewable heat resources by 2.3%, while the gas resource is reduced by 24.4% as it is replaced by waste heat. Notably, the share of gas consumption replaced and saved by waste heat in southwest Lausanne is greater than in the total Lausanne network. However, the ratio of electricity consumption to heat sold to the DHN increases by 1.35% due to the electricity consumption of the heat pump used to raise the waste heat temperature.

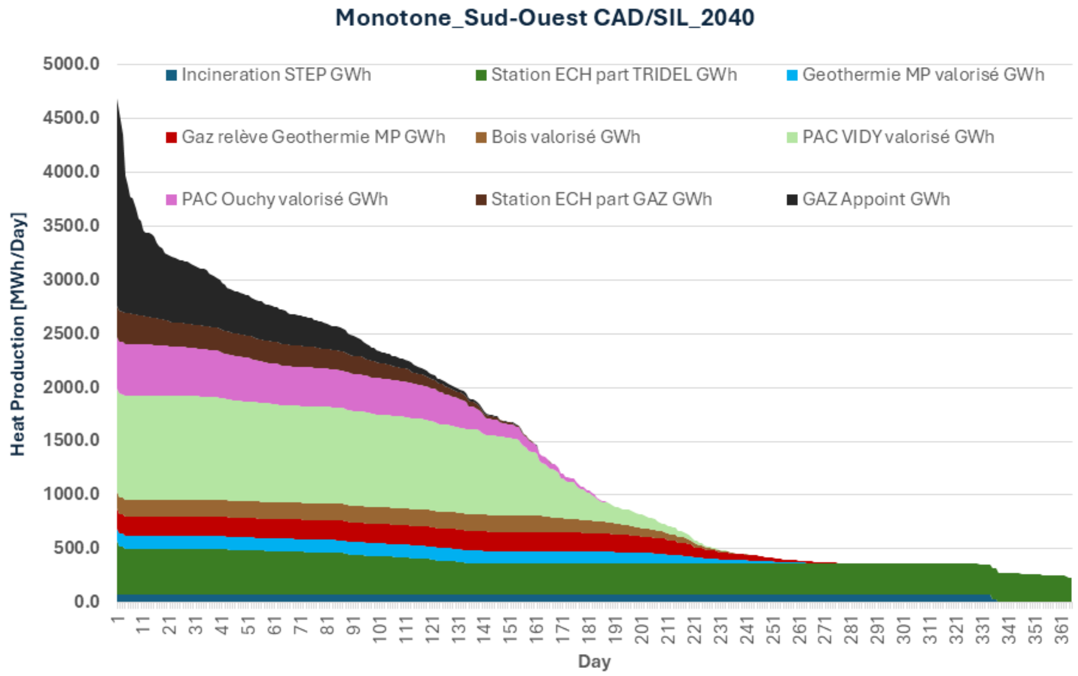


Figure 121 : Southwest Lausanne monotone for the 2040 horizon without data center waste heat.

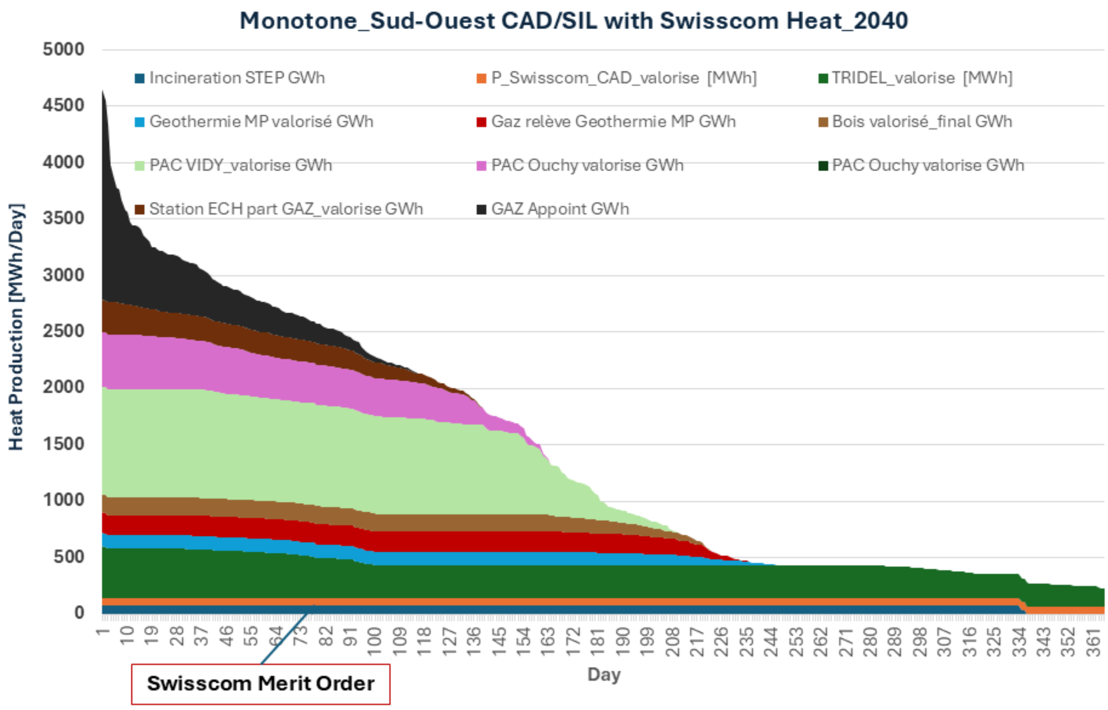


Figure 122 : Southwest Lausanne monotone for horizon 2024 with data center waste heat.

Table 31 : Indicators of the southwest Lausanne DHN in two modes: with and without data center waste heat.

INDICATORS: Without Swisscom	Value	Unit
Rate of EnR&R	77.95	%
CO2 Content (production)	92	gCO2/kWh
CO2 Content (sales)	105	gCO2/kWh
Geothermal Electricity	1	GWh/an
Electricity for the VIDY Heat Pump	51	GWh/an
Electricity for the LAC Heat Pump	19	GWh/an
Percentage of electricity consumption for the heat sold to SST	15.33	%

INDICATORS: With Swisscom	Value	Unit
Rate of EnR&R	80.22%	%
CO2 Content (production)	69	gCO2/kWh
CO2 Content (sales)	79	gCO2/kWh
Geothermal Electricity	1	GWh/an
Electricity for the VIDY Heat Pump	50	GWh/an
Electricity for the LAC Heat Pump	18	GWh/an
Electricity for the Swisscom HP	8	GWh/an
Percentage of electricity consumption for the heat sold to SST	16.68%	%
Amount of gas savings	2.5	GWh/an
Percentage of gas savings	24.4	%

2.6.6.5. Simulations for the integration of data center waste heat into the Lausanne DHN - Summary and key findings

As a summary of WP3 for Lausanne test-case, this section examines the potential integration of Swisscom's data center waste heat into the existing district heating network (DHN) of Lausanne, focusing on the Dufour micro-DHN (m-DHN) and the main Lausanne DHN, aligned with WP3 objectives. The analysis evaluates multiple scenarios with varying temperature levels, waste heat potentials, and configurations. The key findings can be summarized as follows:

1) The study examined scenarios where the Dufour m-DHN, powered by 1.5 MW or 3 MW of waste heat from Swisscom's data center, integrates in Lausanne's DHN with different temperature levels 65/40, 40/25 and 22/16. Scenarios included temperature reductions in the DHN to optimize heat recovery. For instance, the waste heat availability at 22°C in free cooling mode required the use of a heat pump to raise temperatures to 65°C or higher for efficient integration. Based on seasonal mass flow limitation of Lausanne DHN – namely 580 m³/hr in winter and 80 m³/hr in summer - as well as on Dufour demand and temperature limitation of heat exchanger, the operational parameters can be adjusted to transfer the heat between Dufour micro-DHN and Lausanne DHN.

2) By analyzing Lausanne's DHN monotone at the 2040 time horizon and integrating the data center's waste heat (up to 3 MW in future scenarios), it was shown that the latter leads to an increase in renewable energy share by 1.5% and reduces natural gas consumption by 9.3%, with a minor rise in electricity usage due to heat pump operation.

3) Regarding the Southwest Lausanne DHN, a more significant impact is observed, with a 2.3% rise in renewable resources and a 24.4% reduction in natural gas consumption due to the smaller network scale.

2.6.7. Lausanne test-case – Possible decrease of distribution temperature

This section examines the impact of reducing the distribution temperature in the developed Dufour DHN. To define temperature reduction strategies, relevant findings from HEIG-VD's studies on the Lausanne test case were used. These results, which include both the temperature reduction strategies and the associated temperature levels, have been incorporated into the simulation tool developed for the Dufour micro-DHN.

The main objective of this study is to address the following question: If renovations on the primary or secondary side lead to changes in the network's temperature level and temperature difference (ΔT), how will the network's operation be affected, and how can it be managed by controlling key operating parameters such as mass flow?

For conducting this study, two strategies are defined: the first strategy is the base case, which is the same scenario we used for the design and operational simulation of the Dufour DHN in section 2.3. The second strategy is the renovation strategy, which implements temperature reduction in the Dufour m-DHN based on the finding from HEIG-VD.

Table 32 presents the two cases along with the features of the secondary side and their temperature levels for both the base case and the renovated case. It is important to note that, in the base case, we developed the Dufour DHN based on the temperature levels of the secondary side, without considering the substation model.

In the renovated case, we take into account the Dufour DHN temperature as well as the required temperature for the secondary side to facilitate a comprehensive comparison.

For this analysis, we considered two scenarios for developing the Dufour DHN (section 2.3): a high-temperature Dufour DHN at 65 ºC/40 ºC and a low-temperature DHN at 19 ºC/14 ºC. This allows us to evaluate the impact of temperature reductions in both high- and low-temperature networks with different structures. In this study, we maintain the original Dufour DHN design and assess how temperature reductions can be managed through operational parameter control.

Table 32 : Base case and renovated case for temperature reduction of secondary side, based on the finding from HEIG-VD

Scenarios	Based Case – Without renovation	Renovated Case
Features	Current building with high-temperature radiators (65°C-55°C)	Decentralized topology with a local auxiliary generator for ECS and floor heating (40°C-35°C)
Departure Temperature of Secondary Side [ºC]	65	55

2.6.7.1. Scenario 1: High temperature DHN with central HP

Figure 123 illustrates the simulated high-temperature Dufour DHN for the first scenario, which includes both the base case and the renovated case. As shown, the network temperature is reduced from 65 ºC/40 ºC to 55 ºC/35 ºC, and the temperature difference (ΔT) decreases from 25 ºC to 20 ºC.

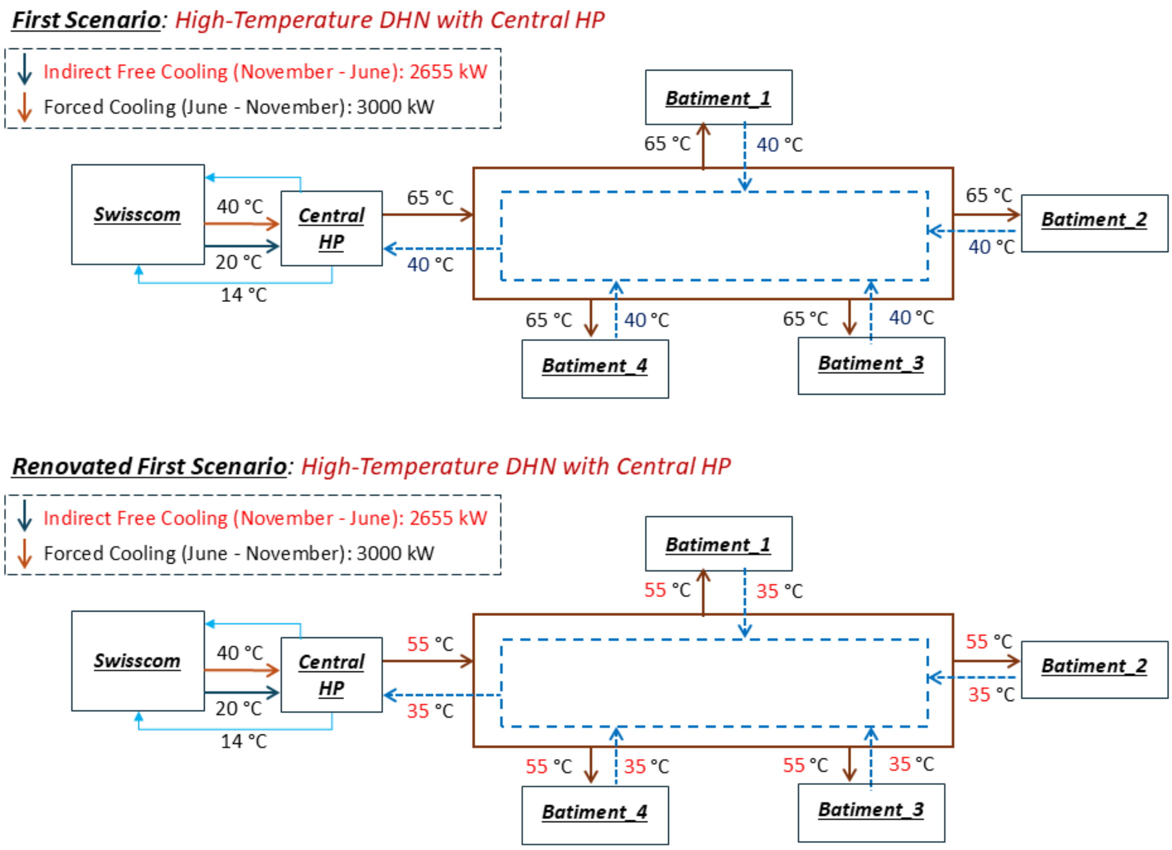
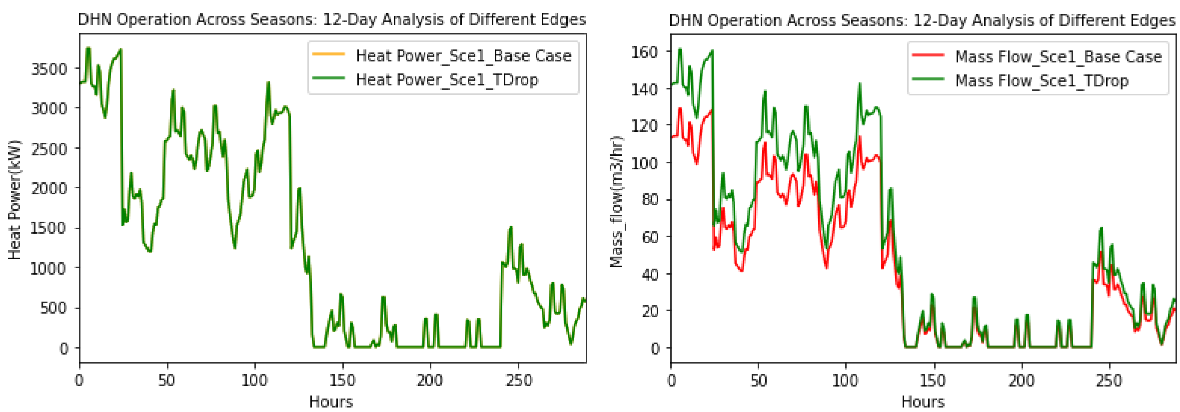


Figure 123 : Implementation of the temperature reduction strategy in the DHN corresponding to the first scenario: high-temperature Dufour DHN.

In Figure 124, the hourly simulated operational parameters of high temperature Dufour DHN, including heat power, mass flow, pressure drop, and pump electricity consumption, are presented based on a 12-day simulation for both the base case and the renovated case. In this scenario, reducing the network temperature difference (ΔT) from 25 ºC to 20 ºC while maintaining the heat power demand causes an increase in the network's mass flow to meet the heat demand of the buildings. Consequently, the pressure drop rises due to the increased mass flow, which in turn leads to higher pump electricity consumption.



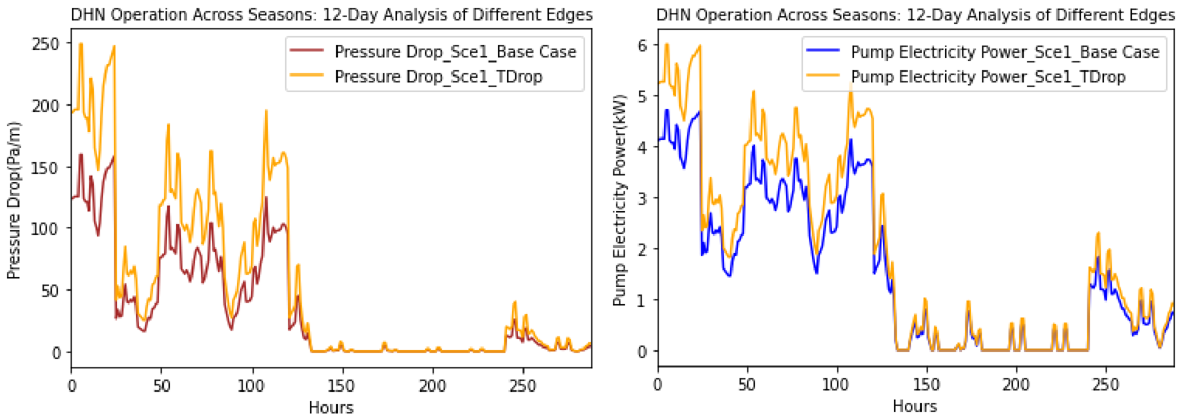


Figure 124 : Simulated hourly operational parameters in base case and renovated case corresponds to first scenario, high temperature Dufour DHN

Table 33 summarizes the numerical results of implementing the temperature reduction strategy by simulating 12 operation days of the Dufour DHN. The key results we can derive include:

- The electricity consumption of the central heat pump (HP) in the renovated case decreases by 21%. This is due to the reduction in network temperature, which increases the COP of the central HP, leading to lower electricity consumption.
- As the COP of the central HP increases and electricity consumption decreases, the heat produced by the HP also reduces. Consequently, the required heat power for the network (DHN including the central HP) increases from 2740 kW to 2938 kW, and there will be a greater power shortfall since the heat output from the data center waste heat remains constant at 2655 kW in the free cooling state that happens in winter.
- The annual heat losses of the network decrease as the temperature level drops.
- Finally, pump electricity consumption increases due to the higher mass flow rate needed to compensate for the reduction in NETWORK temperature difference (ΔT).

Table 33 : The numerical results of implementing the temperature reduction strategy by simulating 12 operation days of the high temperature Dufour DHN - first scenario

	HP Electricity Consumption	DHN Heat Consumption	Lack of Heat Energy	Excess Heat Energy	Q_loss	Max Required Heat Power	Lack of Heat Power	Pump Electricity Consumption
Units	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	[kW]	[kW]	[MWh/year]
First Scenario	2759	1085	10	541	872.8	2740	86	37
Renovated First Scenario	2185	1084	62	524	718.8	2938	283	54.4

2.6.7.2. Scenario 3: Low temperature (Cold) DHN with decentralized HPs

Figure 125 illustrates the simulated low-temperature Dufour DHN with decentralized heat pumps (HPs) corresponding to the developed third scenario, which includes both the base case and the renovated case. As shown, the secondary side departure temperature is reduced from 65 ºC/40 ºC to 55 ºC/35 ºC by implementing the renovation strategy. Thanks to the existing decentralized HPs that adjust the temperature between the network and each building, the temperature level of the network remains fixed and does not change.

In Figure 126, the hourly simulated operational parameters of the low-temperature Dufour DHN, including heat power, mass flow, pressure drop, and pump electricity consumption, are presented based on a 12-day simulation for both the base case and the renovated case.

In this scenario, reducing the secondary side temperature from 65 ºC/40 ºC to 55 ºC/35 ºC leads to an increase in the COP of the decentralized heat pumps. Subsequently, with the increased COP of the HPs and the heat power demand of the buildings (Q_H) maintained, the required heat power from the network to each building (Qc) increases.

Therefore, the network must deliver more heat power to each substation, resulting in an overall increase in the network's heat power, as illustrated in this figure.

Since the Dufour DHN and its piping diameters are fixed, the mass flow in the pipes must also increase to compensate for the additional heat power. Consequently, this results in increased pressure drops and, subsequently, higher pump electricity consumption.

Table 34 summarizes the numerical results of implementing the temperature reduction strategy by simulating 12 operational days of the developed Dufour DHN in the second scenario. The key results include:

- The total electricity consumption of the decentralized heat pumps in the renovated case decreases by 19%. This reduction is attributed to the decrease in secondary side temperature, which increases the COP of the decentralized HPs, leading to lower electricity consumption.
- As the COP of the decentralized HPs increases and electricity consumption decreases, the heat required from the network (Qc) rises to meet the fixed heat demand of the buildings (Q_H). Consequently, the required heat power for the network (DHN, including the decentralized HPs) increases from 2724 kW to 2917 kW. This results in a greater power shortfall since the heat output from the data center waste heat remains constant at 2655 kW.
- Finally, pump electricity consumption increases due to the higher mass flow rate required to compensate for the increase in network heat power.

Table 34 : The numerical results of implementing the temperature reduction strategy by simulating 12 operation days of the low temperature Dufour DHN - second scenario

	HP Electricity Consumption	DHN Heat Consumption	Lack of Heat Energy	Excess Heat Energy	Q_loss	Max Required Heat Power	Lack of Heat Power	Pump Electricity Consumption
Units	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	[kW]	[kW]	[MWh/year]
Second Scenario	2924	7900	7	505	148	2724	69	122
Renovated Second Scenario	2367	8460	55	488	148	2917	262	134

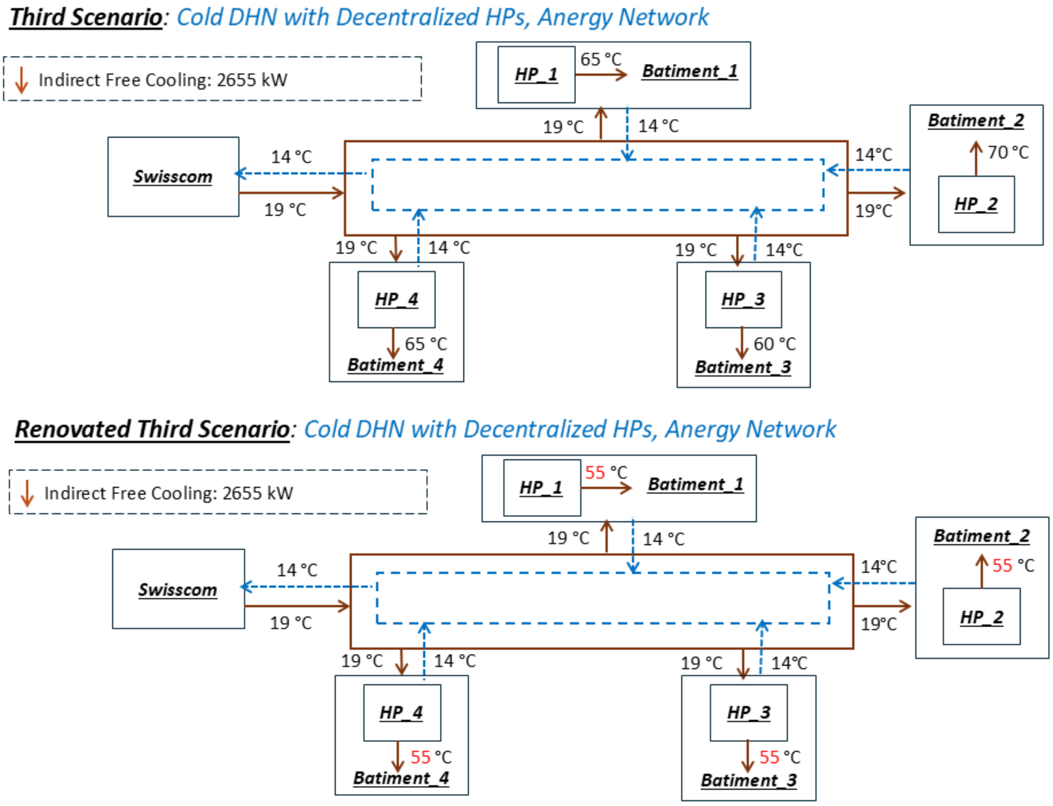
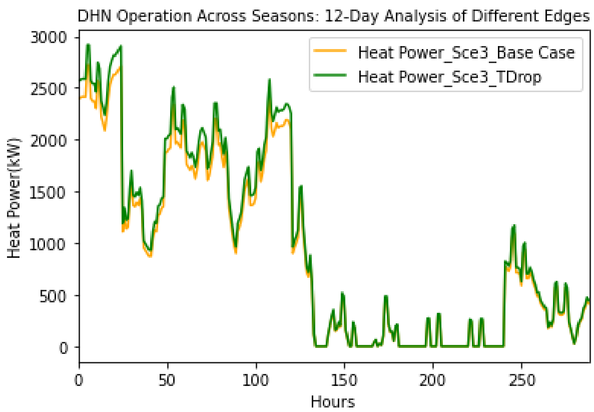
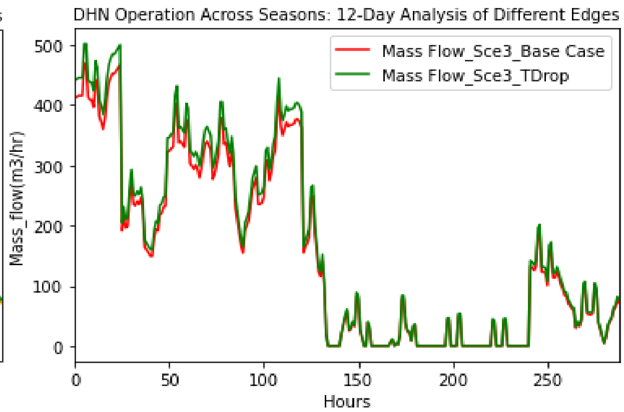


Figure 125 : Implementation of the temperature reduction strategy in the DHN corresponding to the third scenario: low-temperature Dufour DHN





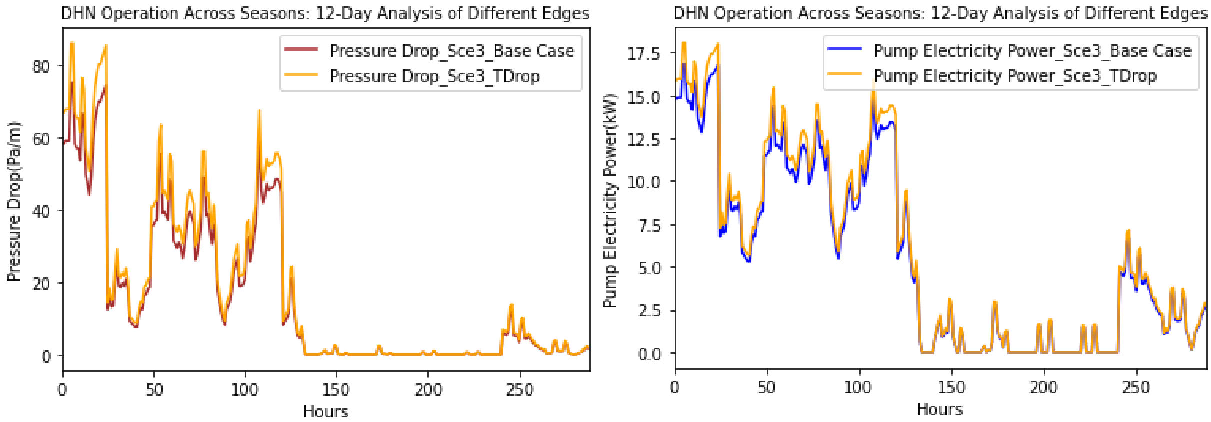


Figure 126 : Simulated hourly operational parameters in base case and renovated case corresponds to third scenario, low temperature Dufour DHN

2.6.7.3. Possible decrease of distribution temperature – Summary and key findings

In conclusion, the effects of reducing distribution temperatures in the Dufour district heating network were explored in two scenarios: a high-temperature Dufour network with a central heat pump (HP) and a low-temperature Dufour DHN with decentralized HPs. Key findings are :

1) In the high-temperature scenario, lowering the secondary side temperature from 65ºC/40ºC to 55ºC/35ºC resulted in a 21% reduction in electricity consumption of the central heat pump. However, this led to a decrease in the heat power produced (QHQ_HQH), causing a shortfall in meeting the total heat demand. While the annual heat loss of the network decreased with the reduced temperature, pump electricity consumption increased due to a higher mass flow rate required to compensate for the reduced temperature difference.

2) In the low-temperature scenario with decentralized HPs, a 19% reduction in electricity consumption was observed. The COP of decentralized HPs increased, leading to a decrease in the heat power (QHQ_HQH) produced by each HP. Consequently, the network had to deliver more heat power (QCQ_CQC) to each HP to meet the building's demand. As a result, pump electricity consumption increased due to the higher mass flow rates required.

3) The balance between total heat supply and demand varied across scenarios. In some cases, the supply exceeded the demand, while in others, it fell short. Changes in operating parameters, such as temperature reductions, also affected this balance, emphasizing the need to adjust network parameters like mass flow rates to maintain energy efficiency and meet heat demand.

Conclusions on the two test-cases contemplated in WP3 are shared over the four sections above, namely 2.6.4, 2.6.5.6, 2.6.6.5 and 2.6.7.3. In all the test-cases, the fundamental research questions of FOSTER_DHN have been studied in details, within different scenarios, namely:

1) integration of renewable (or low-carbon) energy sources to supply DHN,

2) opportunities and constraints linked to decreasing primary distribution temperatures

3) identification and exploitation of synergies by connecting subnetworks.

Some specific scenarios chosen in the two test-cases include natural gas, renewable gases and wood combustion which are not supported in federal and some cantonal strategies but are nonetheless considered – at least as transition solutions – by local energy utilities.

3 Conclusions and outlook

3.1 Conclusions

3.1.1. Conclusions on substitution of fossil sources - Workpackage 1

The district heating networks in Switzerland are presently mainly supplied by heat from MWIP, wood and natural gas. The share of the latter shall decrease in the future, although mainly for baseload operation since it has been shown that peak covering might be more difficult, due to the lack of alternatives to gas-fired backup boilers.

Renewable energy sources, as well as waste heat stemming from various industrial or commercial installations, have the potential to become the major heat suppliers of the DHN, while taking into account other important territorial parameters such as overall availability and situationality of the resources.

On-site available resources, such as geothermal or lake water, should be used in priority, in order to shift the use of non-situational vectors, such as biogas or wood, to regions that cannot exploit local renewable energies. It shall be taken into account that geothermal resources may need regeneration, e.g. by using solar thermal collectors or a seasonal excess heat from a local plant (e.g. municipal waste incinerator).

While overall wood availability for energy purposes is becoming limited in some regions in Switzerland (e.g. Canton of Fribourg and others), it is still expected to bring a substantial contribution to renewable DHN supply. The federal strategy on usage of wood for energy purposes must moreover be taken into account, including the concept of cascade valorization.

Concomitantly, the use of thermal solar collectors should be fostered, along with the integration of thermal storage facilities that can contribute to coverage of peak loads and a more efficient use of renewable primary energy.

3.1.2. Conclusions on decrease of distribution temperatures - Workpackage 2

In WP2, a strategy has been defined to simulate the temperature required for space heating and DHW production of building after retrofitting. This strategy is based on building typologies and SIA specific space heating demand limits. Using the specific space heat demand and the building typologies, the heat demand and the secondary forward/return temperature for space heating and DHW production were generated on an hourly basis.

The results from the TDROP project were also relevant to FOSTER_DHN. However, due to scheduling incompatibility, only a limited portion of the TDROP results could be incorporated into the FOSTER_DHN project. TDROP project intermediary report has been published on ARAMIS database, https://www.aramis.admin.ch/Default?DocumentID=71292&Load=true.

The results obtained within the WP7 DecarbCH[39] project have been useful to define good practices for DHN substation design, operation and optimization [21].

The main conclusions of this project can be summarized as follows:

1) Faults in substations primarily originate from issues within the substation itself, such as improper sizing of components or regulation problems, as detailed in [22]. Therefore, addressing substation faults in a district heating network (DHN) requires prioritizing the analysis of the substation and its components.

[39] S. Callegari, PhD Thesis, University of Geneva (2023)

2) DHW production is often the limiting process to reduce the forward and return temperature in existing substation. It is therefore important to define strategies to optimize DHW production in order to have to improve forward/return temperature difference

3) The excess flow method enables the quantification of the additional water volume consumed by a substation due to a limited temperature difference between the forward and return flows. This approach is particularly valuable as it facilitates the rapid identification and prioritization of substations for interventions aimed at reducing the return temperature in a DHN.

4) Substation with two heat exchangers (one for space heating and one for DHW production) are more efficient to reduce both forward and return temperature

In the situation given by the second test-case in Lausanne, FOSTER_DHN explored the effects of reducing distribution temperatures in the Dufour district heating network in two scenarios: high temperature Dufour network with central HP and low-temperature Dufour DHN with decentralized HPs.

1) In the first scenario, that corresponds to the high temperature Dufour network, by lowering the secondary side temperature from 65ºC/40ºC to 55ºC/35ºC, we found that the electricity consumption of the central heat pump decreased by 21%. However, based on the central heat pump equation $W=Q_H-Q_C$, simultaneously with the reduction in electricity consumption (W), Q_H will also decrease. Here, Q_C remains constant at 2655 kW because it represents the waste heat power from the data center. The reduction in Q_H, which is the heat power produced by the heat pump and injected into the network, results in a decrease in the supplied heat power. Consequently, this reduction leads to a shortfall in meeting the total heat power demand. This highlights the complexity of maintaining energy efficiency while adapting to new temperature levels. The annual heat losses of the network decreases as the temperature level drops, from 872.8 MWh/year to 718.8 MWh/year, and finally, pump electricity consumption increases from 37 MWh/year to 54.4 MWh/year due to the higher mass flow rate needed to compensate for the reduction in network temperature difference (ΔT).

2) In the third scenario, that corresponds to the low-temperature Dufour DHN with decentralized heat pumps we observed a 19% reduction in electricity consumption for the heat pumps when the temperature was lowered. However, in this scenario, the COP of decentralized heat pumps (HPs) installed near each building increases. Based on the heat pump equation $W=Q_H-Q_C$, a reduction in the electricity consumption of the heat pump (W) leads to a decrease in Q_H, which is the heat power produced by the HP to supply the building's heat demand. Here, Q_C represents the heat power delivered by the network to each HP. Consequently, as the COP of each HP increases, the network must supply more Q_C to each HP to ensure that Q_H matches the heat power demand of each building. Total Q_C that the network must supply increases from 2724 kW to 2917 kW for all buildings. Finally, pump electricity consumption increases from 122 MWh/year to 134 MWh/year due to the higher mass flow rate required to compensate for the increase in network heat power.

3) Overall, the findings suggest that reducing distribution temperatures (from 65°C/40°C to 55°C/35°C) can significantly enhance energy efficiency in district heating systems. Indeed, this temperature reduction leads to a decrease in heat losses from 872.8 MWh/year to 718.8 MWh/year in the first scenario, a reduction in heat pump (HP) electricity consumption from 2759 MWh/year to 2185 MWh/year still in the first scenario and from 2924 MWh/year to 2367 MWh/year in the third scenario. However, careful management of operational parameters is essential to address challenges such as increased mass flow and heat demands. By optimizing both temperature settings and operational strategies, more efficient and sustainable heating networks can be achieved.

Overall, the findings suggest that reducing distribution temperatures (from 65ºC/40ºC to 55ºC/35ºC) can improve energy efficiency in district heating systems. However, careful management of operational parameters is crucial to address the challenges of increased mass flow and heat demands. Hence, by optimizing both temperature and operations, more efficient and sustainable DHN can be designed.

3.1.3. Workpackage 3 – Test-case Yverdon-les-Bains

The district heating network of Yverdon-les-Bains is expected to expand over the whole city until the foreseeable future with different steps in between. Currently only two small scale heating networks exist connecting only few buildings. In a first step until 2035 around 500 heat consumers will be connected to four different separate district heating networks. In a second step this sub networks are supposed to be inter-connected to enable an interaction between them. In this project we analysed the proposed district heating network by Yverdon Énergies for separate networks as proposed in step 1 and as inter-connected network as proposed in step 2. In addition, the impact of the heat source technologies in the grid has been evaluated based on heat production, supply, emissions and network efficiency.

For this purpose, a simulation tool has been designed which is capable of a detailed simulation of a large-scale district heating network. Whenever possible available data about the expected network design and operation has been implemented and missing data has been either generated or are based on hypotheses.

3.1.3.1. Evaluation of synergy benefits between sub-networks in YIB test-case

The possibility of inter-connection between different district heating networks, showed three main points.

1) The smaller 70°C network of CAD STEP is not capable of operating in autarky with the assumed heat demand and heat sources and requires support during high heat demand periods from the neighbouring sub-grid CAD Iris.
2) The connection of the sub-grids allows a more efficient use of low emissions and situational (i.e. on-site, locally available) heat sources. This configuration is especially beneficial for heating networks with different heat sources. This can be seen with the important synergy that could be implemented between CAD STEP and CAD Iris but also with the synergy between the two major sub-grids of CAD Santal and CAD Iris -albeit for a more limited amount of exchanged energy -, who are both equipped with similar heat source technologies and heat capacities.
3) The simulation of the networks showed that the connection of the networks completely based on reducing the total production emissions, could lead to other undesired negative effects on the grid. During low-heat demand periods, a connection of the grids could result in one specific heat source supplying consumers but from a position far away, thus resulting in substantial heat losses and therefore lower efficiencies. An optimal control strategy [2] should take into account both heat losses, as well as the high distribution density of heat sources in YLB's district heating network as factors.

3.1.3.2. Evaluation of heat source scenarios in the YLB test-case

The decision regarding the DHN heat sources options has been previously evaluated and selected by the local energy utility Yverdon Énergies. However, since the project is still in a relatively early phase, the impact of this decision has been thoroughly evaluated in this project from the point of view of the selection of uncertain technologies and the heat injection temperatures. Henceforth, two major questions regarding the heat sources were discussed:

1) The geothermal heat sources require a supplementary heat source technology to operate at the desired grid temperature. The use of natural gas combustion as supplementary technology would result in a low-availability issue, at least in the near future, on top of not being in line with federal and cantonal regulatory frameworks. By using wood combustion instead, an important reduction of GHG emissions can be achieved. However, the amount of wood consumption would increase by around 50% during winter and more than double during summer in relative terms.

2) It is therefore possible to replace fossil natural gas potential used in conjunction with geothermal energy by either wood or another renewable primary energy as biogas; however, both are considered to be non-situational in the Vaud cantonal regulatory framework.

3) A reduction of the general injection temperature on the primary side showed a great impact on reducing emissions even for the scenario where natural gas is used as supplementary technology with the geothermal source, although this scenario must be considered as “exploratory” since it does not fit with federal and cantonal heat strategies. But in general, lower injection temperature on the primary side also results in lower heat losses overall and therefore a higher efficiency. The simulation shows a stable solution for the 70°C configuration; however, the required changes of the buildings for the changed primary temperature would go beyond the project’s scope.

3.1.4. Workpackage 3 – Test-case Lausanne

This part of the project (WP3 and the Lausanne test case) explores integrating Swisscom's waste heat into Lausanne's district heating network. It first assesses the potential for incorporating the Dufour m-DHN, which uses waste heat from a data center, into the existing network.

Several scenarios are evaluated, including lowering the DHN temperature and varying the amount of waste heat available. The study also examines the effect of using the data center's waste heat in the Lausanne DHN monotone and compares its priority as a heat source with others in Lausanne.

3.1.4.1. Integration of Dufour micro-DHN and existing Lausanne DHN

The assessment of various integration scenarios between the Dufour micro-DHN and the existing Lausanne DHN reveals that effective utilization of data center waste heat can significantly impact the operation of both networks. The results are promising, particularly in scenarios involving higher waste heat potential.

The integrated scenarios are presented in Table 27 of the report. The different scenarios were developed based on combinations of waste heat potentials of 1.5 MW and 3 MW, with varying network temperature levels: 65°C/40°C, 40°C/25°C, and 22°C/16°C. In total, there are 6 scenarios. The purpose of introducing these scenarios is to evaluate the effect of waste heat potential on the network at different temperature levels.

For instance, in the second scenario, which integrates the high-temperature Dufour network with a waste heat potential of 3 MW, the heat pump achieved a maximum output temperature of 94°C. This scenario, while beneficial in terms of heat transfer and heat exchanger capacity, exhibited the lowest coefficient of performance at 2.9, leading to higher electricity consumption. Nevertheless, the substantial heat transfer potential to the Lausanne DHN, along with the high HEX capacity, makes this a viable high-output solution.

In contrast, the third scenario involved a lower waste heat potential of 1.5 MW, coupled with a low-temperature Dufour network (40°C/25°C). Here, the HP reached an output temperature of 73°C, which resulted in a higher COP of 3.6, reducing electricity consumption, especially in the summer months. This integration enabled a heat transfer of 2.2 MW, demonstrating the efficiency of using lower-temperature networks for optimizing energy use.

The lower waste heat potential of the data center does not necessarily correspond to lower network temperatures. In the first and second scenarios, the waste heat potentials are 1.5 MW and 3 MW (representing the current and future plans, respectively), while the network temperature level remains the same at 65°C/40°C. Similarly, for the third and fourth scenarios, the waste heat potentials are 1.5 MW and 3 MW, but the network temperature level is fixed at 40°C/25°C. Finally, in the fifth and sixth scenarios, the waste heat potentials are again 1.5 MW and 3 MW, with the network temperature level set at 22°C/16°C.

The analysis of the six integration scenarios highlighted the flexibility of heat transfer between the Dufour m-DHN and the Lausanne DHN. The winter and summer modes illustrated that the direction of heat transfer varies according to demand, enhancing the robustness of the overall heating strategy. Particularly, scenarios where the Dufour DHN's demand exceeded the data center's waste heat demonstrated a well-balanced operational approach by utilizing the existing DHN's capacity in an effective fashion.

3.1.4.2. Integration of Swisscom Waste Heat and Existing CAD_SIL: Evaluating the Monotones

In the second phase, the impact of integrating data center waste heat into the Lausanne DHN was quantified, focusing on the 2040 horizon projections. In conclusion, the integration of Swisscom's data center waste heat into the Lausanne DHN offers significant environmental and operational benefits for both the total network and the southwest Lausanne DHN.

By incorporating this renewable heat source, the reliance on gas as an energy resource is notably reduced, with the total network experiencing a 9.3% decrease in gas consumption and the southwest network achieving an even greater reduction of 24.4%. Additionally, the share of renewable energy in the total DHN increases by 1.5%, and by 2.3% in the southwest DHN.

While the system's efficiency is enhanced through these reductions, there is a slight increase in electricity consumption due to the operation of heat pumps, which raise the waste heat temperature for optimal use. Overall, the integration of waste heat provides a strategic opportunity to reduce carbon emissions, optimize energy use, and improve the sustainability of Lausanne's DHN by 2040, aligning with future energy targets.

3.2 Outlook and perspectives

The FOSTER_DHN project reached the goals that were described in the original proposal, as explained and shown above.

The python-based frameworks that have been developed can be used for the planning, design and dimensioning of future networks, but also for exploring changes to the operational conditions of existing ones, provided the heat demand of connected buildings is known in some detail. The code has been tested in real urban environments, both for small neighbourhoods, as well as for an entire city network in a medium-size town.

The frameworks allow to display results on detailed maps to facilitate communication, as well as a large number of other relevant indicators, ranging from fluid mechanics parameters to GHG emissions, from primary energy evaluations to economic calculations. Hence, they clearly represent valuable decision-support tools for both multi-energy utilities, as well as local authorities.

The test-cases have represented the necessary validation of the developed python codes. But, as importantly, they have provided a large swath of results for the two implementation partners on concrete ongoing projects they are actively working on. The frameworks have the necessary flexibility to be used in other urban contexts and even more so by the fact that they have been developed on an open-source base and contain no “black boxes”.

Regarding the future perspectives that have been opened by FOSTER_DHN, the research team has identified the following ones:

1) The renewable wood energy resource is considered only for combustion in this project. However, it would be important to consider other forms of valorization via pyrolysis and/or gazeification, since the latter technologies allow a more efficient usage of the wood and drastically decrease non-GHG emissions such as fine particles.

2) As explained above, the timing of the TDROP project did not allow to explore in more depth the impact of the temperature decrease on the primary network side on the secondary (demand) side. Thus, within FOSTER_DHN, the latter is treated as a «black box». This unsatisfying situation should be improved and the dynamic behaviour of both connected systems simulated concomitantly, including the exchange substation.

3) Thermal storage is presently not considered dynamically in the simulation framework. Due to its importance with respect to an increased supply from renewable heat sources and the crucial role it could play in case of thermal load peaks, thermal storage components should be included in the computation. In turn, this would increase the numerical complexity and the computational power needed.

4) The control strategy of the DHN simulation implemented in pandapipes is presently dominated by an environmental merit order. As mentioned in the report, a more sophisticated control strategy (optimization) should be implemented (and the results compared) in order to take into account other important operational parameters, such as minimized heat losses, pumping power and global OPEX.

4 National and international cooperation

The project has been realized on the basis of a close collaboration of two research institutes within the HES-SO, namely

1) Institut des Energies, Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud (HEIG-VD), Yverdon-les-Bains (VD)
2) Institut Energie et Environnement, HES-SO Valais-Wallis, Sion (VS)

The two implementation partners are the multi-energy utilities Yverdon Energies (SEY) and Services Industriels de Lausanne (SIL), in collaboration with whom the two test-cases have been realized. The energy directorate of Canton de Vaud (DIREN) has also followed closely the project evolution.

In addition, a part of the pandapipes codes has been tested on the DH networks of the City of Neuchâtel, in close collaboration with VIteos SA, albeit the latter company is not formally a member of FOSTER_DHN consortium.

The pandapipes simulation framework developed at HEIG-VD is currently used within an Innosuisse Flagship project, namely "GREENHUB", in close collaboration with OST.

No internnational collaborations have been set up for this project.

5 Publications and other communications

A specialized article on the project FOSTER_DHN has been published in 2023 in the SVGW journal "Aqua & Gas" (number 12, available at https://arodes.hes-so.ch/record/13457?ln=FR&v=pdf).

While this first article was more focusing on the methodological aspects, a second article is currently foreseen and will be specifically devoted to the concrete results obtained within the project.

A peer-reviewed publication to be submitted to the journal "Applied Energy" is currently in preparation.

As per workplan, it is also foreseen to organize a specialized seminar on the future of district heating decision-support tools in the first half of 2025 at HEIG-VD.

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7 Appendix

7.1 Appendix A: python class for processing energy demand profiles

The Python class "ChargeCurve.py" was developed to process and retrieve energy demand and temperature profiles derived from the Polysun simulation for different building categories and refurbishment scenarios. The class allows retrieving the hourly profiles of the building specific energy demand (in [kWh/m2]). But while in the base building model case the profile has to be denormalized to correspond to the annual energy need provided in input for the pre-refurbishment case, the specific energy demand profiles for the limit and target scenarios can be adopted after rescaling on the effective REA of the building under investigation.

7.1.1. Class Overview

- **Class Name**: `ChargeCurve`
- **Purpose**: To retrieve building-specific energy demand and temperature profiles based on different refurbishment scenarios and annual energy need of the building.
- **GitHub repository**: [ClassChargeLoad](https://github.com/LESBAT-HEIG-VD/ClassChargeLoad)

7.1.1.1. Inputs

Keyword	Type	Description
affectation	str	Building category, chosen among the following: Administration, Commerce, Education, Hospital, Industry, Res_ind (i.e., single family house), Res_multi (i.e., multi-dwelling housing)
annual_consumption	float	The annual energy demand of the building. Value used to de-normalize the energy demand profiles; in [kWh/an]
SRE	float	The reference energy area (A_E) in [m^2]
Lausanne	bool	Flag to select the refurbishments scenarios with change in sub-station design to a decentralized solution for DHW preparation for the "res_multi" case only.
index_year	int	year to be used in the construction of an hourly index

7.1.1.2. Methods

- ***pd.dataFrame=load_DB(self):***
  Returns the local database contained in a Pyarrow archive with the specific load curves corresponding to the building use type provided in the "affectation" attribute and for the REA provided in input (Load1 → normalized energy demand hourly profile for base model; Load2 → "limit" refurbishment; Load3 → "target" refurbishment.

7.1.1.3. Output

- Object of Class chargeCurve
- Dataframe with all curves: chargeCurve.DB
- Columns of Output Dataframe: [Load1, Ts_o_1, Ts_i_1, Tp_o_1, Tp_i_1, Load2, Ts_o_2, Ts_i_2, Tp_o_2, Tp_i_2, Load3, Ts_o_3, Ts_i_3, Tp_o_3, Tp_i_3]

7.1.1.4. Usage example

- To retrieve the DB with all curves (Load1, Load2 and Load 3) in the case of Lausanne DHN "res_multi" category:

profile_Lausanne = chargeCurve(annual_consumption=116000, SRE=800, Lausanne=True)

- To retrieve the DB with all curves (Load1, Load2 and Load 3) in the cases other than the Lausanne DHN:

profile_Yverdon=chargeCurve(affectation="Industries",annual_consumption=10000, SRE=1000, Lausanne=False, index_year=2021)

then, "profile_Yverdon.DB.Load1" is the base load curve for a building in the Industries category, with an annual energy demand of 10000 kWh/y and a REA of 1000m^2

7.1.1.5. Code availabilty

The Python code used for energy demand profile processing, including the `EnergyProfile` class, is available in the following GitHub repository: https://github.com/LESBAT-HEIG-VD/ClassChargeLoad

Instructions for running the code, along with additional documentation, can be found in the repository's README file.

7.2 Appendix B – Master thesis Joris Ferroni

Within FOSTER_DHN, a separate Master thesis has been realized in collaboration with the multi-energy utility Viteos, which is active in the Canton of Neuchâtel. The student was Joris Ferroni who successfully defended his thesis according to HES-SO rules in February 2024.

The main idea of the Master thesis was twofold:

1) Develop the first version of the python code that permits to identify synergies among DHN networks in a given urban territory, exploit them and then compute operational indicators
2) Test the code on an existing city DHN, namely in Neuchâtel, directly on two existing DHN on the basis of the same merit order among the heat resources as applied in YLB

Joris Ferroni has worked six months in close collaboration with Marten Fesefeldt and Massimiliano Capezzali at HEIG-VD.

The complete Master thesis is given as an annex to the present report, with the agreement of the company Viteos SA. Although some simplifications were adopted in the thesis and have been improved in the present FOSTER_DHN code, the thesis has brought some interesting conclusions:

1) The synergy code is able to perform calculations on large networks, with hundreds of buildings connected and multiple heat sources, in conjunction with the FOSTER_DHN network simulation code.
2) The merit order can be implemented successfully and allows a classification of heat resources in terms of CO_2 emissions and renewable content.
3) The synergies identified between two existing networks gives rise to significant results, with a substantial increase in the renewable share and -50% GHG emissions.
4) The computational power required for the calculations is kept reasonable even on a rather large urban zone comprising hundreds of buildings and networks with hundreds of nodes.

8 Project progress (confidential)

8.1 General project status and budget

The project «FOSTER_DHN» has officially started in November 2022 and ended on October 31st, 2024.

At the start of 2023, one of the partners has changed, with the demise of CREM and the transfer of activities to HES-SO Valais-Wallis. Correspondingly, Jakob Rager has officially left the project, while Prof. Jessen Page and two members of his team (see below) have joined the project. However, due to ongoing projects, the work of the HES-SO Valais-Wallis team has effectively been able to start only during Summer 2023. Hence, the project has experienced some delay, about which SFOE and the implementation partners have been duly informed. The official funding agreement has been amended according to the above-mentioned changes.

The official kick-off meeting of the project has taken place in mixed mode on March 30th, 2023. SFOE was represented by Nadège Vetterli, the City of Lausanne by Francesco Barone and Clément Dromart, the city of Yverdon-les-Bains by Fabien Poumadère and the Canton of Vaud by Antoine Boss.

The members of the project's Steering Committee, namely Dr. Pierre Hollmüller from the University of Geneva and Andreas Hurni of Thermische Netze Schweiz, have also attended and given very useful inputs. The steering committee has met two times over the course of the project, namely on 2023, March 30th (as part of the kick-off meeting) and on 2024, May 23rd.

Over the first half of 2023, the project partners have agreed to sign a contract that notably settles issues related to data confidentiality, intellectual property, co-funding financial fluxes and publications. It has been signed by all partners.

The official budget of the project is presented below:

Description of the activity designated as work package	Cost type	Cost centre (institution)	Function* (staff)	Hourly rate** [CHF/h]	Person-hours [h]	Costs [CHF]	SFOE contribution *** [CHF]	Third party funds*** [CHF]
WP 1 + 2	Forschung/Entwicklung	CREM	Damien Chiffelle	100	600	60 000	35 000	25 000
WP 1 + 2	Forschung/Entwicklung	CREM	Vincent Moreau	100	600	60 000	35 000	25 000
WP 1 + 2	Forschung/Entwicklung	HEIG-VD	Alexis Duret	80	60	4 800	10 000	
WP 1 + 2	Forschung/Entwicklung	HEIG-VD	Xavier Jobard	80	190	15 200	10 000	
WP 3	Forschung/Entwicklung	HEIG-VD	Marten Fesefeldt	65	1 500	97 500	50 000	47 500
Projekt Koordination	Projektmanagement	HEIG-VD	Massimiliano Capezzali	115	110	12 675		12 675
Projekt Koordination	Projektmanagement	CREM	Jakob Rager	140	85	11 900		11 900
Total						262 075	140 000	122 075

Only staff expenses have been incurred by this project. Official financial reporting sheets will be sent separately by the Ra&D services of HEIG-VD.

Additional researchers have contributed to the project, with respect to the initial planning. Namely, Stefano Pauletta (WP2), Fabrice Gendre (WP1) and Sara Eicher (report) for HEIG-VD, as well as Tristan Rey and Atefeh Behzadiforough (WP2 and WP3) at HES-SO Valais-Wallis. A substantial part of the activities foreseen at CREM have been performed by HES-SO Valais Wallis.

8.2 Status of work packages

All work packages have been completed according to the workplan of the proposal. Detailed results and discussions thereupon are presented in the chapters above.

Two intermediary reports have been submitted to SFOE and to implementation partners, namely in December 2022 and November 2023.

9 Data management plan and open access/data/model strategy (confidential)

Access to project codes will be discussed with the financing partners of the project after the acceptation of final report.