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José F. CASTRO FLORES

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Low-temperature based thermal micro-grids: Operation and performance assessments

Micro-réseaux de chaleur urbains basse température : Evaluation du fonctionnement et de la performance

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Low-Temperature Based Thermal Micro-Grids

Operation and performance assessments

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Abstract

Energy use in the urban environment is vital for the proper functioning of our society, and in particular, comfort heating –or cooling– is a central element of our energy system often taken for granted. Within this context, district energy systems and especially, district heating (DH) systems must evolve to adapt to the upcoming decades-long transition towards a sustainable energy system. This dissertation seeks to introduce, discuss, and assess from a techno-economic perspective the concept of low-temperature (LT) based thermal micro-grids (subnets) as active distribution thermal networks. It explores the role of the subnet at the system distribution level supervised by an active agent (DH substation), performing tasks of heat supply and demand management (storage and dispatch), as well as coordinating bidirectional flows.

Here, a mixed methodological approach based on analytical simulation for the assessment of alternatives to evaluate a set of technologies is developed and discussed. This approach covers: the identification of knowledge gaps through the state-of-the-art analysis; a collection of incremental technical and/or economic performance assessments; and the analysis of a measurement data set from an existing LTDH demonstration project.

Key findings of this work include: an updated and improved model of aggregated heat loads; identification of differences in load and temperature patterns for certain LT subnets; analysis of benefits and drawbacks of active substations with distributed heat sources and/or storage; and the impact on the reduction of the primary network return temperature as a consequence of the increase in the share of LT subnets, leading to lower generation and operating costs.

These outcomes reveal that the integrated design and operation of the active thermal micro-grid have the potential to improve both the performance of the subnet, and that of the primary network. It further enhances the capability of the overall system to integrate unconventional and distributed heat sources together with energy efficient buildings by increasing the system's flexibility and controllability. Active thermal

distribution networks will likely become a subsequent step in the technological development of DH technologies, to address the matter of providing comfort heating in an effective and cost-efficient manner. This work advances the current DH knowledge by identifying synergies and challenges that arise with these new developments, in order for DH technology to play a key role in the future smart and sustainable energy system.

Keywords

low-temperature district heating; active thermal micro-grid; substation operation; performance assessment; distributed heat resources

Sammanfattning

Energianvändning i stadsmiljö är avgörande för att vårt samhälle ska fungera väl, och i synnerhet är komfortvärme eller -kylning centrala element i vårt energisystem som ofta tas för givet. I detta sammanhang måste distributionsnätverk för energi och i synnerhet fjärrvärmesystem utvecklas för att anpassa sig till de kommande årtiondenas övergång till ett hållbart energisystem. Denna doktorsavhandling syftar till att analysera och diskutera koncept med lågtemperaturbaserade termiska mikronät, sekundära nät och deras roll som aktiva termiska distributionsnätverk. Såväl driftsstrategier som systemprestanda undersöks. Det sekundära nätets inverkan på det övergripande distributionsnätet utforskas med särskilt fokus på smarta undercentraler (fjärrvärmecentraler) som hanterar flödesreglering i två riktningar, lagring samt behovsuppfyllelse.

Studien är baserad på ett metodiskt tillvägagångssätt där analytisk simulering har använts för utvärdering av alternativa tekniklösningar. Utgångspunkten är en kunskapssammanställning där viktiga frågeställningar som behöver svar har identifierats. Därefter har simuleringar utförts så att tekniska och/eller ekonomiska prestationer kunnat undersökas stegvis. Vidare har mätdata från en befintlig installation av lågtemperaturbaserad fjärrvärme analyserats, och delvis använts för att verifiera resultat från simuleringen.

Viktiga resultat av detta arbete är: en uppdaterad och förbättrad modell av aggregerade värmebelastningar; identifiering av skillnader i belastnings- och temperaturmönster för vissa lågtemperatur fjärrvärmenät; analys av fördelar och nackdelar med aktiva fjärrvärmecentraler där distribuerade värmekällor och/eller lagring hanteras; samt effekten av minskningen av primärnätets returtemperatur som en följd av ökningen av andelen lågtemperaturnät, vilket leder till lägre produktion- och driftskostnader.

Dessa resultat visar att den integrerade utformningen och driften av det aktiva termiska mikronätet har potential att förbättra både prestanda hos delnätet och det primära nätverket. Det ökar dessutom det övergripande systemets potential för att integrera okonventionella och distribuerade värmekällor tillsammans med energieffektiva byggnader genom att öka

systemets flexibilitet och styrbarhet. Aktiva termiska distributionsnät visar sig vara en intressant del av framtida fjärrvärmesystem där komfortvärme erbjuds på ett resurs- och kostnadseffektivt sätt. Detta arbete fördjupar befintlig kunskap kring lågtemperaturbaserad fjärrvärme i det att synergier och utmaningar har identifierats. Därmed bidrar avhandlingen till att fjärrvärmeteknik kan utvecklas för att fortsatt spela en nyckelroll i smarta och hållbara energisystem.

Nyckelord

lågtemperatur fjärrvärme; aktiv fjärrvärmemikronät; fjärrvärmecentral operation; prestationsbedömning; distribuerade värmekällor

Résumé substantiel

Préliminaire

La recherche qui a donné lieu à cette thèse a été réalisée dans le cadre du programme Erasmus Mundus Joint Doctorate SELECT+ « *Environomical Pathways for Sustainable Energy Services* », financé en partie par l'Agence Exécutive Education, Audiovisuel et Culture (EACEA) de la Commission Européenne.

Ce travail a été effectué dans deux universités européennes : l'institution de coordination du programme KTH « Royal Institute of Technology » à Stockholm, Suède, et l'établissement partenaire IMT Atlantique à Nantes, France (anciennement École des Mines de Nantes - EMN). Les deux institutions ont uni leurs forces dans la supervision coordonnée de ce travail. La plupart de la recherche a été réalisée à KTH dans la division « Heat and Power » (HPT / EKV) au sein du département « Energy Technology » (EGI). L'autre partie de cette recherche a été réalisée au sein du Département des Systèmes Énergétiques et Environnement (DSEE), membre de l'UMR CNRS GEPEA à l'IMT Atlantique.

Cette thèse aborde l'évaluation des réseaux de chaleur basse température à travers la simulation analytique. Une partie des recherches ici présentées ont été publiées dans des journaux scientifiques et des articles de conférences évalués par des pairs. Ce travail présente la technologie du chauffage urbain, la modélisation et la simulation technico-économiques, l'analyse de données (mesures) d'un projet de démonstration existant et l'analyse système correspondante.

« Micro-réseaux de chaleur urbains basse température : évaluation du fonctionnement et de la performance »

Contexte et Motivation

L'utilisation d'énergie en milieu urbain est essentielle au bon fonctionnement de notre société, où notamment le chauffage urbain –et du froid– est un élément central de notre système énergétique, souvent considéré comme allant de soi. Avec une volonté d'œuvrer pour un développement durable, d'atténuer le changement climatique et de garantir un environnement sain, il est nécessaire de trouver des pistes de développement résilientes au changement climatique, économes en ressources et à faible émission de carbone, pour couvrir nos exigences

énergétiques. On estime que près de 40 % de l'usage totale d'énergie dans l'environnement bâti est attribuable au besoin d'assurer un espace de vie confortable; par conséquent, c'est un élément pertinent du système énergétique.

Les systèmes énergétiques de chauffage urbain modernes sont considérés par de nombreuses villes comme l'approche la plus efficace pour assurer un service de chauffage et de froid durables. Ils rassemblent déjà les meilleures pratiques pour garantir un approvisionnement énergétique local, économique et à faible émission de carbone [2]. Cependant, pour atteindre les objectifs du système énergétique durable, il est nécessaire de mener des recherches plus poussées, de développer de nouvelles solutions technologiques et de faire la démonstration de leurs performances. Ces systèmes (électriques, thermiques, à gaz, et de transport) devront, par ailleurs, être intégrés pour offrir des solutions énergétiques rentables et durables.

Dans ce cadre, les systèmes énergétiques urbains, en particulier les réseaux de chaleur, ont besoin d'évoluer pour offrir des services de chauffage efficaces, économes et faiblement émetteurs de CO₂. Dans la filière de chauffage urbain, cette transition nécessitera plusieurs années, voire décennies, de sorte que les technologies actuelles et les nouvelles générations de réseaux de chaleur urbains fonctionneront simultanément, en se complétant mutuellement pour répondre à la demande. Cela représente un défi pour les collectivités publiques qui devront s'adapter aux nouvelles conditions et planifier soigneusement leurs investissements, en particulier dans les pays où les réseaux de chaleur sont déjà bien répandus.

Les réseaux urbains de production et de distribution de chaleur ont été conçus de manière appropriée, sur le plan technique et économique, pour desservir les usagers qui ont une demande de chaleur « traditionnelle ». Cependant, en raison de facteurs tels que les nouvelles politiques d'efficacité énergétique mises en place, la demande de chaleur dans les zones urbaines devrait progressivement diminuer à l'avenir [3], [4]. La demande de chaleur et la densité de chaleur linéaire sont deux paramètres connexes clés pour déterminer la rentabilité d'un système de chauffage urbain. Cependant, la densité de chaleur diminuant en raison de multiples causes, dont la rénovation de bâtiments et le réchauffement climatique [5], [6], les coûts

d'investissement et d'exploitation de l'approvisionnement et de la distribution de chaleur augmentent par rapport aux ventes totales de chaleur.

Les taux de construction de nouveaux bâtiments et de rénovations en Europe varient de 1 % à 2 % par an par rapport à l'infrastructure existante. Ce chiffre, bien que faible, offre l'opportunité d'étendre les réseaux urbains de chaleur et notamment d'introduire des technologies innovantes appartenant à la quatrième génération de chauffage urbain (4GDH) [3]. Ces développements impliqueront : le développement de réseaux à basse température, l'intégration de sources de chaleur renouvelables et de stockage de l'énergie thermique innovant, et leur intégration avec d'autres réseaux énergétiques. De cette manière, les réseaux de chaleur pourront mieux contribuer à répondre aux enjeux du développement durable (économiques, environnementaux et sociaux).

Objectifs des travaux, portée et structure

Ce travail de recherche se propose de présenter, de discuter et d'évaluer, d'un point de vue technico-économique, le concept de micro-réseaux de chauffage urbains basse température, en tant que réseaux de chaleur urbains secondaires (sous-réseaux) actifs au niveau distribution du système. Il explore le rôle du micro-réseau thermique actif : supervisé par un agent actif (sous-station de chauffage urbain) effectuant des tâches d'agrégation de charge thermique et de gestion des ressources (stockage et expédition) de même que la coordination des flux bidirectionnels de chaleur. Cette exploration est faite du point de vue des performances technico-économiques, bien que le sujet du contrôle se trouve hors de portée de ce travail.

Le travail réalisé est axé sur les sous-réseaux de chauffage urbain basse température comme une solution efficace et rentable pour satisfaire les besoins de chaleur d'ensembles des bâtiments à haut efficacité énergétique (neufs ou rénovés) et pour intégrer les ressources d'énergie thermique locales disponibles. Il est centré sur le niveau distribution du système, en particulier sur les sous-systèmes de distribution de chaleur : (1) un sous-réseau de chauffage urbain basse température alimentant des charges à haute efficacité énergétique, (2) une sous-station active en tant qu'agrégateur,

coordonnant les flux de chaleur et les sources et (3) des ressources d'énergie thermique à faibles émissions et de réservoirs de stockage locaux.

Cette thèse est un travail original du type monographique et, de plus, la plupart des recherches ici présentées ont été publiées dans des journaux scientifiques et dans des articles de conférences évalués par des pairs, rédigés tout au long de ce projet de recherche. La thèse est divisée en cinq parties : la première présente ce travail, les motivations et les objectifs. La deuxième partie présente une revue bibliographique, l'identification des limites des connaissances actuelles et l'introduction du concept proposé. La troisième partie décrit la méthodologie générale et les techniques de modélisation et de simulation utilisées. Elle est suivie par la quatrième partie où les résultats de l'application de cette méthodologie sont présentés sous la forme d'une série d'évaluations. La dernière partie discute les conclusions principales et les perspectives de recherches ultérieures.

Une brève description chapitre par chapitre est illustrée à la **Figure 1-1** 'Diagramme de la structure de la thèse' montrant une description visuelle de la structure du manuscrit et les principaux sujets traités dans chaque chapitre. Le **Tableau 1-1** donne un résumé des contributions générées le long de cette thèse ainsi que les publications listées précédemment sur la 'Publications List' en soulignant les domaines de recherche, les points importants et les méthodes.

État de l'art et limites des connaissances

Le chauffage urbain (DH) est un concept apparu à la fin du XIXe siècle, en tant que moyen de transférer la chaleur à distance, depuis des installations de production de chaleur, à un groupe d'utilisateurs finaux, par exemple des bâtiments dans une ville. Un système de chauffage urbain peut être grossièrement divisé en trois sous-systèmes principaux : production, distribution et utilisation. La **Figure 2-1** montre un schéma simplifié du système de chauffage urbain : une centrale thermique (producteur de chaleur) qui augmente la température d'un fluide caloporteur (HTF) qui est pompé à travers un réseau de distribution –conduites d'alimentation et de retour– aux utilisateurs finaux ou leurs installations.

Dans les postes de livraison de la chaleur, ce fluide peut traverser une sous-station de chauffage urbain (illustrée à la **Figure 2-3**), où la chaleur est transférée au réseau secondaire c'est-à-dire au système de chauffage interne du bâtiment. Le chauffage urbain est une solution technologique qui répond au besoin du confort dans l'espace de vie. Les deux principaux services fournis, en particulier dans l'utilisation résidentielle, sont la fourniture d'eau chaude sanitaire (DHW) et le chauffage des locaux (SH).

Il a été souligné dans [8] et [58] que pour la gestion et le fonctionnement rentables des systèmes de chauffage urbain, les principaux défis auxquels la technologie se confronte sont les suivants : l'utilisation des réseaux à basse température pour diminuer les déperditions de chaleur et augmenter leur efficacité, l'interaction avec les bâtiments basse consommation d'énergie et les réseaux électriques, et la gestion et l'acheminement efficaces des sources de chaleur en coordination avec le stockage d'énergie thermique (TES).

Les réseaux urbains de chaleur du futur intégreront probablement un mélange de sources de chaleur [3], [7], [8]: sources renouvelables fluctuantes, chaleur fatale de procédés intermittents et chaleur valorisée à partir de ressources résiduelles. La plupart de ces ressources interagiront avec les réseaux de chaleur de manière décentralisée et distribuée. Cette situation crée le besoin de « réseaux actifs de distribution de chaleur » (ADTN) qui sont des réseaux secondaires de distribution de chaleur avec des systèmes en place pour contrôler une combinaison de ressources énergétiques distribuées (sources, charges et stockage) et centralisées.

Les réseaux urbains de chaleur devront alors fonctionner en coordination avec des sources et des réservoirs de stockage d'énergie thermique pour adapter la fourniture de chaleur à la demande et fournir une alimentation régulière. Les interactions entre réseaux conventionnels et réseaux basse température avec production et stockage distribués, ont été peu étudiées. Ainsi, les concepts d'approvisionnement possibles en chaleur par un mélange de multiples sources à haute et à basse températures doivent être étudiés plus en profondeur. Par ailleurs, d'autres topologies ou configurations de connexion entre les composants des réseaux doivent également être prises en compte, ainsi que des concepts hybrides, tels que les sous-réseaux de « consom'acteurs » avec, entre autres, des capteurs solaires, des pompes à chaleur ou des micro-CHPs.

Le chauffage urbain basse température (LTDH) fait partie des technologies de la 4^{ème} génération de réseaux de chaleur (4GDH), caractérisées par des températures de distribution plus basses et une plus grande flexibilité. Les paramètres de fonctionnement de ce type de réseaux peuvent varier en fonction des modes d'opération. Contrairement à la température d'alimentation de 80 °C du chauffage urbain de 3^{ème} génération et aux systèmes « très basse température » (dont les températures moyennes d'alimentation sont inférieures à 40 °C), les réseaux considérés comme étant « basse température » fonctionnent à des niveaux de températures de distribution au-dessous de 50 °C pour l'aller (moyenne annuelle) et aussi basses que 25 °C pour le retour [6].

L'importance de l'abaissement des températures de fonctionnement et de distribution a été démontrée auparavant dans des études [6], [7], en concluant que cela contribue à diminuer l'utilisation d'énergie primaire : les pertes de chaleur plus faibles conduisent à des abaissements de température sur le réseau de distribution et donc à une demande plus faible de l'énergie de pompage à une charge thermique donnée. Ceci entraîne une réduction des dépenses de production et d'exploitation. En outre, les températures plus basses induisent moins de contraintes thermiques dans les tuyauteries. Par conséquent, le risque de fuites dans les tuyaux et les coûts de maintenance associés sont réduits. Cette réduction prolonge également la durée de vie utile des composants du réseau de distribution [22].

Une méthodologie ayant pour objectif d'estimer les économies et les gains de productivité en raison de températures de retour plus faibles a été décrite et détaillée dans [29] et résumée et appliquée dans quelques exemples dans [28]. Ce dernier travail montre comment (1) les températures du réseau influencent les dépenses d'investissement et d'exploitation de tous les composants, et (2) comment l'abaissement de ces températures peut avoir des effets divergents et contradictoires sur les dépenses.

Le chauffage urbain basse température pourrait également aider à rendre économiquement faisable le raccordement aux réseaux des zones à faible densité de chaleur, telles que les zones des bâtiments basse consommation d'énergie (LEB). La faisabilité technique et économique de ces systèmes a déjà été étudiée du point de vue théorique [19] et testée dans des projets de démonstration décrits dans [43], [22], entre autres. Ces résultats montrent

que le chauffage urbain basse température est viable et permettra des économies d'énergie à l'avenir. Il y a quelques systèmes de ce type déjà en fonctionnement qui ont dépassé la phase de démonstration, confirmant la faisabilité technique du concept et les faibles pertes de chaleur. Un résumé de certains des projets les plus pertinents de chauffage urbain basse température est présenté au **Tableau 3-1**.

En ce qui concerne l'intégration distribuée des systèmes de stockage d'énergie thermique (TES) dans les micro-réseaux de chaleur, les sous-stations actives offrent un potentiel d'avantages substantiels du point de vue économique et environnemental. Cependant, ces avantages varieront en fonction de la configuration choisie pour le réservoir de stockage. Jusqu'à présent, peu de travaux de recherche ont été réalisés au sujet du stockage d'énergie thermique intégré aux réseaux de chauffage urbain basse température, et encore moins concernant les systèmes actifs de stockage à chaleur latente (LH-TES). Bien qu'elle ne soit pas incluse dans le corps principal de ce texte, une discussion plus détaillée sur les caractéristiques et le rendement des systèmes actifs de stockage d'énergie thermique à chaleur latente est présentée à l'**Annexe A**. Cette discussion aborde également les problèmes potentiels de compatibilité avec le chauffage urbain basse température basé sur les développements les plus récents.

Les réseaux urbains de chaleur au niveau distribution évolueront vers les micro-réseaux de chaleur plus complexes : intelligents, hybrides et à basse température. Ces systèmes d'énergie thermique à petite échelle se composent de trois sous-systèmes principaux : (1) un sous-réseau de chauffage urbain basse température associé à des charges caractéristiques d'une haute efficacité énergétique, (2) une sous-station active en tant qu'agrégateur (y compris l'équipement de mesure et de contrôle) et (3) des ressources d'énergie thermique à faibles émissions et de stockage locaux. Ces trois sous-systèmes sont illustrés par la **Figure 4-1**. La sous-station deviendrait un lien clé entre les systèmes en tant qu'interface de gestion au niveau de la distribution. La **Figure 4-2** montre une disposition possible du concept de sous-station active couplée avec une source à basse température ou un système de stockage.

Même si des recherches antérieures ont démontré la faisabilité du chauffage urbain basse température et des technologies de la 4GDH, il existe encore des limites de connaissance qui doivent être abordées pour favoriser la mise en œuvre de ces technologies. Le **Tableau 4-1** '*Comparaison de l'état de l'art, des pistes de recherche et des objectifs*' présente un résumé des pistes de recherche que cette thèse explore pour contribuer à combler quelques défis identifiés dans l'analyse de l'état de l'art.

Méthodologie

Afin d'évaluer les technologies décrites précédemment, une approche méthodologique mixte basée sur la simulation analytique pour l'évaluation des alternatives a été développée et est discutée. À travers d'un ensemble d'évaluations des performances techniques ou économiques, il est démontré que la solution de micro-réseaux de chaleur basse température est potentiellement efficace et rentable.

Cette méthodologie systématique comprend tout d'abord l'identification des limites de connaissance suite à une analyse de l'état de l'art. Ensuite, un ensemble d'évaluations des performances technique ou économique a été réalisé en employant une approche de simulation / scénario. Plusieurs cas différents sont comparés au travers des modèles thermodynamiques et économiques, ainsi que diverses stratégies de fonctionnement possibles. De plus, les données issues d'un projet de démonstration de chauffage urbain basse température existant sont analysées afin de discuter ce type de réseau basé sur le concept de « températures en cascade ». L'analyse de ces données est centrée sur les signatures énergétique et de température agrégées du sous-réseau. Un schéma de haut niveau du processus global est illustré à la **Figure 5-1** '*Diagramme de processus de l'évaluation technico-économique de cette thèse*', décomposé en ses éléments principaux avec les blocs des sous-systèmes et les flux d'information.

La modélisation du système et de ses composants est centrée sur la couche de distribution du système de chauffage urbain en mettant l'accent sur la sous-station en tant qu'agrégateur de la dynamique du réseau. Pour étudier et comparer les performances du réseau, des sous-stations et des sous-réseaux, un modèle de simulation thermodynamique de chaque système a été développé. Un diagramme du processus plus détaillé de la sous-station à

basse température est présenté à la **Figure 6-3**. L'environnement de simulation choisi est un logiciel commercial : *Matlab*® et *Simulink*®. Une bibliothèque de Simulink « *Thermolib* », détaillée dans [88], a été employée contenant les modèles thermodynamiques de la plupart des composants, qui sont disponibles sous forme de blocs [88], [89]. Les modèles sont donnés avec des entrées, des sorties et des paramètres internes avec un certain degré de personnalisation possible. La **Figure 7-3** montre les blocs principaux utilisés dans les modèles ici assemblés : (a) échangeur de chaleur, (b) vanne à trois voies, (c) mélangeur et (d) pompe.

En ce qui concerne la simulation globale du système et les entrées / sorties de données des modèles, le **Tableau 7-2** présente un résumé des informations. Le flux de données, la simulation du système et l'analyse des sorties ont été effectuées en trois étapes. Tout d'abord, le profil de charge de chaleur et les courbes de température de départ sont pris comme entrées pour des conditions ambiantes spécifiques, une approche itérative est appliquée pour ajuster les débits afin d'atteindre la température de départ minimale pour le réseau secondaire à basse température. Les sorties de cette simulation englobent les débits des conduites d'alimentation et de retour au côté primaire de la sous-station ainsi que les températures de fonctionnement à chaque condition de charge. Puis, les données de sortie sont traitées pour déterminer l'énergie provenant de chaque flux. Enfin, en utilisant les données de distribution annuelle de températures ambiantes d'un lieu spécifique, la part de l'énergie annuelle et l'efficacité exergetique sont évaluées. Dans cette étape, les paramètres économiques sont pris en compte pour effectuer l'analyse économique des cas sélectionnés.

Sur la base de ces différents résultats, les indicateurs des performances clés sont estimés et discutés. Comme la modélisation des charges est basée sur des valeurs moyennes horaires, la simulation des systèmes est effectuée sur des pas de temps horaires en état stationnaire, pour une gamme de conditions à charge partielle et à pleine charge.

Par ailleurs, il est nécessaire de définir un scénario global qui sert de point de départ à cette étude. Ce scénario est basé sur le projet de démonstration du sous-réseau à basse température discuté dans [22] et [10] et détaillé dans la *section 8.1.1*. Les caractéristiques choisies du réseau de chaleur secondaire sont celles des clients résidentiels exclusivement, avec une surface chauffée

totale combinée de 10 000 m² environ. Il pourrait s'agir par exemple d'un bâtiment basse consommation d'énergie à plusieurs logements ou de plusieurs bâtiments isolés regroupés dans le réseau secondaire. La distribution de température ambiante est obtenue à partir d'une base de données météorologiques uniformes (*Meteonorm*) en sélectionnant un endroit spécifique, dans ce cas Stockholm, en Suède.

Résultats clés et discussion

Les principaux résultats de ce travail sont regroupés en fonction des sous-systèmes des sous-réseaux. Sont ainsi présentés : un modèle des charges thermiques agrégées amélioré et mis à jour ; l'identification des différences sur les profils de charge et de température pour des sous-réseaux spécifiques basse température ; l'analyse des avantages et des inconvénients des sous-stations actives avec des sources de chaleur ou des réservoirs de stockage distribués et quelques stratégies de fonctionnement possibles ; et les effets de l'abaissement de la température de retour du réseau primaire en conséquence de l'augmentation de la proportion des sous-réseaux basse température. De plus, cette recherche a abordé l'intégration des ressources d'énergie thermique locales à faible émission, à travers l'analyse d'un concept hybride de sous-station solaire actif et une brève discussion sur les implications des applications de stockage de chaleur latente et sa compatibilité avec le chauffage urbain basse température.

Du point de vue de l'exploitation des micro-réseaux de chaleur, l'analyse des données du projet de démonstration de chauffage urbain basse température a montré que la température de retour agrégée du sous-réseau (**Figure 8-1** et **Figure 8-4**) suit un schéma différent de celui d'un réseau de chaleur classique : la température de retour du sous-réseau est plus basse pendant les périodes de forte demande de chaleur (**Figure 8-5** et **Figure 8-6**). Après avoir pris en compte d'autres facteurs tels que le manque de réservoirs de stockage de chaleur individuels dans les installations des clients et la température d'alimentation constante du sous-réseau, il est possible d'affirmer que dans ce cas la température de retour agrégée dépend fortement de la charge de chaleur agrégée du sous-réseau.

Cela pointe la possibilité de définir une signature de température de retour spécifique comme une caractéristique unique du sous-réseau à basse température avec une température d'alimentation constante et sans réservoirs de stockage individuels. Vu que contrairement aux réseaux de chauffage urbain classiques, le ΔT ($t_s - t_r$) dépend pour la plupart de la température d'alimentation primaire définie par l'opérateur de la centrale de production.

Du point de vue des performances du sous-réseau, l'analyse thermodynamique réalisée sur les données du projet de démonstration (**Figure 9-8**) a étendu les résultats présentés dans [10],[43],[9] où il est indiqué que le flux de retour du réseau primaire couvre environ 80 % de l'approvisionnement de chaleur total du sous-réseau. Cette affirmation est précisée par le travail réalisé ici. Il est ainsi montré que, bien que plus de 75 % du flux proviennent de la conduite retour primaire, en réalité, en termes d'énergie, seulement 35 % de la demande annuelle est couverte par le flux de retour primaire (**Figure 9-9**, **Figure 9-10** et **Tableau 9-3**). En effet, la plupart de la demande annuelle d'énergie est toujours couverte par le flux d'aller du réseau primaire.

Bien que ce résultat puisse sembler paradoxal, les principes thermodynamiques expliquent la situation comme suit: le flux d'alimentation a une température plus élevée, donc pour un ΔT donné, la chaleur transportée par unité de masse est en moyenne deux fois supérieure à celle du flux de retour primaire, et ainsi une plus grande quantité de chaleur est transférée du flux d'alimentation primaire au sous-réseau. Seulement pendant la période estivale, il est possible de préciser que 75 % de l'approvisionnement de chaleur total provient du flux de retour primaire, mais cette période englobe moins de 10 % de la demande annuelle totale de chaleur, et un peu plus de 25 % des heures de fonctionnement dans une année.

Cette analyse détaillée des données a également servi de référence pour comparer les résultats de la simulation présentée dans la section précédente et ainsi valider et vérifier les modèles (**Figure 9-2** et **Tableau 9-2**). Ces résultats montrent qu'environ un quart à un tiers de la demande de chaleur annuelle totale du sous-réseau à basse température peut être couverte par le flux de retour du réseau primaire. Cette part de la demande

couverte peut être potentiellement majeure dans les réseaux ayant des températures de retour plus élevées, ce qui est généralement la norme dans les systèmes de chauffage urbain conventionnels dans de nombreux pays. Avec une telle disposition « en cascade », la température de retour moyenne annuelle du côté primaire de la sous-station diminue entre 2 à 3 °C par rapport aux sous-stations conventionnelles. Ceci est le résultat de la combinaison de la disposition « températures en cascade » et d'une plus grande longueur thermique nécessaire de l'échangeur de chaleur à basse température.

De plus, les effets à grande échelle de la disposition « températures en cascade » et des sous-stations à basse température ont été analysés. En déterminant comment réaliser l'intégration de ces technologies dans les réseaux existants, on peut identifier les différences par rapport aux systèmes de chauffage urbain classiques. Selon le scénario où plusieurs sous-réseaux / sous-stations à basse température sont situés les uns après les autres branchés sur un réseau urbain de chaleur conventionnel (**Figure 9-13**), ces postes de livraison de la chaleur ne seraient pas toutes également capables de récupérer la même quantité de chaleur en raison de la réduction progressive de la température de retour primaire (**Figure 9-14**). On suppose que toutes les charges conventionnelles sont situées vers la fin du réseau.

Dans les conditions données ($t_r = 43 \text{ °C}$), il a été estimé qu'en fonctionnement nominal, le maximum d'énergie récupérée à partir du flux de retour du réseau primaire se produit lorsque le pourcentage de charges à basse température atteint près de 58 %, en termes de taux de pénétration de la charge totale de chaleur. En outre, l'énergie récupérée du flux de retour du réseau primaire atteint un maximum de ~5 % de la charge thermique nominale. Avec une température de retour du réseau primaire encore 10 degrés supérieure ($t_r = 53 \text{ °C}$), il serait alors possible de récupérer ~10,5 %.

Les résultats présentent également la quantification des effets des sous-réseaux à basse température alors qu'ils augmentent leur part dans la demande totale de chaleur du réseau (voir **Ch.10**). La méthodologie décrite dans [19] a été appliquée à un scénario mixte avec du chauffage urbain traditionnel et basse température (**Figure 10-1**). Il a été conclu que, bien que la demande de chaleur annuelle diminue en raison des économies réalisées

du fait de l'utilisation finale d'énergie, atteintes grâce à la rénovation, les dépenses d'approvisionnement de chaleur par MWh diminuent aussi.

La réduction de la température de retour agrégée du réseau primaire inférieure maintient les taux de pertes de chaleur à un niveau similaire, et le coût par MWh fourni reste donc relativement constant (**Figure 10-2**). Lorsque l'on considère les économies réalisées et les revenus supplémentaires, le gradient de réduction des dépenses (économies par MWh produit par °C réduit sur la température de retour du réseau primaire) ne présente pas de comportement linéaire. Ce gradient diminue, dans un premier temps, à mesure que le taux de pénétration du chauffage urbain basse température augmente, puis il augmente légèrement à nouveau (**Figure 10-4** et **Figure 10-5**). En d'autres termes, les premières charges ou sous-réseaux qui sont remplacés ou rénovés contribuent aux économies par °C, que les charges qui sont remplacées après que le taux de pénétration ait atteint 20 % environ.

De même, il a été estimé que pour un abaissement de 10 °C de la température de retour du réseau primaire, il y a une réduction de 6.7 % des pertes de chaleur totales et de 23 % de l'énergie de pompage (section 10.3). Selon une étude précédente [18], pour une diminution de 10 °C de la température de retour, la réduction des pertes de chaleur attendue serait d'environ 6 %, et l'énergie de pompage serait réduite de 40 % environ. La différence concernant l'énergie de pompage est attribuée en partie au fait que dans le présent travail elle est estimée en utilisant les courbes de rendement des équipements existants, et donc les pompes qui sont dimensionnées pour un fonctionnement nominal à pleine charge présentent une forte diminution d'efficacité à flux faibles.

Cette constatation est également confirmée par l'analyse de sensibilité réalisée sur les données mesurées du projet de démonstration existant (**Figure 9-11**). C'est là que les estimations révèlent que pour une diminution de 10 °C de la température de retour du sous-réseau, il y a une réduction de 36 % du débit requis. Cela entraînerait une diminution de 27 % de l'énergie de pompage, malgré la mise en place d'une pompe à vitesse variable [9].

Dans le cas du système de la sous-station actif solaire (**Figure 11-1**), c'est à dire un système solaire thermique sur bâtiment connecté au chauffage urbain, il a été constaté que l'utilisation de différentes topologies et stratégies de fonctionnement pourrait augmenter l'efficacité et les performances des panneaux solaires (**Tableau 11-1**). En modifiant les niveaux de température des flux d'entrée et de sortie du capteur solaire dans les plages étendues rendues possibles par d'autres dispositions des conduites de distribution, les performances du système peuvent être améliorées. Par exemple, en branchant directement la sortie du capteur à l'alimentation de la sous-station, la température de sortie du capteur peut être inférieure à 65 °C, augmentant ainsi les heures de fonctionnement annuelles. En outre, le capteur solaire peut profiter d'un T_m inférieur donné par le sous-réseau à basse température au travers du flux de retour du primaire de la sous-station. Il a été souligné aussi que les compteurs de chaleur et les contrats d'exploitation devraient prendre en considération les différentes topologies afin d'assigner équitablement les coûts et les tarifs.

Les travaux de recherche développés ici ont conduits à des résultats précieux au regard des objectifs établis et de l'identification des recherches complémentaires nécessaires. Cette recherche a montré comment un fonctionnement intégré et coordonné des sous-systèmes peut bénéficier l'ensemble du réseau à grande échelle, en intégrant les concepts de sources de chaleur multiples, des postes de livraison actifs et des stratégies de fonctionnement plus complexes. Les résultats présentés ont montré que le fonctionnement stratégique d'un micro-réseau thermique actif en tant qu'unité peut potentiellement augmenter les performances du sous-réseau et avoir des effets positifs sur l'ensemble du réseau urbain de chaleur.

Observations finales

Ce manuscrit de thèse explique et discute le contexte, la méthodologie et les résultats qui soutiennent le développement des micro-réseaux de chaleur basse température, hybrides et actifs qui deviendront probablement l'étape suivante du développement technologique des réseaux de distribution des systèmes de chauffage urbain. Au travers d'un ensemble d'évaluations des performances techniques ou économiques, cette thèse a évalué la combinaison de technologies montrant qu'il s'agit d'une solution potentiellement efficace et rentable. En outre, elle a permis l'identification

des synergies et des enjeux qui découlent de l'exploitation du sous-réseau en tant que système intégré en coordination avec le réseau principal. Dans cette thèse, les résultats obtenus ont généré des contributions précieuses au regard des objectifs de recherche initialement définis. Par ailleurs, les objectifs secondaires ont été également formulés pour donner lieu à des contributions plus concrètes et spécifiques, dans le cadre d'une évaluation technico-économique.

Il reste encore du travail à faire en ce qui concerne le développement des micro-réseaux de chaleur actifs et l'évaluation de leur rapport coût-efficacité. Il y a plusieurs enjeux qui ont besoin de recherches plus poussées pour identifier et surmonter les obstacles les plus importants afin de développer et améliorer la technologie. La discussion du concept lui-même ouvre plusieurs pistes de recherche. En particulier, il est nécessaire de comprendre clairement la valeur de la flexibilité et de la contrôlabilité donnée par les réseaux actifs de distribution de chaleur.

Alors que les avantages techniques tels que la sécurité et la fiabilité peuvent suivre une analyse directe, pour tester les avantages économiques, il est nécessaire d'examiner la filière énergétique dans son ensemble, en considérant les aspects politiques et des cadres juridiques qui amélioreront la compétitivité de la 4GDH. Les économies potentielles liées à ces nouvelles technologies en lien avec les mesures nécessaires d'accompagnement devraient ensuite être comparées aux investissements ou à la dépréciation, de manière à ce que l'alternative la plus adéquate soit sélectionnée.

D'une part, les effets des sous-réseaux à basse température qui augmentent leur contribution aux réseaux de chaleur existants demeurent une question ouverte, tandis que des topologies alternatives des réseaux sont également étudiées. D'autre part, les micro-réseaux urbains de chaleur actifs ont également le potentiel de devenir le premier pas vers le développement nodal du système de chauffage urbain (approche *bottom-up*), c'est-à-dire, le développement initial de petits réseaux d'énergie centralisée, indépendants, qui peuvent être interconnectés dans le futur pour former un / des réseaux dans une région.

Ce travail a permis de faire progresser les connaissances actuelles sur le chauffage urbain en identifiant les synergies et les défis associés à ces

nouveaux développements. Il révèle que la conception et le fonctionnement intégrés du micro-réseau ont le potentiel d'améliorer les performances du système en sa totalité. Cela accroît encore son potentiel d'intégrer des ressources de chaleur non conventionnelles et distribuées, ainsi que des charges -bâtiments- à haut efficacité énergétique, en augmentant la flexibilité et la contrôlabilité du système. Les réseaux actifs de distribution de chaleur deviendront probablement l'étape suivante dans le développement des technologies de chauffage urbain, afin de relever les défis de ce secteur d'une manière efficace et rentable. Cette recherche contribue à frayer la voie à la prochaine génération de technologies de chauffage urbain pour la reconcevoir, l'optimiser et la développer, avec l'objectif que le chauffage urbain joue un rôle clé dans le système énergétique intelligent et durable à venir.

Mots clés

chauffage urbain basse température; micro-réseaux de chaleur urbains actifs; fonctionnement de la sous-station; évaluation de la performance; sources de chaleur distribuées

Low-temperature based thermal micro-grids: operation and performance assessments

Preface

The research that led to this dissertation was conducted within the framework of the Erasmus Mundus Joint Doctorate SELECT+ ‘Environomical Pathways for Sustainable Energy Services’ as part of the Work Package 3: 2013 Thermal energy generation and distribution, which is partly funded by the Education, Audio-visual, and Culture Executive Agency (EACEA) of the European Commission.

This work was performed in two European universities: the coordinating institution KTH - Royal Institute of Technology in Stockholm, Sweden; and the partner/host institution IMT Atlantique in Nantes, France (formerly École des Mines de Nantes - EMN). Both institutions joined forces in the coordinated supervision of this work. Most of the research was performed at KTH in the Division of Heat and Power Technology (HPT/EKV) within the Department of Energy Technology (EGI), part of the School of Industrial Engineering and Management. At IMT Atlantique the host institution, the rest of the research was conducted at the Department of Energy Systems and Environment (DSEE), part of UMR CNRS GEPEA during two periods as visiting researcher.

This dissertation addresses the assessment of low-temperature based thermal energy networks through analytical simulation. It partly features content supported by both published journal papers, and peer-reviewed conference papers. It includes a district heating technology overview, techno-economic simulation modelling, data analysis of an existing demonstration project (measurements), and system analysis as well.

Acknowledgements

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I am also very grateful to many people at the EGI department at KTH, and DSEE at IMT Atlantique who directly and indirectly supported me throughout these years. I want to express my sincere gratitude to *Chamindie Senaratne*, SELECT+ programme manager, for your advice and help with countless administrative matters, and for always having an open door at your office when needed.

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- The Department of Energy Systems and Environment (DSEE) at IMT Atlantique (formerly EMN) that hosted me during two periods and operated as my primary employer;
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A very special recognition goes to the academics that accepted to review this dissertation and provide feedback to improve its quality: *Mark Howells* from KTH, *Catherine Azcaro Pantel* from INP ENSIACET, and *Stéphane Grieu* from UPVD. I would also like to express my appreciation to all my co-authors who contributed to the work produced throughout this research project. I want to sincerely thank *Peter Kaarup Olsen*, former COWI A/S employee, who supplied the data set and measurements of the LTDH demonstration project from Sønderby in Høje Taastrup, DK. Likewise, special thanks to *Alberto* who completed his master’s thesis under my supervision and whose motivation and ideas helped me to explore supplementary research paths.

I want to express my warmest appreciation to my PhD colleagues and friends who joined me at some point of this journey and whose advice and support prevented me from getting lost in the labyrinth of the PhD. In particular, I thank my office mates across the years: *Ivan, Charlotte, Nadia, Guido, Natalia, Rachid, Subodh* and *Mabrokb*, for sharing countless hours, lunches, jokes, discussions, and advice; as well as *Saman* who guided me upon my arrival to KTH, along with all my other colleagues both in Stockholm and Nantes, as well as the InnoEnergy crowd all over Europe. Some more thanks go to the rest of the students that have been part of this Erasmus Mundus joint PhD program across the other partner universities. In 2013 I was given the opportunity to join in as part of the second intake, and since then I have shared this experience with you with its ups and downs, and I want to let you know that I feel very proud and fortunate to belong to such a *SELECT+’ed* group of people.

Finally yet importantly, I want to dedicate this work to my family in Mexico, and my friends, here and there, who are also the family that we choose. All of you, in one way or another, contributed to ultimately materialize this

work. *I cherish you so much.* Muchas gracias a mis padres *Carolina* y *Fiacro* por su amor y su apoyo; e igualmente a mis hermanos *Ale* y *Mario*, que tanto los quiero por estar ahí siempre. Gracias a *Sbaron* y *Lucía*, que por estar un poquito más cerca y haber podido encontrarnos a menudo, hicieron que tenga presente y valore aquello que se ha quedado lejos. Asimismo, quiero recordar a *Virginia* y *Celia*, y aquellos que, desde algún momento durante esta etapa, velan por mí en espíritu. También muchas gracias a *Oscar*, *Oswaldo* y *Brenda*, cuya amistad me ha dado fuerzas en estos años; al igual que a mis tíos, primos y sus familias, con quienes año con año tengo la oportunidad de compartir un poco de nuestras vidas. A pesar de la distancia, a todos ustedes los he sentido aquí conmigo.

Stockholm, 2018

José Fiacro

Publication List

This doctoral dissertation is presented as a monograph thesis, which in turn features content from five published or submitted scientific articles written throughout the course of this research project. With the purpose to deliver a single coherent document, the content from these articles is distributed throughout this dissertation together with supplementary research work. These five articles are listed as follows:

- [A]** J.F. Castro Flores, B. Lacarrière, O. Le Corre, and V. Martin (2014). Study of a district heating substation using the return water of the main system to service a low-temperature secondary network. In: *DHC14: Proceedings of The 14th International Symposium on District Heating and Cooling*; Sep 7-9, 2014; Stockholm, Sweden. Swedish District Heating Association: ISBN: 978-91-85775-24-8, <http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-185715>
- [B]** J.F. Castro Flores, J. NW. Chiu, O. Le Corre, B. Lacarrière, and V. Martin (2016). Energetic and exergetic analysis of alternative low-temperature based district heating substations arrangements. *International Journal of Thermodynamics - IJOT*, 19(2): 71-80, ISSN: 1301-9724, <http://dx.doi.org/10.5541/ijot.5000148882>
- [C]** J.F. Castro Flores, J. NW. Chiu, B. Lacarrière, and V. Martin. Performance assessment of solar-assisted low-temperature district heating substations topologies. (*manuscript to be submitted*)
- [D]** J.F. Castro Flores, B. Lacarrière, J. NW. Chiu, and V. Martin (2017). Assessing the techno-economic impact of low-temperature subnets in conventional district heating networks. *Energy Procedia*, 116C: 260-272, ISSN: 1876-6102, <http://dx.doi.org/10.1016/j.egypro.2017.05.073>
- [E]** J.F. Castro Flores, A. Rossi Espagnet, J. NW. Chiu, V. Martin, and B. Lacarrière (2017). Techno-economic assessment of active latent heat thermal energy storage systems with low-temperature district heating. *International Journal of Sustainable Energy Planning and Management - IJSEPM*, 13: 5-18, ISSN: 2246-2929, <http://dx.doi.org/10.5278/ijsepm.2017.13.2>

The specific contributions of the authors involved in the production of these articles are described with more detail in the introductory chapter of this dissertation.

Other publications (not referenced in this dissertation)

During the course of this thesis work, other articles have been produced in collaboration, some of which lead to part of the investigations presented in this thesis. These articles are listed as follows, but they are not referenced in this dissertation nor discussed in detail:

- J.F. Castro Flores, B. Lacarrière, O. Le Corre, and V. Martin (2015). Energetic and exergetic analysis of a low-temperature based district heating substation for low energy buildings. In: *ECOS 2015: Proceedings of 'The 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems'*; Jun 29 – Jul 3, 2015; Pau, France.
- J.N.W. Chiu, J. Castro Flores, V. Martin, and B. Lacarrière (2016). Industrial surplus heat transportation for use in district heating. *Energy*, 110: 139-147, ISSN: 0360-5442, <http://dx.doi.org/10.1016/j.energy.2016.05.003>
- J.F. Castro Flores, B. Lacarrière, J N.W. Chiu, and V. Martin (2016). Techno-economic assessment of low-temperature district heating subnets impact on a district heating network. In: *DHC15: Proceedings of 'The 15th International Symposium on District Heating and Cooling'*; Sep 4-7, 2016; Seoul, South Korea. Korea District Heating & Cooling Association.

Conference abstracts / presentations (non-refereed):

- J.F. Castro Flores, J N.W. Chiu, B. Lacarrière, O. Le Corre, and V. Martin (2015). Conceptual study of a solar-assisted low-temperature district heating substation. In: *4DH 2015: Book of abstracts 'The International Conference on Smart Energy Systems and 4th Generation District Heating'*; Aug 25 – 26, 2015; Copenhagen, Denmark.

- A. Rossi Espagnet, J.F. Castro Flores, J. NW. Chiu, V. Martin, and B. Lacarrière (2016). Techno-economic assessment of latent thermal energy storage integration with low-temperature district heating. *In: 4DH 2016: Book of abstracts 'The 2nd International Conference on Smart Energy Systems and 4th Generation District Heating'*; Aug 27 – 28, 2016; Aalborg, Denmark.
- J.F. Castro Flores (2017). District heating and cooling systems for a sustainable built environment: a standpoint on the potential in Mexico, *in Spanish (Sistemas de climatización de distrito para un medio urbano sostenible y su potencial en México)*. In: *Memorias 6° Simposio CONACyT: '6th Symposium CONACyT Fellows in Europe'*; Mar 29–31, 2017; Strasbourg, France. http://www.mufm.fr/sites/mufm.univ-toulouse.fr/files/evenement/Simposio2017/Memorias/Energias/jose_fiacro_castro_flores.pdf

Nomenclature¹

Acronyms & Abbreviations

4GDH	Fourth generation district heating
ADTN	Active distribution thermal networks
CHP	Combined heat and power
DES	District energy systems
DH	District Heating
DHW	Domestic hot water
DL	Distribution losses
DRT	Difference of return temperatures
DSM	Demand side management
FGC	Flue gas condenser
FPC	Flat plate collector (solar thermal)
GHI	Global horizontal irradiation
HE _x	Heat exchanger
HLV	Heat load variations
HP	Heat pump
HPU	Heat production unit
HTF	Heat transfer fluid
ICT	Information and communications technology
LCA	Life cycle assessment
LDC	Load duration curve
LEB	Low energy building (energy efficient building)
LH-TES	Latent heat thermal energy storage
LHV	Low heating value
LT	Low-temperature
LTDH	Low-temperature district heating
NTU	Number of transfer units
PCM	Phase change material
QP	Quadratic programming
RMSE	Root mean squared error
R-R	Return-to-return
R-S	Return-to-supply

¹ The main nomenclature used in this dissertation is here given for easy access. Throughout this dissertation, additional specific notation is introduced as required.

sR-R	Substation return-to-return (primary)
SH	Space heating
SH-TES	Sensible heat thermal energy storage
SLP	Standard load profile
SSM	Supply side management
SSE	Sum of squares due to error
TES	Thermal energy storage
TMY	Typical meteorological year

Latin Symbols

[units]

A	(collector) area	[m ²]
a	heat demand coefficient at low temperature	[kW]
a_1	1st order collector heat loss coefficient	[W/K·m ²]
a_2	2nd order collector heat loss coefficient	[W/K ² ·m ²]
b	inflection point temperature coefficient	[°C]
C	cost	[EUR]
C_r	heat capacity ratio	[-]
c_p	specific heat capacity at constant pressure	[J/kg·K]
d	temperature dependent losses coefficient	[kW/°C]
e	specific exergy	[kJ/kg]
E	exergy	[kJ]
e	temperature independent losses coefficient	[kW]
f	temperature dependent variation coefficient	[1/°C]
g	temperature independent variation coefficient	[kW/kW]
G	global solar radiation	[W/m ²]
h	specific enthalpy	[kJ/kg]
l	(pipe) length	[m]
\dot{m}	mass flow rate	[kg/s]
P	power	[kW]
\dot{q}	heat load	[kW]
Q	heat	[kWh]
s	specific entropy	[kJ/kg·K]
t, T	temperature	[°C] or [K]
U	heat exchange coefficient	[W/m ² ·K]
UA	HEx heat transfer rate	[W/K]
W	work	[kW]

Greek Symbols

		[units]
α	power-to-heat ratio	$[\text{MW}_{\text{el}}/\text{MW}_{\text{th}}]$
Δ	delta, difference	/
ε	HEx effectiveness	[-]
ξ	exergy efficiency	[-]
λ	thermal loss coefficient	$[\text{W}/\text{m}\cdot\text{K}]$
η_0	solar collector maximum efficiency	[-]
η_c	solar collector operating efficiency	[-]

Subscripts and Superscripts

0	reference state
a	ambient/outdoor
c	collector
el	electrical
eq	equivalent
g	ground
ip	inflection point
in	inlet
loss	heat loss related
m	arithmetic mean
max	maximum
mc	marginal cost
mch	mechanical
min	minimum
PH	physical component
pump	pumping
r	return pipe
ref	reference
s	supply/forward pipe
sav	savings related
sr	substation return
th	thermal
tot	total
out	outlet
w	water

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Part I. Introductory Section

The first part of this dissertation consists of one main chapter that introduces this research work and helps the reader appreciate the overall work and the sections to follow. Firstly, the background and context of this research focused on district heating are discussed. This is followed by a review of motivations and an overall problem description, as well as a simple overview of the research approach. The thesis structure is then outlined, and a short summary of the peer-reviewed publications that support this dissertation is provided.

1. Introduction

This chapter presents the overall context and motivations for the development of this research work. Then, the general problem description is discussed, passing through the scope and focus, to then state the research objectives. Next, the thesis outline and structure is described and a preliminary overview of the research approach is given. Finally, a summary of the publications that support this dissertation is presented.

1.1. Context & motivation

Our world's sustainable development goals comprise climate change alleviation and ensuring a healthy environment, while eradicating poverty and social inequality. Achieving these goals will require moving towards climate-resilient, resource-efficient, and low-carbon pathways, and consequently a sustainable energy system. With such transformation, it will be possible to achieve the sustainable energy objectives of universal access to modern energy services, energy efficiency, and a major share of renewables in the global energy mix [1].

Global energy use in the form of heat accounts for more than 50% of the final energy use, and it has significant implications on energy-related CO₂ emissions and energy security. Moreover, the urban environment, cities in particular, account for more than 70% of the global energy demand, therefore they have a central role in the transition to a sustainable energy system. In the urban environment, electricity, heat, and transport systems will need to be better integrated to deliver cost-efficient and low-carbon energy solutions [2].

Thanks to their flexibility in scope, fuel sources, and technology, modern district energy systems (DES) are envisioned as the most effective approach for many urban centres to transition to sustainable energy use, including but not limited to heating and cooling. DES systems create synergies among the production and supply of heat, cooling, domestic hot water and electricity, and can be integrated with other systems such as waste management, sewage treatment, and transport. Up to now, they assemble the best practices for

providing a local, affordable and low-carbon energy supply, through economies of scale, diversity of supply, energy balancing and storage. Still, to enhance the possibilities of DES to reach their full potential under the increasingly challenging circumstances, further research, demonstration and technological development are needed. Thus, in a future sustainable energy landscape, district energy systems must evolve to provide more flexibility, in particular in the fields regarding the development of low-temperature DH networks, the integration of renewable energy sources together with innovative thermal storage, and the interaction with other energy networks (e.g. electricity and gas) [3].

Many renewable heat sources and technologies are already mature and can provide heat at costs that are competitive with fossil fuel-based heat in an increasing number of applications and locations. Nevertheless, due to the lack of attention on renewable heat, efforts to replace fossil-fuel generated heat with renewable energy sources are only slowly gaining momentum in spite of their substantial potential. In addition to renewable heat sources, a range of technologies, including efficient heat pumps, the use of waste heat from co-generation and industry, or the use of renewable electricity for heating, also have significant potential to contribute to the global energy share in heat supply and usage.

1.2. Problem description

District heating (DH) systems enhance the efficiency and flexibility of the overall energy system, and although these technologies are mature and robust, the concept still faces challenges and is continuously evolving. Existing DH production and distribution networks have been appropriately designed technically and economically for traditional levels of heat demand. However, due to factors such as new energy efficiency policies in place, the heat demand in urban areas is expected to gradually decrease in the future [3], [4]. Thus, the current district heating technology is facing changing circumstances that will eventually challenge the profitability of the DH industry. New directives on the construction and refurbishment of buildings define higher requirements regarding building energy performance, so the existing DH system may not be as technically and economically effective to cope with a decrease on heat demand and heat density.

The DH industry and conventional DH technology will face challenges on effectiveness and profitability when servicing the newly built energy efficient buildings that would lower the heat density in the existing networks. Heat demand and linear heat density (i.e. the ratio of the annual heat delivered to the total length of the DH piping network) are two related parameters that determine the profitability of a DH system. However, heat density in the future will decrease due to multiple factors, including building renovation and global warming [5],[6]. Consequently, relative distribution heat losses are higher, and so, from the supply and distribution perspectives, investment and operating costs increase relative to total heat sales. As the return of investment in DH systems is based on heat sales, which depend on the heat demand over periods of several years, the profitability of new DH networks, expansions and/or refurbishment of the existing ones should be carefully planned and analysed [7]. Thus, the system requires an enhancement to effectively adapt to the changing conditions so as to maximize their benefits.

In light of new developments, the 4th generation DH technologies (4GDH, detailed in [8]) are envisioned as an environmentally friendly set of solutions able to cope with the coming challenges and to cost-effectively provide heating services to the building stock. Besides the challenges that the deployment of the new technologies represent, there is also a need to efficiently integrate other thermal energy sources such as geothermal and solar-thermal, or industrial surplus heat, which are low-grade (temperature), fluctuating, intermittent, or decentralized in nature, but that increase the levels of energy efficiency, sustainability, and security of the entire system.

It is expected that the DH sector will experience a transition period of several decades during which the current and the new generation of DH technologies will be operating simultaneously, complementing each other to meet the thermal energy demand of the building stock [8]. In locations with a large share of well-established DH systems, this deployment will occur in parallel to the existing networks, and will likely require secondary networks (subnets) operating at lower temperatures and pressures, to provide heat to energy efficient building areas. In the longer term, a nearly full penetration of the new generation DH technology is the target [3].

1.3. Scope & focus

The work hereby presented is focused on low-temperature based district heating (LTDH) at the network distribution level. It is therefore centred on LTDH subnets/secondary networks servicing energy efficient buildings either new or refurbished, and integrating distributed low-grade thermal energy sources. It defines and implements a collection of cumulative technical and/or economic performance assessments as an approach to evaluate and compare the technologies. Based on the state-of-the-art analysis of plausible and existing LTDH technologies, a hypothetical scenario of such thermal-micro grid was conceived based on the location and weather of Stockholm, Sweden. The identified knowledge gaps and challenges were used to define several cases to evaluate potential contribution of the technologies.

Previous research has demonstrated the feasibility of LTDH and 4GDH technologies. Their deployment together with the integration of long-term storage and decentralised thermal energy sources paves the way for the redesign of the system and the creation of new networks concepts. Most of the individual technologies that enable the integration of 4GDH are already available or in a test phase at small- and medium-scale demonstration projects [9]. Thus, this dissertation extends its focus to the integration of LTDH subnets in conventional DH networks with cascading piping layouts, including distributed heat sources.

Following the identified research paths, which will be further discussed and detailed, this work covers the high-level design and modelling of an active DH substation and outline some possible operating strategies. The analysis covers the aggregated heat load and temperature at the substation/subnet, thus individual human behaviour inside the buildings is not considered. In the case of substations and subnets, the data from an already existing LTDH demonstration project is analysed to perform pattern identification on aggregated heat load and operating temperatures and expand the knowledge in the area. This work also presents an evaluation of the integration of locally available low-grade thermal energy sources, by analysing a hybrid concept of a solar-assisted LTDH substation. Then, an introductory discussion of the implications of active latent heat storage applications and LTDH compatibility, layouts and operating strategy is also addressed.

This work uses a techno-economic approach to quantify the overall impact of LTDH on conventional DH systems operation, using ‘temperature cascading’ and subnets, and the interaction load/subnet/substation/sources, which has been so far left in the background in previous research. In summary, the scope of this work covers the DH technologies at the distribution layer of the system focused on low-temperature thermal micro-grid subsystems: (1) a low-temperature DH subnets feeding energy efficient loads/sinks; (2) an active substation as aggregator, coordinating heat flows and sources; and (3) local low-grade thermal energy sources and/or storage.

1.4. Research objectives

This research project has as overall purpose to present, define, and assess from a techno-economic perspective the concept of low-temperature based active thermal subnets as an effective and cost-efficient solution to meet the thermal energy demands of energy efficient building stock. The main objective is to present an evaluation of performance variation, technically and economically, given by the integrated operation of a low-temperature based active thermal micro-grid subsystems.

Following the main objective and the context of the active thermal micro-grid, the analysis follows a set of secondary objectives defined based on the state-of-the-art analysis later presented in Chapter 3, together with the identified research paths discussed in Chapter 4, where the novelty of these objectives is also discussed (refer to Figure 4-1). These secondary objectives are stated as follows:

- a) Delimit and define the concept of ‘active thermal micro-grid’ (distribution network) and conduct technical feasibility and performance assessments.
- b) Perform a high-level design and modelling of the active DH substation system and layouts, and evaluate possible operating strategies through thermodynamic performance analysis.
- c) Validate the feasibility assessment/proof of concept of the active LT substation/subnet system through a comparison with the available measurement data set of an existing LTDH demonstration project.

- d) Characterize the aggregated LT subnet operating parameters through patterns identification and modelling of aggregated heat load and temperature signatures.
- e) Perform the high-level design and modelling of an active DH substation system and layouts, and evaluate possible operating strategies through thermodynamic performance analysis.
- f) Quantify the overall impact of LTDH subnets on conventional DH systems operation through techno-economic performance analyses.

This work is an attempt to expand the current knowledge in the field of district heating by introducing, analysing and discussing the concept of secondary networks/subnets as small-scale, multi-source, grid-connected, active thermal energy systems. Likewise, it takes a further step, assuming that the low-temperature based subnet can be seen as an active thermal micro-grid, possibly with bidirectional heat flows. This work presents a collection of techno-economic performance assessments of such thermal energy subnet subject to certain operating strategies. In this manner, it has the intention to pave the way to identifying the synergies and challenges that arise by operating the subnet as an integrated system and its impact on the primary network, which have not been studied in detail.

1.5. Thesis outline & structure

This dissertation is in the form of monograph supported by peer-reviewed publications and divided into five parts: The first one introduces the research work, motivation and objectives, and the second part presents the literature review that leads to the identification of research paths and to the proposed concept that is object of study. Part 3 describes the general methodology, and modelling and simulation techniques. Part 4 follows, where the results of applying the methodology are given in the form of a series of incremental studies. The last part discusses the main conclusions, and perspectives for further research. A brief chapter-by-chapter description is depicted in **Figure 1-1** showing the dissertation structure and main topics treated in each chapter.

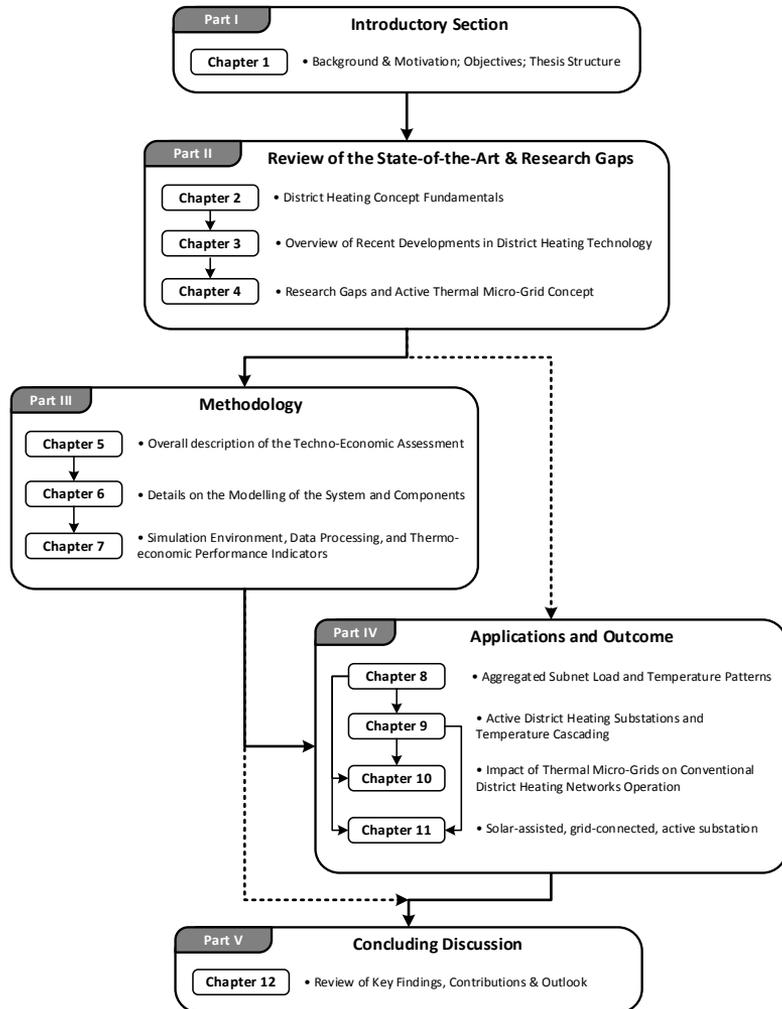


Figure 1-1. Diagram of the thesis structure

The diagram in Figure 1-1 illustrates how this dissertation is organized. It consists of 12 chapters distributed in five main parts. Part I contains one main introductory chapter. Next, Part II comprises three chapters that present the DH essentials, literature review and knowledge gaps. Part III explains the research approach and methodology divided in three chapters. Part IV discusses the results of applying the described methodology distributed in four chapters. Finally, Part V consists of one chapter that discusses the conclusions, key findings, review of contributions and outlook.

1.6. Research approach overview

This dissertation is the result of a mixed methodological approach focused on system modelling and analytical simulation, supported by other methodologies, including literature review, and measurement data analysis for validation. In order to gauge the performance of the LT thermal micro-grid, and to evaluate the potential benefits and drawbacks, the subnet system is divided into three subsystems: (1) aggregated low-temperature load, (2) active substation, and (3) local source/storage, which are modelled first separately and then as a unit. In addition, to complement the validation & verification of some of the subsystems, measurement data from of an existing LTDH demonstration project in Taastrup, Denmark was used [10].

The software of choice has been *Matlab*®/*Simulink*® used for the programming of the modelling and simulation, as well as for data analysis, curve fitting, solution of non-linear systems, and optimization. The performance analysis is conducted through thermodynamic and economic models of the subsystems operating at full/partial loads (steady state), and so the selected main performance indicators are: primary energy use, exergy, operating temperatures and related operating costs/revenues. The results of this assessment are presented as a set of consecutive and incremental performance assessments based on selected developed cases within the main scenarios.

1.7. Summary of referenced publications & individual contributions

This dissertation is presented as a monograph, which in turn features content from five publications (peer-reviewed scientific articles) written throughout the course of this research project. Moreover, this subsection presents a brief description of these papers, with key findings and emphasizes the contributing role of the author of this dissertation in each work. A summary of the publications already listed in previously in the ‘*Publication List*’ together with the highlighted contributions presented in this dissertation are given in **Table 1-1** describing research fields, focus, and methodologies.

Paper A: ‘*Study of a district heating substation using the return water of the main system to service a low-temperature secondary network*’ (2014) introduces and presents the concept of the LTDH substation with temperature cascading

by comparing its energetic performance to a conventional substation. It includes a concise preliminary literature review of LTDH applications and demonstration projects. By means of the design, modelling and simulation of a LTDH substation system and layout, the feasibility of the concept was tested and confirmed, and the main benefits and drawbacks were drawn. This paper was presented at *DHC14: 'The 14th International Symposium on District Heating and Cooling'*. For this publication, the author of this dissertation identified the main concept and then further developed it through discussions with the other authors; then performed the modelling and simulation as well as the writing of the manuscript, which the other authors reviewed and discussed.

Paper B: *'Energetic and exergetic analysis of alternative low-temperature based district heating substations arrangements'* (2016) takes the concept of the LTDH substation with temperature cascading a step forward by developing a more detailed energy analysis and introducing an exergy analysis. For this publication, the author of this dissertation performed more detailed modelling, and the exergy analysis was deeply discussed with the other authors. The author of this dissertation wrote an earlier version of the paper which was presented at the *ECOS 2015: 'The 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems'*. It was later revised and updated as per invitation for a journal for which the other authors reviewed the paper and provided feedback. This paper sheds light on the relevance of pumping power from the exergy perspective, which becomes the major exergy source for the whole heat network during the summer period and thus also the major source for exergy destruction or irreversibilities. An extended version including a single-objective optimization performance comparison is included in this dissertation.

Paper C: *'Performance assessment of solar-assisted low-temperature district heating substations topologies'* (to be submitted, manuscript under revision) introduces a multi-source concept for the LTDH subnet, by means of an active grid-connected, solar-assisted, LTDH substation without a heat storage system. Alternative layouts for the prosumer substation are modelled and simulated, and a simplified operating strategy to coordinate both subsystems is applied. The outcomes show that LTDH operation benefits the solar collector yield and thus increases the operating savings. The need for a different metering scheme is indicated and discussed. The results of this analysis were first presented at *4DH 2015: 'The International Conference on Smart Energy Systems'*

and *4th Generation District Heating*'. The author of this dissertation developed the concept in cooperation with the other authors who also provided feedback before the manuscript submission. For this paper, the author also performed the thermodynamic modelling and simulation of the systems, introduced the economic assessment, and wrote the manuscript draft. A revised and updated version of the results has been included in this dissertation.

Paper D: '*Assessing the techno-economic impact of low-temperature subnets in conventional district heating networks*' (2017) develops an effort to quantify the impact of LTDH subnets on a conventional DH network from the perspective of thermodynamic performance analysis, leading to an economic assessment. It shows that thanks to the reduction of primary return temperature due to the LT subnets, the relative heat losses are maintained despite the heat demand reduction. The benefits also account for reduction in pumping effort requirements, and a potential increase in CHP electricity generation and FGC heat recovery. This paper was first presented at *DHC15: The 15th International Symposium on District Heating and Cooling*, then an updated and revised version was submitted for publication. The author of this dissertation performed the problem definition, scenario delimitation, and modelling and simulation for the techno-economic assessment. The other authors discussed the problem definition and scenario, and revised the manuscript draft.

Paper E: '*Techno-economic assessment of active latent heat thermal energy storage systems with low-temperature district heating*' (2017) identifies the benefits and drawbacks of latent heat TES in combination with LTDH as well as key aspects on their compatibility. This paper was developed on the base of a MSc. thesis project described in [11]. The results of this analysis were first presented at *4DH 2016: The 2nd International Conference on Smart Energy Systems and 4th Generation District Heating*', and then a full paper was submitted for journal publication. The author of the present dissertation defined the conceptual framework and supervised the modelling and simulation, which was performed by the second author. The other authors provided feedback on the manuscript draft. As most of the modelling and techno-economic assessment were performed by the second author, these results are not included in this dissertation, and thus only the conclusions from the literature review and discussion regarding TES performance and layouts with LTDH subnets are covered.

Table 1-1. Summary of referenced publications in this dissertation and contributions

<i>Reference Publication(s)</i>	<i>Field(s) of Research</i>	<i>Focus</i>	<i>Methodology</i>	<i>Contributions</i>
Dissertation -Ch. 3 & 4- (2013 - 2014; 2017)	Low-Temperature District Heating (LTDH) and the 4GDH	Analysis of the state-of-the-art in LTDH technology and subnets	Literature Review	<ul style="list-style-type: none"> • Identification of knowledge gaps in the state-of-the-art analysis in LTDH and 4GDH at the system distribution level • Introduction and discussion of the concept of low-temperature based, active thermal micro-grid
Paper A (2013 – 2014)	District heating substations, LTDH subnets, and network layouts	Feasibility assessment of active LTDH substation (indirect connection) with temperature cascading	Literature Review; Thermodynamic Performance Analysis; Modelling and Simulation	<ul style="list-style-type: none"> • Feasibility analysis of an active LTDH substation (indirect connection) with temperature cascading • High level design and modelling of the LTDH substation system and layout
Paper B, Dissertation -Ch. 9.1; 9.3- (2015 - 2016)	District heating substations, LTDH subnets, and network layouts	Performance analysis of an active LTDH Substation and subnet (indirect connection; temperature cascading)	Thermodynamic Performance Analysis; Modelling and Simulation (Energy & Exergy)	<ul style="list-style-type: none"> • Application of energy and exergy analysis to a LTDH substation/subnet with temperature cascading • A single-objective optimization strategy applied to control the substation operation using thermodynamic performance indicators as objective functions • Estimation of the maximum energy recovery from temperature cascading
Dissertation -Ch. 8.1; 9.2- (2014 - 2015)	Performance of LTDH subnets and layouts	Performance analysis of a LTDH demonstration project: subnet with direct connection and temperature cascading	Case Study: Thermodynamic performance analysis; used of a measurement data set from an existing LTDH demonstration project	<ul style="list-style-type: none"> • Presentation of a detailed thermodynamic performance analysis of a LTDH subnet case study with temperature cascading • Identification of specific seasonal and weekly, load and temperature patterns of the LTDH subnet case study • Comparative validation of the proposed LT subnet concept (indirect connection), from the modelling and simulation feasibility analysis

Table 1-1 (continued). Summary of referenced publications in this dissertation and contributions

<i>Reference Publication(s)</i>	<i>Field(s) of Research</i>	<i>Focus</i>	<i>Methodology</i>	<i>Contributions</i>
Dissertation -Ch. 6.1; 8.2- (2016 - 2017)	Aggregated load and temperature patterns of LTDH subnets	Modelling of hourly aggregated heat load and temperatures of a LTDH subnet	Case Study: Modelling & Validation using the available measurement data set	<ul style="list-style-type: none"> • Simplified and updated model of aggregated heat loads, application to a LTDH subnet • Simplified model of aggregated return temperature (return temperature signature) of a particular LTDH subnet
Paper C, Dissertation -Ch. 11- (2015 - 2016; 2017)	Distributed heat sources with LTDH, and heat prosumers	Solar-assisted active LTDH substation: multi[source, grid-connected, subnet prosumer	Techno-economic performance analysis; Modelling and Simulation	<ul style="list-style-type: none"> • Introduction of a concept for a multi-source, grid-connected, solar-assisted, LTDH active substation (no storage) • High level design and modelling of the solar-assisted LTDH substation system and layouts • Quantification of the impact of the multi-source system on the subnet operating costs
Paper E (2016 - 2017)	Distributed active heat storage integrated with LTDH	Active thermal energy storage (latent heat) applications to LTDH subnets	Techno-economic performance analysis; Modelling and Simulation	<ul style="list-style-type: none"> • Identification of key aspects of latent heat thermal energy storage compatibility with LTDH • A cost analysis of various PCM materials for TES in LTDH applications • Discussion of possible piping layouts and operating strategies for the proposed system
Paper D, Dissertation -Ch. 10, 9.3- (2015 – 2017)	Low-temperature based subnets within conventional DH networks	LTDH subnets effects on conventional DH network performance and operation	Techno-economic performance analysis; Modelling and Simulation	<ul style="list-style-type: none"> • Quantification of the impact of LTDH subnets on a conventional DH networks • Thermodynamic performance analysis of the primary network return temperature as a result of the introduction of LTDH subnets • Quantification of the potential increase on savings and extra earnings due to LT subnets

Part II. District Heating Technology Fundamentals and Current Challenges

The second part of this work elaborates on the background and problem description supported by a literature review. First, the fundamental concept of district heating and its fundamentals are introduced to help the reader identify the main concepts and definitions required to follow the development of this work. The state-of-the-art on district heating technology focused on the distribution level of the system is discussed. Next, the benefits and drawbacks of these new developments are reviewed leading to the identification of knowledge gaps and challenges to be addressed. Then, based on the review of the interaction load/subnet/substation/sources, the proposed concept of low-temperature based active thermal micro-grid is explained and discussed.

2. Fundamentals of District Heating

In this chapter, the fundamental concept of district heating is reviewed, including the basics on network dynamics and operation. The main purpose is to highlight the concepts and definitions required to understand the development of this work, and to describe the main benefits and drawbacks of the technology. The distribution level of the system is the focus of this review, including its operation, components, and operating parameters. The reader with advanced knowledge in the field may choose to just skim through this chapter.

2.1. The District Heating concept and its role in the energy system

District heating (DH) is a concept that came into existence since the late 19th century as a means of moving bulk heat from heat sources to a group of end users or consumers for example, buildings within a city. In this way, heat generation was centralized and shifted to a location away from the end users. Today, the fundamental idea of district heating is to find a way to use local thermal resources to meet the demand of a local heat market, allowing the use of surplus heat from existing sources that would otherwise be rejected directly to the environment [12].

A district heating system can be roughly divided into three main subsystems: production, distribution and utilization, see **Figure 2-1**: a heat plant (heat producer) increases the temperature of a heat transfer fluid which is pumped through a distribution grid (pipes) to the end users or consumers facilities. There, it may pass through a district heating substation where heat is transferred to the internal heating system of the building.

From a historical perspective, the state-of-the-art DH technologies that are currently being developed and deployed belong to the 4th generation of DH technology (4GDH). By contrast, The 1st generation of DH systems used steam as a heat carrier, it was introduced at the end of the 19th century and was used well until the first half of the 20th century. Steam-based DH is an outdated technology, due to high heat loss, high operating and maintenance

costs, and safety reasons. The second generation changed to pressurized hot water as thermal carrier ($T_{supply} > 100^\circ\text{C}$, high temperature water systems) and emerged in the third decade of the 20th century, and was deployed until the 1970s. The third generation of systems came after, and was a success in the 1980s. The energy carrier is invariably pressurized water, but the supply temperatures are lower ($T_{supply} < 100^\circ\text{C}$, medium temperature water systems) and are often combined with the use of two-pipe systems and prefabricated pipes when possible [8],[12]. They are the most used systems in both the refurbishment of existing networks and in new projects.

DH has reached very different levels of success in different European countries. The reasons for such disparities are better explained by historical and socio-economic factors rather than by climatic differences; in fact according to [13], only about half of the variations in residential space heating demand in Europe can be explained by climatological influences and geographical distribution. The other influencing factors are heat costs, effective indoor temperatures², and hot water use. Therefore, average specific space heating demands (yearly kWh/m²) are comparable in western, central, eastern and northern Europe. For instance, space heating demand in Stockholm should only be 20% higher than in Brussels or Strasbourg, while in Florence only 20% lower than those cities.

In "consolidated" countries, DH systems are well established, have a large market share (Denmark, Sweden, Finland, >50%) and form an essential part of the energy infrastructure. In the "refurbishment" countries, DH systems also have high market shares (Eastern Europe, 20-50%), but require renovation. In the "expansion" countries, DH is present in specific urban contexts. There, total market share is low (France, Italy, Germany, Norway <5-15%), but could potentially increase by expanding existing systems and establishing new ones. A limited number of DH systems appear in "new development" countries (Spain, United Kingdom, Portugal <1%), with a negligible share although there is growing interest in the technology [14], [15].

² Effective indoor temperature is some degrees lower than the actual indoor temperature in order to compensate for internal temperature gains, such as human activity and indoor electricity use, and is also influenced by solar gains. Effective indoor temperature depends on the building insulation, such that its magnitude tends to be lower with better insulation and vice versa [13].

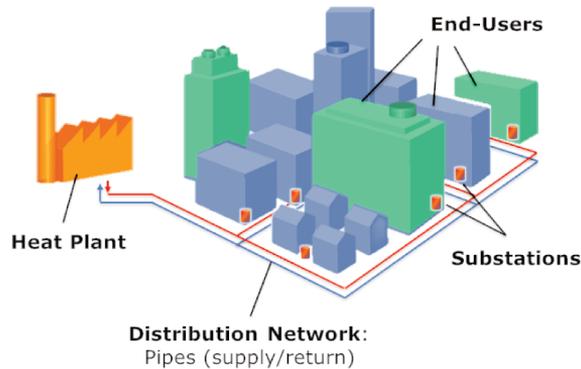


Figure 2-1. A high-level depiction of a District Heating system

The figure shows the main elements of a District Heating system in a simplified high-level depiction. There, the heat plant transforms the primary energy into heat that is circulated by pumping a heat transfer fluid (hot water) through a distribution network. The network consists of several branches of supply and return pipes that reach the buildings DH substations. In indirect connection systems, the substations separate the primary network from the building system via a heat exchanger (HEX) the customers circuits are equipped with radiators for SH, or to heat up DHW.

DH systems both enable and benefit from the concept of ‘sequential energy supply’ also known as ‘energy cascading’ that is based in on the idea of ‘serial supply structures’ in the energy system. The concept consists on identifying excess energy from a process, and using it to feed a subsequent energy demanding process. This leads to increased energy resource optimization that in turn reduces the aggregate primary energy demands for the sum of processes engaged in the synergy chain [16]. In heat demanding processes, rejected heat flows from primary energy conversions are recovered to be used at industrial facilities or distributed in district heating systems, satisfying low-temperature heat demands with already converted energy (secondary heat that would otherwise be wasted), instead from other primary energy resources.

DH also benefits from the ‘economies of scale’ of heat mass production from heating plants and technology that recovers residual heat from processes related to energy conversion, such as power generation in CHP stations or industrial processes. Large central heat production offers environmental benefits for combustion-based heat generation through

economical exhaust gas filtering, and efficient combustion. This contributes to lower heat generation related emissions.

2.2. District Heating system dynamics and operation

District heating is a technological solution that addresses the need of a comfortable indoor living environment. The two main services provided by district heating, especially in residential use, are the delivery of heat for domestic hot water (DHW) and space heating (SH). Other uses, such as drying and washing facilities, absorption cooling and industrial applications, are not considered in this work. Domestic hot water and space heating systems are not specific to district heating, and so can be found in all types of buildings, regardless of the source of heat. However, the design and operation of DH systems depend in various ways on the final use on the consumer side; for instance, human (mis)behaviour significantly affects the magnitude of the heating demand and heating peak load with respect to reference values of low energy buildings [6].

2.2.1. Heat supply

The heat in a DH system can come from a number of different sources. Some production sites use primary energy to generate heat from fossil fuels or renewable energy sources. Some typical examples of heat production facilities are combined heat and power (CHP), and waste incineration heat-only boilers. Due to the 'low' temperature required for space heating and hot tap water, DH systems temperatures are relatively low, allowing the use of heat from a wider range of heat sources. This can be the excess heat from industrial or commercial processes. The fact that the district heating system can utilize a wide variety of heat sources is one of the greatest advantages of the system. The wider range of heat sources also increases security of supply for the customers, because the systems will not heavily depend on a specific type of fuel, such as oil or gas. It also means that more renewable energy sources, cleaner fuels and fewer primary energy sources can be used [12].

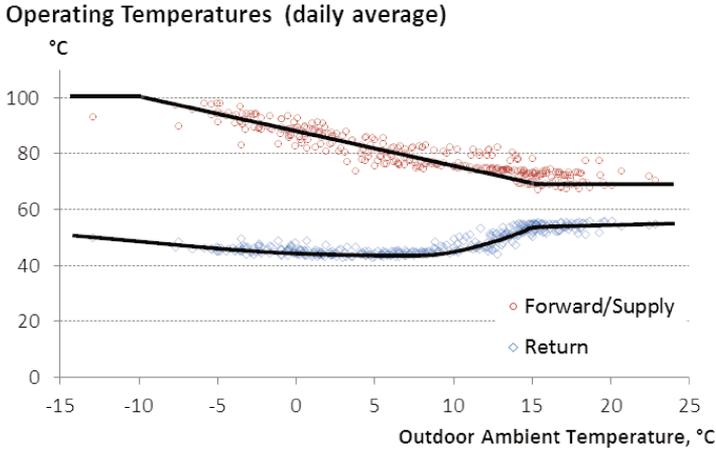
Heat producers set the supply temperatures to optimise their operation, minimize costs and maximize profit. The conventional operation of the forward/supply water temperature follows an outdoor temperature

compensation strategy, to be described and detailed in the next section. This strategy is widely used because of its benefits: by reducing the water temperature when the heating demand decreases, lower return temperatures are also obtained, and consequently energy losses in the distribution network are reduced. The lower operating temperatures also reduce the effects of pressure fluctuations and increase considerably the life of the hardware [17], which in turn reduces maintenance efforts.

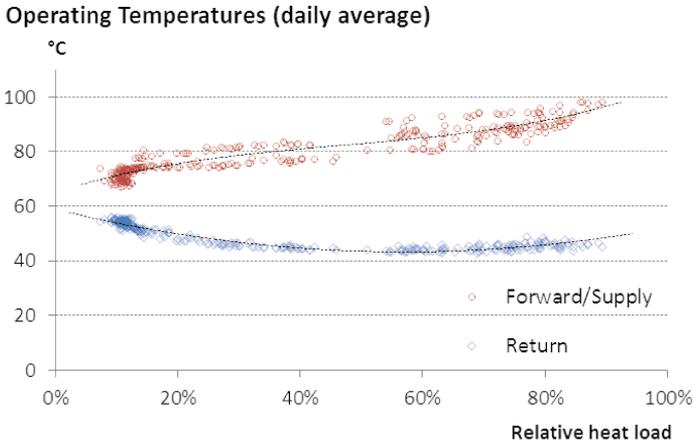
2.2.2. Distribution network & operation

The distribution system consists of a network of insulated pipes through which a heat transfer fluid of choice circulates. The fluid of choice is usually water, but in older systems, steam was also common. The conventional network design and operation follows a passive distribution network. This type of distribution network is designed to carry the bulk heat from the central heat plants and distribute it to the customers (passive loads). The distribution system includes supply pipes, which carry the fluid at high temperature and return pipes, which take the fluid at lower temperature back to the heat plants. The temperature difference between the fluid in the supply and the return is called cooling or ΔT . The typical supply and return temperatures curves as a function of the outside temperature are shown in **Figure 2-2**.

The supply temperature is usually higher during the colder months because of the higher heat demand. It is set by the utility (heat plant) and follows an *ambient temperature compensation strategy* described as follows: from the maximum supply temperature at nominal load, the supply curve decreases linearly until the break point; after this point, the supply temperature is rather constant. In reality, the utility sets the supply temperature, which varies according to their own operating algorithms that take into consideration different heat generation technologies, the current network ΔT , pumping power, centralized thermal energy storage, and forecasted heat demand. On the other hand, the aggregated return temperature coming into the heat plant is the result of a combination of different factors including the outdoor ambient temperature, human behaviour, the actual condition of the DH substations, and the network itself. The return temperature follows approximately the supply temperature behaviour, except during the summer months.



a) Operating temperatures vs. outdoor temperature



b) Operating temperatures vs. relative heat load

Figure 2-2. Typical supply/return operating temperature curves*

Figure 2-2a shows typical operating temperature curves for a District Heating network supply and return. In (a), the supply temperature ambient temperature compensation strategy is shown in the solid line. In (b), the same points are plotted but as a function of the relative heat load.

*Figures originate from the data set of the LTDH demonstration project described in [10].

Heat distribution is subject to heat losses that occur during transmission from the production site to the end users. The temperature difference between the heat transfer fluid passing through the pipes and the surroundings is responsible for the heat losses that may range from 5% to 20% annually, even when the pipe system is well insulated.

To provide DH to the buildings heating systems, a pressure difference must be created between the supply and return pipes to circulate the heat carrier (water) in the system and reach the end users installations. Differential pressure is created on production sites using electric-driven pumps, which means that the pressure in the supply pipe is higher near the heat plant and then it decreases further in the network due to pressure drops inside pipes and geography. The pressure of the heat carrier is transformed into heat throughout the distribution network due to friction in pipes, valves and heat exchangers, resulting in a small decrease in the need for heat supply at production sites.

A very common element of the distribution system and network layouts that is often overlooked is the bypass. A bypass is a direct ‘short-circuit’ connection from the supply to the return line of the thermal networks, and they fulfil purposes related to system maintenance and robustness. For maintenance purposes, manually operated bypasses may be installed to allow flushing and water treatment, and they are usually located above each substation unit. Likewise, bypasses are installed to maintain minimum pump flows or ensure minimum supply temperatures. For the latter, thermostatic valves operate as bypasses such that each substation delivers DHW at a minimum temperature within an acceptable time to the user. These bypass valves are often placed on the DHW circuit of the substations, at the end of long DH lines, and/or at the tops of buildings, to also maintain minimum pump flows. As the bypasses increase the temperature of the return substantially by pulling in hot water directly from the supply to the return, their use should be as limited as possible [18],[19], and their effective control is essential for good system performance.

The commonly used control strategies for bypass valves are: manual control and thermostat control. Manually operated valves are usually left open regardless of the situation except for long periods of absence of the users. This results in a small, but constant flow from the supply line to the return line. Thermostatically controlled valves only open if the supply water drops

below a temperature set-point value, and they reduce operational costs related to bypass flows significantly. Some improvements in this matter include the use of the ‘undesirable’ bypass mass flow for bathroom floor heating systems [20], or the study of new theoretical control benchmarks for a just-in-time delivery of DHW [21].

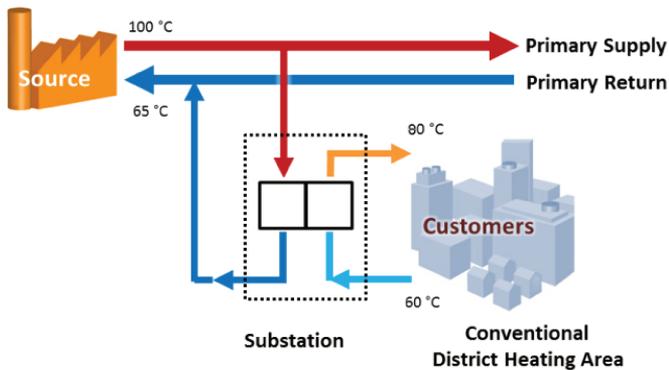


Figure 2-3. Conventional District Heating substation and subnet

A conventional indirect connection type DH substation has as main component a heat exchanger with a primary and a secondary circuit, giving hydraulic separation. The primary side receives the flow from the main network at a high temperature. The heat from this flow is transferred via the heat exchanger to the flow coming into the secondary side circuit, raising its temperature to a selected set-point value. On the primary circuit, the flow at a lower temperature leaves the circuit by joining the main return flow.

2.2.3. District heating substations

District heating substations are located at the customers' buildings, and are used to transfer heat from the primary supply system to the building heating system, which consists of SH and DHW preparation. Space heating equipment and systems refer most often to radiators, but it may also include floor heating or ventilation systems.

The transfer of heat from the primary network to the heating system of the building may be direct or indirect. In the direct connection, there is no separation between the circuits of the systems, so that the heat transfer medium from the primary network supply directly feeds the building heating

system. In the indirect connection, the substation provides hydraulic separation, so the heat is transferred via a heat exchanger (HEX) to a secondary heat circuit with a different heat carrier.

A high-level diagram of a typical DH substation with hydraulic separation is shown in **Figure 2-3**. The substations are equipped with control equipment to allow different flow, pressure and temperature of the heat carrier, and with heat metering equipment for the heat used [12]. They also have safety valves to close the heat distribution in the event of maintenance or disturbances.

2.2.4. Aggregated heat loads and heat load composition³

The heat load is the heat power provided by the supply that satisfies certain heat demand. Substations serve as heat load aggregators from individual customers loads to the primary network and then to the heat supply units. The total heat load in a district heating network is the aggregation of individual customer substations, their dynamics, which in turn include the buildings internal heating systems dynamics and heat losses. These are superposed and propagate through the district heating network to the distribution substations and then reach the heat supply units. For a typical district-heating system, the four main load components that shape the total heat load are [12],[23]:

- Space heating (SH)
- Domestic hot water (DHW)
- Distribution Loss (DL)
- Heat load variations (HLV): additional daily and/or hourly

These main load components can be classified as mostly weather-dependent and weather-independent heat demand. The space heating (SH) load is weather-dependent, as well as the distribution losses (DL), although the

³ *Note:* The plots used throughout this section that illustrate *operating temperature curves* and *heat load curves* were created from raw data originating from a demonstration project of a low-temperature subnet discussed in [10] and [22]. Further details on the characteristics and size of this network, as well as the measurement data set are given and detailed in *Section 8.1 Data source description: case study measurements*.

latter is rather constant throughout the year. The DHW demand profile is mostly weather-independent, as well as the daily heat load variation (HLV) which, in turn, depends on the day of the week (workday, weekend, and holiday) and on the hour of the day (human schedule). SH load is small or not present during the summer season, while the other components are present all year round.

The base load for heat demand is the average DHW use, plus distribution losses (DL). Any heat losses from internal equipment and internal transmission, in the customer's substations may be considered balanced: as this equipment is usually located inside heated spaces in most buildings, these heat losses become internal gains during the heating season.

Daily average heat load (time-series), kW

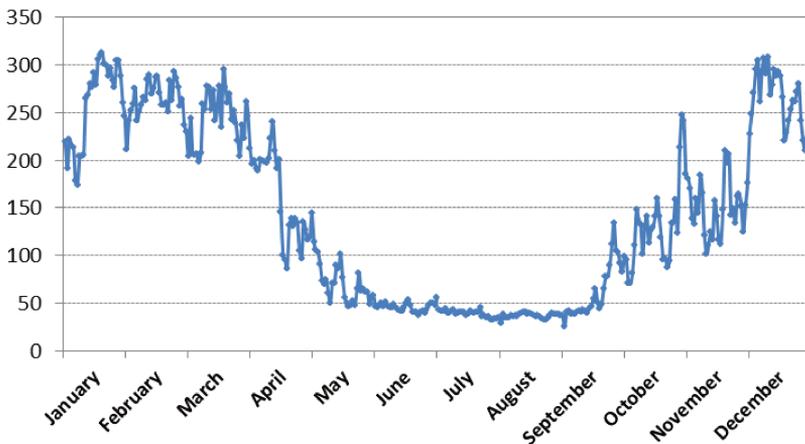


Figure 2-4. Heat load time-series diagram for the LTDH subnet example*

The time-series chart of the daily average heat load shows the typical behaviour of the aggregated heat load of a DH network throughout the year. In the middle part of the chart, during the summer months, when there is little or no space heating demand, the load is the lowest and with small variations; it represents only domestic hot water demand. On the sides, the higher load is due to the space heating demand present during the colder months.

*Figure originates from the data set of the LTDH demonstration project described in [10].

a) Heat load weather dependence and seasonal load variations

Heat load depends on the weather and consequently has a strong seasonal component. Space heating is demanded during periods of low outdoor temperatures. A typical *time-series heat load diagram* based on daily average heat loads is used to depict the seasonal heat load variations in **Figure 2-4** for a residential type heat demand. This plot originates from the measurement data set of the LTDH subnet demonstration project (detailed in section 8.1).

The time-series heat load diagram shows relevant information of each occurring load regarding its situation throughout the year. However, in order to get other relevant information from the network, such as the frequency of winter heat load peaks as well as the lowest loads of the year occurring during the summer period, a *heat load duration diagram* is used instead (see **Figure 2-5**).

Hourly average heat load duration diagram

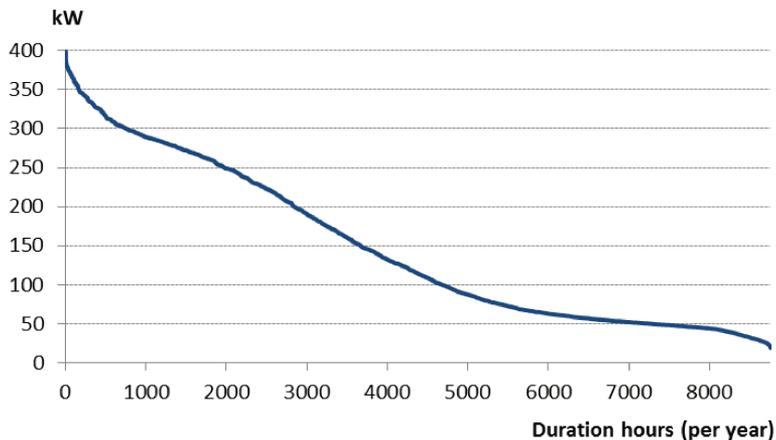
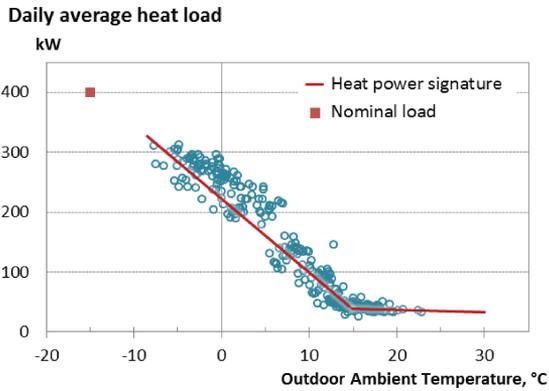


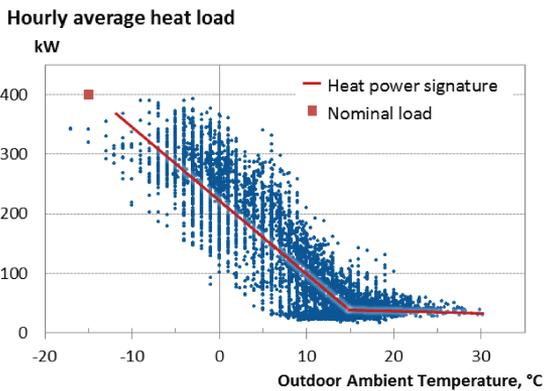
Figure 2-5. Heat load duration diagram for the LTDH subnet example*

The heat load duration diagram presents the same data points as the time-series diagram but ordered from the highest to the lowest value, also known as load duration curve (LDC). This type of data representation is useful to identify relevant information such as the frequency and magnitude of heat load winter peaks, on the left, as well as the lowest loads of the year, on the right, occurring during the summer period at night. This diagram is used by utilities to plan heat generation.

*Figure originates from the data set of the LTDH demonstration project described in [10].



a) Daily average



b) Hourly average

Figure 2-6. Aggregated load and heat power signature of the LTDH subnet*

Figure 2-6a shows typical daily average heat load as a function of the outdoor temperature for one-year period. This plot is used to determine the heat power signature of the network: the linear function to the left represents the dependency of the space heating demand on the outdoor temperature until the break point (~15°C). From this point to the right only domestic hot water demand is present. Figure 2-6b shows the hourly average heat load from the same data set with the heat power signature superposed. The large spread of the data in (b) shows the daily variation of heat load with respect to the expected daily average value.

*Figures originate from the data set of the LTDH demonstration project described in [10].

To show the weather dependency of the heat load, the values of the heat load are plotted with their corresponding outdoor temperatures in **Figure 2-6**. The *heat power signature* –or energy signature- shows the existing quasi-linear interdependence between the space heating demand and outdoor temperatures. Its slope is related to the heat transmission constant of the buildings, their ventilation rate constants, and the distribution pipes loss coefficients.

The nearly horizontal line, from $\sim 18^{\circ}\text{C}$ onwards, represents a combination of heat distribution losses (DL) and average domestic hot water (DHW) load during the summer period. The threshold value ($15\text{-}17^{\circ}\text{C}$) where these two lines intersect reflects the need for intermittent heating to maintain an average indoor temperature of $20\text{-}21^{\circ}\text{C}$ accounting for heat gains and the thermal capacity of the building stock.

As seen from **Figure 2-6**, hourly values vary around the average represented by the red line. These deviations are present due to load components such as DHW use, internal and solar gains, wind chill, and transient heat demands. This could also be due to intermittent operation of ventilation systems and ventilation heating.

b) Daily heat load variations and hourly profiles

The main driver of the daily and hourly heat load variations is the DHW component, and at a lesser extent the weather fluctuations. DHW use depends on a large range of factors related to human behaviour. An example of such behaviour is, for instance, several households taking showers at the same time, which is influenced by the simultaneousness of user loads.

Although mostly weather-independent, residential DHW has also a seasonal variation. There is a higher DHW demand during winter, when the degree of household occupancy is high. Conversely, during summer the degree of occupancy is lower, because dwellers spend more time outside, resulting in lower residential DHW demand [12].

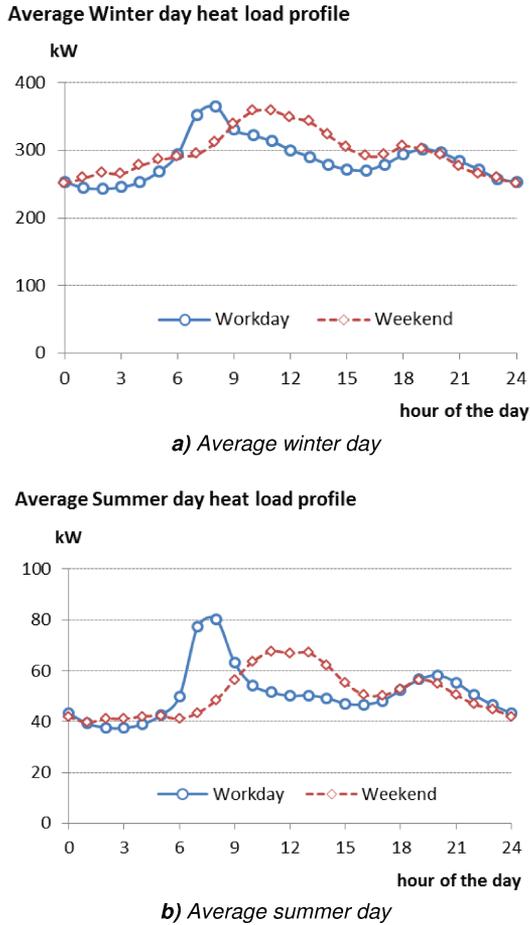


Figure 2-7. Average day, hourly heat load profiles for the LTDH subnet*

Figure 2-7 shows typical hourly aggregated heat load profiles for the (a) average winter day and (b) average summer day. Even though the average winter load can be as high as fourfold the average summer load they share the location of the peaks during the day. The shape of the profile is due to human schedules and behaviour. As it is a residential load, the morning peak comes from the hot water demand from showers and cooking, as does the evening peak when most people come back home. There is a shift on the morning peak when comparing weekdays and weekends, where it occurs 3 hours later and with a lower magnitude.

*Figures originate from the data set of the LTDH demonstration project described in [10].

Typical hourly heat load patterns in a day (**Figure 2-7**) have two distinctive peaks: the highest peak in the morning and the second one in the evening. The peaks are most likely due to domestic hot-water demand from showers in the mornings, and for cooking in the evenings. In addition, the weekday has an impact on this profile, due to different human activities and schedules for workdays and weekends. The reason to differentiate daily load patterns into workdays and weekends is that these patterns are at a large extent dependent on the social behaviour of people inside the building. Therefore, the social component of the heat load pattern can be expected to recur weekly.

There are other weather dependent factors that affect the heat load, such as solar gains and wind chill, as well as transient heat demands due to thermal inertia. There are also weather-independent internal gains and changes in demand due to user behaviour. However, these variations are small, compared to seasonal variations and represent only 5% over the average daily heat load [12].

2.3. Cost-effectiveness of District Heating systems

As in most projects, the economic viability of DH systems depends mainly on the relation between capital costs, operating costs and revenues. In DH networks, the capital costs are those associated to the construction of the heat plants and the distribution network, while the operating costs are those related to heat production and delivery including fuel, the price of recycled heat, heat losses, pressure loss and pumping power, as well as service and maintenance costs [24]. The incomes are determined by the heat demand and heat sales. Thus, the long-term profitability of the system depends on the heat demand over periods of several years. In dense areas like cities, the capital costs are low relative to the total heat demand, making the annual payback of the investment and operational costs faster and easier. For this reason, DH is more economically attractive in areas with high urban density.

To assess heat demands, two indicators have been traditionally used in order to evaluate the economic performance of DH systems in a city district: the *building specific heat consumption* which is the annual heat consumption per unit building net floor area (kWh/m²); and the *plot ratio* which expresses how much building net floor area there is per area of land, and, is small in park

areas with detached houses, and it is high in inner city areas. The plot ratio and building specific heat consumption are often multiplied resulting in the *area specific heat consumption* (kWh/m² per yr).

More recently, for the feasibility assessment of DH projects, two other indicators such as *connection density* (connections per km²) and *linear heat density* (MWh/m) are used to evaluate potential areas or consumers. Linear heat density is, in its usual form, the ratio between the heat sold in a year and the trench length of a DH network. This figure is especially valuable because the distribution capital costs depend primarily on the network construction costs [25], which in turn are influenced by the linear heat density of the network.

Both *linear heat density* and *area specific heat consumption* are good predictors of the relative heat losses from DH distribution networks. High values will result in low relative heat losses, whereas low values give high relative losses. Furthermore, in [7] the authors estimate that a linear heat density of 0.55MWh/m is a reasonable lower limit for the cost-effective and energy efficient development of DH networks. The challenge is to accurately estimate these values before DH is established in a city district.

The profitability of new DH networks, expansions and/or refurbishment of the existing ones should be carefully planned and analysed. The cost efficiency analysis of DH deployment in energy-efficient building areas may be critical. Due to the lower energy demand of energy efficient buildings, investment and operating costs increase relative to total heat consumption or sales and thus, the DH technology might be uneconomic. Yet, when the DH system has low investment costs, and marginal operating costs, DH systems in sparse areas may still be viable.

Another significant aspect that determines the cost-effectiveness of DH systems is the comparison with alternative heating strategies, such as competitor and substitute technologies. Individual heating technologies, such as boilers or heat pumps are common heating strategies in a range of countries. Still, the DH solutions are among the most cost-effective options when considering total costs (heat savings) and in comparison, the high investment costs of DH systems are not dominating [26]. It has been found that, the expansion of DH systems is competitive and feasible up to market

shares of 60%. Considering the current European DH share average of 20%, there is room for deployment [27]. Thus, district heating can provide a competitive and cost-effective way to cover heat demands in buildings.

When comparing alternative heating strategies, it has been found [26] that DH is a more cost-effective solution than individual heat pumps in urban areas (a study based in Denmark). This is due to two main reasons: firstly, the investment costs for installing individual heat pumps in each building are larger compared to the investment in centralised heat plants and a DH network sharing thermal capacity (economies of scale); and secondly, the additional investment in 'residual' power plants to supply electricity for the heat pumps adds to the total investment costs. These conclusions are also valid when considering demand decrease, although individual heat pumps become more competitive at very low demands, because of the lower production capacity needed.

In the short-term, the costs of heat pumps outside dense urban areas are to be found at the same level as DH. Their cost-efficiency is highly dependent on the distance to existing DH network, the cost being a little higher close to the grid, but a little lower in houses further away. In the long-term perspective, in a 100% renewable energy system, individual heat pumps may be approximately equal to DH in cost-efficiency and environmental impact. Yet, this implies very high fuel efficiencies and that the electricity sector is mostly based on renewables.

2.3.1. Influence of district heating operation parameters and production/distribution costs

Nominal and operating network temperatures (supply/return) influence investment and operating costs of the DH system components. Production and distribution costs are closely related to these temperatures that are key factors in the overall techno-economic design and operation of the system, as well as its optimisation [28]. While heat producers are able to set the network supply temperatures to optimise their operation and profits, the return temperature is the result of the combination of the customer base substations, which should comply with minimum design and operating conditions, although malfunctioning is common. Heat production units (HPU) and network administrators have little influence over this parameter,

except for establishing economic penalties on high return temperatures and large substation flows. Improved operation and settings of the substations can lead to lower network return temperatures, and therefore a more efficient network operation.

Regarding heat generation costs, the influence of the supply temperature depends on the heat generation technology in place. On the other hand, the impact of the return temperature on these costs is usually larger, and lower levels benefit the efficiency of heat pump systems, renewable energy systems such as solar and geothermal, as well as heat recovery from industrial processes and exhaust gases. Likewise, lower return temperatures enable a higher electricity yield at CHP plants.

Heat losses increase the required heat supply and thus the required (primary) energy source to generate the heat, which will increase both the production and distribution costs relative to the actual demand. This is due to the fact that the total amount of heat supplied in a district heating system consists of the heat demand from the end users and the heat distribution losses. Lower operating temperatures in both, supply and return flows, lead to heat loss reduction.

Concerning heat distribution costs, a decrease on the return temperature (or increase of supply temperature) increases the delivery capacity of the network, i.e. the heat transport per unit mass of water (heat transfer fluid). As a result, the mass flow rate required will be lower and thus will be the pressure drop. Assuming the same amount of heat shall be supplied, increasing the temperature difference between the supply and return flows (ΔT) leads to lower pumping costs, all else being constant. On the other hand, reducing the ΔT of the network increases the pumping power required to distribute the same amount of heat. Although the pumping power is usually less than 2% of the annual heat supplied, the cost of electricity is not negligible just as the investment costs in larger pumps are not either, in the case of the system design; therefore, it becomes a techno-economic optimization problem for the utility.

Within relevant contributions, a methodology to estimate cost savings and additional production resulting from lower return temperatures has been described and detailed in [29], and summarized and applied in some

examples in [28]. The latter work pinpoints how (1) network temperatures influence investment and operating costs of all components, and (2) the influence of these temperatures can be conflicting for different costs. Thus, temperature reduction is of great importance and each aspect has to be considered carefully for the overall technical and economic optimisation of the system. This methodology is applied on the 3rd gen DH systems with conventional operation without integration with LTDH. Therefore, the application of this methodology to the 4GDH technology presents a learning opportunity, that in this thesis is applied in a mixed LTDH scenario in *Ch. 10*.

3. Recent developments on District Heating systems technology

This chapter presents the review of the stat-of-the-art of District Heating system technology focused on the distribution level of the system. The review includes: heat supply and distributed generation, energy efficient loads, alternative network layouts and operation, low-temperature operation, distributed heat storage, substations and smart metering. The overview is accompanied by a discussion of trade-offs of these new developments.

3.1. Heat generation and supply: new actors

In order to increase the energy system efficiency and energy security, the DH networks of the future will require flexibility to be able to efficiently use local heat sources and integrate surplus heat or waste heat. It has been estimated [26] that there is up to three times more renewable and surplus heat available in some European countries, than it is required to meet high levels of district heating demand. However, these heat resources can only be utilised if a heat grid is put in place to connect them to the end-users.

Most likely the DH networks of the future will integrate a blend of heat sources [3],[8],[7]: fluctuating renewable resources, intermittent surplus heat from industrial processes, and heat from residual resources, such as waste incineration or biomass in centralised plants. Many of these heat sources are expected to be assimilated to thermal energy networks in a distributed and decentralised manner. This situation creates the need for *Active Distribution Thermal Networks* (ADTN), which are secondary networks with systems in place to control a combination of distributed energy resources (sources, loads and storage), on top of the conventional centralized resources. The DH networks will then have to operate in coordination, together with responsive thermal energy storage units to match the heat supply to the demand and provide a stable feed. This integration will take place at various levels of the DH system.

Concerning a higher share of renewables, the integration of distributed solar heat plants to the conventional DH network is an issue that has been addressed and analysed with either heat storage or using the network as a storage buffer. Its effects on the network load patterns and on the economics of the main heating plants have been studied in [30],[31],[32]. Some conclusions point out that distributed penetration of solar-thermal with a typical average solar collector area per building has a very low contribution on a yearly basis. Yet, with a strategic expansion and coordination with thermal energy storage, it could be possible to reach 100% renewable fraction during summer. Likewise, a low-temperature operation of the network should be encouraged not just from the energy perspective, but also considering the resulting cost-efficiency of the systems.

One of the barriers for the integration of distributed heat sources is the low exergy content or low-temperature nature of their supply. Frequently, a temperature boost or lift is required using active heat recovery technologies supported by heat pumps. This is the case of the heat collection from data centres cooling [33],[34] or electricity transformer substations [35]. District heating networks with lower operating temperatures that could directly use the low temperature resources can address this issue. Another advantage is that they allow the extraction of a larger portion of thermal energy by increasing the efficiency of the recovery systems. For instance, solar heat plants feeding hybrid low-temperature networks with seasonal storage have already been in operation [36],[37]. In this aspect, the overall advantage of lower operating temperatures lies on the possibility to efficiently exploit the locally available low-temperature or low-grade thermal energy resources [7], including other surplus heat resources.

3.2. Heat demand & heat loads within the context of energy efficiency

The building sector will play a significant role in achieving substantial reductions in energy and emissions in the future. As buildings represent the largest energy-demand sector, with more than one-third of all final energy use and half of global electricity consumption, they are also responsible for roughly one-third of global carbon emissions. Thus, it is expected that if an energy efficient and low-carbon pathway for the building sector is followed,

a 25% reduction in total energy use compared to business-as-usual can be achieved according to [38]. Due to energy efficiency policies and directives, it is recognized that renovating dwellings and commercial buildings in the EU will have a large impact on energy use.

The shift in final energy use due to *energy efficient* buildings –also referred to as *low energy* buildings– will impact the district heating industry with respect to relative heat sales. As energy users, low energy buildings are highly efficient; they have low annual thermal energy demands for space heating (SH); and therefore, lower linear heat densities than the existing building stock [4]; thus the mismatch between the requirements of quality and quantity of the heat supply and the energy efficient demand becomes marked. From the supply and distribution perspectives, with falling linear heat densities investment costs increase relative to total heat consumption or sales; relative heat losses are higher; and thus, the DH technology might lose competitiveness or become unprofitable.

Until now, there are only limited studies on the impact of end-use energy savings on conventional DH systems in terms of heat distribution losses and pumping energy. In one study [39], proposing a methodological approach to assess the minimization of losses and pumping energy, the authors optimize both a conventional DH scenario and a LTDH one; however, only in a supplementary scenario they considered a heat demand reduction of 20% due to end-use energy savings.

It has been shown in [7] that with the conventional DH technology a linear heat density of 0.55MWh/m is a reasonable lower limit for the cost-effective and energy-efficient development of DH networks. Yet, when the DH system has low investment costs, and marginal operating costs, DH systems in sparse areas are may still be viable [40]. Lower network operating temperatures have shown to be able to push the linear heat density limit even lower, making economically feasible to supply DH to areas with linear heat density as low as 0.20 MWh/m [6]. This shows that it is possible to integrate low energy buildings (including terraced/detached houses) in the existing networks without decreasing the DH system performance by appropriately designing and using the system.

In countries already with large penetration of DH there is a latent risk of falling heat densities, and rising relative costs. Moreover, in expansion countries where DH is envisioned as a potential lever for energy efficiency, these falling figures may discourage investment in new and expanding DH systems. Therefore, the DH supply will need to adapt and transform to be able to provide thermal energy services to energy efficient building areas in a cost-efficient manner.

3.3. Improvements in network operating parameters: Low-Temperature District Heating (LTDH)⁴

The low temperature district heating (LTDH) operating parameters may vary from one particular network to another, depending on their specific characteristics and needs. In contrast to the 3rd gen DH average operating supply temperature of 80°C, and the developing ‘very low temperature’ DH with average supply temperature below 40°C, the networks considered hereafter as ‘low-temperature’ are those with distribution temperatures as low as 50°C annual average in the supply and as low as 25°C in the return [6]. Low-temperature DH is part of the 4GDH technologies characterized by lower and more flexible temperatures in the distribution networks.

The importance of lowering the operating temperatures has been shown in previous studies [6],[7] contributing to a lower primary energy use overall: lower operating temperatures lead to lower temperature drops and heat losses along the network; thus a lower flow rate at a specific heating power, and so less demand for pumping energy. In addition, lower temperatures induce less pipeline thermal stresses. Therefore, the risk of pipe leakage due to thermal stress and related maintenance costs are reduced. Furthermore, this reduction also extends the lifetime of the distribution network components [22].

Distribution heat losses are of special interest because in areas with low linear heat densities they can account for a large share of the energy supplied (nearly 40% in old systems supplying detached buildings and with deficient

⁴ Some segments of this section are based on excerpts from **Paper [A]**, referred in the ‘Publication List’ of this dissertation, and published in 2014 as part of *the Proceedings of ‘The 14th International Symposium on District Heating and Cooling’*.

maintenance and refurbishment). Particularly during the summer, when low heat demands reduce the network flow rates to a minimum, heat losses due to flow stagnation may exceed the actual heat consumption during certain periods, as pointed out in [6] where a network in Denmark was studied. LTDH could help in making the connection of low heat density areas such as low energy building areas (LEB) to the DH network economically feasible. Lower temperature levels improve the quality match between the heat supplied and the actual heat demands: lower quality heat sources can be used for the low quality demands of SH and DHW preparation [41],[42].

The technical and economic feasibility of LTDH systems has already been investigated from the theoretical point of view [19] and tested in demonstration projects described in [43],[22] among others. These findings show that LTDH is viable and will provide energy savings in the future. One study [6] also established that *'the effect of the temperature on the heat loss is more significant than the effect of the media pipe diameter'*. It also concludes that even though the energy used for pumping purposes may increase about 3 times, its share in primary energy supply only reaches about 2% of the total. Another study [41], which focused in energy and exergy analyses of LTDH, estimated the pumping energy for the secondary networks to be 0.5-1% of the total thermal energy input to the network. The results of these studies have been confirmed in demonstration projects in [43] and [22], where pumping energy for the LT network represents 1.5-2% of the total energy input (thermal and electrical) to the system.

One of the main concerns regarding networks with lower operating temperatures, are possible health issues due to bacterial growth. It has been studied and shown that is feasible to operate with lower supply temperatures by using substations without DHW storage at the end user, and pipes with only a small volume between the heat exchanger and the tapping points. In this way, the potential issues with bacterial growth (*legionella*) are minimised according to [44].

Still, supply temperatures can be further lowered by separating the heat supply circuits for space heating (SH) and the DHW heat exchangers, adding a temperature booster system in order to heat up DHW to the desired temperature level while also avoiding bacterial growth issues [45]. Thus, it is possible to introduce building heating systems that operate with

supply temperatures as low as 40°C, such as floor heating or wall heating. These systems called ‘very-low’ or ‘ultra-low’ temperature can provide space heating with an average water temperature that is just a few degrees higher than room temperature, with the drawback that a larger radiating area is needed to guarantee the same level of thermal comfort.

LTDH systems have potential for enhancing energy use efficiency and energy savings by improving the supply/demand quality match. In overall, lower distribution temperatures can deliver financial benefits such as savings due to lower production costs, less distribution losses, and a larger share of low-cost and environmentally friendly thermal energy sources [4]. It integrates two main requirements for future energy use: high energy efficiency and a higher share of renewable energy.

3.3.1. Examples of full-scale applications of LTDH

There are a few LTDH systems already in operation and that have moved beyond the demonstration phase. These demonstration projects have proven the technical feasibility of LTDH and have confirmed that the LTDH networks have the expected low heat losses. A summary of some of the most relevant LTDH projects is presented in **Table 3-1**.

These set of demonstration projects have paved the way for LTDH technology application in the case of renovated buildings and refurbished networks. In [46], detailed discussions about technical and practical aspects are given, among other factors, regarding: (a) pipe dimensions, insulation thickness, and maximum pressure levels, that lead to reduced capital costs; (b) adequate customer units/substations for domestic hot water preparation and space heating; (c) effects on electric consumption for pumping and pressure losses; and (d) the thermostatic bypass, required to ensure a sufficient temperature level. The report concludes that LTDH leads to reduced heat losses, reduced thermal stress in steel pipes, and reduced boiling risk. It also opens the possibility of using other pipe materials. Yet, for individual customer substations, novel heat exchangers (HEX) with a higher unit heat transfer rate, and faster and more accurate responsive thermal control should be developed.

Table 3-1. Examples of low-temperature district heating projects already in operation

Location [Reference]	Operating Year	Operating Temperatures (supply/return)	Heat Sources and/or Technologies	User types (dwellings)	Heat Demand Covered	Nominal Load	Losses	Network Characteristics
<i>Kırşehir, Turkey [53]</i>	1994	57/38 °C	Geo-thermal heat	1800 existing buildings	SH and DHW	18 MW	15%	Auxiliary peak boiler, used 2 weeks per year
<i>Okotoks, Canada [36]</i>	2007	40/32 °C	Solar thermal	52 detached energy efficient houses	90% of SH (since 2012)	n/a	5%	Large seasonal heat storage; separate solar DHW systems with short-term storage
<i>Heerlen, The Netherlands [54]</i>	2008	35/24 °C to 45/28 °C	Geo-thermal MineWater (main source) upgraded with heat pumps	Combinations of various buildings in the city centre	SH and DHW (and Cooling)	n/a	17%	The project is being developed into multiple source, smart thermal grid (Minewater 3.0)
<i>Crailsheim, Germany [37]</i>	2011	65/40 °C	Grid-connected solar thermal plant and conventional DH	260 apartments, school and gymnasium	SH and DHW	5,1 MW	n/a	Long-term seasonal heat storage (Solar fraction of 50%)
<i>Slough, UK [46]</i>	2010	51/35 °C	Mix of biomass, heat pumps and solar thermal	10 single family energy efficient houses	SH and DHW	35 kW	26%	Heat from stand-alone renewables with thermal storage;
<i>Lystrup, Denmark [45]</i>	2011	52/34 °C	Mixed flow from secondary return and primary supply	40 low-energy detached houses	SH and DHW	150 kW	20%	Direct connection to existing DH system using a mixing shunt; no individual customer substations
<i>Høje Taastrup, Denmark [10]</i>	2012	55/40 °C	Mixed flow from primary supply and return	75 detached houses, with floor heating	SH and DHW	500 kW	14%	Refurbished network; direct connection to the existing DH system using a mixing shunt
<i>Nottingham, UK [49]</i>	2017 (projected)	55/35 °C	Mixed flow from primary supply and return	94 low-raised flats	SH and DHW	13,5 MW	n/a	Refurbished network; indirect connection using a mixing shunt in the primary side

For instance, in the Danish governmentally funded project “EUDP 2010-II: Full-Scale Demonstration of Low-Temperature District Heating in Existing Buildings” the low temperature DH concept has been investigated, designed and tested. The latest deliverable consisted of a set of guidelines for low-temperature DH in [22] that includes recommendations, lessons learned and expertise obtained from the ongoing experiences. As this list is not exhaustive, prospective projects are also described in [46], and [47], and other ‘very low-temperature’ DH projects in [9].

These projects also showed that human behaviour is a crucial factor for the overall consumption pattern in energy efficient building areas and should be included in the analyses. They have also shown that, even though more pumping power is required than in conventional DH operation, it is less than expected, and it only accounts for a minimal share in the total primary energy demand.

3.4. Distribution network layouts: temperature cascading and subnets

For 4GDH technologies, new piping layouts and usages are being developed or are under investigation (e.g. multi piping systems). One alternative layout is ‘temperature cascading’ that is an application of the concept of ‘sequential energy supply’ to DH systems. This concept consists in creating networks operating at lower supply/return temperatures fed by the return line of a higher energy content network, and so on further decreasing the return temperature [16].

The implementation of temperature cascading in DH is a step forward to appropriately match the quality and quantity of the buildings’ thermal energy demand, for SH and DHW, to the supply. The secondary networks can be then supplied by means of direct or indirect connections [48],[43]. This layout enables the increase of the DH system operating efficiency by allowing a further recovery and use of the thermal energy already present in the DH network.

Temperature cascading is already widely used in small individual customer substations [12] that combine SH and DHW, but it has not been deployed at the distribution scale due to the current operating temperature levels of

the DH grids. The increased deployment of cascade usage at the distribution level requires improvements in planning and design. Furthermore, this concept may also be used to integrate unconventional heat sources to the existing DH networks.

In the case of the direct connection of a LTDH subnet through temperature cascading, two arrangements have already been tested successfully in Denmark as discussed in [22]: (a) mixing shunt, and (b) 3-pipe connection shunt. However, only a limited analysis on the performance of these arrangements has been conducted. On the other hand, the use of an indirect connection (HEX substation) has not been analysed. A first demonstration project with this type of connection is planned for the end of 2017 described in [49]. The indirect connection could better match the low energy customers' demands, giving the benefits of flexibility and control over those of a direct connection. The outcome and analysis of this demonstration project are expected to provide sound evidence of the techno-economic possibilities of this layout.

3.5. Enhancement of heat management and distribution: DH substations

DH substations constitute the interface between the distribution network and the customer building heating system, and they are mainly equipped with a heat exchanger (indirect connection), regulating valves, control and metering equipment. Currently, DH substations mostly have a passive role in heat management and distribution: they implement what is called automated meter reading (AMR) and they typically respond to a load-following operating mode. Thus, they require an enhancement to be able to effectively incorporate a wider variety of thermal energy sources, and to assist in the local supply/demand matching.

Conventional DH network components often show sub-optimal performance due to over-sizing and high operating temperatures. Traditionally, the DH networks guidelines account for design margins to connect future additional consumers. These recommendations usually result in over-sized systems and components mostly running at low-efficiency operating points even during peak periods [50]. Already there are studies on consumer substation design [20] and their impact on the overall return

temperature levels of the network [19]. However, these works analyse either the overall DH system performance [6] or the individual consumer substations; thus leaving the management of the heat resources at the distribution level of the DH system in the background.

Another issue that is being addressed is fault detection in DH substations [51]. These faults can be divided into three major groups: construction faults, component faults, and operational faults. The first group is becoming the least common due to prefabrication and modular equipment, but for the other two groups as time goes by, components can break and operation settings can be changed [52]. As the aggregated dynamics of the DH network is the combination of all the customer subnets/substations, errors and deviations in substations and the buildings internal heating systems propagate through the DH network. Thus, as many of these faults increase the return temperatures in substations and customer secondary systems, to achieve overall network decreased supply temperatures, these faults have to be detected and eliminated.

Due to the expected reduction in customer and heat supplier costs, the demand for more intelligent substations has arisen. Automatic meter reading systems are the first step, which makes hourly readings available at low cost. Yet, substations with the capability to self-diagnose errors and deviations in operation and in heat supply systems in connected buildings are a necessary step.

3.6. Thermal Energy Storage (TES) integration with DH systems⁵

Thermal energy storage (TES) is a set of technologies with the potential to enhance the efficiency and flexibility of the 4GDH systems. TES consist of a substance (storage medium) used to store thermal energy that can later be re-used for heating/cooling applications [55]; it is the temporary 'holding' of energy for later use [56]. The introduction of TES systems into the DH network results, among other benefits, in an increase in flexibility leading to

⁵ Some segments of this section are based on excerpts from **Paper [E]**, referred in the 'Publication List' of this dissertation, and published in 2017 in the *International Journal of Sustainable Energy Planning and Management – IJSEPM*.

lower heat production costs. Water typically is the storage medium of choice for DH applications [57] due to several techno-economic factors. In these systems the energy is stored by changing the temperature of the medium, using the sensible heat storage capacity of the material; thus they are called sensible heat TES systems (SH-TES).

Concerning the aspects of heat supply/demand management, the dispatchability of thermal energy sources, and the integration with electricity networks, thermal energy storage (TES) will be strategic for the management and optimization of the DH network and the energy system [58] if distributed storage is managed in a coordinated manner. Already widely used in a centralized manner, coupling TES systems to DH networks has several benefits. For heat generation units, TES serves as a buffer between demand and supply, and helps to perform load balancing and peak shaving, avoiding the need to install additional generating capacity. In other words, TES systems are common supporting equipment for heat generation plants, to serve as back-up in case of unusually high heat demands, or in case of failures. Moreover, in combined heat and power (CHP) plants, TES is used to maximize profits by partially decoupling the electricity and heat generation [56]. There are also a few projects with seasonal TES that have shown improved benefits compared to short-term storage [59], and with an effective strategy TES can decrease the network energy consumption.

Regarding latent heat (LH-TES) systems, some applications for heating and the built environment have already been studied [57], [60]. Latent heat is the heat transfer that occurs when a material changes from one phase to another (gaseous-liquid-solid), and the storage medium used is often referred to as phase change material (PCM). Most of the LH-TES applications exploit the phase change between solid and liquid phases to store/release thermal energy, due to the higher heat storage capacity per volume and low volume difference between these two phases [56]. The main advantage of LH-TES over SH-TES is a higher storage capacity per unit of mass (and volume), resulting in lower space requirements. In addition, during a phase change, there is only a narrow phase change (PC) temperature range, and thus temperature swings are reduced.

Most LH-TES applications are based on the usage of PCM in passive systems [60]. These applications include, for instance, the integration of PCM within walls, floor or ceiling of buildings for indoor temperature control in order to store larger amounts of solar radiation, internal gains, or waste heat, and so increasing the effective thermal mass of the buildings. Some active LH-TES applications have also been proposed and studied: these systems consist of a vessel where the PCM is stored and a heat transfer fluid (HTF) is pumped through the vessel to/from the load/supply and vice versa. Yet, active LH-TES systems are technologies under development, which are slowly reaching a commercialization stage.

The development of active LH-TES systems is deeply linked to the specific applications [61]. The operating temperature range and temperature fluctuations are the main parameters to consider for system design. In order to choose a suitable PCM, it is necessary to compare its phase change (PC) temperature, the required system operating temperatures, and the temperature range of the application. In terms of thermodynamic performance, a lower volumetric heat storage density is a significant disadvantage of SH systems as compared to LH systems; hence a wider temperature range is required to store a given amount of energy [60].

Current studies focus on the use of TES systems in conventional DH networks, and extensive research has been carried out on integrating TES to the 3rd gen DH [62]. Thus, with the coming 4GDH, a gap has emerged since limited research has been developed regarding TES integrated with LTDH, and more specifically concerning active LH-TES systems. Moreover, TES technologies other than water storage in DH applications are very rare [63], especially as active LH-TES applications with 3rd gen DH have been found to be considerably uneconomical compared with water tanks, which is further discussed in **Annex A**. TES enables a smoother integration of distributed, renewable energy generation technologies, having positive benefits from increased system flexibility in terms of lower fossil fuel consumption and consequently lower emissions [57]. On the other hand, the high investment cost connected to TES is a major drawback. Together with space constraints, complex planning, and the lack of adequate supportive legislation [64], these are the set of main challenges in LT-TES to be tackled, among others.

3.7. Upcoming developments for ‘intelligent’ substations and smart metering

Although not the focus of this work, the reader should be aware that an active thermal energy network requires the integration of at least 3 layers of ‘intelligence’ [65]: (1) the first layer consists of separate agents, with heat production units, conventional substations and loads and their individual self-controls; (2) the second layer involves more complex measurement equipment and controls including, sensors, flow meters, actuator valves and variable speed pumps; and (3) the third layer comprises the active resource management, with the aggregators performing on-line supply/demand matching.

There is already certain degree of intelligence in the conventional DH networks. However, it is limited in functions and extent. Existing systems function properly in the first layer both on the supply and demand sides. There the network operators perform balancing schemes, a combination of functions between the second and third layers, which are possible due to the centralized, top-down, and one-directional architecture of the system. Yet on the distribution level, the coordination occurs between the first and second layers only, for instance the substations performing straightforward load-following control actions.

In order to develop active distribution thermal subnets that are able to effectively coordinate and manage local heat resources efficiently, a third layer of active resource management is needed at the distribution level. By enhancing DH substations with smart meters and more complex measurement and control equipment, they should be able to perform local supply side management (SSM) tasks bringing improvements on operation for all subsystems involved.

The increasing number of distributed heat generation systems in thermal networks will likely drive the technological development of smart thermal meters [65]. It is expected that they will follow smart electricity meters as market-ready products soon. There is potential of cost effective applications of smart thermal meters for large loads or group of loads such as commercial buildings, industrial depots, or aggregated residential loads including apartment buildings. Moreover, their installation will probably

trigger demand side management (DSM) strategies as well. In this respect, Multi-Agent Systems (MAS) as a distributed control approach for DH systems has already been proposed and analysed [66] and [67].

The introduction of intelligent substations with smart thermal meters can also encourage and facilitate the implementation of time sensitive heat delivery tariffs. With the appropriate feed-in contracts or storage contracts, future investments in distributed heat sources and prosumer operation can be analysed more clearly. This will be decisive to define the business models that will encourage an increase in the share of distributed heat generation.

Active thermal distribution networks will require substations able to perform complex control tasks with a substantial integration of ICT. The next generation of DH networks will require flexibility and adaptability to ensure a smooth and competitive integration to the existing infrastructure. An efficient and effective smart energy system will be sustained and supported by these smart energy networks and components among others.

4. Low-temperature based active thermal micro-grids as a strategy to address current challenges in District Heating

This chapter revisits the main takeaways from the state-of-the-art analysis regarding open issues in the development of the district heating system at the distribution level. Then, as a proposed approach to address these challenges, the concept of low-temperature based active thermal micro-grids is explained and discussed. Finally, by bridging this concept to the current issues, the knowledge gaps addressed in this work are outlined.

4.1. Focal challenges in District Heating technology development

The gradual deployment of the 4GDH technologies in the coming years will influence the existing DH system. In areas with a large share of well-established DH systems, building renovation, climate change and global warming will affect the operation of the existing networks. Energy efficient buildings will be integrated into the networks, and most likely, their heat supply will have lower temperature levels in favour of efficiency. Thus, there are many open questions regarding the effects of the integration of these buildings to the existing system [8],[65]. What is more, it is necessary to learn how the aggregated behaviour of energy efficient buildings will affect the existing networks, and to identify the differences with respect to conventional buildings. This requires the identification of patterns in energy-efficient loads and operating temperatures and the modelling of these patterns for future DH system planning.

Specifically in already established DH networks, where buildings are gradually being renovated, there is a latent risk of falling heat densities, and rising relative costs. The DH system administrators will need to adapt their supply and operation to be able to provide heat to energy efficient buildings in a cost-efficient manner. Previous research has demonstrated the feasibility of LTDH networks and detected their advantages regarding the

integration of energy efficient building areas by keeping relative losses at margin, and potentially making the connection of low heat density areas more cost-efficient. Thus, the impact of low-temperature subnets as they increase their share in the network becomes an open question, while alternative layouts to the conventional system should also be studied. Thus, this study includes in its scope low-temperature based subnets, reduction in heat demand on DH networks, and considers the study of temperature cascading layouts.

An advantage of low-temperature operation is the possibility to efficiently couple locally available low-temperature or low-grade thermal energy resources [7] without the need for a temperature boost. Many of these heat resources are expected to be integrated to thermal energy networks in a distributed and decentralised manner. This will require a higher degree of flexibility and coordination from the network. Therefore, it becomes necessary to study network operation in coordination with these sources, together with active thermal energy storage units to match the heat supply to the demand and provide a stable feed, and while keeping low heat production and distribution costs.

Until now, the interactions between low-temperature networks with distributed generation and storage have not been studied in detail. Thus, possible concepts to supply heat by a mix of multiple high and low-temperature resources should be investigated more deeply. Then, possible alternative connection layouts & compatibility should also be taken into account, as well as hybrid concepts such as prosumer subnets, with a mix of heat sources.

In the near future, the changes in the structure and organization of the district heating networks will likely allow multiple producers to supply heat, similarly to what happens in the electric grid. The characteristics of the heat supplied vary depending on its source and may require a temperature boost via heat pumps for example. At the same time, customers with heating systems operating at lower temperatures will also be connected to the DH network. This raises the question whether not only the amount of heat should be properly accounted for, but also its quality. In such scenario with a mix of sources and sinks, the link to heat quality should be considered in order to properly weight the characteristics of the supply and users.

In particular, low-temperature users should be treated in a different way than users requiring the same amount of heat, but with higher quality [68]. Low-temperature operation improves the quality match between the heat supplied and the actual heat demands: lower quality heat sources can be used to cover the low quality demands of SH and DHW preparation [41],[42]. Provided that the return temperature decreases, and a more effective heat recovery is obtained in the heat plants, it benefits the overall energy system, since, low-temperature heating systems use lower quality heat than conventional heating systems.

The simultaneous deployment of 4GDH technologies, together with the integration of decentralised thermal energy sources paves the way for the redesign of the system and the creation of new networks concepts. Based on the assessment presented so far, the author puts forward the hypothesis that low-temperature based, multi-source distribution networks, coordinated by an active agent such as an intelligent substation can evolve into low-temperature based active thermal micro-grids, opening the path to synergies by designing and operating the subnet as an integrated system. Thus, this research project proposes an assessment of this concept to evaluate its performance and cost-efficiency as to meeting the heating demands of new or refurbished building stock.

4.2. Active thermal micro-grids: concept delimitation

The DH system is experiencing the gradual deployment of 4GDH technologies, and it has been pointed out in [8], [58] that some of the key challenges the DH technology is facing can be grouped as: (a) the use of low-temperature grids to decrease heat losses and increase efficiency; (b) the interaction with low-energy buildings and electricity grids; and (c) the effective management and dispatch of thermal energy sources in coordination with thermal energy storage (TES).

Already in [8] the authors define the concept of ‘smart thermal grids’ as *“a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralised plants as well as from a number of distributed heating and cooling producing units including individual contributions from the connected buildings”*. It focuses on the integration and efficient use of renewable energy sources and distributed generation allowed by a network structure that may

also involve the interactions with end users, and prosumers. The concept is parallel to that of ‘smart electricity grids’ but they differ in their dynamics resulting from the distinctive nature of the resource flowing through these networks. Yet, the two concepts will complement each other in order to face common and particular challenges, and are regarded as necessary for the implementation of a sustainable energy systems.

In areas with a large share of well-established DH systems, it is possible to integrate energy efficient buildings to the existing heat grids by means of secondary networks (subnets) operating at lower temperatures and pressures in [65]. The feed to these LTDH subnets can be supported by using local, low-grade, renewable and/or surplus heat sources to meet the thermal energy demands within the subnets. This combination of loads and sources within a secondary distribution network has the potential to evolve into a smoothly integrated local subsystem that if taken a step further with the appropriate design and ICT, it can create valuable synergies among the subsystems. These subnets result in *Active Distribution Thermal Networks* (ADTN) with systems in place to supervise and control a combination of distributed energy resources (sources, loads and storage), on top of the conventional centralized resources.

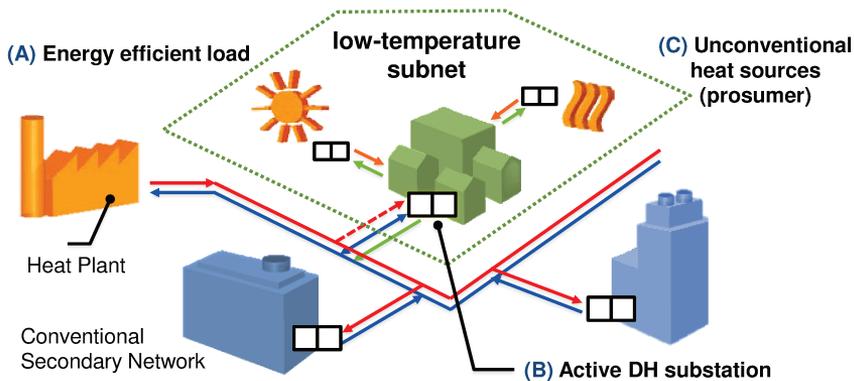


Figure 4-1. Diagram of a LT based active thermal subnet system and subsystems

Figure 4-1 depicts the low-temperature based active thermal micro-grid within the context of a conventional DH network. The main elements of the subnet are also shown: a low-temperature subnet supplying energy-efficient buildings; an active DH station connected to the primary network; and decentralised/distributed heat sources operating at different temperatures.

From the energy systems perspective, these ADTN have specific characteristics being *small-scale, grid-connected, hybrid thermal energy systems*. They are small-scale and grid-connected because they are subnets integrated to a larger DH system. Likewise, they are hybrid and multi-source because they are locally supplied by several distributed heat sources besides the primary network. These subnets comprise three main subsystems: (1) a low-temperature DH network supplying energy efficient loads/sinks; (2) an active substation as aggregator (including metering and control equipment); and (3) local low-grade thermal energy sources and/or storage. These three main subsystems are depicted in **Figure 4-1**.

a) Low-temperature based subnets for energy efficient loads – Low energy buildings (LEB) differ from conventional buildings in terms of the low annual thermal energy demands and loads. Thus, LEB areas present lower linear heat densities than the existing building stock [4], [6]. Due to new energy efficiency policies regarding new and refurbished building, it is expected that LEB areas will gradually increase their share within the building stock. Hence, there is a significant potential for energy efficiency enhancement and energy savings by supplying LEB with LTDH [4]. The aggregated behaviour of energy efficient buildings with LT subnets will affect the existing networks, operating in a different manner with respect to the conventional buildings.

b) LTDH substation as an active aggregator – The substation is the key component in setting and managing the low-temperature subnet. This subsystem allows hydraulic separation from the primary network, as well as the operation at different temperature and pressure levels. The various load and temperature dynamics inside the subnet are aggregated in the substation. The substation as aggregator coordinates the DH supply at the local distribution level with the heat demands from the LT subnet loads, the low-grade heat sources, and possibly responsive thermal storage [45]. Still, its main purpose is to meet the heat load coupled at the substation's secondary side, the LT network. Within this context, the substation will become enhanced with (bi-directional) smart metering and controls, as an active agent able to perform local heat management tasks assisting in local heat supply/demand matching. With this concept, all subsystems can be effectively coupled.

c) Low-grade distributed heat sources – While on the primary side of the network there are centralized, base load heat plants and storage, at the local level the network will integrate a blend of thermal energy sources in a distributed and decentralised manner: fluctuating renewable resources, intermittent surplus heat from industrial processes, and price-sensitive generation such as micro-CHP [3],[8],[7]. Thus, the network will have to operate by coordinating these sources together with responsive heat storage units to perform continuous local supply/demand matching. In this way, the subnet becomes a *prosumer* that, in the framework of thermal energy networks, is defined as a customer that both produces and consumes district heat [69].

In the next generation of DH technologies, active thermal distribution networks will lead the integration of low-temperature heat resources. DH technologies will require flexibility to ensure a smooth integration to the existing infrastructure [70]. To reach such an acceptable level of flexibility, it will be necessary to integrate active components and controls [48],[71], coupled to responsive thermal energy storage, so that the system can efficiently cope with the task of supply/demand matching. In parallel, the issues of large investments, space constraints, complex planning, and the lack of adequate supportive legislation [64], are some of the relevant challenges to be tackled, among others.

Low-temperature based thermal micro-grids can evolve into a promising concept to address the issue of supplying thermal energy services to energy efficient building areas in an efficient manner. In order to foster a fast expansion, this concept must be: (a) cost-effective, by reducing heat losses and total costs; (b) competitive with the existing heat pump solutions (either centralized or decentralized); (c) replicable, by showing modularity and standardization; and (d) flexible, being able to manage variations in the network operation and layout, and to integrate alternative heat sources optimizing energy use.

4.3. Development of novel research towards active thermal micro-grids

The 4GDH encompasses a set of technologies from multiple engineering fields. With respect to ADTNs, the individual technologies enabling the development of low-temperature networks and new piping layouts are

already available (heat exchangers, pipes, storage technologies etc.), or in a test phase at small- and medium-scale demonstration projects. Thus, the installation of new network structures and usages is at present possible [65].

For the development of active thermal micro-grids, as well as for the operation at lower temperature levels, the DH substation will be a key link among the subsystems that constitute the subnet. In this way the LT subnet becomes an extension of the existing DH network, with a connection point where a cluster of customers with low energy demands are serviced. Besides providing hydraulic separation from the main network, as well as operation at different temperature levels, the substation will act as a coordinating agent. Its function can be seen as analogous to power electronics in electric grid-supported systems that connect intermittent renewable energy sources and electricity storage to the local loads and the electricity grid.

It is necessary to study enhanced and active substations able to cope with and manage decentralised heat sources and storage. The research hereby presented intends to generate valuable knowledge as it is focused on the interaction and integration of LT substations with complementary systems such as thermal storage, other types of surplus heat and/or renewable thermal energy sources within the subnet and the district energy system. Certain studies have analysed some of this issues from the perspective of the overall DH system performance [6] or at the individual consumer substations, but leaving the management of heat resources at the system distribution level on the background.

The substation would be the interface managing low-temperature loads, distributed thermal energy sources, local industrial surplus heat, and thermal energy storage (see **Figure 4-2**). In this way, all interacting agents at the distribution level could be effectively coupled despite differences in energy quality and quantity, while smart controls will provide the added benefits of flexibility. The development of these substations is already on its way, at a certain extent. For instance, there are already some efforts of smart substations based on conventional units enhanced with a controller and with the capabilities of remote communication [72]. The online control focuses in reducing heating costs and flow charges by managing internal flows via cascading in the secondary side and by aiming for the lowest return temperature on the primary side. The expected next step in development is

the management of flows on the primary side as well, which is explored in this dissertation.

Regarding distributed solar heat, prefabricated substations have been fully developed and available in [73] Sweden, and a number of these systems have already been installed connected to the primary network. Furthermore, the combined impact of a set of these distributed substations, in terms of technical operating parameters, was studied in [69]. There, the authors realized that as the thermo-solar collectors supply temperature (ranging 65-90°C) is often lower than the network primary supply itself. Thus, their contribution may result in increased flow velocity, and a pipe pressure pattern with multiple and variable pressure cones. The authors conclude that the introduction of distributed collectors is possible, but a more complex network management and control is also necessary. Thus in this work, additional proposed topologies and operating strategies for the active DH substation and solar collector are investigated and evaluated.

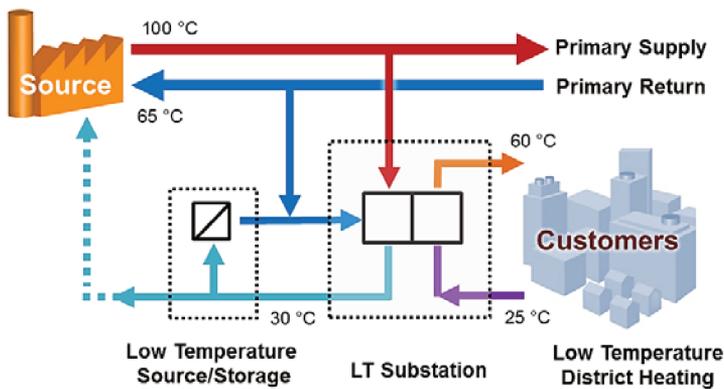


Figure 4-2. Low-temperature substation with low grade heat source/storage

The diagram in Figure 4-2 shows a possible layout of the active substation concept as a supporting interface for the management, at distribution level of the system, of the integration of low-temperature thermal energy sources. The diagram shows a low-temperature substation using temperature cascading and coupled with a low-temperature source or storage. The substation is a potential link among low-temperature systems, renewable thermal energy sources, industrial surplus heat, thermal energy storage, and energy efficient heat demands from low-energy buildings.

The integration of distributed TES systems to thermal micro-grids and intelligent substations has the potential to bring substantial benefits, both from the economic and environmental points of view. Still, the extent of its benefits and limitations will vary depending on the configuration chosen for the TES. As discussed previously, limited research has been developed regarding TES integrated with LTDH, and more specifically concerning active LH-TES systems. Therefore, assessing active LH-TES systems coupled to LTDH networks, focusing on the difference in operating temperature ranges, is an important step in order to expand the knowledge in this field. Although not included in the main body of this research, a more detailed discussion on the performance characteristics of active latent heat TES systems with LTDH is discussed in **Appendix A**. It also focuses on possible issues that may arise regarding compatibility with LTDH based on the most recent developments.

Even though previous research has demonstrated the feasibility of LTDH and 4GDH technologies, it has been discussed that there are knowledge gaps that require particular attention to foster a smooth implementation of these technologies. **Table 4-1** (A to D) shows a summary of the previously identified knowledge gaps (through the state-of-the-art analysis) that helped define the research paths that this dissertation follows. The table shows the relations among these research paths and the formulated research objectives. In this manner, the analysis intends to identify the synergies and challenges that arise through the integrated operation of the subnet, load, substation, and sources, as well as its impact on the primary network.

In order to reach the objectives regarding the assessment of performance improvement of the integrated system, and to evaluate the potential benefits and drawbacks, this work follows a mixed research approach discussed in Section 5.3. It is based on a techno-economic performance assessment to evaluate and compare the technologies, via modelling and simulation supported by other methodologies. The resulting methodology is a combination of cumulative studies including literature review, system modelling and simulation, and performance assessments. The systems are modelled divided into main subsystems, first separately and then as a unit. Moreover, the results are supported by a comparison with the analysis of a measurement data set from an existing demonstration project.

Table 4-1. Comparison of stat-of-the-art, research paths and research objectives

Technology Field: **A) Low-temperature subnets and network distribution layouts**

<i>State-of-the-art</i>	
→	Low-temperature district heating (LTDH) feasibility has been studied and confirmed through recent demonstration projects [19],[22],[43]
→	New piping layouts and usages are being developed or under investigation [9], [48], [65] (e.g. multi piping systems), but limited performance analysis have been conducted
→	Alternative 'temperature cascading' layouts have not been deployed at the system distribution level [16] due to current operating temperatures of the DH networks
→	Lower network operating temperatures are able to push the lower limit for linear heat density, making cost-efficient supplying heat to energy efficient building areas [6], [40]
→	Limited studies on the impact of LTDH layouts and subnets on conventional DH networks, and total network heat demand share [46]
<i>Research Paths (knowledge gaps)</i>	
→	Estimation of (techno-economic) benefits and drawbacks of LTDH to decrease heat losses and increase efficiency
→	Development of alternative layouts (temperature cascading) including detailed thermodynamic performance analysis
→	Impact of low-temperature based subnets on conventional DH networks as they increase their share in the total heat demand
<i>Research Objectives</i>	
→	(a) Delimit and discuss the concept of 'active thermal micro-grid' (distribution network) and conduct technical feasibility and performance assessments
→	(f) Quantify the overall impact of LTDH subnets on conventional DH systems operation through techno-economic performance analyses

Table 4-1 (continued) Comparison of stat-of-the-art, research paths and research objectivesTechnology Field: **B) District heating substations**

<i>State-of-the-art</i>	
→	Conventional DH substations respond to a load-following operating mode assuming a typical passive role in heat management and distribution
→	Additional layouts and operating strategies for DH substations are being investigated and evaluated, including primary side temperature cascading (first demonstration projects) [49], [52]
→	Some studies on consumer substation design and interaction and integration with the overall DH network [19], [20], such as the impact on the overall return temperature levels
→	Recently developed 'smart' substations [72] based on conventional units enhanced with a controller and remote communication capabilities (online control) focused on secondary side flows
<i>Research Paths (knowledge gaps)</i>	
→	Evaluation of the trade-off between simplicity and flexibility for active DH substations (as smart heat meters) with operation optimization capabilities and alternative layouts
→	Online control to reduce heating costs and return temperatures through the management of heat supply streams on the primary side and to assist in the local supply/demand matching (distribution level)
→	Enhanced substations able to effectively coordinate distributed systems such as local surplus heat and/or renewable thermal energy sources together with thermal energy storage
<i>Research Objectives</i>	
→	(b) Perform the high-level design and modelling of an active DH substation system and layouts, and evaluate possible operating strategies through thermodynamic performance analysis
→	(c) Validate the feasibility assessment/proof of concept of the active LT substation/subnet system through a comparison with the available measurement data set of an existing LTDH demonstration project

Table 4-1 (continued) Comparison of stat-of-the-art, research paths and research objectives

Technology Field: **C) Low-temperature and energy efficient loads**

<i>State-of-the-art</i>	
→	Aggregated behaviour of energy efficient buildings with lower linear heat densities has not been studied in detail [4], [38]
→	Limited studies on the impact of end-use energy savings (such as from building renovation) on conventional DH networks [6], [39], [42]
<i>Research Paths (knowledge gaps)</i>	
→	Conditions and strategies that foster the effective integration of energy efficient buildings to the DH system
→	Recognition of patterns of energy-efficient loads, energy signatures, and operating temperatures for DH system planning
→	Simplified modelling of aggregated (low-temperature) heat loads
<i>Research Objectives</i>	
→	(d) Characterize the aggregated LT subnet operating parameters through pattern identification and modelling of aggregated heat load and temperature signatures

Table 4-1 (continued) Comparison of stat-of-the-art, research paths and research objectivesTechnology Field: **D) Unconventional heat sources/storage**

<i>State-of-the-art</i>	
→	Surplus heat recovery from low-temperature sources require temperature boosts supported by heat pumps to match the DH network [34], [35], [54]
→	Centralized renewable (solar) heat plants feeding hybrid low-temperature networks with large seasonal storage are already in operation [36], [37], [53]
→	Prefabricated solar collector substations have been developed and deployed connected to the primary network [73] in a distributed manner
→	Few test projects on distributed heat sources and active/responsive TES; and limited studies on the combined impact of distributed solar collectors on DH networks [69]
<i>Research Paths (knowledge gaps)</i>	
→	Effective management and coordination of local distributed heat sources and active/responsive thermal energy storage
→	Coordinated network operation, with alternative connection layouts & operating strategies for resource management
→	Prosumer subnets: hybrid and multi-source concepts, and substation layouts
<i>Research Objectives</i>	
→	(e) Perform the high-level design and modelling of a multi-source active substation to investigate the opportunities regarding the integration of distributed and low-grade thermal energy sources (or storage)

Part III. Methodology and Research Approach to the Performance Assessment of LTDH subnets

This part describes the methodology followed through this dissertation, including the modelling and simulation techniques. After a short introduction regarding energy system analysis and techno-economic performance assessment, a high-level description of the modelling and simulation approach is given. Then, the basic theory behind the performance models is discussed, and details regarding the modelling are given. Finally, the simulation techniques and data processing procedures are described, including the software and simulation environment used for this purpose.

5. Techno-economic performance assessment: District Heating systems focus

This chapter describes the overall methodology followed in this dissertation. As it is focused on a modelling and simulation approach, firstly some notions of energy system analysis are introduced, and an overview of techno-economic performance assessment applied to district heating systems is given. Then a high-level description of the methodological approach followed is discussed.

5.1. Approaches to energy system analysis

Energy use can be assessed in different ways. The main purpose of this assessment is usually to assist in the design, planning and implementation of energy systems. Yet, the preferred approach often depends on the desired objectives of the evaluation. According to these objectives, examples of evaluation methods for energy use in buildings include: Thermodynamic performance analysis and primary energy use; Economic performance; and Environmental performance, such as Life Cycle Assessment (LCA).

In order to conduct such energy system analyses, there are two main modelling approaches or strategies that can be identified, although overlapping hybrid approaches are also common. These two strategies are (a) *optimisation* modelling and (b) *simulation* modelling [74]. In short, the main difference is that simulation modelling only intends to picture the performance of a specific system, given certain variations; whereas optimisation modelling searches for the one path or design giving an optimal performance.

In simulation (or scenarios) modelling, a system is represented and used to estimate the behaviour of such system under a given set of conditions [75]. This approach is used to analyse and compare options and/or scenarios by calculating different combinations whose consequences differ in relation to variations in key parameters such as costs, emissions, energy supply,

among others. It can also be referred as *descriptive* modelling to demonstrate what will happen in terms of selected key parameters, for instance if a specific plan or strategy is adopted. Thus, this approach is suited when decision-makers need to have an overview of the implications of a range of current choices. It is assumed that there is a range of possible paths and end states with various direct and indirect consequences to reach a specific goal, instead of one 'optimal' solution.

In the optimisation approach, it is assumed that there is such a thing as an optimal solution. Here, a number of decision variables are computed to minimize or maximize an objective function subject to constraints. These decision variables are typically the energy system design characteristics. The choices of objective function together with the optimization algorithm have a significant impact on the result. The algorithm is used to identify the optimal solution on the basis of predefined goals, established in various ways using e.g., linear programming, mixed integer linear programming and/or non-linear programming [76]. Thus, the optimal solution is typically either the least costly way of reaching a specific goal (the cost-effectiveness approach) or the optimal balance of economic costs and benefits (the cost-benefit approach, e.g. Pareto optimum). In this strategy, some assumptions often have a significant impact on the result, and therefore sensitivity tests are recommended, where calculations are made within a range of values of the most uncertain or controversial parameters.

These sensitivity analyses, in a broad sense may be applied to both simulation and optimization strategies, and they exist in two types: *global* and *parametric*. Global sensitivity analysis techniques typically are applied when the goal is to characterise the relationships among model inputs and outputs over a wide range of input conditions. Global sensitivity analysis involves perturbing multiple model inputs simultaneously and evaluating the effects of each input or combinations of inputs on model outputs, e.g. Monte Carlo simulations. In contrast, parametric sensitivity analysis (or local sensitivity analysis) is used to evaluate the response to a change in a single input, holding all other inputs constant [77]. The latter is very useful for both modelling strategies to characterise incremental responses to changes in inputs from a base or reference case.

The methodology followed in the present work is based on an analytical simulation approach where multiple cases are compared according to variations in layouts and subsystems. This comparison consists on simulating the systems and adding or modifying subsystems, layouts, or operation strategies. The simulation/scenario approach was chosen as basis in order to make incremental analyses and compare the performance of the different cases. Yet, the simulation of these multiple scenarios includes some optimization of the internal operation. This slightly hybrid strategy is limited to operating parameters, and assumes fixed design criteria. Its purpose is to investigate the effects of different objective functions in the operation strategy and compare the thermodynamic performance. Lastly, the overall approach also includes a more detailed parametric (or local) sensitivity analysis to investigate the link between technical operating parameters and economic performance. This combined methodological approach is selected to compare the performance of the scenarios while maintaining focus on the techno-economic relationships among key parameters.

5.2. Techno-economic performance assessment for District Heating

Technology development and design are iterative processes that require careful consideration of their economic implications. Techno-economic analysis is a practical generic tool for cost-benefit analysis and the comparison of competitiveness of technologies and applications. It is a systematic assessment that links economic considerations using simulation models and develop suitable cost models. It can be used for costing purposes, improvement and optimization of the design and operating conditions. The output of the process is valuable for those purposes, and can be used on the iterative design evaluating the technical and economic performance.

The design and operation of energy systems has to take a holistic approach that simultaneously addresses several issues. A design focused on technical performance may lead to high costs and to economic unviability. On the other hand, focusing on cost reduction alone may lead to low energetic performance and efficiencies and to possible environmental concerns.

Therefore, the solutions should balance these issues to meet the needs of the society within its context.

For district energy systems, there are some approaches to performance analysis that attempt to combine thermodynamic optimisation with economics and hybrid investment simulation/optimisation models. For instance, energy and exergy approaches are combined with simulation and/or optimization strategies and sensitivity analysis, that is, exergo-economics [68],[78],[79] and *eMergy* approaches [80].

Techno-economic assessment for district heating systems is used to obtain useful information regarding the plant design and operation, with respect to the system load and demands. It is related to changes in the operating strategies, connection of new users, and energy saving measures in buildings connected to the network, among others. It can make a significant contribution to the design procedure of the whole system. For instance, in [68] thermo-economic analysis showed that the use of different energy forms, their quality (exergy content) and cost affect the marginal cost of the heat supplied.

5.3. Analysis of low-temperature based thermal micro-grids: a high level description

For the small-scale, grid-connected, hybrid thermal energy systems, it is necessary to evaluate not only the thermodynamic performance, but also the costs and savings that the design and operation of the system may yield. As these systems operate most of the time under part load conditions, designing and analysing such system at nominal operation is not sufficient as such; it is necessary to analyse the part-load operation to determine its output and performance in a yearly basis. Moreover, in the case of fluctuating or intermittent supply, such as renewable or surplus heat, the system operation and thus its performance are strongly dependant on local meteorological conditions, which vary significantly throughout the year.

For the analysis of the active thermal micro-grid system as described previously, this work follows a specific techno-economic analysis approach, based on modelling and simulation analyses. A high-level description of the

overall process is illustrated in **Figure 5-1**, where it is broken down in its main components showing the subsystems blocks and information flows within. This systematic methodology is developed as a possible approach to conduct the performance analysis of the subnet system previously described. Moreover, from a high-level perspective, it is generic enough to be replicated for the analysis of other cases of active distribution thermal networks. The chapters and sections to follow in this dissertation present more details regarding the steps of this methodology. In addition, in order to guide the reader, **Table 5-1** indicates the connection between these blocks and the sections of this document where their content is described and where the simulation results are presented and discussed.

The core of the process (refer to **Figure 5-1**) consists of the thermodynamic model of the subnet subsystems (Block A): load, substation and heat sources. Within the subnet system, the subsystems –load (A-1), substation (A-2), and heat sources (A-3)- have fixed nominal design parameters tuned according to existing equipment. The output of part (A) of the model is used as input for the performance model evaluation (Block B) that yields the key performance indicators as main outcomes. The performance evaluation is conducted in two stages: first the technical analysis (B-1) and secondly the economic analysis (B-2). Then, the impact on the main DH network in terms of operating parameters (B-3) is also estimated. The steady-state partial load operation is simulated to determine the resulting operating points in an hourly basis. Using meteorological data (i-2) and established operating strategy and parameters (i-1), an entire year's worth of operation is simulated. This is done using in-house programming in commercial software: *Matlab*® and *Simulink*® environment.

In some cases, the simulation process also involves an internal optimization of the substation operation parameters (C-1), with the purpose of giving additional value in terms of thermodynamic efficiency or another predefined objective. In case that there is operation optimization involved, following an objective function based on thermodynamic variables, the output of the technical analysis is used to adjust the variables into a better performing operating point (C-1) in an iterative loop. The modified/optimised output, is then used to evaluate the economic performance of the system.

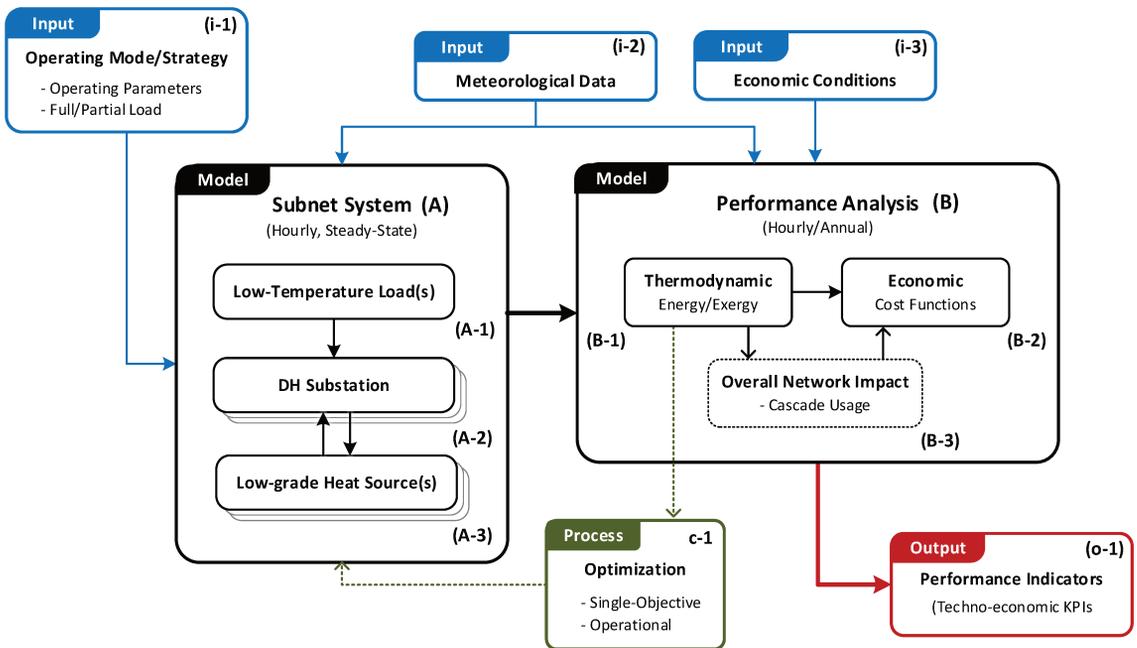


Figure 5-1. Process diagram of the techno-economic assessment of this dissertation

The overall modelling and simulation methodology is depicted in Figure 5-1 showing the models subsystems blocks and steps in the flow of information among the processes, emphasizing their type: input, model, process and output.

In the economic analysis performed here, mainly operating costs are considered. Economic conditions and energy prices are required inputs in this step of the process (i-3). Dedicated cost functions and calculations from various sources together with the system operating conditions are used to estimate the annual operating costs and savings. Finally, this combination of analyses produces techno-economic indicators (o-1) which are used to evaluate and measure the benefits and drawbacks in operating performance of the subnet in terms of thermodynamic, and economic indicators.

Table 5-1. Relation between the techno-economic assessment process and the sections discussed within this dissertation

Process Diagram Block [Figure 5-1]	Block ID	Methodology <i>discussed in section(s):</i>	Outcome <i>presented in section(s):</i>
Low-Temperature Load(s)	A-1	6.1	8.1, 8.3
DH Substations	A-2	6.2, 9.1,	9.1, 9.1
Low-grade Heat Source(s)	A-3	6.3, 11.1	11.2
Thermodynamic Performance	B-1	7.3	9.1, 9.1, 9.3
Economic Performance	B-2	7.1, 10.2	10.3, 11.2
Network Performance Impact	B-3	6.2, 10.1	9.3, 10.3
Operating Mode/Parameters	i-1	6.2, 7.4	-
Meteorological Data	i-2	8.3	-
Economic Conditions	i-3	10.2	-
Operation Optimization	c-1	7.4	9.1
Performance Indicators	o-1	7.2, 7.3, 7.5	9.1 - 11.2

Following the simulation approach, it is necessary to define an overall scenario that will serve as a basis for this study. This scenario is inspired on an existing demonstration project of a low-temperature subnet discussed in [22] and [10] that will be detailed further in Section 8.1.1. The chosen characteristics are those of residential customers only with a total heated area of 10,000 m² approximately. This could be for instance a multi-dwelling energy efficient building or several detached low-energy buildings grouped in a secondary network. A conventional DH substation is used as baseline for reference. It is assumed that one full year hourly measurements of heat and outdoor temperatures are available. The outdoor/ambient temperature distribution data are obtained from a uniform meteorological database in a

selected location that in this case is Stockholm, Sweden. From this point, the models are built accordingly, and subject to the constraints selected for this scenario.

6. Thermal micro-grid modelling: system and components

In this chapter, the basic theory behind the various performance models that describe the micro-grid is discussed. Details regarding the modelling are presented: aggregated heat load modelling is addressed first; then, thermodynamic modelling of the distribution system and components such as the substations is tackled; then the last section includes some basics on the modelling of a small-scale solar collector in line with the selected technology. Further details on the modelling will be introduced as required throughout Part IV of this dissertation in order to discuss the results.

6.1. Heat load modelling for aggregated loads

The operation of the district heating network and management of heat sources under optimal conditions requires realistic modelling of the heat loads and demands. Their estimation is a complex task, and for large-scale systems, it involves many consumers and consumer types.

There are several approaches suggested and implemented for aggregated heat load modelling ranging from simple steady-state models to complex computer simulation methods. The underlying concept is to construct a load profile by combining weather data, based on a fluctuating temperature distribution, with the historical load and weather curves. This approach, used in this section, is based on measured data, typically hourly data, and follows a statistical “multiregression analysis” method in order to identify the relevant load components and assign the model coefficients [81].

Within district heating, a very simple and useful approach for heat load modelling is the *heat power signature* method. It is used to model the weather dependant components of the aggregated load and estimate the daily average value. It is complemented with a *load factor multiplier*, used to account for seasonal (and hourly) variations [82]. In this method, the average daily heat loads are computed and plotted versus the daily average outdoor temperatures (refer to **Figure 2-6a**). Then, a line with negative slope is

fitted to the points below a fixed point of outdoor temperature (between 15°C to 18°C depending on a visual inspection of the data and the characteristics of the building comfort heating system). This line represents the average space heating demand for a given temperature, and another line is fitted for the points after the break point that represents the average domestic hot water use.

Outside of the district heating field, most load modelling applications consider the prediction of electric power loads. Unlike power systems where the network dynamics are critical to fractions of seconds, in district heating networks, delays of seconds and even minutes do not pose significant threats to the system stability, due to the physical nature of the network. Thus, the most significant difference in contrast to district heating loads is that significant time delays and buffers do not occur in a stable power grid [81],[83].

Another load modelling application occurs in natural gas grids. For instance, in order to calculate the natural gas demand in kWh, the method followed by the German Federal Association of Energy and Water uses *Standard load profiles* (SLPs) which are revised periodically –initially developed at the Technical University of Munich, and last revision [84] published in June 2015. The natural gas SLPs are composed by a sigmoid function term and a linear term (*Sig-Lin*). The sigmoid function term is related to the heat load and network capacity, while the linear term relates to the average load during the warm months, and adjusts the profile for the cold temperatures. It is therefore referred as the *SigLin* model [85]. This model is also complemented by seasonal and weekday factors in order to account for seasonal (and hourly) variations.

A general heat load model, such as the heat power signature or the *SigLin*, may assume that the total load is composed by several additive elements based on deterministic physical properties [12],[23]. It is also assumed that there is little or no correlation between these elements and thus the model is linear and follows the superposition property. The general model is thus the addition of linear models with coefficients that describe at a certain extent the physical system components.

6.1.1. Aggregated heat load model at the DH Substation

The aggregated load at the substation has the same components as described for district heating systems in section 2.2.4. Therefore, it is possible to create a heat load model based on actual hourly measurements at the substation. This will cover mainly the demand for space heating and tap water as well as the subnet distribution losses. Knowing that for LEB areas, the *heat power signature* method leads to reasonable results, and even better if system wide load data are available [23], the same approach is hereby followed. As with previously mentioned models, this model is based on the assumption that the heat load can be sufficiently well described as a function of the outdoor temperature and regular daily load variations. This methodology assumes that one year hourly measurements of heat and outdoor temperatures are available. Similarly as in other methods, in this case the hourly data is used to find the best fit of coefficients for a set of functions described hereafter.

The load modelling method proposed in this analysis is the combination of (a) the *heat power signature* method, and (b) the *SigLin* –from the natural gas load model–, which are then corrected by using (c) the hourly load factor multiplier as a function to account for seasonal and hourly variations, see **Eq. (1)**. In other words, the overall layout of the heat-load model implements the heat-load components as follows: (1) space heating (SH) and (2) heat distribution losses (DL) as weather dependent components using the heat power signature based on the *SigLin* function; and (3) Domestic hot water (DHW) use and other hourly and seasonal load variations, as semi-weather dependent through the load factor multiplier function. The the terms of the proposed function to describe the aggregated heat load are explained with more details in **Figure 6-1**.

$$q_{tot}(T_{out}, hr_{i=1}^{24}) = [q_{SH}(T_{out}) + q_{DL}(T_{out})] \cdot f_{DHW}(T_{out}, hr_{i=1}^{24}) \quad \text{Eq. (1)}$$

In Eq. (1), the aggregated load (q_{tot}) as a function of the outdoor temperature (T_{out}) and hour of the day is described in terms of the space heating load (q_{SH}) the distribution losses (q_{DL}), which are in turn influenced by the load factor (f_{DHW}) describing the weather dependent and weather independent part of the domestic hot water load.

	Space Heating	Distribution Losses	Load Factor, DHW use
$q_{tot}(T_{out}, hr_{i=1}^{24}) =$	$[q_{SH}(T_{out})$	$+ q_{DL}(T_{out})]$	$\cdot f_{DHW}(T_{out}, hr_{i=1}^{24})$
	(Sigmoid Function)	(Linear Function)	(Set of Linear Regressions)
$q_{tot}(T_{out}, hr_{i=1}^{24}) =$	$\left[\frac{a}{1 + \left(\frac{b}{T_{ref} - T_{out}} \right)^c} + d \cdot T_{out} + e \right]$		$\cdot (f_{i=1}^{24} \cdot T_{out} + g_{i=1}^{24} + 1)$
	Temperature Dependent		(Seasonal) (Hourly)
		Temp. Indep.	Temp. Dependent Temp. Indep.

Figure 6-1. Description of the aggregated heat load model components based on the *Sig-Lin* function terms

The heat load model given in Eq. (1) is detailed in this figure. The terms are related to their physical meaning: space heating, distribution losses, domestic hot water demand. These terms are also described as temperature dependent and temperature independent. The load factor multiplies the main function and is a set of linear equations obtained by linear regression.

Within the space heating part (sigmoid function in **Figure 6-2**), coefficient **a** is the heat demand (in kW) at very low temperature and is related to the space heating only design load, without hourly/daily load variations. Coefficient **b** (in °C) determines the temperature where the inflection point of the sigmoid function is located ($T_{ip} = T_{ref} - b$) this inflection point is close to the average annual temperature. Coefficient **c** is dimensionless and represents the slope of the SH phase.

For the distribution losses part (linear function in **Figure 6-2**) coefficient **d** (kW/°C) gives the temperature dependent part of the losses and coefficient **e** (in kW) the temperature independent part, such as recirculation, bypass and parasitic losses. The latter is related to the lowest measured load values at night time during warm summer nights. T_{ref} is the reference temperature, in °C, which is recommended to be 40°C, or higher if the maximum outdoor temperature in a year exceeds this value, according to the procedure described in [85]. This point geometrically undefined, represents the sigmoid function reaching a value of zero and a change in its inflection.

Thus from this point to the right the function has no physical meaning with respect to this application.

The domestic hot water (DHW) use and other daily load variations are estimated using the load factor multiplier function f_{DHW} in kW/kW. Coefficient f (in $1/^\circ\text{C}$) gives the seasonal temperature dependant part of the DHW use, and coefficient g , which is dimensionless (kW/kW), represents the temperature-independent part. The hourly profiles are given by coefficient g , thus its magnitude will be always positive and within an approximate magnitude range less than 1. On the other hand, as coefficient f deals with seasonal variations of the hourly profiles its order of magnitude is near $10^{-2} - 10^{-3}$ around zero, either positive or negative.

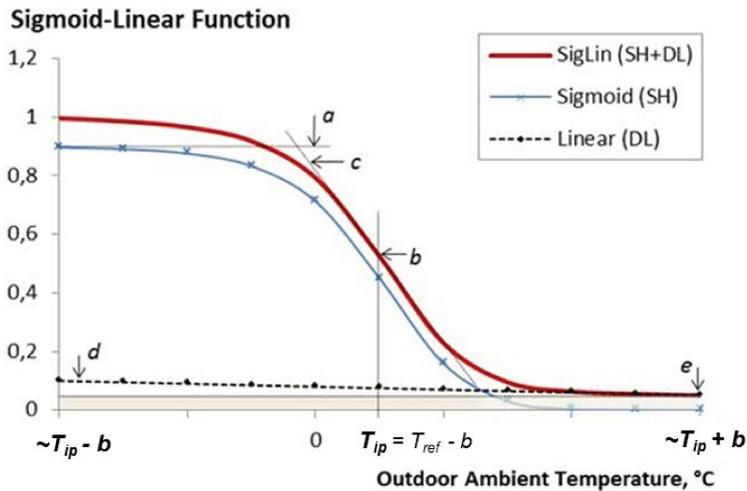


Figure 6-2. Depiction of the Sigmoid-Linear function and its coefficients

Figure 6.2 shows a plot of combined Sigmoid-Linear function in red on a normalized load y-axis in a usual outdoor temperature range for DH operation. The blue curve and the dotted line represent the individual Sigmoid function and Linear function respectively. The function coefficients a, b, c, d, e are also marked to depict its influence on the resulting curve.

As the daily load profile is also dependent on the weekday (work day, weekend, holiday) as well as the hour of the day, a set of 24 functions –one for each hour of the day– are used for working days and another set for the weekends and holidays. Thus, two sets of 24 functions are calculated.

This results in a 24-h load profile for workdays and another for weekends. Although in principle, we have not considered other weather dependent factors such as solar gains and wind chill, neither internal gains due to user behaviour nor transient heat demands due to thermal inertia, the dynamics of these heat load components are embedded in the daily load profile.

The choice of the *SigLin* function is based on the assumption that the temperature dependence is only linear within a certain outdoor temperature range that is lower than 15-18°C. For relatively high outdoor temperatures, the temperature has less influence on the load. In the *energy signature* method, when using this threshold as a transition from one linear curve to another significant estimation errors arise around this point and for higher outdoor temperatures. Moreover, although fitting the coefficients of a non-linear function (sigmoid) through the least squares method is more complex; with the current computing capabilities, it is computationally inexpensive.

Alternatively –although not applied in this work– a simplified version of the load factor multiplier function f_{DHW} can be used. It could be useful if load variations in an hourly basis are not of interest, but instead daily average loads, as it occurs in the typical *heat load signature* model (refer to **Figure 2-6**). In this simplified model, coefficient g is set to be equal to zero, and so the load factor multiplier function takes the form: $f_{DHW}(T_{out}, S_i^n) = (f_i^n \cdot T_{out} + 1)$. With this simplification, only seasonal variations are taken into account by the f coefficient.

6.1.2. Estimation of the function coefficients

As previously mentioned, the main assumption of this model is that the heat load can be sufficiently well described as a function of the outdoor temperature and daily load profile variations. First, the temperature-dependent components are estimated and then by removing the estimated temperature dependent part from the measurements, the daily load variation profile can be identified. The methodology for the estimation of the function coefficients consists of an algorithm with three main steps, in order to find: (1) the coefficients of the linear function for distribution losses (d and e), (2) the Sigmoid function coefficients (a , b , and c), and (3) the set of coefficients of the load factor multiplier (f and g). This methodology can also be applied to shorter time ranges, less than one year, but the resulting

model would have limited forecasting or prediction capabilities to the same time range.

Step 1. *Coefficients for the distribution losses linear function*

To determine the coefficients of this linear function, only the measurements from the summer period are considered. It is assumed that the lowest measured values during summer night time, which usually occur between 01 and 05 in the early morning, represent the heat loss from the distribution system including recirculation, bypasses and parasitic losses.

Therefore, a subset of data containing all the daily minimum load values and their corresponding temperatures is extracted. Depending on the length of the summer period, there will be about 90 pairs of points. The coefficients of the linear function for distribution losses (***d*** and ***e***), are then estimated by fitting a linear function in a typical least squares problem.

Step 2. *Coefficients for the sigmoid function (space heating)*

With the know parameters of the linear part of the *SigLin* function it is then possible to estimate the sigmoid function part coefficients (***a***, ***b***, and ***c***). This is done using the complete set of data (1 year) and fitting the *SigLin* function (see Eq. (2)) with the known coefficients (***d*** and ***e***) using a non-linear least squares regression.

$$q_{SH+DL}(T_{out}) = \frac{a}{1 + \left(\frac{b}{T_{ref} - T_{out}}\right)^c} + d \cdot T_{out} + e \quad \text{Eq. (2)}$$

Step 3. *Coefficients for the set of load factor multiplier functions*

In order to determine the coefficients for the set of linear functions that compose the load factor function, a set of least squares problem for a linear regressions is made. It is necessary to remove the weather dependent part from the load predicted by the *SigLin* function, with all the known coefficients. The resulting profiles represent the daily load variations where several patterns can be identified and modelled.

The temperature dependent part is removed by computing the residuals: subtracting the predicted values from the *SigLin* function to the actual load measurements (assuming that the actual values are in general larger in

magnitude than the predicted values). Then, in order to obtain the set or raw load factors the residuals are divided by the predicted values from the *SigLin* function (see Eq. (3)) to obtain the relative residuals.

$$\bar{r}_i = \frac{q_i - q_{SigLin}(T_{out})_i}{q_{SigLin}(T_{out})_i} \quad \text{Eq. (3)}$$

The set of hourly residuals obtained for the yearly measurements is then sorted into two main subsets: weekdays and weekends (including holidays). Because daily load variations have different patterns depending on human activity around these two types of days and are recurring weekly. Then, this set is divided into 24 bins each for every hour of the day. The result is two sets of 24 bins each, which in turn will become two sets of 24 linear functions. The final task is to fit a linear function to each subset of hourly values (relative residuals) that is done as a typical least squares problem.

$$f_{DHW}(T_{out}, hr_i) = f_i \cdot T_{out} + g_i + 1 \quad \text{Eq. (4)}$$

Again, as an alternative –although not used in this work– when daily load variations in an hourly basis are not of interest for the model, but instead daily average loads (or maximum daily loads) then a simplified version of this model can be used where the load factor multiplier function takes the form:

$$f_{DHW}(T_{out}, S_i) = f_i \cdot T_{out} + 1 \quad \text{Eq. (5)}$$

In this simplified alternative, the inputs used could be the daily average or daily maximum loads and their corresponding temperatures. It is then possible to choose the number of subsets of residuals according to the desired model resolution. The number of load factor functions is defined according to the purpose of the model, for instance one function per weekday –from Monday to Sunday– that will give a total of 7 subsets of relative residuals with only one bin each, and thus a total 7 linear functions. The resulting daily load could be fairly easy to use for estimating the yearly aggregated heat profile.

6.1.3. Model validation & verification

It is necessary to assess the performance of the model in terms of its capacity to describe the system or phenomenon that it is intended for. The 'goodness' of the model is evaluated by determining its degree of authenticity, which can also be used to compare among models. As the 'improved' aggregated heat load model was developed to analyse a particular problem, it may have different levels of validity within the range of conditions of this particular system. Yet, it is expected to be generic enough to be replicated to model the aggregated load of a DH system in general.

In the case of such simulation model, there are several manners to perform verification and validation. The first step of this process, model verification, concerns the structure of the model: compliance with the specifications and the mathematical representation of the system [86]. In a deterministic model, it refers to consistency in results for variations in input parameters, as well as for extreme values of the system within the desired modelling range of parameter values. The second part of the process, model validation is more practical. Validation concerns the accuracy of representation that the model produces in comparison with the system of interest. The model should be able to reproduce the system behaviour with enough fidelity to satisfy the objectives of the analysis [86].

Actual system measurements comparison with a real system is the most reliable and preferred way of simulation model validation. In case measurement data is available for the system being modelled, verification is often blended into the validation process: *"If a comparison of system measurements and model results suggests that the results produced by the model are close to those obtained from the system, then the implemented model is assumed to be both a verified implementation of the assumptions and a valid representation of the system."* [87]

As this model is based mainly on curve fitting through nonlinear regression, in order to validate the model accuracy it is possible to use goodness-of-fit criteria. The indicators used in this assessment include relative and absolute residuals, as well as statistics of goodness of fit including the sum of squares due to error (SSE); R-square; and Root mean squared error (RMSE).

Sum of Squares Due to Error (SSE)

This figure is a measure of the total deviation (difference) between the actual values and the fit. It is also called the sum of squares of residuals. A value closer to 0 indicates that the model, with the estimated coefficients, has a smaller random error component, and that the prediction is more useful.

R-Square (r^2)

This statistic is a measure of how successful a fit is in explaining the variation of the actual data. It is calculated as the square of the correlation coefficient between the actual values and the predicted values. This number can take any value between 0 and 1, with a value closer to 1 indicating that a greater share of variance is accounted for by the model. For instance, in this case, a value above 0.8 is taken as an indication of a relatively good fit, meaning that the model can explain 80% of the variation in the system, although the exact figure may vary in literature depending on the application. It is also called the *square of the multiple correlation coefficient* and the *coefficient of multiple determination*.

Adjusted R-Square

Correspondingly referred as *degrees of freedom adjusted R-Square*. This statistic adjusts the *R-Square* figure based on the residual degrees of freedom defined as the number of response values minus the number of fitted coefficients. It is used to avoid the situation in which R-Square value increases by the addition of fitted coefficients to the model, even though the fit may not improve in a practical sense. Thus, this statistic is a useful indicator when comparing a series of models each of which adds coefficients to the previous one.

Root Mean Squared Error (RMSE)

This figure estimates the standard deviation of the random component of the data. It is also known as the standard error of the regression or the fit standard error. Similarly to SSE, a value closer to 0 indicates a more useful prediction.

In this application, using a nonlinear least squares fitting method, all the coefficients of the load model are estimated, by fitting the curve of the proposed model to the actual values. Then, in order to generate the load profile it is only necessary to use the hourly outdoor temperature measurements, as well as the differentiation between workdays and weekends as inputs. With this, the synthetic data set of the heat load profile is generated given the temperature distribution. This is the set of predicted values, which is used to evaluate the model accuracy by calculating the goodness-of-fit statistics and then compare among models.

6.2. Distribution network components: substations and layouts

The modelling of the active thermal micro-grid system and components is focused at the distribution layer of the DH system emphasising the substation as an aggregator of the network dynamic. The substations are modelled as the indirect connection type, providing hydraulic separation and lower temperatures and pressures. The key components that form the substations are: heat exchangers, mixing equipment, and valves, overseen by control equipment.

The models of the substation components are taken from already available modelling software and platform library blocks [88],[89]. The thermodynamic properties of water as heat transfer fluid are taken from the internal "Chemical Media Database" which in turn was generated from [90]. The model of the heat exchanger (HEX) is the counterflow type and is based on the NTU (number of transfer units) method, as shown in the following equations:

$$\varepsilon = \frac{1 - e^{-N(1-C_r)}}{1 - C_r \cdot e^{-N(1-C_r)}} \quad \text{Eq. (6)}$$

where

$$NTU = \frac{U A}{\dot{C}_{min}} \quad \text{Eq. (7)}$$

$$C_r = \frac{\dot{C}_{min}}{\dot{C}_{max}} \quad \text{Eq. (8)}$$

$$\dot{C}_{min} = \min(\dot{m}_1 c_{p1}, \dot{m}_2 c_{p2}) \quad \text{Eq. (9)}$$

$$\dot{C}_{max} = \max(\dot{m}_1 c_{p1}, \dot{m}_2 c_{p2}) \quad \text{Eq. (10)}$$

UA is heat transfer rate between the flows [W/K]. It takes into account heat transfer coefficient and effective heat exchange area between the flows. It represents the heat transfer between the flow and wall, as well as the heat conduction in the wall. This heat transfer rate is assumed to be a constant mean of the heat exchange rate over the area of the heat exchanger. For a liquid/liquid heat exchanger for water with turbulent flows on both sides a typical range for the heat exchange coefficient is 2000 to 6000 W/(m²K). Regarding the temperature programme, substations in Sweden for such applications are usually designed for nominal operation primary/secondary at 100-63/60-80 or 100-43/40-60 °C; operating pressures are 16/6 and 16/10 bar, e.g. in [91].

An approach to use temperature cascading at the DH substation is analysed in this project. Firstly, a conventional substation is used as baseline or reference and a high-level schematic was shown in in **Figure 2-3**. In this substation, the flow from the DH supply goes through the primary side of the substation heat exchanger to transfer the heat to the secondary network. However, the low-temperature substation proposed benefits of temperature cascading by using a mix of the primary supply and return flows.

A more detailed process flow diagram of the LT/cascading substation is given in **Figure 6-3**. The diagram shows how the flows from the primary supply and return are mixed via a jet-pump arrangement, where the jet-pump [92] is used to regulate the ratio between these two flows that yields the desired primary side inlet temperature (also possible with a 3-way control valve and circulating pump). Next, the mixed stream passes through the substation heat exchanger, properly sized for lower operating temperatures, where the stream rejects some of its energy to the return flow in the secondary side rising the temperature to the desired level. The mixed stream from the primary side exits the substation at a temperature close to

the secondary LT return temperature level. As there might be different layouts or arrangements to approach the use of cascading flows in a substation **Figure 6-3** describes one of the simplest, while another option will be discussed and analysed in Chapter 9.

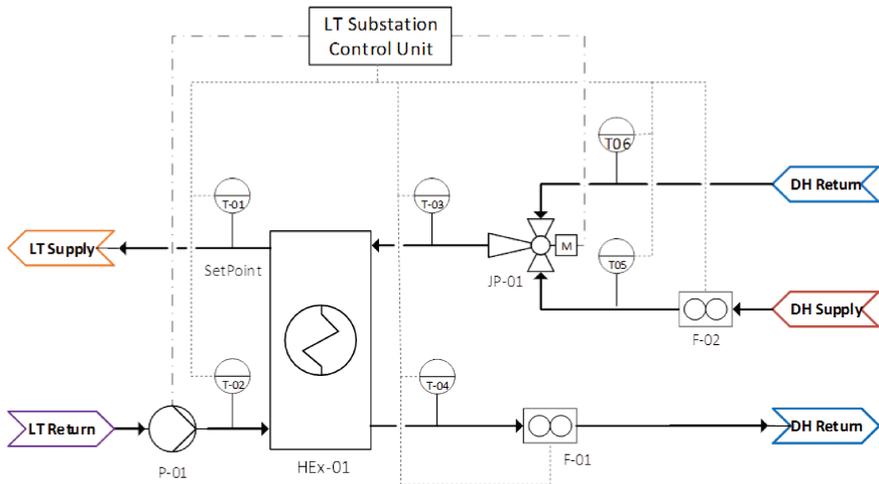


Figure 6-3. Customised low-temperature substation with temperature cascading

A process flow diagram (PFD) of the proposed low-temperature substation with temperature cascading is shown in Figure 6-3. The subnet (secondary) circuit is shown on the left with the main pump and temperature sensors. The heat exchanger (HEX) provides the hydraulic separation between the primary and secondary networks. On the right, in the primary side a jet-pump is in charge of mixing the flow from the primary supply and return, and it is regulated by the LT substation control unit. Temperature and flow measurements on this side are necessary for control and metering tasks, so that the unit also serves as heat meter. Note that in this diagram some equipment has been omitted for simplicity, such as safety circuits and corresponding components.

The water leaving the substation return at the primary side outlet is cooled at a lower temperature than the primary DH return. This flow could be used to recover additional low-grade heat from other sources with applications such as condensation heat recovery. This would improve the performance and efficiency of heat recovery and delivery of the DH network, potentially leading to cost reductions and savings for both the supplier and end user.

6.3. Modelling of small-scale solar-thermal collectors⁶

Distributed solar heat plants consist of a solar collector field that by means of a heat exchanger deliver heat to either a heat storage tank, the heating network, or directly to the load. Solar collectors can be coupled directly to the primary DH network or to a local network of a building (see a typical layout in **Figure 6-4**).

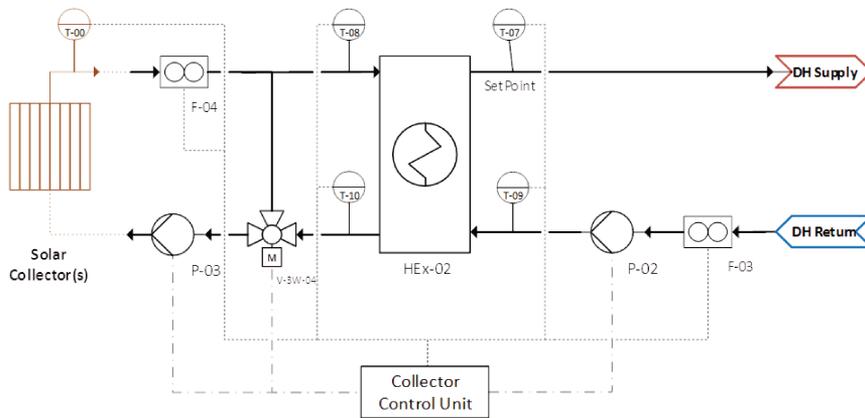


Figure 6-4. Grid-connected solar collector system process flow diagram

The process flow diagram (PFD) of a grid-connected solar collector system is depicted in Figure 6-4, based on the prefabricated solar district heating sub-station from [73]. On the right side, the primary circuit from/to the district heating network is shown with the corresponding temperature sensors, flowmeter, and variable speed pump. On the solar collector circuit, to the left, also the main temperature sensors are shown, the flowmeter and a constant speed pump. In this circuit, a 3-way-valve is used to create a short-circuit to prevent freezing/overheating of the solar collector. The heat exchanger (HEX) provides the hydraulic separation between the primary network and the solar collector circuits. Note that some equipment has been omitted for simplicity, such as safety circuits and their corresponding components.

In case that the solar heat plant is owned by a DH customer and grid-connected (coupled to the primary network), this customer may be called a prosumer. This term was introduced to thermal grids in [69], as an analogy

⁶ This section is based on excerpts from **Paper [C]**, referred in the Publication List of this dissertation, and to be submitted for publication.

from the context of electric power systems, and in the framework of thermal energy networks, it is defined as a customer that both buys and sells district heat.

The integration of distributed solar heat plants to the conventional DH network is an issue that has been addressed and analysed with either heat storage or using the network as a storage buffer. Lessons learned from decentralized solar district heating systems already in operation have facilitated the formulation of guidelines for the connection of solar collectors to the district heating network: different hydraulic architectures, with or without local use of solar energy are possible [94],[93].

6.3.1. Solar-thermal collector model

A flat plate collector type is selected following the main scenario described in section 5.3 based on the available roof area for a large apartment building in Sweden. The collector area (A_c) is then 200m² (with 150 kW_{th} peak at standard global solar radiation (G) of 1000 W/m²). The collector is modelled according to the European standard EN12975. Following this standard recommendations, the incidence angle modifier (45° for Stockholm) is embedded in the maximum efficiency (η_0), and thus for simplicity, the effects of orientation are not considered. The collector's operating efficiency (η_c) and power output (P_c) are described by the following equations [95]:

$$\eta_c = \frac{P_c}{A_c \cdot G} \quad \text{Eq. (11)}$$

$$P_c = A_c \cdot (\eta_0 \cdot G - a_1(T_m - T_a) - a_2(T_m - T_a)^2) \quad \text{Eq. (12)}$$

and

$$T_m = \frac{T_{in} + T_{out}}{2} \quad \text{Eq. (13)}$$

Where η_0 is the collector's maximum efficiency without losses; a_1 is the 1st order heat loss coefficient; a_2 is the 2nd order heat loss coefficient; T_m is the mean collector fluid temperature; T_a the outdoor ambient air

temperature. T_{in} and T_{out} are the temperatures of the fluid coming into the collector and the fluid leaving the collector respectively.

The flat plate solar collector parameters used are ($\eta_0 = 0.75$, $a_1 = 2.0 \text{ W}/(\text{K} \cdot \text{m}^2)$, $a_2 = 0.02 \text{ W}/(\text{K}^2 \cdot \text{m}^2)$) which are within the typical range for this application, independent of their location. The performance indicators for the solar collector investigated in this study, besides the recovered heat, are: the collector efficiency, and the collector specific annual yield (annual output per m^2 of installed collector area).

6.3.2. Solar-thermal collector system layout

There are several connection layouts for solar collectors. **Figure 6-4** shows a typical layout that can be connected to either the primary DH network or the secondary network. When coupled to the primary DH network [96] they can use the primary network as short term storage buffer. The two main layouts for primary side connection are: (1) *return-to-supply* and (2) *return-to-return*.

In (1) **R-S assisted** (return-to-supply), the collector is fed from the primary return. When the recovered heat is enough to reach a minimum temperature level (minimum 65°C during summer), the flow is pumped into the primary supply pipe. For a precise operation, a flow/temperature control strategy with a variable speed pump is needed. This hydraulic scheme has two limitations: (1) the collector average temperature T_m is relatively high and hence its efficiency is rather low; and (2) the installed pump has to overcome the pressure difference between the return and supply networks, which requires substantial pumping power.

Another option to couple the solar collector is (2) **R-R assisted** (return-to-return) layout. In this case, the collector is also fed from the primary return. However, the heated flow is pumped into the primary return pipe. In this case, there is no minimum output temperature level, so when the collector is able to recover solar heat, it starts operating. When compared with the first topology (*R-S assisted*), this second scheme has two advantages: (1) the collector output temperature can be lower than 65°C , thus lowering the operating T_m and increasing the collector efficiency; and (2) the pumping power required is also lower because it is not necessary to overcome the

pressure difference between the return and supply lines. The disadvantage of these connection is that it increases the temperature of the DH return flow. Yet from an energetic perspective alone, it has been found in [30] that this arrangement is the most effective strategy to integrate the solar thermal collectors into the network.

The overall increase in return temperature of the primary network has a negative impact on the efficiency of heat production plants, and heat distribution losses increase as well [93]. Moreover, the DH contracts in some countries such as Sweden [12], may introduce a monetary penalty for high substation return temperatures. In this thesis, a modification in the layout and control strategy is proposed to avoid this issue that will be discussed in Ch. 11.

7. Thermal micro-grid system: simulation and performance indicators

In this chapter, the modelling and simulation process are described, including the software and simulation environment used for this purpose. The performance indicators are pointed out and linked to the simulation inputs and outputs resulting from the data processing, which is described as well. Moreover, the operation strategies are explained as well as the internal optimization algorithms employed within the simulation models.

7.1. Thermal micro-grid system simulation and output

One of the main complexities of a district heating network is that it is typically a multi-product system: because each heat flow supplied to the final users has characteristics different from the others, as well as the flow returned by the users themselves. The modelling of these systems must account for the combined effects that the characteristics of the various agents (mainly their position and their thermal needs) have on the heat supply cost and on the total primary energy requirements. This implies that there are links between the design/operation conditions of the network and the performance of the heat supplies, and thus the heat production cost.

Furthermore, the construction of the model is only a part of the process of analytic simulation evaluation but it is the basis for a robust analysis. Many choices are made before the modelling process itself. First, it is necessary to define the purpose of the analysis, and how the model will serve such purpose. Next, constructing the model inevitably means identifying and including certain parts of reality, while other parts are excluded or simplified given specific assumptions. In this way, the model will represent more accurately the most important aspects of reality in relation to the purpose of the analysis. Thus, those aspects less relevant to the analysis will be only roughly represented or perhaps omitted. For instance, the choices on data inputs and outputs will have an impact on the simulation outcome, giving as much useful information depending on the level of detail of the representation of the system.

The methodology used in this work combines computer simulations using of commercial software and the development of in-house computer models. The calculations were made possible by the intensive use of software and models created through computer programming in *Matlab*® and *Simulink*®. It is a digital computing environment and a 4th generation programming language widely used in academic and research institutions as well as in industry. The choice of this specific software and digital environment was done according to the level of detail required for the models considers partial load operation and the changes in parameters, in combination with the availability of existing modelling blocks, as well as the access to optimization routines that allow customization. A drawback is that if a component model block is not already available or it is, but not enough detailed for our purpose, an in-house model should be developed. Another possible issue with *Simulink*® is that its solver can become numerically unstable in certain scenarios. For large-scale systems and other practical purposes, more simple tools might be enough as the computation time can be large in comparison.

7.2. Techno-economic performance indicators

The objectives of the analysis serve as the main guideline that help to define the performance indicators of the techno-economic assessment and with these indicators the format of the input and output data of the model. That is, if the analysis has a thermodynamic, environmental or economic performance as main purpose, the indicators may be then in terms of energy consumption, environmental consequences such as CO₂-emissions, or the most typically in economic terms.

In the case of DH and low-temperature networks, important design/operation variables are the supply and return temperatures. These variables are linked to the heat losses, which is a resulting operating parameter, and to the pumping effort, which depends on both the ΔT between supply and return as well as on the heat losses. Thus energy use and exergy destruction are further thermodynamic parameters that depend on these previous ones. In general, the performance indicators depend on the system configuration of each option or scenario, but the previous parameters are always of interest, as they may be used to determine thermodynamic efficiencies.

On the economic part of this assessment, the indicators are divided in costs and benefits. The costs are usually the investment related costs and the operation related costs. On the other hand, the benefits are divided into earnings from selling products and premiums for green generation. This analysis will consider the earnings from selling products such as electricity as well as those savings coming from increase in operating efficiency. As this part of the assessment is focused on operation of the system, the investment costs are not yet examined. In addition, the time horizon is just one year of operation, thus discount rates are not taken into account. Yet, the results on economic performance improvement will be helpful in further studies to establish the case for investment required by the new technologies, and to understand the level of capital expenditures that may be paid by the additional operating profits of the DH system in a longer time horizon for project evaluation over several years.

7.3. Exergetic analysis of the subnet at the aggregating substation⁷

Exergy analysis is a useful tool to quantify the energy quality, and to determine the potential for improvement of the energy systems efficiency [78],[97]. By performing exergy assessments, solutions can be proposed to reduce the irreversible exergy destruction at the level of individual components, leading to an increased energy system performance. Exergy analysis has already been applied to the built environment [41],[19]. The low-exergy concept in the built environment challenges the current system, in which mostly high quality energy sources, such as fossil fuels or electricity, are used to meet the heat demands. In reality, exergy demands in the built environment for space heating (SH) and domestic hot water (DHW) are low, due to the 'low-temperature' level that these applications require.

Several studies reviewed in [4] have established that there is a high potential for exergy savings and increased energy efficiency by improving the quality match of the energy used in such applications, by bringing the temperature

⁷ Some segments of this section are based on excerpts from **Paper [B]**, referred in the Publication List of this dissertation, and published in 2016 in the *International Journal of Thermodynamics – IJoT*.

level of the supply closer to the demand's. Previous investigations have concluded that in order to increase the total DH system efficiency, it is necessary to (a) strive for a larger ΔT between the forward and return temperatures of the network, and (b) to decrease both forward and return temperatures to cut both energy and exergy losses [52]. These conclusions are also confirmed in [41], where the authors find that for a given supply temperature, lower return temperatures lead to an increase in the exergy efficiency. Subsequently, the same study confirmed that lower supply temperatures have a greater influence over the exergy performance of the DH system than variations on the return temperature.

The aforementioned studies focus strongly in overall yearly efficiencies, or evaluate the exergy losses of components at nominal or annual average operating conditions. Still, most DH components operate at part load conditions and outside of their nominal operating range most of the time. In the present investigation, the exergy analysis is used to study the system at part load conditions, as an addition to the current knowledge. Within this context, this analysis is especially valuable to investigate the trade-off between primary energy required for heat production and pumping because of two main reasons: LT operation requires higher flows and therefore more pumping power, and during the summer period, pumping power takes a larger share of the energy supplied relative to the total demand.

7.3.1. Exergy modelling at the substation

In the exergy analysis applied in this work, the *reference temperature* (T_o) is defined as a restricted dead-state with only mechanical and thermal equilibrium (thermomechanical equilibrium) conditions such that kinetic and potential exergy are assumed negligible compared to the physical exergy. The direction of heat transfer to the system is defined as positive. The physical component for the specific exergy of a flowing stream of matter is expressed as:

$$e^{PH} = (h - h_o) - T_o(s - s_o) \quad \text{Eq. (14)}$$

The change on the specific exergy content of a flowing stream of matter as it undergoes a process (from 1 to 2) is defined as the difference between the net exergy transfer through the process boundaries and the exergy destroyed

within, as a result of irreversibilities [4],[97],[98]. Therefore, the change on physical specific exergy is then:

$$\Delta e^{PH} = e_2 - e_1 = (h_2 - h_1) - T_o(s_2 - s_1) \quad \text{Eq. (15)}$$

Assuming a functional exergy efficiency definition [19],[97],[41], in this application the useful output (recovered exergy) corresponds to the increase of exergy in the flow supplying the load, and the main exergy inputs (expended exergy) come from the thermal energy of the DH network flows correspondingly, plus the electricity used for pumping (**Figure 7-1**).

$$\varepsilon_{system} = \frac{E_{recovered}}{E_{expended}} = 1 - \frac{E_{destroyed}}{E_{expended}} \quad \text{Eq. (16)}$$

$$E_{destroyed} = E_{expended} - E_{recovered} \quad \text{Eq. (17)}$$

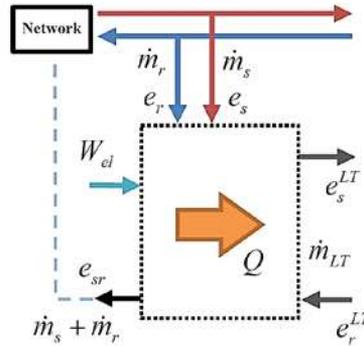


Figure 7-1. Control volume and exergy flows for the exergy analysis of the substations

The figure shows the control volume at the DH substation as well as the inward and outward exergy flows. The exergy is transferred from the primary network to the subnet via the substation HEX.

The functional definition of exergy efficiency emphasizes the use of the exergy flow as a resource. Yet, for this application and the typical operating temperatures, if the efficiency were defined following a total input/output approach, a slightly higher overall value can be expected. This may however,

be misleading, because it would not accurately reflect the relation between the exergy sources and sinks.

In Eq. (16) and Eq. (17) the exergy destruction occurring in the processes of mixing and heat exchange are embedded within the expression. However, with the purpose of quantifying the exergy destruction occurring in the individual processes, the steady-state exergy balances for the mixing (**Figure 7-2a**) and heat exchange (**Figure 7-2b**) used are respectively:

$$\dot{m}_{hot}e_{hot} + \dot{m}_{cold}e_{cold} = (\dot{m}_{hot} + \dot{m}_{cold}) \cdot e_{mix} + \dot{E}_{dest-mix} \quad \text{Eq. (18)}$$

$$\dot{m}_{hot}e_{hot}^{in} + \dot{m}_{cold}e_{cold}^{in} = \dot{m}_{hot}e_{hot}^{out} + \dot{m}_{cold}e_{cold}^{out} + \dot{E}_{dest-HEX} \quad \text{Eq. (19)}$$

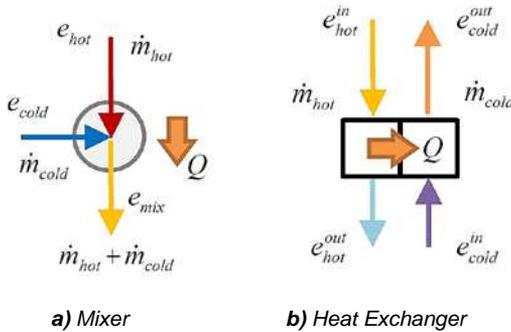


Figure 7-2. Exergy flows for mixer and heat exchanger components of the substation

Figure 7-2a depicts the exergy flows that model the mixing of the primary supply and primary return flows. In this process, the equilibrium temperature of the mixed flow is reached while the primary flow exergy content is transferred to increase the temperature of the mixed flow. Figure 7-2b illustrates the heat exchanger process where the exergy content of the flow on the primary side decreases, and is transferred to the secondary side flow with exergy losses in between.

7.3.2. Exergy modelling of the pumping duty

Electrically-driven pumps are used to create a flow of water by overcoming the pressure head of the distribution network. Even though the electric input needed for pumping power takes only a marginal share of the total energy supplied, from the perspective of the exergy analysis, it should not be

neglected. As the pumping power provided by an electric-driven pump is pure exergy its quality decreases considerably when converted into mechanical, and then thermal energy; therefore the exergy destruction due to pumping takes more relevance.

Thus, a rigorous exergy analysis in a DH network must account for the exergy destruction at the pump. The exergy loss occurs when the electricity, which is pure exergy, is transformed into mechanical energy at the pump, and then when it dissipates into low quality thermal energy due to friction. The exergy of the heat dissipated is much lower than the exergy of the electrical work input W_{el} [99]. Thus, the exergy losses due to pumping are:

$$\dot{W}_{el} = \frac{T_w - T_0}{T_w} \dot{W}_{el-pump} + \dot{E}_{dest-pump} \quad \text{Eq. (20)}$$

$$\dot{E}_{dest-pump} = \frac{T_0}{T_w} \dot{W}_{el-pump} \quad \text{Eq. (21)}$$

In this analysis, an arithmetic average flow temperature $T_w = (T_s^{LT} + T_r^{LT})/2$ is considered as in [99].

7.3.3. The influence of the reference temperature in low-exergy systems

Note that exergy efficiency is strongly dependent on the reference temperature (T_0). Therefore, special attention should be paid to choose the appropriate value. This is especially relevant for DH systems because the systems' operating temperatures are close to outdoor ambient conditions (T_0). In addition, these systems operate mostly on partial load conditions and their exergy performance may be influenced by the dynamic behaviour of the outdoor ambient temperature where the system is located. DH systems in Scandinavia supply most of the heat demand (>90%) at ambient temperatures below 15°C. In contrast to power generation systems, where for power plant applications a nominal operating temperature between 20°C to 25°C is usually chosen, in DH systems the equipment is sized for operating temperatures lower than -10°C.

A number of authors have previously performed steady-state exergy analysis of district heating systems [19],[41],[52],[100]. These studies defined an average outdoor temperature (annual, seasonal, weekly or daily) as their reference temperatures. Some of these studies have already addressed the effect of varying the reference temperatures on the performance of DH systems, concluding that using lower reference temperatures result in higher overall exergy efficiencies [41],[101]. As partial-load operation at different times and outdoor temperatures is fundamental to this analysis, in this manner a variable reference temperature is used to calculate the exergy depending on the outdoor temperature. This has the drawback that total annual exergy efficiency cannot be computed, but instead an average value could be estimated.

Exergy demands for space heating (SH) and domestic hot water (DHW) production in the built environment are low, due to the low temperature level demanded for these applications. Still, mostly high-grade energy sources, such as fossil fuels or electricity, are used to meet these demands. Therefore, there is a high potential to achieve energy and exergy savings by improving the quality match of such applications, by bringing the temperature levels of the supply and the demand closer to each other. In this way, it is expected that the quality of the energy supplied to the LTDH network is a better match to the quality of the energy demand for space heating and domestic hot water preparation. This objective can be realized by substituting high-quality fossil fuels for low thermal quality energy sources such as waste heat or low-temperature renewables.

7.4. Operation strategies & optimization

The conventional DH substations are designed at the nominal operating point with symmetrical flows between the primary and secondary sides of the heat exchanger, i.e. the flow rate in the primary or hot side equals in magnitude the flow rate in the secondary or cold side (flow rate ratio equal to 1). Yet, some DH substations are also designed with asymmetrical flows at the nominal operating point, in order to reduce the required heat exchanger area [102]. Thus, for this type of operation the flow rates have a different magnitude on each side of the heat exchanger.

Conventional DH substation controllers attempt to minimize the transmission losses of the counter-flow heat exchangers by targeting the lowest possible return temperature on the primary (hot) side while maintaining the supply set-point temperature of the secondary (cold) side, as shown in Eq. (22) target; and Eq. (23), constraint. Here t_s^{LT} refers to the supply temperature of the low-temperature network, t_r^{LT} the return temperature on the secondary side, and t_{sr} is the substation return temperature on the primary side.

This strategy is called DRT limitation (difference of return temperatures), and is a dynamic limiting function based on the measured return temperature of the secondary side, and results in minimum volumetric flow at the primary side and a maximum temperature differential [103]. This strategy is particularly advantageous for substations operating outside the typical operation (nominal/design conditions), to maintain the temperature differential between the primary and secondary return temperatures at a maximum of $\Delta 3^\circ\text{C}$ according to the characteristic design specification. As the supply temperature on the primary (hot) side is determined by the DH utility, the operation objective is to find the DH supply mass flow rate that satisfies the set-point temperature on the LT subnet.

$$t_s^{LT} = t_{min} \quad \text{Eq. (22)}$$

$$t_{sr} - t_r^{LT} < 3^\circ\text{C} \quad \text{Eq. (23)}$$

In the proposed LTDH substation (refer to Figure 6-3), the energy is extracted from two different flows which are eventually mixed. In this situation, an additional degree of freedom is now available. This would not be possible with a conventional substation. It is possible to take the advantage of this additional degree of freedom in order to optimize the substation operating performance.

The objective function consists of simultaneously achieving a target while satisfying some constraints. The independent variables are then the DH supply and return flow rates while the optimization objective can be chosen, for instance: minimum supply flow rate, minimum substation return temperature, or maximum exergy efficiency, among others. **Table 7-1**

summarizes the operation strategies goals for the district heating substation simulated.

Table 7-1. Optimization objectives, variables and constraints for the operation strategies

Operation Strategy	Target	Variables
Conventional	$min(\dot{m}_s)$	\dot{m}_s
Minimum Supply Flow Rate	$min(\dot{m}_s)$	\dot{m}_s, \dot{m}_r
Minimum Return Temperature	$min(t_{sr})$	\dot{m}_s, \dot{m}_r
Maximum Exergy Efficiency	$max(\varepsilon)$	\dot{m}_s, \dot{m}_r

As the proposed substation has the advantage to be able to modify the flow mix coming from the DH supply and return, another strategy is simulated where symmetrical operation (Eq. 24) is targeted for all part load operation, when possible: that is, as long as the previous constraints are satisfied.

$$\dot{m}_s + \dot{m}_r = \dot{m}_{LT} \quad \text{Eq. (24)}$$

Moreover, an additional constraint is needed, especially during high load operation such that the total flow going through the substation does not surpass the maximum allowed, as in Eq. 25, and thus the maximum pressure drop is within the design specification.

$$\dot{m}_s + \dot{m}_r \leq \dot{m}_{max} \quad \text{Eq. (25)}$$

In the case of the conventional substation operating at low-temperature levels, a low flow in the primary side is expected due to a larger than usual temperature difference between the supply and the return on the primary side, as the outlet flow leaves the substation at a temperature close to temperature level of the secondary LT return. In practice, the difference in mass flow rates between the primary and secondary should be kept as low as possible to prevent additional stresses in the heat exchanger.

7.5. Simulation environment, algorithms and model data inputs/outputs

To study and compare the performance of the network, substations and subnets, a thermodynamic simulation model of each system was developed. A third-party *Simulink*® library ‘*Thermolib*’, detailed in [88] and based on *Matlab*®/*Simulink*®, was employed containing the thermodynamic models of most of the components, and the numerical models were then solved by the software internal optimization algorithm.

Regarding the simulation environment, *Simulink*® is a block diagram environment for Model-Based Design. In other words, it is a graphical programming environment for modelling, simulation and analysis supported by a customizable set of block libraries. It offers integration with the rest of the *Matlab*® environment. Different type of blocks can be accessed from the Simulink library browser. The third-party software employed in this work ‘*Thermolib*’ is a library of thermodynamic models. The models are given in blocks with inputs, outputs and internal parameters with a certain degree of freedom of customization. **Figure 7-3** shows the main blocks used in the models hereby used: (a) heat-exchanger, (b) 3-way valve, (c) mixer, and (d) pump.

In the *Simulink*® environment, the system is simulated by computing its states at successive time steps. This is done using an internal program called ‘solver’, which applies a numerical method to iteratively solve the set of ordinary differential equations that represent the model. More detailed documentation is available in [104]. A variable-step solver was selected, based on the *Runge-Kutta* method and interpolation implemented using a trapezoidal rule, as it delivered sufficient accuracy in a fair amount of time.

In the case of the optimization strategies, another function is used to achieve the optimization objectives. In this case an objective function was defined as described in the previous section, and then a nonlinear programming solver is used through the *Matlab*® function *fmincon* (find minimum of constrained nonlinear multivariable function). This function attempts to find the minimum of the objective function subject to linear and/or nonlinear equalities or inequalities. It uses a sequential quadratic programming (SQP) method. In this method, the function solves

a quadratic programming (QP) subproblem in each iteration. The QP subproblem is solved using an active set strategy called Active Set Algorithm. See also *Matlab*® documentation for more details on the algorithm used [105].

Regarding the overall modelling and simulation of the system and the data inputs/outputs, **Table 7-2** shows a summary of this information. It makes reference to the model blocks shown in **Figure 5-1**. With respect to the data flow, the system simulation and analysis of the output was performed in three steps. First, taking the heat demand profile and flow temperature curves (i-2, A-1) as inputs for a specific outdoor ambient condition, an iterative approach is applied to adjust the flow rates to meet the minimum supply temperature for the LT network (i-1). The output of this simulation includes the flow rates from the main DH supply and return lines, as well as the substation's operating temperatures at each load condition (A-2, A-3).

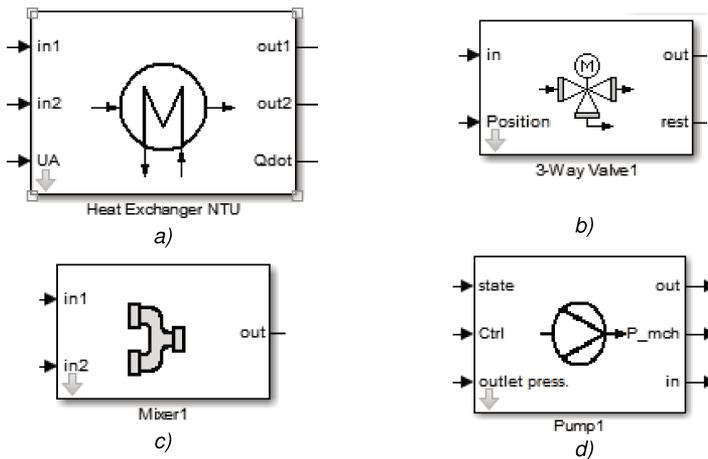


Figure 7-3. 'Thermolib' library blocks employed in the systems modelling

Figure 7-3 shows the main blocks from the *Thermolib* [88] library used in the Simulink models of the substation system and the solar collector system. The main four components are: (a) heat-exchanger, (b) 3-way valve, (c) mixer, and (d) pump.

Table 7-2. Models inputs and outputs

Model (Block in Figure 5-1)	Inputs	Modelling Method	Outputs
LT subnet Load (Block A-1)	<ul style="list-style-type: none"> • outdoor temperature• measured load 	- Curve fitting (<i>section 6.1</i>)	<ul style="list-style-type: none"> • LT load function – adjusted (<i>section 8.3.1</i>)
LT return in the subnet (Block A-1)	<ul style="list-style-type: none"> • hourly measured load • hourly measured return temperature 	- Curve fitting (<i>section 8.1.4</i>)	<ul style="list-style-type: none"> • secondary return temperature function -adjusted (<i>section 8.3.2</i>)
Primary supply temperature (Block A-1)	<ul style="list-style-type: none"> • hourly measured load • hourly measured return temperature 	- Curve fitting (<i>section 6.1</i>)	<ul style="list-style-type: none"> • primary supply temperature function (<i>section 8.3.3</i>)
Primary return temperature (Block A-1)	<ul style="list-style-type: none"> • hourly measured load • hourly measured return temperature 	- Curve fitting (<i>section 8.3.3</i>)	<ul style="list-style-type: none"> • primary return temperature function (<i>section 8.3.3</i>)
Substation (Block A-2)	<p><u>Design parameters:</u></p> <ul style="list-style-type: none"> • layout & components • heat exchange coefficient • heat exchanger area • secondary supply temperature (target) <p><u>Operating parameters:</u></p> <ul style="list-style-type: none"> • LT subnet load • subnet return temperature • primary supply temperature • primary return temperature 	- Simulink library block diagrams (<i>sections 6.2, 9.1</i>)	<ul style="list-style-type: none"> • primary supply mass flow • primary return mass flow • pumping power (<i>section 9.1.1</i>)

Table 7-2 (continued). Models inputs and outputs

Model (Block in Figure 5-1)	Inputs	Modelling Method	Outputs
Energy Analysis (Block B-1)	<ul style="list-style-type: none"> • thermodynamic properties of water • LT subnet load primary supply temperature + mass flow • primary return temperature + mass flow • substation return temperature • secondary return temperature + mass flow 	- Matlab function block diagrams 'in-house models' (<i>sections 7.1, 7.2</i>)	<ul style="list-style-type: none"> • power from primary supply • power from primary return • load duration curves solar thermal power/energy (<i>several sections Ch. 8-11</i>)
Exergy Analysis (Block B-1)	<ul style="list-style-type: none"> • inputs and outputs from Energy Analysis 	- Matlab function block diagrams 'in-house models' (<i>section 7.3</i>)	<ul style="list-style-type: none"> • total exergy destruction • exergy destruction by component • exergy efficiency (<i>section 9.1.2</i>)
Network Branch -Overall Network Impact- (Block B-2)	<ul style="list-style-type: none"> • primary supply temperature • total load • piping network characteristics • CHP plant and FGC characteristics • substation operation at nominal conditions • secondary return temperature 	- Matlab scripts 'in-house models' (<i>sections 9.3, 10.1</i>)	<ul style="list-style-type: none"> • return temperature at the heat plant • heat losses • pumping power • CHP electricity • FGC heat (<i>section 9.3, 10.3</i>)
Economic Analysis (Block B-3)	<ul style="list-style-type: none"> • results from Energy Analysis • heat costs electricity prices 	- Matlab scripts 'in-house models' (<i>sections 10.1, 10.2</i>)	<ul style="list-style-type: none"> • savings in heat losses and pumping electricity • earnings from extra CHP electricity and additional FGC heat recovery (<i>section 10.3</i>)

Then, the output data is processed to determine the energy coming from each flow as a function of the outdoor ambient temperature. Finally, using the temperature distribution data from a specific location, the annual energy share and exergy performance is evaluated (B-1, B-3, c-1). Together with this step the economic parameters (i-3) are taken into account to perform the economy analysis in the selected cases (B-2). From all the different outputs key performance indicators (o-1) are selected and discussed. As the load modelling is based on hourly average values, the simulation of the systems is conducted on hourly steady-state steps, for a wide range of partial load conditions, to full load operation.

Part IV. Applications and Results of the Performance Assessments of Low Temperature Based Thermal Micro-Grids

*This part features the application of the previously described methodology in the form of a series of performance assessments. As a consequence of the organization and sequence of these incremental studies, certain information and results from one study may be used in the following ones. Therefore, in order to help the reader understand this flow of information **Figure 8-0** serves as a guideline clarifying the relation among these studies and the order they are presented concerning chapters and sections of this dissertation.*

First, in Chapter 8 the aggregated heat load model is validated using the available measurement data set. Thus, the data source that is the existing LTDH demonstration project is described in detail. Then, the data is analysed showing load and temperature patterns. Next, Ch. 9 shows the results of the thermodynamic performance analysis of the subnet with an active substation using temperature cascading. Then, the results of combining the thermodynamic model of the subnet substation with the economic model of the primary network are presented in Ch. 10 to evaluate techno-economic impact of the low-temperature based subnets. Finally, this study covers the integration of locally available low-grade thermal energy sources, through the examination of a hybrid concept of a solar-assisted, grid-connected, active substation in Ch. 11, where the assessment focused on the thermodynamic performance, and a clean-cut analysis regarding operating costs/savings.

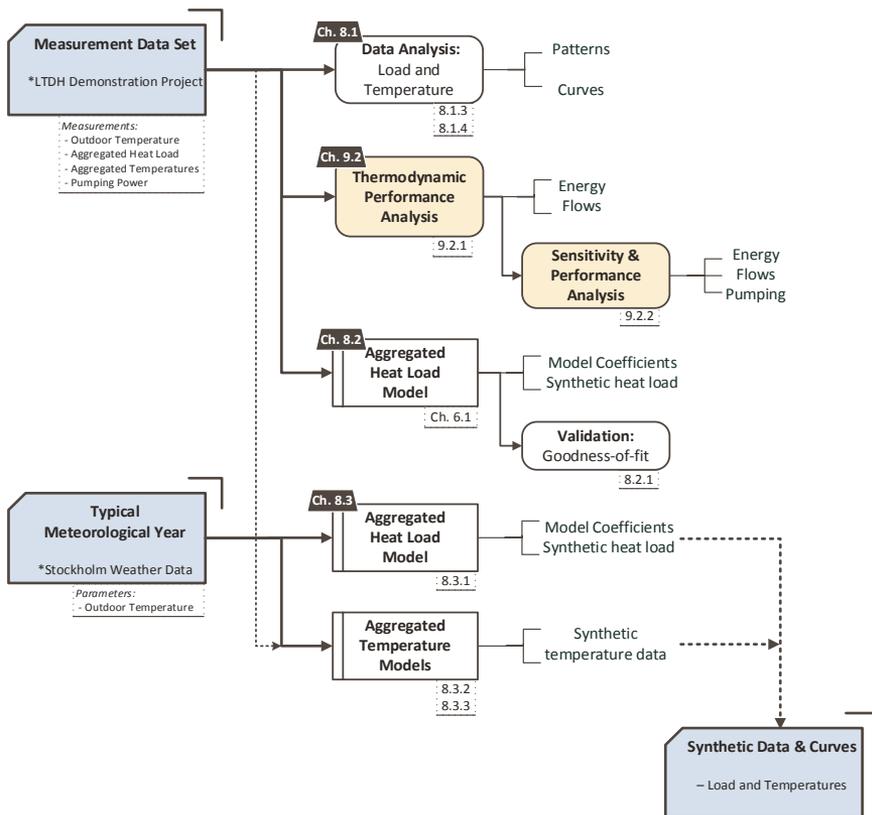


Figure 8-0a. Organization and sequence of the performance assessments presented in Part IV of this dissertation

This figure shows a diagram of the performed studies presented in part IV of this dissertation. The diagram serves as a guideline to understand and follow the flow of information from one study to the subsequent ones. It is organized in a sequential manner, showing the corresponding chapters and sections where the studies are described.

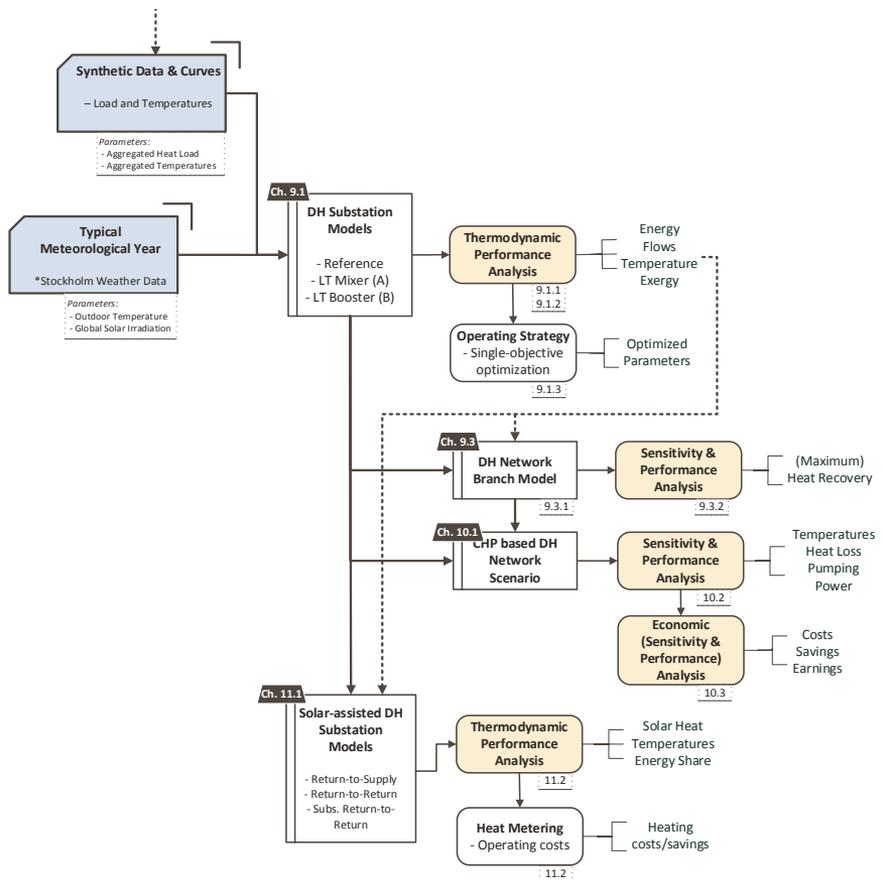


Figure 8-0b. Organization and sequence of the performance assessments presented in Part IV of this dissertation

This figure shows a diagram of the performed studies presented in part IV of this dissertation. The diagram serves as a guideline to understand and follow the flow of information from one study to the subsequent ones. It is organized in a sequential manner, showing the corresponding chapters and sections where the studies are described.

8. Aggregated heat load model and temperature curves in a low-temperature subnet

In this chapter, the measurement data set from the existing LTDH demonstration project is analysed and used as input to validate the improved aggregated heat load model. First, the dataset source project is described, and the findings from the data analysis are presented as aggregated load and temperature patterns, as well as average hourly variations. Next, the data is employed to assess and validate the aggregated heat load model and compare it to other typical models, and lastly the results from generating synthetic load and temperature curves are presented.

8.1. Aggregated load & temperature patterns analysis of a low-temperature subnet

As LTDH is still in its early stages of development, in order to understand the characteristics of a LT subnet, such as aggregated load and temperatures, this work analyses a data set of measurements from a LTDH demonstration project located in Denmark. Hereafter, the main characteristics of this network are described in relation to the relevance for this study; yet information that is more detailed is available in [22] and [10].

8.1.1. Data source description: case study measurements

This demonstration site is situated in an existing housing area called Sønderby (Soenderby) in Høje Taastrup (Hoeje Taastrup), a suburb to the Danish capital, Copenhagen. The neighbourhood consists of 75 detached single-family brick houses, built in 1997-98 with floor heating in all rooms. Typically, 2-5 people live per household. The houses living area is in the range of 110-212 m² with a combined heated area of 11,230 m².

The layout of this local DH network renovated for the LTDH project is shown in **Figure 8-1**. The original piping of the local grid was replaced with prefabricated insulated twin pipes. In the houses, new substations were

put in place with instantaneous water heaters for DHW preparation. Hot water storage tanks were removed. The space heating systems are supplied indirectly with DH via a heat exchanger in the consumer substations. Høje Taastrup Fjernvarme is the company that supplies heat to the new LTDH area at 55°C fixed during the year.

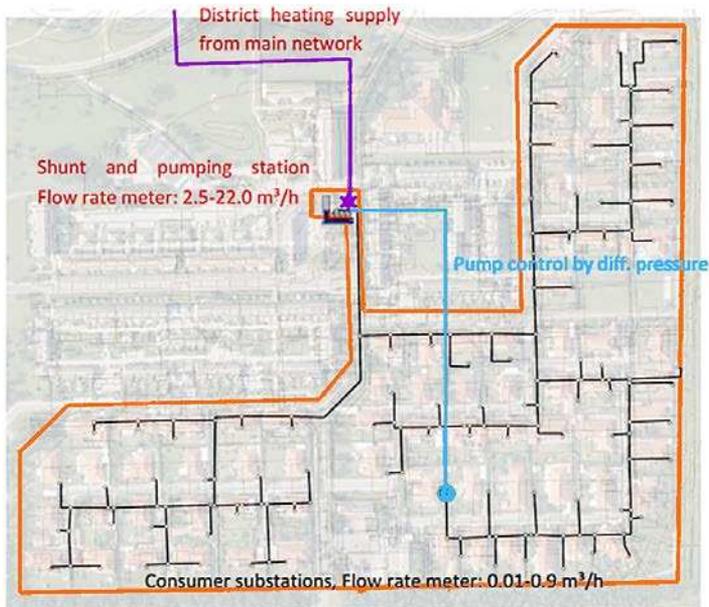


Figure 8-1. Layout of the LTDH demonstration project subnet in Sønderby(from [22])

The layout of the refurbished low-temperature subnet is shown in Figure 8-1. The 'substation' consisting of the mixing shunt (3-way valve) and pump is shown in the centre. The location of the lowest differential pressure point for pump control is also marked. Every connection point in the figure corresponds to one of the 75 detached single-family households.

The measurement data set comes from an extensive data acquisition system established for monitoring the demonstration project at the DH substation. Data from 2012-2013 are available, and the period from July 2012 to June 2013 (one full year) is selected, because it exhibits the least measurements errors, and thus more reliable data is available. The data was sampled every 5 mins, but for this work hourly averages were computed, as hourly resolution is enough for the purpose of this analysis, see **Figure 8-2**.

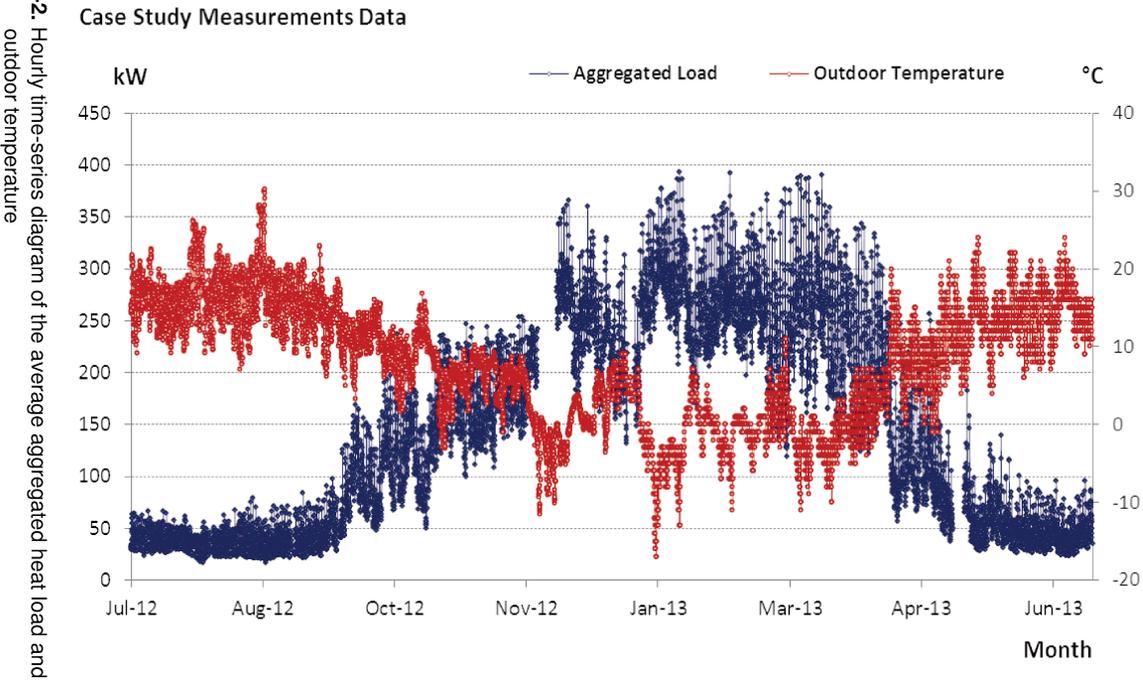


Figure 8-2. Hourly time-series diagram of the average aggregated heat load and outdoor temperature

The hourly averages of the aggregated heat load at the substation is shown together with the corresponding outdoor ambient temperature in a time-series diagram. The period from July 2012 to June 2013 is presented due to the availability of the collected data to complete one full year of measurements of the demonstration project, therefore the winter load period lies in the middle and the summer load period on the sides.

For an average annual outdoor temperature of 7.6 °C, the total heat supplied in 2012 for the refurbished system was 1251.8 MWh, that is 112.3 kWh/m², and with a peak load of 400 kW (5 min meas.) From this supplied heat, 13-14% are heat losses. The total pumping energy input was 12 MWh for the same period. The heat delivered is expressed as hourly average heat loads (heat delivered during 1 h periods). The unit of the heat demand/supply is then kWh/h. In a few data points, unreasonable values (probable measurement errors) appear distributed over the time series. These values have been deleted and they represent less than 5% of the 8760 hours, thus the figures presented have been adjusted considering the missing data points.

8.1.2. Aggregated data by heat demand periods

In order to better understand the load and temperature patterns of the LTDH demonstration project, the 12 month data is clustered into four demand periods, with similar outdoor temperature and heat demand characteristics, as seen on **Figure 8-3** and detailed as follows:

- **High Heating Demand** period : *Winter*, 13 weeks between December and March
- **Medium Heating Demand** period : early Spring, late Autumn, 12 weeks in total from November, December, March and April
- **Low Heating Demand** period : late Spring, early Autumn, 12 weeks in total from September, October, April and May
- **No Space Heating Demand** period : *Summer*, 15 weeks between June and September

Based on these periods and on the annual performance, **Table 8-1** shows a summary of the relevant indicators of the subnet. As 15 weeks are included in the period without heating, the number of operating hours is slightly larger compared to the others. The return temperature has the higher average during the summer period also. Notice that pumping energy during the summer period is the lowest, but it is almost half of that from the winter period, while the heat supplied is five times larger, which points to an issue on the system pumping efficiency.

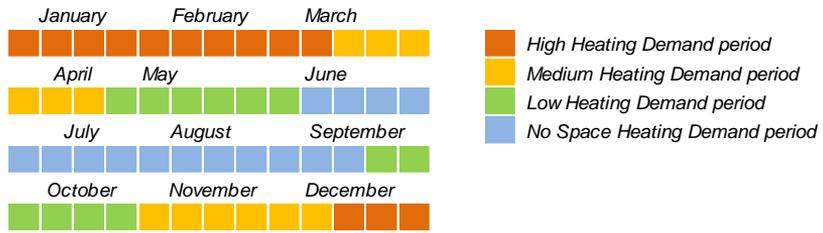


Figure 8-3. Annual per week distribution of the analysed heat demand periods

The data is grouped in four different periods, as seen in the figure, in order to perform an analysis that is representative of the LTDH demonstration project. These periods are determined according to calendars weeks considering outdoor temperature and heat demand such that every period is more consistent and presents less dispersion within. The summer period is slightly longer, when outdoor temperatures are higher and there is nearly no space heating demand.

Table 8-1. Summary of performance indicators for the LTDH demonstration project

	Average Outdoor Temp.	Operating Hours	Energy Supply*	Pumping Energy*	Secondary Supply Temp.	Secondary Return Temp.
	°C	h	MWh	MWh	°C	°C
Annual	7,6	8760	1252	25,5	55,1	40,2
<i>Winter</i>	-1,6	2232	551	9,6	55,0	37,1
<i>Medium Heating</i>	3,8	1992	417	7,4	55,0	37,6
<i>Low Heating</i>	11,0	1992	184	4,4	55,0	41,1
<i>Summer</i>	15,7	2544	101	<u>4,2</u>	55,1	44,3

*Revised values accounting for 5% of missing data points

8.1.3. Aggregated heat loads: seasonal and hourly variations

Figure 8-4, depicts both the seasonal load variations together with the hourly patterns. For each period, the average value is for every hour during a week, where Monday 00.00–01.00 is the first hour and Sunday 23.00–24.00 is the last in each week, is plotted in **Figure 8-4**. As all the buildings in this network are single-family houses it is possible to assume that they all

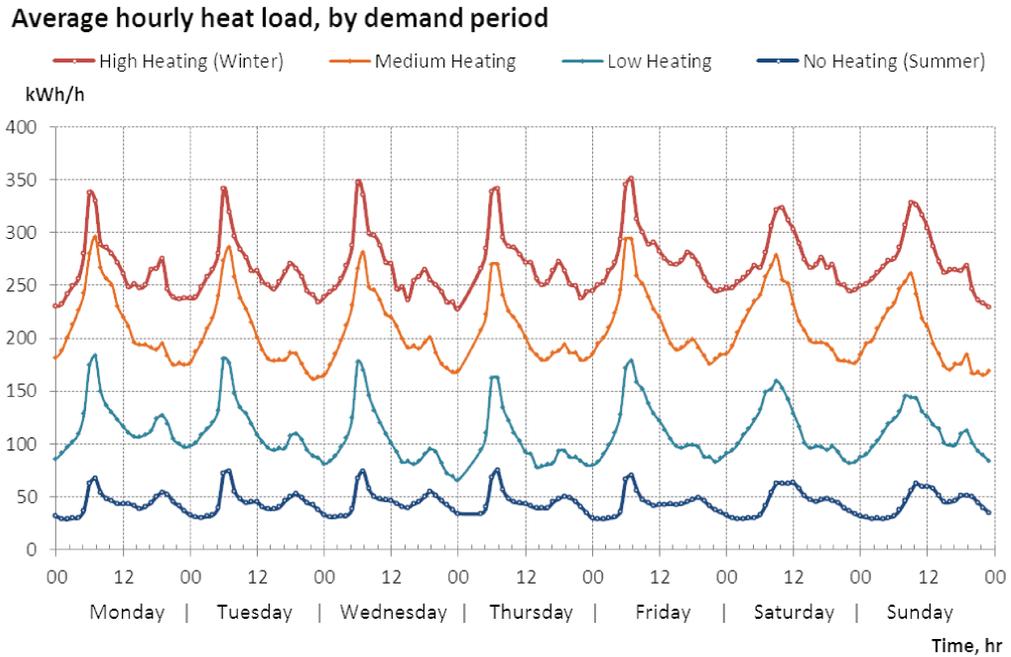
have similar heat load patterns due to the comparable activities that take place. The figure also shows that the heat load pattern is slightly different for workdays than for weekends. During workdays the peak load takes place between 7-8 am, while in weekends it is between 9-10 am and its magnitude is slightly lower. This peak load is due to the DHW preparation that occurs in the morning (for example, for showers). As there are no water storage tanks in the houses, the peak load is clearly visible in all periods. The other smaller peak occurs in the evening after 19.00.

8.1.4. Low-temperature subnet temperature patterns

The substation feeding the LT subnet provides supply temperature control, which in this case, was set to be constant. The set-point value is the subnet supply temperature (55°C). **Figure 8-5a**, shows the average supply temperature by heat demand period, which is constant during all demand periods, and it is slightly higher during summer, when the LT return temperature is also higher. **Figure 8-5b**, shows the seasonal and hourly variations of the return temperature. In the seasonal variation, it is noted that the return temperature is lower during cold periods of higher heat demand. In the hourly patterns, there are two daily minimums that correspond to the daily maximum loads.

The aggregated subnet return temperature is the result of the mixed flows from all substations, and thus some customer behaviour information is embedded in it. The return temperature was in average 40°C for the entire 12 months (see **Table 8-1**). This value was higher than the expected (25-30°C design temperature) due to faulty settings or defective components in some customer substations. Further troubleshooting in individual substations is expected to lower the aggregated return temperature [106] of the LT subnet. Another factor is the bypass flow for DHW, which is controlled by thermostatic by-pass valves, set to 35°C, and is necessary to ensure that each substation delivers DHW at the minimum temperature within an acceptable time [52] to every customer. Moreover, at the end of each DH line thermostatic by-pass valves, set to 40°C, are installed in order to avoid the supply flow to cool off during summer when there is no heat demand for SH [19]. This explains the high return temperatures during this period.

Figure 8-4. Average week of hourly aggregated heat load at the 'substation' ' by heating demand period



This figure shows the hourly aggregated heat load of the LT subnet at the substation, in an average week by demand period. The pattern of the curves shows a distinctive peak during weekdays occurring around 07:00 and a smaller one around 18:00. During weekends the peak is smaller in magnitude and occurs around 09:00 and the evening peak is less evident. On the other hand, the minimum occurs between 10:00 and 24:00 except during the summer period when it occurs between 02:00 and 05:00.

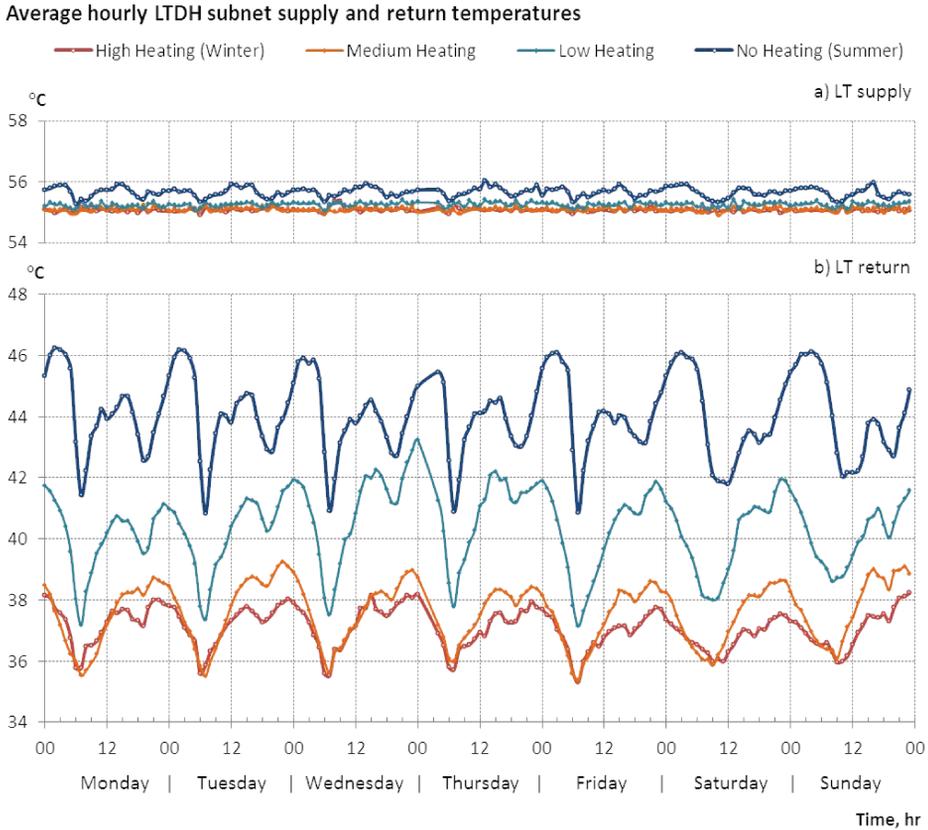


Figure 8-5. Average week aggregated supply and return temperatures by heat demand period

This figure shows the hourly average supply and return temperatures of the LT subnet at the substation in an average week by demand period. The supply temperature is fairly constant, except during summer when it presents small variations. Compared to the previous Figure 8-4 the minimum return temperatures match the maximum heat demands and vice versa. Moreover, given the demand periods it is also shown that for lower heat demands, the return temperature is higher and viceversa.

In overall, there seems to be an inverse correlation between the LT load and the LT return. When computing the correlation coefficient between these two parameters a value of -0.921 is found, indicating a strong negative correlation. To investigate further on this correlation, **Figure 8-6**, shows a plot of the return temperature versus the LT load. From the figure, it is possible to identify a clear trend, and to fit a function, assuming that the aggregated return temperature is strongly dependant on the aggregated load of the subnet above other factors.

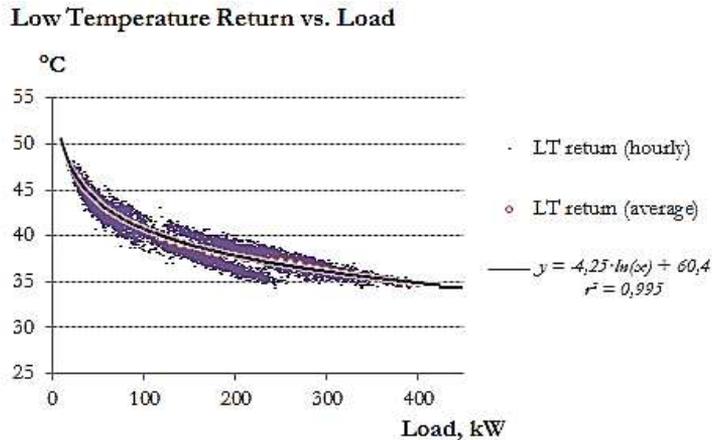


Figure 8-6. Low-temperature subnet return temperature as a function of the aggregated heat load

Figure 8-6 shows the low-temperature return in hourly average values at the substation plotted as a function of the corresponding aggregated heat load. As seen from the figure, the return temperature increases at lower loads, corresponding to higher outdoor temperatures. In addition, a curve with average values is shown and a function is fitted to the hourly values. The function resulting in a higher r^2 value is a logarithmic function whose corresponding coefficients are given.

Figure 8-6 illustrates the strong correlation between the load and the subnet return temperature; compared to **Figure 2-2b** where the conventional return temperature vs. load is a concave curve with an opening facing upwards, and presenting an increase in temperature at lower outdoor temperatures (higher loads), in the case of the LT subnet the curve falls continuously. This behaviour is attributed to the nearly fixed supply temperature of the subnet, and so it can be assumed that it is the aggregated

load that influences the return temperature. In conventional DH networks the ΔT ($t_s - t_r$), and thus the return temperature, strongly depend on the forward temperature defined by the supplier [12]. On the other hand, although correlation does not equate causation in this case, given the different factors that might affect the aggregated return temperature, it is proposed that the return temperature strongly depends on the aggregated load on a network with such physical and operating characteristics.

Moreover, as there are no individual water storage tanks, it could be possible to define a *return temperature signature* as a function of the aggregated load of this particular type of subnet. For the modelling and optimization of LT subnets, identifying this behaviour could be useful for future analyses and should be considered when planning and sizing the equipment at the substation. This is a unique characteristic of this LT subnet with constant supply temperature, since it is not valid for the existing DH networks with conventional supply temperature control. Behind this temperature signature, it becomes clearer that the settings of the individual substations and thus the flow that passes through them will have a direct impact on the return temperature.

8.2. Improved aggregated heat load model: application and validation

Based on the methodology described in section 6.1, the coefficients of the aggregated heat load model functions were estimated. The resulting model was implemented using the available measurement data from the case study and then the results are compared and validated.

The model is presented in two parts: the first part consists of the coefficients for the *Sig-Lin* function (from Eq. (2)) which include the results of the linear regression for distribution losses (DL) and the non-linear regression for the total space heating (SH); the second part includes the coefficients for the linear regressions corresponding to the hourly load factors. The resulting coefficients are shown in **Table 8-2** and **Table 8-3**. Then, using as inputs for the model the temperature distribution as well as the workday and weekend subsets, and the model coefficients, the model generates the hourly heat load.

Table 8-2. Fitted coefficients for the *Sig-Lin* function model from Eq. (2)

Coefficient	Value	Units
<i>a</i>	290.3	kW
<i>b</i>	34.22	°C
<i>c</i>	7.6	-
<i>d</i>	-0.3	kW/°C
<i>e</i>	24.5	kW
<i>T_{ref}</i>	40	°C

Table 8-3. Coefficients of the hourly load factor for workdays and weekends from Eq. (4)

Hour (i)	Workday		Weekend/Holidays	
	<i>f_i</i>	<i>g_i</i>	<i>f_i</i>	<i>g_i</i>
01	-1,579·10 ⁻⁰²	-0,1974	-1,348·10 ⁻⁰²	-0,1726
02	-1,896·10 ⁻⁰²	-0,1929	-1,995·10 ⁻⁰²	-0,1638
03	-2,169·10 ⁻⁰²	-0,1710	-2,427·10 ⁻⁰²	-0,1283
04	-2,293·10 ⁻⁰²	-0,1353	-2,606·10 ⁻⁰²	-0,1208
05	-2,462·10 ⁻⁰²	-0,0903	-2,663·10 ⁻⁰²	-0,0983
06	-2,314·10 ⁻⁰²	-0,0081	-2,916·10 ⁻⁰²	-0,0664
07	-6,101·10 ⁻⁰³	0,2069	-2,540·10 ⁻⁰²	-0,0483
08	6,111·10 ⁻⁰³	0,2516	-1,832·10 ⁻⁰²	0,0461
09	6,535·10 ⁻⁰³	0,1370	-2,515·10 ⁻⁰³	0,1449
10	6,937·10 ⁻⁰³	0,1316	1,958·10 ⁻⁰²	0,2220
11	1,112·10 ⁻⁰²	0,1215	3,770·10 ⁻⁰²	0,1682
12	1,658·10 ⁻⁰²	0,0978	4,562·10 ⁻⁰²	0,1225
13	2,346·10 ⁻⁰²	0,0626	5,306·10 ⁻⁰²	0,0740
14	2,819·10 ⁻⁰²	0,0019	5,223·10 ⁻⁰²	-0,0090
15	2,915·10 ⁻⁰²	-0,0397	4,293·10 ⁻⁰²	-0,0272
16	2,764·10 ⁻⁰²	-0,0572	3,774·10 ⁻⁰²	-0,0693
17	3,074·10 ⁻⁰²	-0,0584	3,416·10 ⁻⁰²	-0,0486
18	3,441·10 ⁻⁰²	-0,0434	3,471·10 ⁻⁰²	-0,0340
19	3,967·10 ⁻⁰²	-0,0404	4,056·10 ⁻⁰²	-0,0674
20	3,955·10 ⁻⁰²	-0,0553	3,748·10 ⁻⁰²	-0,0719
21	3,172·10 ⁻⁰²	-0,1171	3,065·10 ⁻⁰²	-0,1380
22	1,541·10 ⁻⁰²	-0,1550	1,319·10 ⁻⁰²	-0,1464
23	1,619·10 ⁻⁰³	-0,1800	2,143·10 ⁻⁰³	-0,1835
24	-8,662·10 ⁻⁰³	-0,1852	-5,631·10 ⁻⁰³	-0,2058

The outcome of the model is shown in **Figure 8-7** and **Figure 8-8**. From the first one, in the heat load duration curve it can be noticed that the model estimates slightly lower loads for certain intermediate cold periods and slightly higher for warmer periods. In absolute terms, the annual heat demand of the model is 1267 MWh while the measured data adds to

1251 MWh, which is 1.3% higher, but already under the 5% of missing data points with errors. For the high heating load season, the model output total heat demand is 3% lower, while for the medium heating load season is 2% lower. In the case of the low heating load season, it is 5% above and during the summer, it is 22% above the measured data. In relative terms the load is underestimated during winter by an average of 9,4% while in summer it is overestimated by 33,6%. However, in absolute terms they nearly balance each other in the total annual heat demand.

Heat load duration diagram

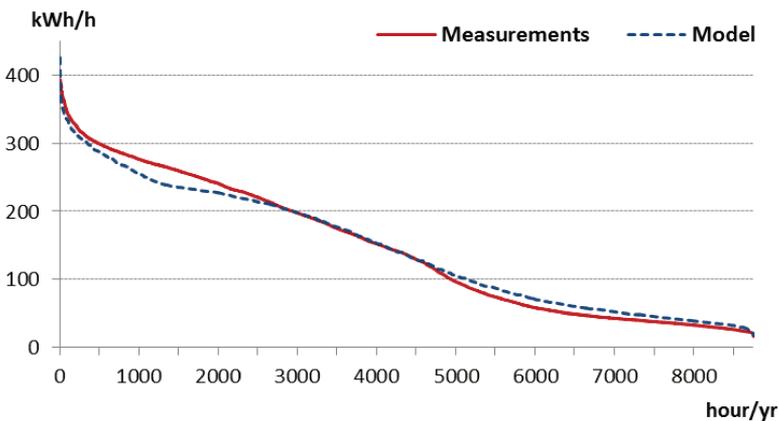


Figure 8-7. Comparison of the heat load duration diagram from measured data and model output

The heat load measurements are presented in the duration diagram, and compared to the *SigLin* model output given the fitted coefficients. The output of the model shows that the model might underestimate some of the medium-high loads while slightly overestimating lower loads.

Using the model, it is also possible to estimate the share of the load components in the annual heat demand. The results yield that approximately 195 MWh/yr are lost as heat distribution losses, which represents ~15% of the heat demand. The SH demand is estimated to be 56% of the total and so the remaining 29% is estimated to be the DHW demand. In comparison to the measurement data set, the heat loss was measured to be 14%, which is 179 MWh/yr. Thus, the model slightly overestimated the heat distribution

losses and may require a slight tuning in the DL function coefficients; yet this 1% difference is still below the 5% uncertainty related to missing data.

Daily Average heat load time-series diagram

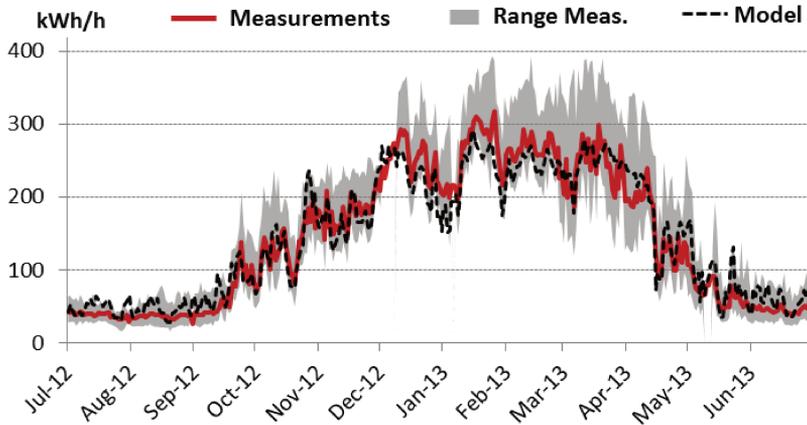


Figure 8-8. Daily average heat load comparison of measured data and model output

The time series diagram compares the heat load measurements to the *SigLin* model output. The red line shows the measurements daily averages while the dotted line the model results in daily averages as well. Also the maximum and minimum measured daily loads are shown in the grey range for a visual comparison.

In overall, the model shows a reasonable agreement between the measured and computed values for the aggregated load of the low-temperature subnet. In this specific case, where measurements are available, parameter fitting was used to obtain the model coefficients. As a large number of unknown factors are embedded in the coefficients, an approach to improve the fits can be achieved by adjusting the hourly heat load factor and tuning the functions coefficients.

8.2.1. Model Validation & Goodness of fit

The validity of the model is assessed by determining the goodness-of-fit of the model output and the actual values. Firstly, the goodness-of-fit statistics are compared including: the sum of squares due to error (SSE); R-square;

and root mean squared error (RMSE). Next, a numerical and visual analysis of residuals is presented. The models to be compared are the following:

1. **Energy Signature model**, the standard model for load estimation consisting in two curves (as illustrated in Figure 6-2, section 6.1.1). In this segmented function, as the load behaves differently in the temperature dependent and independent segments two linear functions are fitted: one for the temperature independent segment (DHW and DL), and another one for the SH load in the temperature dependent segment.

$$q_{tot}(T_{out}) = [q_{SH}(T_{out}) + q_{DL}(T_{out})] \quad \text{Eq. (26)}$$

$$q_{tot}(T_{out}) = \max\{(a \cdot T_{out} + b), (c \cdot T_{out} + d)\} \quad \text{Eq. (27)}$$

The coefficients are the following: $a = -11.33$; $b = 231$; $c = -0.3$; $d = 24.5$

2. **Sigmoid-Linear (*Sig-Lin*) model**, without hourly load factor, or differentiation on workdays and weekends. It consists of a temperature independent segment (DHW and DL) the same as for the energy signature model; and a sigmoid function is added and fitted for the temperature dependent segment of space heating.

$$q_{tot}(T_{out}) = [q_{SH}(T_{out}) + q_{DL}(T_{out})] \quad \text{Eq. (28)}$$

The equation used is Eq. (2), from step 2 defined in section 6.1.1. The coefficients are the same as from Table 8-2 from the previous section.

3. **Sigmoid-Linear (*Sig-Lin*) model with hourly load variations**. The full model used in this study as explained in section 6.1.1, and whose results were briefly presented in the previous paragraphs section 8.2). It is the same as the Sig-Lin model (nr. 2) with the addition of a set of linear functions to account for seasonal and hourly load variations (HLV).

$$q_{tot}(T_{out}, hr_{i=1}^{24}) = [q_{SH}(T_{out}) + q_{DL}(T_{out})] \cdot f_{DHW}(T_{out}, hr_{i=1}^{24}) \quad \text{Eq. (29)}$$

The full equations are defined in section 6.1.1 in Eq. (1) to Eq. (4). All coefficients are from Table 8-2 and Table 8-3 from the previous section.

The goodness-of-fit statistics of the three models described above are shown and compared in **Table 8-4**. The comparison of the measured and the models hourly heat loads shows that both the energy signature method and the *Sig-Lin* fit have overall poorer performance than the *Sig-Lin* method with hourly load variations.

Table 8-4. Goodness-of-fit statistics comparison among the models

	1) Energy Signature	2) Sig-Lin model	3) Sig-Lin with HLV
SSE	$13.86 \cdot 10^6$	$12.84 \cdot 10^6$	$7.56 \cdot 10^6$
R^2	0.8153	0.8330	0.8974
Adjusted R^2	0.8153	0.8329	0.8973
RMSE	43.58	39.49	30.03

The *Sig-Lin* with HLV (hourly load variations) method has a lower SSE (sum of squared due to error) that is nearly half than the other two methods. In addition, the RMSE (root mean square error) is approximately 30% lower. The multiple correlation coefficient R^2 and its adjusted value is higher for this model. The correlation being close to 0.9 indicates that this model can explain nearly 90% of the variation of the aggregated load.

8.3. Synthetic load and temperature curves from meteorological data

In this work, the hourly load and temperatures are generated as a synthetic dataset based on the outdoor ambient temperature distribution, from a uniform meteorological data base, *Meteonorm* [107], which exemplifies a year that statistically represents a typical year at the selected location, in this case Stockholm, Sweden. Based on the temperature dataset, and the data from the LTDH demonstration project described in the previous section, a heat load curve is created as well as the network operating temperature curves.

As shown in **Figure 8-0** diagram, the resulting data sets from this section are used as main input in sections 9.1 and 11.2, and partially in sections 9.3, 10.1 and 10.3.

The heat load is assumed to come from a multi-dwelling energy efficient building (~50 apartments) served by a low-temperature network and located in Stockholm, Sweden. The space heating systems are supplied indirectly with DH via a heat exchanger in the substation. It is also assumed that no heat storage tanks are present and so instantaneous water heaters for DHW preparation are in place. Full load conditions occur at -20°C of outdoor ambient temperature, with a maximum average combined load of $250 \text{ kW}_{\text{th}}$.

8.3.1. Subnet load curve based on TMY outdoor temperature

Following the model of the aggregated heat load function, and the temperature distribution, the coefficients of the *Sig-Lin* function were chosen to satisfy the maximum load parameters and distribution losses (DL). Similar coefficients for the linear regressions corresponding to the hourly load factors were used as in section 8.2. The coefficients used for this *Sig-Lin* function are given in **Table 8-5**:

Table 8-5. Coefficients for the *Sig-Lin* function model for the synthetic load curve

Coefficient	Value	Units
<i>a</i>	175.0	kW
<i>b</i>	36.41	$^{\circ}\text{C}$
<i>c</i>	7.5	-
<i>d</i>	-0.15	$\text{kW}/^{\circ}\text{C}$
<i>e</i>	12.25	kW
T_{ref}	40	$^{\circ}\text{C}$

Using the temperature distribution as well as the workday and weekend subsets, and the model coefficients, in a one-year period the model generates the hourly heat load. The heat delivered is then expressed as hourly average heat loads (heat delivered during 1 h periods). The unit of the loads is then kWh/h. The resulting load is shown in **Figure 8-9** and **Figure 8-10**:

TMY outdoor temperature and synthetic load (time series)

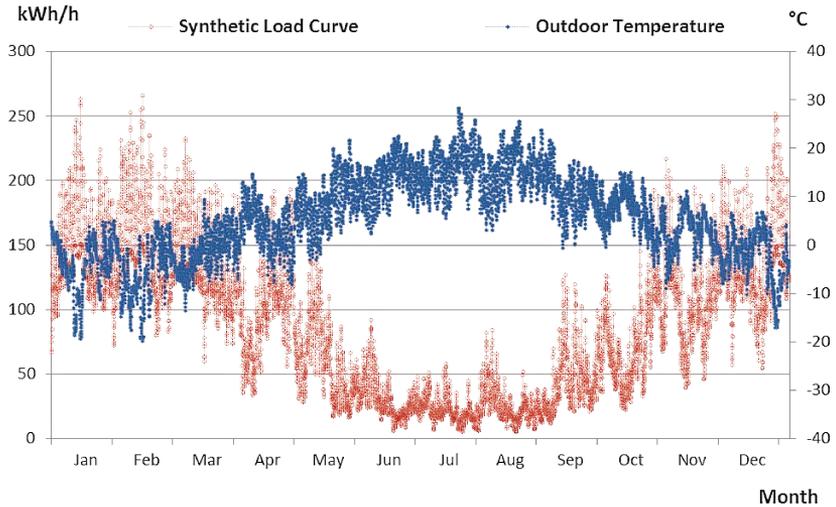


Figure 8-9. Time-series diagram of the hourly synthetic heat load and TMY outdoor temperature

Figure 8-9 displays the result from using the TMY outdoor temperature, in blue, as input for the synthetic load model output, shown in red. The maximum loads occur in the months of January and February reaching nearly 265 kWh/h. During the summer months of June, July and August, the minimum load reaches just below 15 kWh/h.

For an average annual outdoor temperature of 5.3 °C, the total heat supplied in the TMY period for the LT system is 750.5 MWh, and with a peak load of 265.5 kW. The aggregated heat losses are estimated to be 101 MWh; that is 13.5% of the total load; the heat demand for SH is estimated to be 58% and for DHW 28% of the yearly total heat supplied.

8.3.2. Subnet supply and return temperature curves

The substation feeding the LT subnet provides supply temperature control, which in this case, is set to be constant. This set-point value is the subnet supply temperature (55°C). On the other hand, to estimate the aggregated return temperature, assuming there are no individual water storage tanks, a temperature signature is defined with respect to the subnet load, as was

illustrated in section 8.1.4, **Figure 8-6**. The return temperature is defined as in Eq. (31):

$$t_s^{LT} = 55 \pm 1.5 \text{ } ^\circ\text{C} \quad \text{Eq. (30)}$$

$$t_r^{LT} = -3.0131 \cdot \log(\dot{q}_{LT}) + 42.674 \quad \text{Eq. (31)}$$

Heat load duration diagram

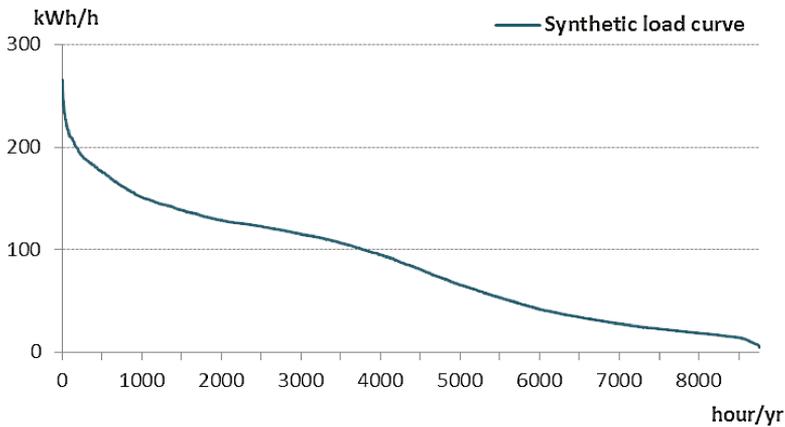


Figure 8-10. Heat load duration diagram of the generated synthetic heat load

This figure shows the output of the heat load model plotted in the form of heat load duration diagram. Based on the observations from Figure 8-7, it could be expected that high loads might be slightly underestimated in the region where this curve seems concave from ~500 to ~2500 hours.

8.3.3. Estimation of primary supply/return temperature curves

The primary DH system is a 3rd gen DH system. As no information is freely available regarding the temperature control operating strategy of the primary network both the supply and return temperature curves are approximated using the measured data and fitted functions. For the supply temperature a Sig-Lin function (as in Eq. (2)) is fitted without the component that gives the slope of the linear term; and without hourly variation coefficients. The resulting fit has an adjusted R² value of 0.8344 which implies a reasonably good fit. The fitted coefficients are shown in **Table 8-6**.

Table 8-6. Coefficients for the *Sig-Lin* function model for the primary supply temperature

Coefficient	Value	Units
<i>a</i>	40	°C
<i>b</i>	37.68	°C
<i>c</i>	3.97	-
<i>d</i>	0	-
<i>e</i>	65.5	°C
<i>T_{ref}</i>	40	°C

In the case of the primary return temperature, as the correlation between the supply temperature and temperature difference is high (0.974), a linear fit is used between the temperature difference and the return temperature, and then it is adjusted for the outdoor temperature. Thus, the primary return temperature is described as in Eq. (32):

$$t_r = T_s - (1,3772 \cdot T_s - 78,133) \quad \text{Eq. (32)}$$

The resulting synthetic hourly temperatures for the primary and secondary networks are shown in **Figure 8-11**. For the LTDH network, the yearly average values estimated are 55.6°C and 30.1°C supply and return respectively, with a higher return during summer. The primary supply temperature is in the range of 65-100°C, but in average 81.9°C; and the return temperature ranges between 41-58°C, but yearly average 46.8°C; which is within the range of DH networks in northern Europe [12].

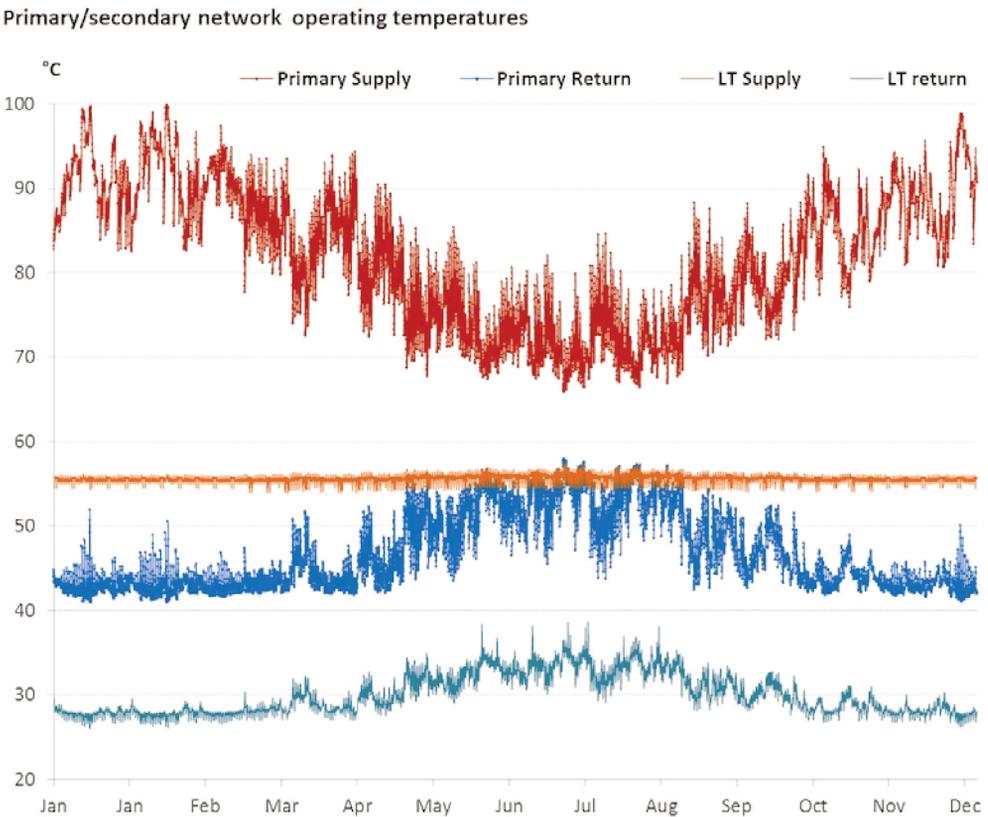


Figure 8-11. Time-series diagram of the generated operating temperature data

Figure 8-11 shows the estimated/synthetic supply and return temperatures from both the primary and secondary networks. These are the result of the model from the given coefficients in Table 8-6 for the primary supply; the approximation in Eq. (32) for the primary return; and the approximation in Eq. (31) for the LT subnet return temperature. The LT supply temperature is assumed to be constant at 55°C with variations of $\pm 2^\circ\text{C}$.

9. Active District Heating substations with temperature cascading

This chapter presents the results from the thermodynamic performance analysis of the subnet with an active substation using temperature cascading. First, the thermodynamic models for the district heating substations are detailed and discussed, it is followed by the results of the energetic and exergetic performance analyses, and then by a comparison among possible operating strategies to optimize the substation performance. These results are then compared with the outcome of the performance assessment of the LTDH demonstration project measurement data set, and then a sensitivity analysis on the subnet return temperature variation is performed. Finally, the potential for maximum heat recovery using the primary return line is estimated from the analysis of the temperature cascading layout.

9.1. Substations and subnet layouts with temperature cascading⁸

In order to analyse the subnet performance using temperature cascading at the substation that is able to recover heat from the primary return, two hydraulic layouts of the DH substation are proposed. To emphasize the performance improvement, a conventional substation is selected as a reference. For this reference, a commercially available substation [108] (as in **Figure 2-3**), is chosen suitable for this type of application. Note that this substation was not originally designed for low-temperature operation (nominal temperature design: 100-43/40-60 in °C). However, the thermodynamic model showed that it is possible to operate under the specified conditions without exceeding the nominal flow rate, and thus maintaining the pressure loss below the maximum limit from the design point of view. The substation is assumed to operate with asymmetrical flows, i.e. the flow rate in the primary (hot side) is different in magnitude to

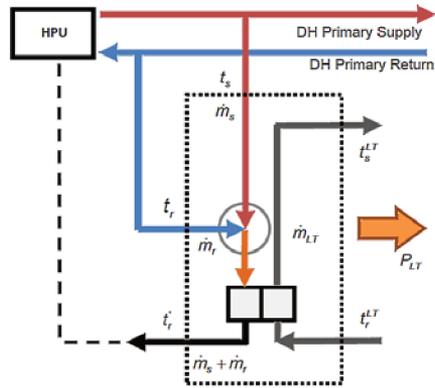
⁸ Some segments of this section are based on excerpts from **Paper [B]**, referred in the 'Publication List' of this dissertation, and published in 2016 in the *International Journal of Thermodynamics – IJoT*.

the flow rate in the secondary (cold side). The substation is treated as adiabatic with respect to its surroundings, since the heat losses to the environment are considered negligible in comparison with the supplied load. The operating pressures are assumed constant at 16 bar and 6 bar in the primary/secondary sides respectively.

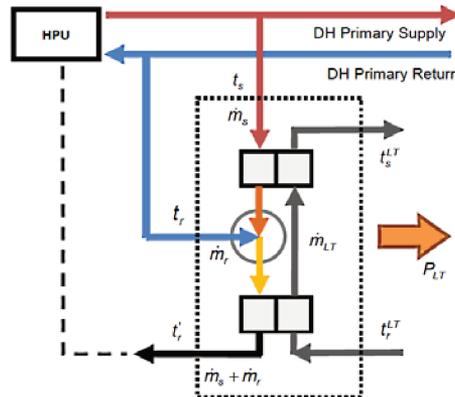
Figure 9-1a shows a high level diagram of the substation **type (A)**, already described in section 6.2 and previously depicted high-level in **Figure 6-3**. Moreover, another layout in two stages is afterwards introduced, with the assumption that it will lead to a slightly lower return temperature, smaller temperature difference between the primary and secondary sides, and thus higher efficiency. While type (A) has one main heat exchanger fed by a mixed flow via a jet-pump arrangement, in layout **(B)**, as shown in **Figure 9-1b**, the substation consists of two heat exchangers: a booster and a preheater.

Substation **type B** works as follows: a small portion of flow from the DH supply firstly goes through the booster where it rejects part of its thermal energy content to the preheated return flow from the secondary network to reach the set-point supply temperature. Then the flow from the outlet of the booster in the primary side is mixed with the flow from the main DH return via a 3-way valve that regulates the ratio between these two flows. Next, the mixed stream passes through the preheater where its energy is transferred to the return flow from the secondary network, and heating it to an intermediate temperature. Similarly to the previous substation type, the mixed stream from the primary side finally exits the substation return at the primary side at a temperature close to the secondary LT return temperature level.

The reference substation layout was modelled and sized according to the recommended European substation guidelines [17],[109], and previous LTDH demonstration projects described in literature [43],[22]. The more complex layouts were modelled, tuned, and verified in such manner that their operation also complies with the aforementioned guidelines. In order to comply with the maximum allowable pressure drop set by the DH substation design guidelines, the flow rate on the primary side of the LT substation was capped at 1.7 kg/s (maximum allowed nominal flow rate).



a) Substation type A with mixer



b) Substation type B with Booster and Mixer

Figure 9-1. Substation configurations: Type A and Type B

The figure shows the simplified process flow diagrams of the proposed low-temperature substations with temperature cascading labelled with the main operating parameters. On both figures the subnet (secondary) circuit is shown on the right side with the heat load. On the left side, the primary circuit receives the flow from the primary supply and return. The substation type A in Figure 9-1a mixes directly the streams before going through the HEx similar to the process flow diagram from Figure 6-3. On the other hand, substation type B, in Figure 9-1b shows a small booster HEx, a mixer and the main (preheater) HEx.

A summary of the substation parameters at full load (design) condition is shown in **Table 9-1**. These design parameters are in line with the conclusions drawn in [102] stating that the area of the heat exchangers and their thermal length should be increased: for space heating the area by a factor of ~ 3 , and the thermal length by a factor of ~ 2.5 as maximum, for sizing of LTDH substations supplying small dwellings.

As seen from **Table 9-1**, due to the heavier thermal duty required for LT operation, the required primary side flow rate is two times larger than for the reference substation. Similarly, the heat exchanger area is nearly three times larger. These resulting parameters were calculated based on HEX design described in Section 6.2. As consequence of having a larger heat exchanger, the cost of the substation increases. These parameters are in line with the conclusions drawn in [102] for LTDH substations supplying small dwellings.

Table 9-1. Substation design parameters: nominal operating point

	Units	Substation Type		
		Reference [91]	Type A	Type B
<i>System Components:</i>	/	Heat Exchanger	Mixer + HEX	HEX + Mixer + Booster HEX
<i>Temperatures (Primary / Secondary)</i>	[°C]	100-30 / 27-55*	70-28 / 25-55	70-28 / 25-55
<i>Flows (Primary / Secondary)</i>	[kg/s]	0.94 / 2.61	1.69 / 2.39	1.69 / 2.74
<i>HEX Area</i>	[m ²]	2.15	5.62	5.79 & 0.45
<i>Overall HEX Coefficient, U</i>	[W/m ² ·K]	~7000	~6000	~5800
<i>Thermal Length (θ)</i>	[-]	4.0 (4.5)*	5.6	5.5

**for low-temperature operation in this study*

By having a narrower temperature difference between the inlet and outlet points at the substation primary side, less heat is extracted from the flow, even though the total flow rate may be larger. The lowest temperature that can be achieved in the primary outlet is limited by the HEx dynamics and it is close to the return temperature from the secondary side.

9.1.1. Cascading performance analysis: energy supply and network temperatures

This section presents the performance results in terms on energy, flows and temperatures, for the subnet fed by the substation described in the previous section with the layouts that take advantage of temperature cascading from the primary return line. The main input operating parameters for the simulations come from the synthetic data of load and temperatures resulting from section 8.3. Overall, the results show that more than $\frac{1}{3}$ to $\frac{1}{2}$ of the total annual heat consumption in the proposed LT network can be covered taking the heat from the main DH return flow by using this concept. See **Table 9-2** where a summary of the energy performance indicators for the one-year period is shown. These are: the total share of energy demand that is covered by the primary supply (DHs) and return (DHr) flows, the yearly average substation return temperature, and the total flow that passes through the primary side of the substation. As seen from the table, the total share of energy supplied from the DH return flow is within 25-30%, with substation type B a slightly larger share.

These results are also displayed in the form of load duration curves (LDC) for substation Type A in **Figure 9-2**. Note that the equivalent figure for substation type B is similar and omitted for conciseness; yet the corresponding information is found in Table 9-2. For higher loads, and therefore lower outdoor temperatures, the return flow takes a larger share. This share is also larger at higher outdoor temperatures, lower heat load, and therefore higher return temperatures. Nonetheless, the total operating hours having these conditions are low.

The substation return temperature (t_{sr}) at the primary side outlet is also a parameter of interest, because lower return temperatures increase the operating efficiency of the substation. In this study, the results show that the yearly average substation return temperature is reduced 2 to 3 degrees

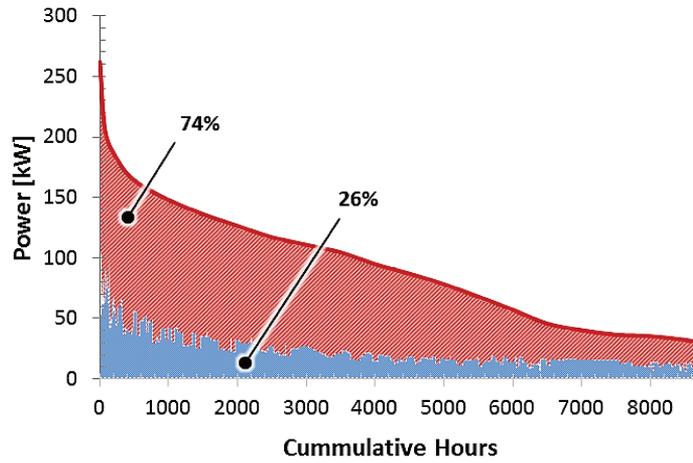
compared with the conventional substation (see **Table 9-2**). The importance of this temperature lies in the fact that this flow could be used for heat recovery in low temperature sources applications, and that having lower return temperatures may increase the efficiency of heat production units. The total pumping power at the substation is not shown but it is within the expected range of the total energy input to the substation: less than 2% of the total energy supply.

Table 9-2. Cascading substation analysis: annual performance indicators

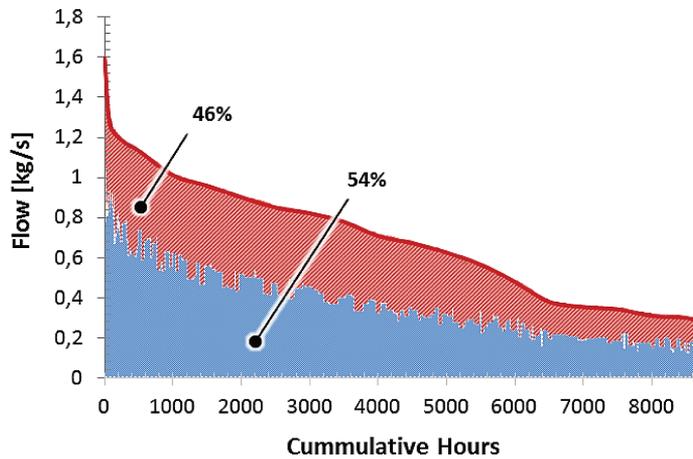
	Yearly Heat Demand Share		Substation Return Temperature
	DHs	DHr	Tsr (avg) [°C]
a) Type A	74%	26%	31.2
b) Type B	70%	29%	30.0
c) Reference	100%	-	33.0

	Volume Flow [m ³ /yr] in thousands		
	Total	DHs	DHr
a) Type A	30.2	54%	46%
b) Type B	30.1	49%	51%
c) Reference	23.1	100%	-

The total share of energy demand covered by the primary DH supply flow is reduced by 25% (**Figure 9-2a**) replaced by the main DH return flow. This reduction can be potentially larger in a network with higher return temperatures, which is usually the norm in conventional systems. This substitution of heat resource should not be interpreted as primary energy savings from the point of view of the heat production unit; but as a more efficient use of the energy already flowing through the DH network. Likewise, from the perspective of the primary distribution network, it means that less pumping power is required from the main distribution pumps to satisfy this particular consumer by using the cascading arrangement of substations type A and B.



a) Supply and return flows power share



b) Supply and return flows share

Figure 9-2. Cascading layout heat load duration curves for substation type A

The figure shows the results from the simulations of the LT substation/subnet given the average temperatures and loads in a heat load duration diagram and the matching flow diagram. The heat load diagram in Figure 9-2a shows that about $\frac{3}{4}$ of the demand is met by the supply flow, while in flow Figure 9-2b, it is less than half of the total flow. Note that the equivalent figure for substation type B is similar and omitted for conciseness; yet the corresponding information is found in Table 9-2.

The total flow passing through the primary side of the substation is approximately 30% higher, than with the conventional arrangement. Nevertheless, there is a net reduction on the flow taken from the primary supply pipe compared to the reference substation. This reduction indicates that for this particular consumer the heat demands are covered more efficiently. In further applications, it would also be possible to replace or add to the low-temperature flow from the main DH return low-temperature flow from a distributed renewable source or surplus heat from the industry.

The results from the thermodynamic analysis show that with this concept it is possible to supply a share of the annual heat demand of a LTDH network using the return flow from the main DH network as substitute for the primary supply flow. Both substation configurations/types proposed deliver similar results, except that type B yields slightly higher performance as shown in **Table 9-2**. The choice on whether choosing one substation type over the other will depend on the cost/benefit trade-off between the complexity of the equipment (its cost) and the benefits of efficiency and flexibility which should be studied in detail with actual prototypes.

In a possible improvement to the design, a heat pump can be coupled at the primary side to lower the primary side outlet temperature below the threshold of the secondary side return temperature while recovering additional heat to feed the network. Yet, an additional energy source would be required for this purpose, but a lower return temperature (e.g. $\sim 15^{\circ}\text{C}$), could also bring possible benefits to balance the costs.

9.1.2. Cascading performance analysis: an exergy perspective⁹

With the purpose to obtain deeper insights regarding the performance of the cascading layout, the substation operation is analysed from an exergetic point of view, and the results are presented in this section. In order to emphasise the influence of the outdoor temperature on the exergetic performance, the figures throughout this subsection show the exergy as a

⁹ Some segments of this section are based on excerpts from **Paper [B]**, referred in the 'Publication List' of this dissertation, and published in 2016 in the *International Journal of Thermodynamics – IJoT*.

function of the outdoor temperature, instead of LDC. In the overall system exergy balance, the exergy input includes the exergy from the DH supply and DH return flows, as well as the pumping energy on the secondary side of the substation.

Figure 9-3 shows the comparison of the exergy supplied as function of outdoor temperature, for substation type A. (Substation Type B is omitted at this point as the curve is equivalent). Notice that the exergy supplied (expended) is slightly higher in the case of the reference substation (dotted line). With the LT substation, the exergy resource is used more efficiently, and so less exergy input is required to meet the same load. Therefore, the exergy losses/destruction due to irreversibilities are lower with this layout.

For a deeper understanding of the exergy destruction occurring within the substation subsystems, it is estimated individually and plotted by separate processes in **Figure 9-4** for each substation type. By comparing the three plots, it is noticed that there is a reduction on exergy destruction in comparison to the reference substation (**Figure 9-4c**, or the dotted line in figures *a* and *b*). Exergy destruction caused by pumping follows a different pattern than the processes of heat exchange and mixing: even though there is a slight decrease in the exergy destroyed from pumping as the temperature increases, it is not as substantial as it occurs with the other two processes. Subsequently, for higher outdoor temperatures when space heating is not needed ($>15^{\circ}\text{C}$) the highest share of exergy destruction is due to the pumping effort.

Focusing on the exergy destroyed in the other processes, in **Figure 9-4a**, substation type A includes the exergy destroyed due to the mixing of the two flows before entering the heat exchanger and then the exergy destroyed at the heat exchanger itself. In substation type B, most of the exergy destruction occurs in the heat exchange processes, at both the booster and the main heat exchanger (**Figure 9-4b**). It is concluded that the exergy destruction at the heat exchange processes is in both cases larger compared to the mixing process, although the latter rather more significant in substation Type A. In the case of the substation type B, the exergy destroyed in the mixing process is marginal, whereas in substation type A, it is shown to be dependent on the temperature difference between the DH

supply/return flows, rather than on the magnitude of the mixing flows. Thus, the heat exchanger design efficiency (ε) from Eq. (6) is more relevant for the substation design.

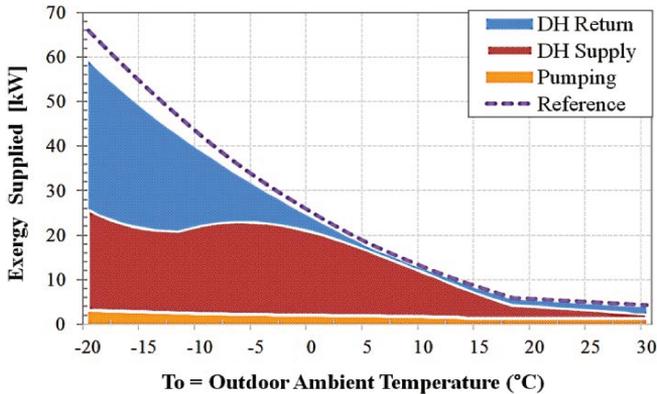
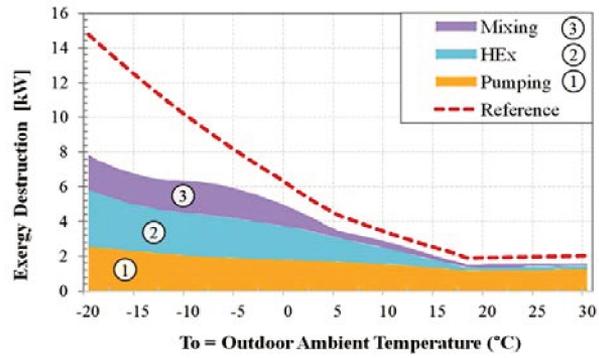


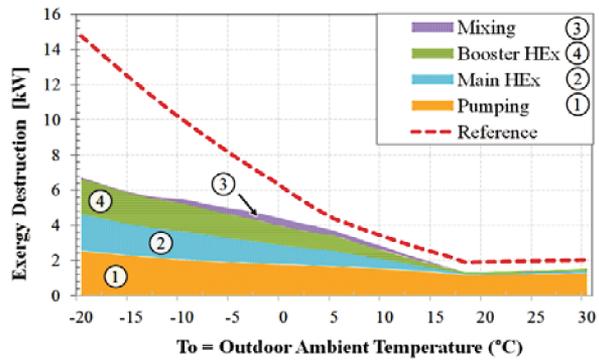
Figure 9-3. Exergy supply at the LT substation Type A

The figure shows the results from the simulations of the LT substation/subnet regarding the comparison of the exergy supplied, as function of outdoor temperature, for substation type A. The exergy supplied (expended) is slightly higher in the case of the reference substation (dotted line). Especially at colder outdoor temperature the LT substation requires less exergy input to meet the demand, thus the exergy resources is used more efficiently. (The equivalent figure for substation type B is similar and omitted for conciseness.)

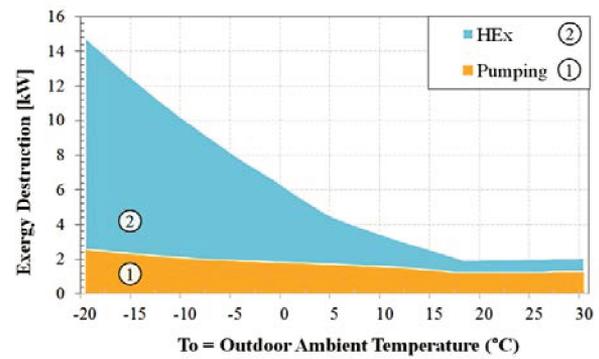
These differences in exergy destruction are clearer when we focus the analysis on the share of exergy supplied for pumping. The exergy destroyed due to the pumping effort seems fairly constant compared to the other processes (**Figure 9-4**). Yet when compared to the exergy supply, for higher outdoor temperatures, the exergy destroyed due to pumping, is more than half of the total exergy destroyed; whereas in the heating season it represents a much smaller share. These results complement and contrast with the energy analysis from the previous section, where the energy demand from pumping is only 3% of the energy supplied on the same conditions. It is noted that the exergy destruction due to pumping does not decrease as much as the exergy destruction related to heat demands. Pumping energy is a considerable input in the exergy analysis, and will influence strongly the system exergetic performance.



a) Type A



b) Type B



c) Reference

Figure 9-4. Comparison of exergy destruction by process and substation type

Figure 9-4 shows the exergy destruction comparing the substation types and the thermo-mechanical processes. In the reference substation (dotted line) most of the exergy is destroyed during the heat exchange process Figure 9-4c. In other two substation types the exergy destruction occurring in the heat exchange processes is also more significant than in the mixing. The exergy destruction due to pumping follows a different pattern, it is relatively constant and at higher outdoor temperatures when space heating is not needed it represents the largest share.

The relatively constant exergy destruction due to pumping could be explained by the fact that the pumping energy input does not have a wide range of variation: from a minimum of 1.4 kW to 6.4 kW for the highest loads. As the pumping energy model is based on the variable speed pump from the demonstration project, the pump is mostly working outside its nominal point (80% eff.), and at low flows its efficiency sharply drops (20-30%), therefore the power demand for pumping does not fall in the same ratio, but instead it just falls slightly. As the pumping energy comes from electricity that is purely exergy and it is mostly destroyed when it is dissipated into mechanical and then thermal energy the exergy losses due to pumping remain fairly constant along the range of operating conditions.

Figure 9-5 shows the exergy efficiency of the substations as a function of the outdoor ambient temperature (T_{amb}), which is also chosen as the reference temperature (T_0) in this case. Substation type B shows higher exergy efficiency, and it is closely followed by substation type A (**Figure 9-5**); the exergy efficiency of the reference substation is lower, as expected. From the exergy efficiency perspective, these curves show that, it is preferable to operate closer to the nominal conditions (low outdoor temperatures) than under the summer conditions (higher outdoor temperatures). Yet, the number of hours that correspond to the undesirable operating conditions and low exergy efficiency may be more than one quarter (25%) of the total, but delivering less than 10% of the total annual energy demand.

Exergy is an extensive property that depends on the thermodynamic states as well as the reference state. In this study, the reference temperature is based on hourly average outdoor ambient temperatures. A combination of lower reference temperatures and larger exergy demands result in higher exergy efficiency during the heating season. Conversely, during summertime, lower exergy demands together with higher reference temperatures decrease

the exergy efficiency considerably. Exergy destruction is proportional to the reference temperature (T_0) and irreversibilities (entropy generation); therefore, the lower the reference temperature, the less exergy destruction with respect to the exergy input, and thus the higher efficiency. This agrees with previous studies concluding that using lower reference temperatures result in higher overall exergy efficiencies [41],[101].

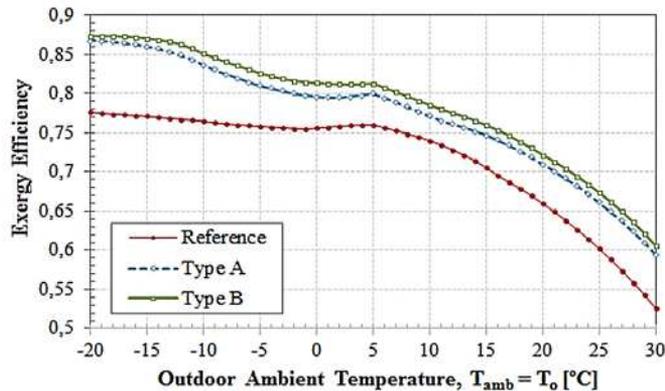


Figure 9-5. Exergy efficiency for the studied substations as a function of outdoor temperature

This figure compares the exergy efficiency of the substations as a function of the outdoor ambient temperature or reference temperature. All substations display higher exergy efficiency at low outdoor temperatures while slowly decreasing at higher temperatures. The reference substation has low efficiency over all the temperature range compared to the two proposed layouts.

The various results give basis to conclude that the improvement on exergy efficiency is achieved by both using a low-quality energy source, and also by maximizing the use of its thermal potential: lowering the return temperature of the flow using an efficient heat exchanger as with a longer thermal length. Similar conclusions have been drawn in [6],[41]. In other words, by simultaneously lowering both supply and return temperatures both exergy and energy efficiencies of the system increase.

This study only considered the system boundaries around the substation defined as in **Figure 7-1**. For the definition of the system exergy efficiency, both the system boundaries as well as the definition of the useful

(recovered) exergy are fundamental. In this case, the useful exergy output was assumed to be the exergy supplied to the LT secondary network. Nevertheless, the substation is a subsystem of a larger network and so a further step would be to consider the useful exergy output to be only the exergy demanded to cover SH and DHW demands. In that case, the exergy efficiency equation should account for additional terms. Thus, the two main components to add are: (1) the exergy losses related to distribution heat losses, and (2) the exergy destruction occurring due to heat exchange at radiators, heat exchangers for hot water preparation, and any other processes, such as heat storage losses when applicable, in intermediate substations.

9.1.3. Performance improvement through operation strategies and optimization

In the previous sections, the overall energy and exergy performance for the conventional substation and for the two internal configurations under conventional flow and temperature limitation have been discussed. As mentioned previously, the substations with two inlet flows have the advantage of being able to modify the ratio of the incoming flow mix. This results in an additional degree of freedom, within the constraints that determine the window of operation for these parameters. **Figure 9-6** shows the operating parameters and variables involved in the substation operation, and identifies them as fixed, independent or dependent variables and constraints.

At this point, we include the results from adjusting the operation of substations following different targets (see **Figure 9-7**)¹⁰. The results here presented compare the (i) reference substation operation (low-flow) and the two substation layouts already described following (i) a symmetric flow constraint operation, and a single-objective optimization with: (ii) minimum DH supply flow, (iii) maximum exergy efficiency, and (iv) minimum

¹⁰ The indicators regarding energy share and flows shown in **Figure 9-7** present some variations in comparison to the results from section 9.1.1 due to slightly different input parameters used. The annual load was normalized to 1000 MWh/yr for simplicity, and the synthetic inputs (load and temperature) were modified proportionally. In spite of these variations, the conclusions hold to the cases described throughout this Chapter 9.

substation return temperature. To make a valid comparison, all other conditions remain the same. **Figure 9-7** shows a summary of the annual average performance indicators calculated as follows: (a) energy supply share, (b) total annual flow supplied to the primary side, (c) annual average exergy efficiency, and (d) annual average return temperature. In general, substation Type B, with a main and a booster HEx, has a better performance compared to substation type A following the different operating strategies. They all overcome the performance of the conventional substation.

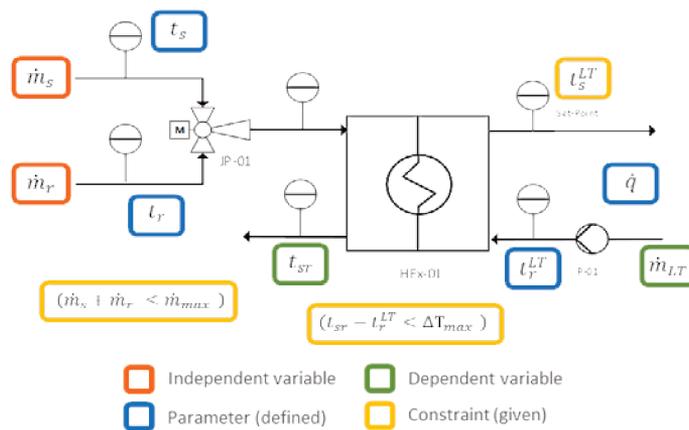


Figure 9-6. Main variables and parameters for the operation optimization

Figure 9-6 shows the thermodynamic parameters, variables and constraints that are used for the optimization in the different operating strategies. There are two independent variables (degrees of freedom); four fixed parameters based on the system conditions; two main dependent variables; and three main constraints that may be modified depending on the selected objectives as discussed in section 7.4 (refer to Table 7-1).

When comparing the operation strategies (cases I, II, and II from **Figure 9-7**), targeting maximum exergy efficiency (Case II) seems to yield better results: the highest exergy efficiency (improving from 79.4% to 84.7% for substation type A or 86.6% for substation type B), the lowest return temperatures (lowering from 33°C to ~29.5°C), and the least flow volumes. This is consistent with the fact that lower return temperatures increase the exergy efficiency, by having as large temperature differences as possible [6],[41]. However, in terms of energy obtained from the DH return flow,

the strategy of maximum exergy efficiency yields the lowest share compared to the other two as seen in the figure. Still, because of a lower total flow supplied in this case, less pumping power would be required. This is a strong motivation to include and consider exergy efficiency calculations in the management of such systems.

In Case III, for a minimum DH supply flow, the results show that the substation return temperature at the primary side outlet also increases. This is occurring because in order to meet the load of the subnet, the mix on the primary side with less DH supply flow has a lower temperature. Then, a larger flow is needed and because of the physical limitations of the heat exchanger, the ΔT at the substation changes. Nevertheless, pumping power would also increase as well as the return temperature, which negatively impacts the system efficiency.

A special situation occurs for the target of minimizing the substation return temperature (Case IV). The optimization shows that this target is achieved when only the supply flow is used. This makes sense, because in order to have the lowest return temperature and meet the load at the secondary side, also the least flow is required. In this way, the flow on the hot side gives as much energy as possible to the secondary side and is cooled the most, given the ΔT dependency, while being able to maintain the target supply temperature on the secondary side. This is an example of how the physics of heat exchange create conflictive objectives for the optimization. If the flow from the primary return were used, because of its lower energy content, a larger flow would be required and thus the substation return temperature would be higher. Hence, this strategy (Case IV) is not recommended. The result is equivalent to using an over-sized DH substation for this specific application. Thus, it follows that by appropriately designing the heat exchanger substation for LT operation, a significant increase in efficiency could be achieved.

From the viewpoint of controllability, a return temperature limiter is preferred to achieve a minimum supply flow since it is already an established strategy, and less processing capabilities and a simpler algorithm are needed. Still, the strategy that follows maximum exergy efficiency seems to achieve similar results, and in certain conditions, such as when a lower substation return temperature is more valuable, it could be a preferred strategy.

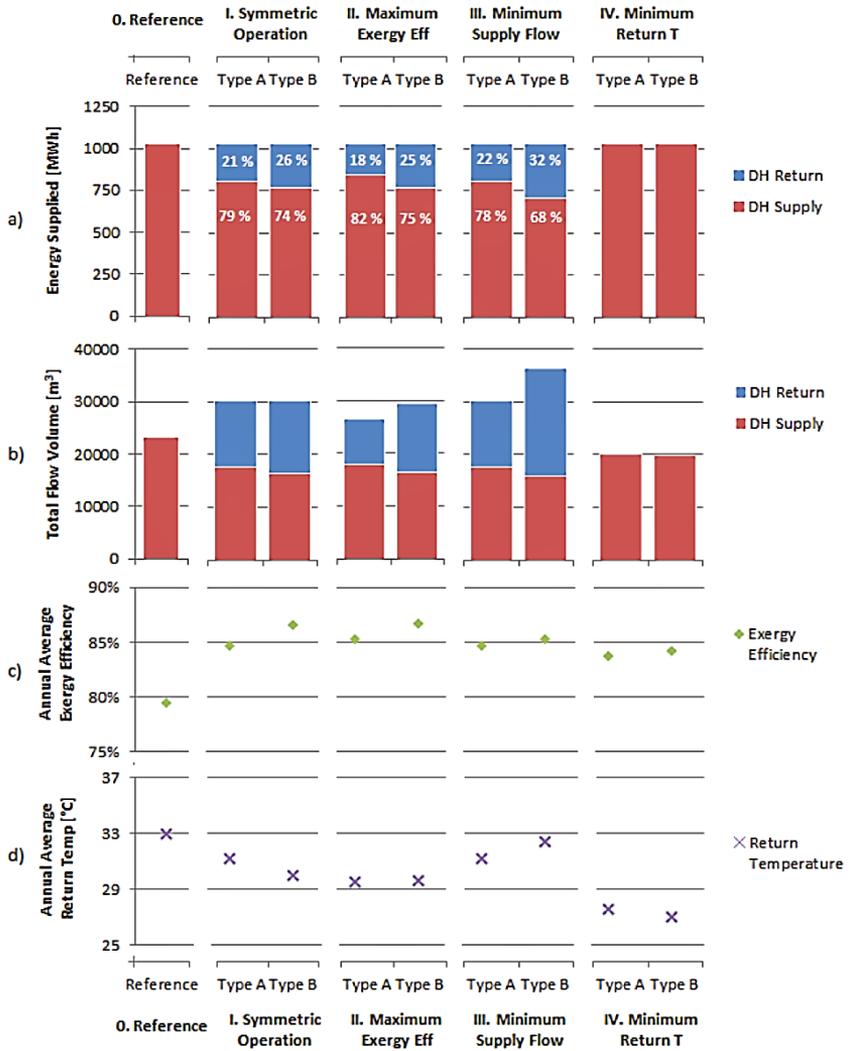


Figure 9-7. Comparison of annual average performance indicators for different operating strategies¹⁰

Figure 9-7 shows a graphical summary of the main performance indicators (energy share, flow, substation return temperature, and exergy efficiency) given the different operating strategies and substation types. The reference substation operating at LT conditions is compared with four other strategies applied to the two LT substation types. Concerning the substation return temperature, the DRT limitation (difference of return temperatures) was removed in order to allow a larger range of operation for the optimisation.

9.2. Temperature cascading in a LT subnet: performance analysis of a demonstration project

The measurements from the demonstration project described in section 8.1 are now analysed from a performance perspective. Previously, the data has been described in terms of temperature and load curves and patterns. In this section, the analysis takes the path to investigate the performance of the system focused on the cascade layout and as a mean to provide a benchmark for comparison for the results from the simulation model presented in the preceding section.

The cascade layout of the ‘substation’ demonstration project discussed in [20] consists of a LTDH subnet with a direct connection to the primary network through a 3-pipe connection shunt. In this connection, a 3-way valve is used to regulate the ratio of the mixture between the primary supply and return flows, which is controlled by a temperature sensor (thermostatic valve) to reach the set-point LT supply temperature as shown in **Figure 9-8**. An additional flow meter was installed to measure the flow rate of the primary return going through the 3-way valve. On the secondary side, a typical heat metering arrangement is placed with a flowmeter and the corresponding temperature and pressure sensors.

9.2.1. LTDH Demonstration project performance analysis: flows and energy sources

The performance analysis is presented in terms on energy and flows and temperatures, for the subnet described in the previous section with a direct connection temperature cascading layout. Overall **Figure 9-9a** shows that more than one third of the annual energy demand was extracted from the primary return flow, still the mayor share is taken from the primary supply. This heat share is also depicted in a heat load duration diagram. It is shown that for higher loads the return flow takes a slightly larger portion. Additionally, this share is relatively large at lower heat loads, and therefore higher primary return temperatures. In addition, the total pumping energy used is less than 2% of the total energy supplied. In terms of flow, **Figure 9-9b** shows that most of the flow feeding the subnet comes from the primary return, reaching nearly 80%. This figure contrasts with **Figure 9-9a**, concluding that although just a small share of the flow comes

from the primary supply, due to the larger temperature difference with the subnet return, the heat carried per unit mass is larger, and thus a large share of heat is taken from this flow.

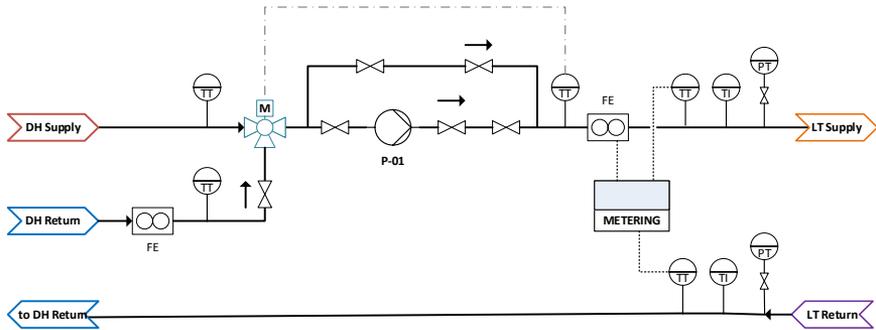


Figure 9-8. Process flow diagram for the LTDH demonstration project from [22]

This figure shows the process flow diagram (PFD) of the low-temperature ‘substation’ from the LTDH demonstration project in Taastrup, DK. The primary network input (supply and return) on the left, is mixed at the 3-way valve, shunt arrangement controlled by a motor that changes the valve position according to the set-point temperature value at the secondary supply circuit. The main pump circuit with a variable speed pump is also shown, driven by the differential pressure of the network (see Figure 8-1). The subnet (secondary) circuit is shown on the right with the main metering equipment. Note that in this diagram some equipment has been omitted for simplicity, such as safety circuits and their corresponding components.

Table 9-3 shows the share of supply to the subnet divided into the corresponding periods as explained in section 8.1.3. As expected, the average supply temperature is the lowest for summer. However, in this period the average return temperature is the highest among the others. The information from the table is also partly depicted in **Figure 9-10** for a graphical interpretation.

The previous information is also depicted in **Figure 9-10** showing the total energy supplied divided by periods and sources. The area of the rectangle represents the 100% annual supply. As seen from this figure, for the periods with heating demand the share between the primary supply and return heat are similar among them. A particular situation occurs in the summer period when more than 75% of the total energy supply comes from the primary return. However, this period totals less than 10% of the annual energy

supplied, although it takes slightly more than 25% of the operating hours in a year. Correspondingly, for this period, it is shown that the energy used for pumping takes a more significant share with respect to the energy supplied. Although less flow is circulated through the subnet during summer, more pumping energy per kWh of heat supplied. In addition, less heat is delivered and this is because the ΔT of the network during summer is narrower.

Table 9-3. Summary of heat and flows shares by heating period for the demonstration LTDH subnet

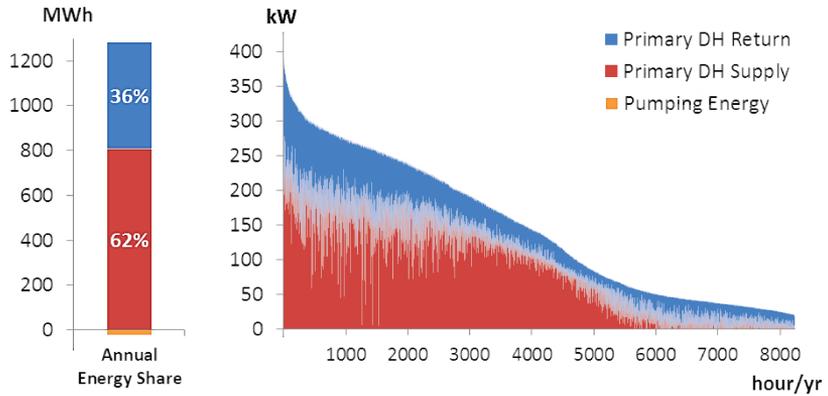
	Total Heat Supplied*	Total Flow (volume)	Primary DH supply		
			Temp.	Flow	Heat*
	MWh	m ³ /yr	°C	m ³ /yr	MWh
Annual	1252	66 814	80,1	15 274	787
<i>Winter</i>	551	26 973	90,1	5 843	346
<i>Medium H.L.</i>	417	21 003	82,2	5 803	291
<i>Low H. L.</i>	184	11 162	77,7	2 980	127
<i>Summer</i>	101	7 815	71,7	614	<u>23</u>

	Primary DH return		
	Temp.	Flow	Heat*
	°C	m ³ /yr	MWh
Annual	47,95	51 540	465
<i>Winter</i>	45,4	21 130	205
<i>Medium H.L.</i>	44,7	15 200	126
<i>Low H. L.</i>	47,2	8 182	57
<i>Summer</i>	<u>53,5</u>	7 141	<u>78</u>

*Values account for 5% of missing data points

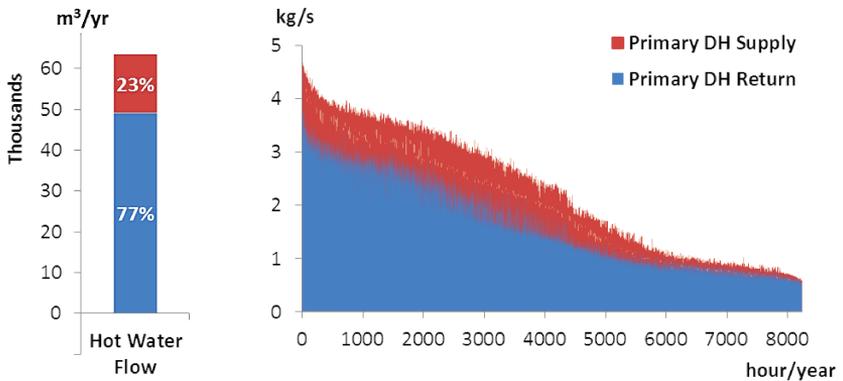
When comparing **Figure 9-10 a)** and **b)**, it is noticed that most of the flow going into the subnet comes from the primary return. Still, most of the heat delivered is taken from the supply flow. The ΔT is the main parameter behind this. As the supply flow has a higher temperature, the heat carried per unit mass in this flow is two times more in average than for the primary return flow.

Annual Heat Demand Share



a) Energy

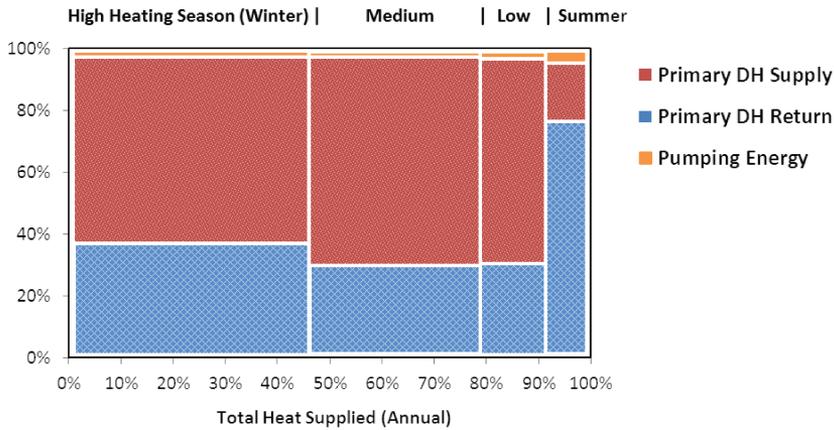
Hot Water Flow Share



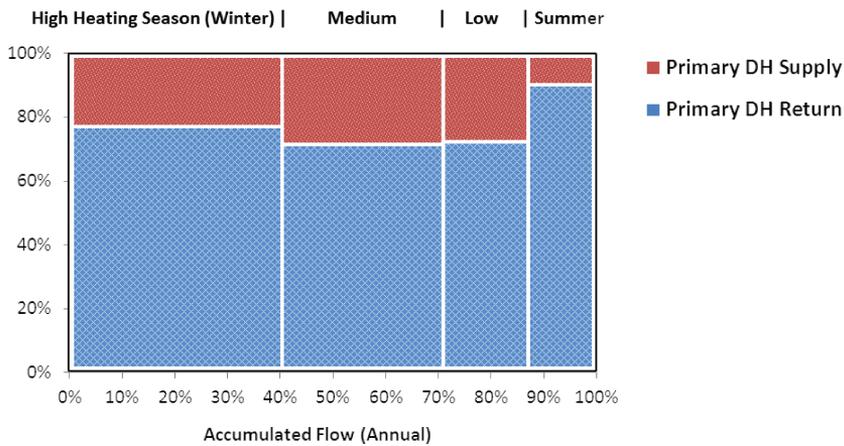
b) Flows

Figure 9-9. Annual heat demand (a), and flows (b) of the subnet, as total share and heat load duration diagram

The figure shows an analysis of the measurements from the LTDH demonstration project in a heat load duration diagram and the matching flow diagram. Figure 9-9a shows that slightly more than 1/3 of the demand is met by the primary return flow, while in flow Figure 9-2b, it is more than $\frac{3}{4}$ of the total. At high loads and very low ones, the return flow takes a slightly larger share. Moreover, pumping energy used is less than 2% of the total energy supplied.



a)



b)

Figure 9-10. Distribution of annual energy supply and flows by heat load period

This figure depicts the share of energy and flow supplied to the subnet in the 12-month period. The total area of the rectangle represents the total energy/flow supplied. It is divided by heat demand periods, and subsequently in primary supply and return flows. Figure 9-10a shows that for all demand periods except for summer most of the heat demand is covered by the supply flow; also in the latter the pumping effort takes a larger share. Figure 9-10b shows that during all the year most of the flow feeding the subnet comes from the primary return in all periods.

9.2.2. Sensitivity analysis to the variation in LT subnet return temperature

It was pointed out in section 8.1.3 that the operating return temperature of the LT subnet was higher than expected (see **Table 8-1**). In this section, we proceed to make a sensitivity analysis on the effect of variations of this temperature on the overall performance of the subnet. The substation was modelled as a simple two-flow mixer and the pumping power is approximated by fitting a curve to the available data measured from the variable speed pump in place (*Grundfos CRE 20-7*), see [10]. The resulting polynomial to approximate the pumps electricity input, as a function of the mass flow rate of the LT subnet is given in Eq. (33). The subnet return temperature was proportionally reduced to reach an annual average of 35, 30 and 25 °C; above a minimum return temperature of 22°C.

$$\dot{W}_{el} = 0,012741 \cdot \dot{m}_{LT}^2 + 0,095975 \cdot \dot{m}_{LT} + 1,2052 \quad \text{Eq. (33)}$$

The results of the sensitivity analysis are shown in **Figure 9-11**, assuming all other independent variables constant. **Figure 9-11a** shows that reducing the subnets return temperature results in an increase share of heat recovered from the primary return line. For instance, for a 10°C decrease in the average subnet return temperature (from the initial 40°C), approximately 15 points (%) are added to the primary return share. **Figure 9-11b** shows the decrease in flow and pumping energy as consequence of reducing the subnet return temperature. In this case, for a 10°C decrease in the average subnet return temperature, there is a 36% reduction in the required flow that leads to a 27% decrease in pumping energy compared to the baseline case of the measurement data set.

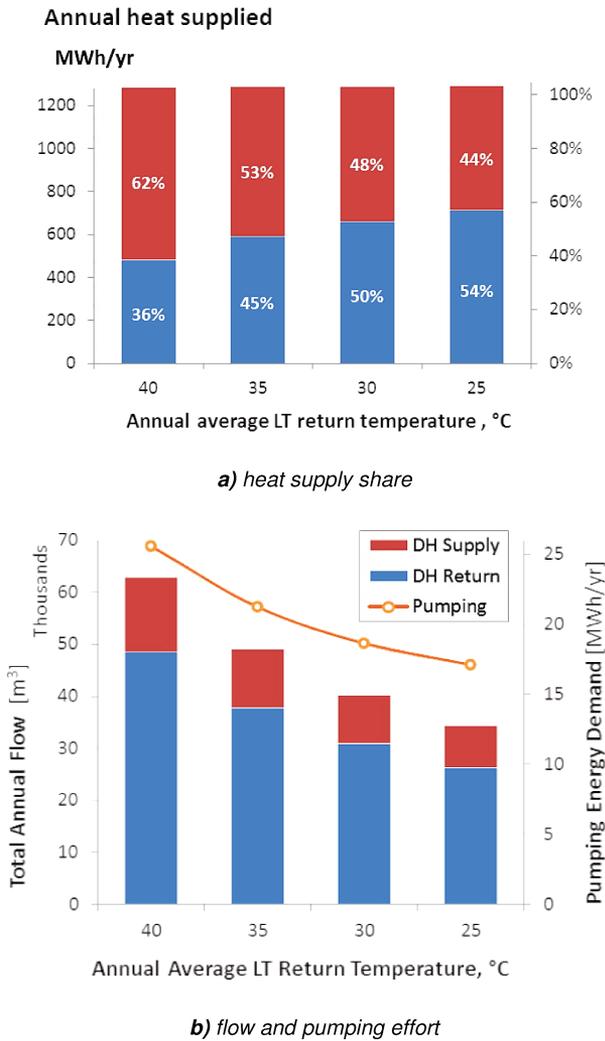


Figure 9-11. Impact of the reduction in the LT subnet return temperature on selected performance indicators

The figure shows the impact that reducing the return temperature of the LT subnet has on the performance indicators of: energy share, flow and pumping effort. The three indicators show an improvement with the reduction of the subnet return temperature: increased share of primary return flow, less flow required to circulate within the subnet and thus less pumping power.

9.3. Temperature cascading potential for heat recovery from the primary return flow¹¹

Temperature cascading allows heat recovery from the primary return to be used in subnets at lower temperature. If using the low-temperature substation layout for this purpose, once the substation recovers this low-grade heat, the return flow is then mixed with the primary return flow. A high-level schematic of the system is depicted in **Figure 9-12**. In such scenario, when having several substations one after the other, because of the incremental reduction in the primary return temperature, not all substations would be able to recover the same amount of heat. Moreover, as the percentage of LTDH subnets would approach 100%, the primary return temperature becomes close to the LT subnets temperature and thus the heat recovery from the primary return would be marginal. It is possible then to presume that there would be one or several optimal configurations to exploit the primary return flow.

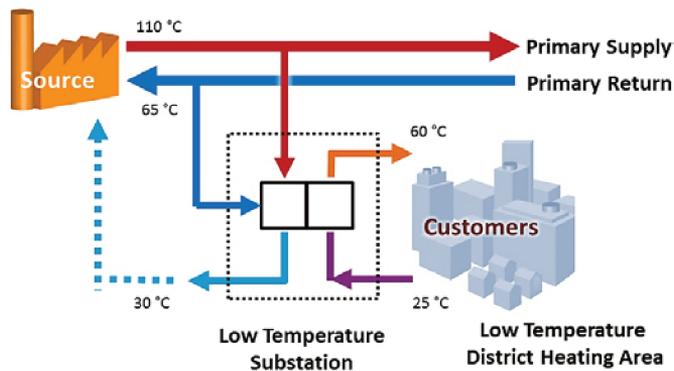


Figure 9-12. Schematic diagram of the low-temperature substation with temperature cascading

Figure 9-12 depicts a high-level schematic of the LT substation (and subnet) with temperature cascading as part of a conventional DH system. The substation uses a mix of the primary supply and return flows to meet the LT subnet demand, and the substation primary side return flow is directed back to the primary network.

¹¹ Some segments of this section are based on excerpts from **Paper [D]**, referred in the 'Publication List' of this dissertation, and published in 2017 in *Energy Procedia*.

9.3.1. Distribution network branch, heat losses, and pumping work: modelling

In order to analyse the aforementioned situation, and to study the temperature profile of the piping in an accurate and simplified manner, a single linear network branch was modelled as in **Figure 9-13**. The loads on this representative branch are assumed to be of the same magnitude and regularly distributed along the length to define a constant baseline. Each load (customer) represents a subnet coupled by an individual DH substation, all with similar load and temperature patterns. In this case, the LT substations were modelled based on the 'mixer' type (A) described in section 9.1.1 and the conventional substations according to the reference substation from the same section, following the flow of information described in **Figure 8-0**.

The temperatures are related to the distribution losses while the mass flow rate to the pumping power. Since the heat production unit defines the supply temperature, the supply mass flow rate is the addition of the flow rates demanded by the individual substations according to their corresponding loads, plus the make-up flow required to compensate for distribution heat losses, modelled as in Eq. (34).

$$\dot{m}_{tot} = \sum_1^n \dot{m}_n + \dot{m}_{q.loss} = \sum_1^n \frac{\dot{q}_n}{(h_s - h_{sr}^n)} + \frac{\dot{q}_{loss}}{(h_s - h_r)} \quad \text{Eq. (34)}$$

where \dot{m} is the mass flow rate, n the number of substations, \dot{q}_n the load per substation, and h the specific enthalpy of the flowing water. The subscripts are s for supply, r for return, and sr for the substation return (outlet).

The return mass flow rate is equal to the supply, but the temperature profile varies depending on the individual substations return temperature and flow. In order to calculate the local temperatures of the return flow a mixing flow equation is used. The temperature is then calculated from the local enthalpy values as in Eq. (35):

$$\dot{m}_{tot} h_{tot} = \sum_1^n \dot{m}_n h_n \quad \text{Eq. (35)}$$

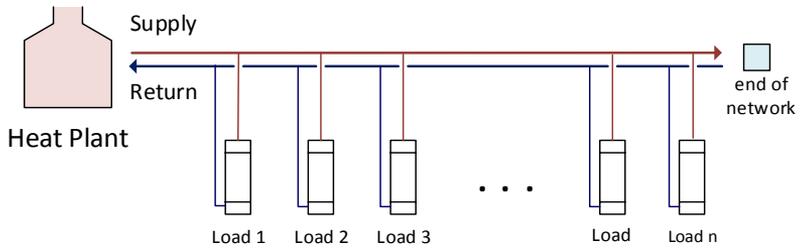


Figure 9-13. Schematic of the simplified DH network section model

Figure 9-13 shows the schematic of the model of the simplified DH network section or branch. Each load represents a substation feeding a subnet. The subnets are arranged one after the other and connected in parallel to the primary network, as is the standard practice.

In this analysis, the distribution losses are calculated for steady-state conditions, and the total heat loss in the network is determined as the sum of the individual heat losses in each pipe section assuming regularly distributed loads. The steady-state loss is estimated using a constant average value for thermal loss coefficient; this approach commonly employed yields acceptable results from the engineering point of view. In this case, two values are used: one for the supply pipe and another for the return, in order to account for the dependence on the average supply/return temperatures: $\lambda_{eq,s} = 0.520 \text{ W/m}_\text{K}$ and $\lambda_{eq,r} = 0.505 \text{ W/m}_\text{K}$, which are within the value range of newly built DH piping in northern Europe [12].

Heat losses are also proportional to the pipe diameters, which are larger near the supply unit or backbone distribution loops, and smaller at the end of branches. In this work, the lambda coefficients used assume an equal average pipe diameter [110]. For the calculations, the temperature drop along the pipes due to distribution heat losses is at this point neglected. The heat losses per pipe section can be calculated as:

$$\dot{q}_s = (t_s - t_g) \cdot \lambda_{eq,s} \cdot l \quad \text{Eq. (36)}$$

$$\dot{q}_r = (t_r - t_g) \cdot \lambda_{eq,r} \cdot l \quad \text{Eq. (37)}$$

Where \dot{q} represents the heat flow from each pipe in kW, t_s and t_r are the supply and return temperature of the pipes respectively, t_g the undisturbed ground temperature, λ_{eq} the equivalent thermal coefficient in W/m·K (for a buried one pipe/conduit in a two-pipe system) and l is the length of the pipe section. The undisturbed ground temperature is approximated [111] as the average air temperature for the defined period for the calculation, for instance, one year, or 3 months for a season.

The overall heat transfer resistance between the DH water and the environment is mainly composed of the thermal resistance of the insulation and the thermal resistance of the ground; the thermal resistance of the pipe wall and the convective resistance at the surface water-pipe are in practice negligible compared to the other two. This heat transfer resistance is in reality dependent on both temperature and time: the time dependency due to fouling and ageing of the pipes, thus increasing with time.

Pumping work is necessary to circulate the flow from the heat production unit to the customers. Thus, the pumps have to be able to overcome the pressure drop due to friction and keep the differential pressure between supply and return pipes of the critical customer above the minimum. For a given load, a reduction in the return temperature increases the temperature difference between the supply and return, and so the delivery capacity of the network. Thus, the total energy input required for pumping and its related costs are lower. In this analysis, the pumping power is calculated using the characteristic curve of an existing pump and determining the power for the different operating points depending on the volumetric flow and head, found in [112]. As variations in pressure drop are neglected, and with a constant pressure difference, the pressure head is assumed constant. Thus, friction losses are neglected as well as their contribution to the working fluid temperature.

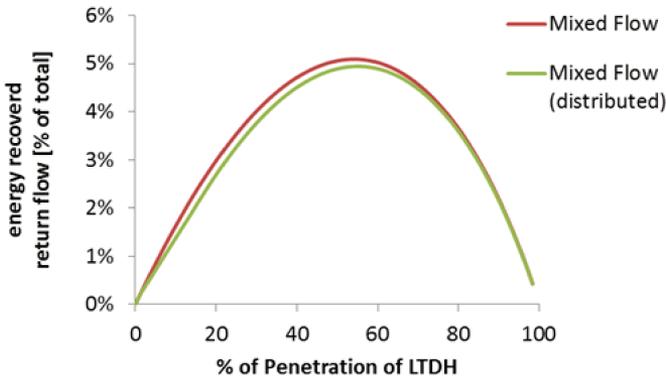
9.3.2. Estimation of maximum heat recovery: sensitivity analysis

To compare the performance of the substations placed one after the other in a DH line and the performance of the DH section in general, a sensitivity analysis with respect to LTDH load share is performed. It is assumed that the network branch has all subnets and loads operating at conventional DH levels, and then they are gradually replaced by LTDH subnets. The space

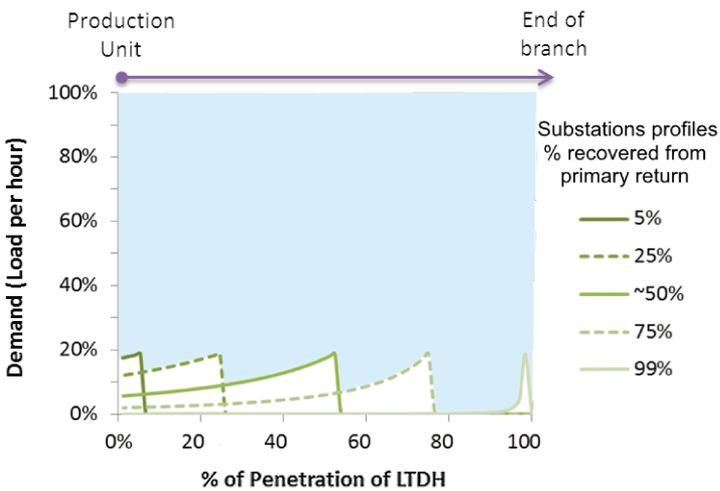
heating load in the LT subnets is 20% lower than in the conventional DH network. This replacement occurs at the subnet level assuming large buildings are renovated or secondary networks with a group of customers are refurbished. The various load and temperature dynamics inside the subnets are aggregated in the substation patterns as hourly steady-state conditions. All substations are presumed to present similar patterns and that they operate at nominal point with a conventional DH temperature programme (100-43/40-60) in °C; while the LT substations nominal temperature programme is (70-28/25-55) in °C.

Figure 9-14a shows the total energy recovered from the primary return as percentage of the total energy supplied to the network at nominal operation. The maximum achievable occurs when the percentage of LTDH is nearly 58% in terms of load. After this point, adding more LTDH substations still results in a decrease of the primary return temperature, but then the substations already present cannot recover as much heat so it starts to decrease again. With respect to the heat demand of the branch, the energy recovered from the primary return reaches near 5% of the total heat load. In addition, the difference between the curves in **Figure 9-14a** shows the influence of the actual location of the substations that are being replaced: when they replacement occurs in a more distributed way along the network section the energy recovery is slightly less than when they are replaced one after the other from the heat plant towards the end of the branch.

This behaviour may be explained physically as follows. Near the end of the branch (on the right), an individual cascading substation can recover more energy due to the higher temperature of the primary return and reach a maximum of 20% for the subnet. This is similar to the results from the previous sections for an individual substation. Then, a substation located at the left of this one will recover less energy from the aggregated primary return flow because the mix with the return flow from the previous substation has already decreased this temperature a few tenths of degree. This happens progressively to the left direction one substation after another. **Figure 9-14b** gives more insight to this situation. The resulting areas under the curves represent the recovered energy according to the substations location: for instance, the area limited by the 50% curve is nearly 5% of the area of the rectangle limited by the figure axes, equivalent to the maximum point on **Figure 9-14a**.



a) Total energy recovery



b) Energy recovery by location of substations

Figure 9-14. Energy recovery from the primary return flow

This figure shows the share of the total heat recovery from the primary return flow as a function of the load percentage of LTDH cascading substations. The figure (a) shows the maximum at ~58%. Then figure (b) shows the areas under the curves represent the recovered energy according to the substations location. The LTDH substations closer to the end of the branch recover more energy due to the higher temperature of the primary return at the respective points.

However, the potential of energy recovery is also dependent on the initial aggregated primary return temperature and the aggregated low return temperature of the subnet. Considering the same low return temperature of the subnet, if the primary return temperature of the network would be 10 degrees higher ($T_r = 53^\circ\text{C}$) it is possible to recover 10.5%, and with 10 degrees more ($T_r = 63^\circ\text{C}$) it is 18%. Thus, the higher the primary return temperature, the more energy that can be recovered from this flow into the subnets. In any case, this maximum is reached at 58% of LTDH subnets penetration, assuming all other parameters constant, so this maximum is independent of the primary return temperature. These results are valid for the nominal operating point of the substation that is a very cold winter day. It would be necessary to repeat iteratively this analysis for a yearly average operating point in order to assess the annual performance. However, from the results previously shown and discussed in the two previous subsections, it is possible to presume that similar performance will hold for the annual operation.

10. Impact of low-temperature based subnets on the primary network¹²

In this chapter, the results of combining the thermodynamic model of the subnet/substation with an economic model of the primary network operation are presented to evaluate the impact of the low-temperature based subnets. First, the scenario of a CHP-based DH network is described and additional details on the selected cost model are given. Then, the findings on savings regarding distribution heat losses and pumping effort are presented together with the additional revenues due to FGC operation and additional electricity generation.

10.1. Scenario description: CHP-based DH network

The impact that the introduction of LTDH subnets poses to the operation of a conventional DH network is assessed in an annual scenario hereafter described. The studied scenario was developed based on a Swedish DH network studied in [113] that is mainly supplied by a CHP plant (two-stage extraction) with FGC (flue gas condensation) and auxiliary boilers. It is very likely that low-temperature based subnets will gradually replace the conventional DH secondary networks, to benefit from LT operation and resulting in a lower aggregated return temperature at the heat plant. In this section, the network is scaled down, with simplifications and assumptions to be described further. The load duration curve (LDC) in **Figure 10-1** depicts the heat production units, with their power and operating hours. The LDC shows that one year of operation could be divided in four periods as far as heat production is concerned:

- During the period of low heat load (3100 hrs/yr), all heat is produced by a heat-only boiler in order to satisfy the domestic hot water (DHW) demand.

¹² This chapter is based on excerpts from **Paper [D]**, referred in the 'Publication List' of this dissertation, and published in 2017 in *Energy Procedia*.

- Throughout most of the year (4980 hrs/yr), the supply comes from a CHP unit delivering heat to the network at part load, and that is producing electricity. The FGC unit does not run during this period, in order to generate the maximum electricity possible in the CHP unit.
- When CHP reaches full load, the flue gas condensation unit (FGC) starts operation (330 hrs/yr), adding a maximum of 14% over the total heat produced. It does not operate during partial CHP load as it slightly reduces its electricity output.
- During the periods of highest load (350 hrs/yr), when both the CHP and the FGC unit are at maximum capacity, an auxiliary (peak-only) boiler enters operation.

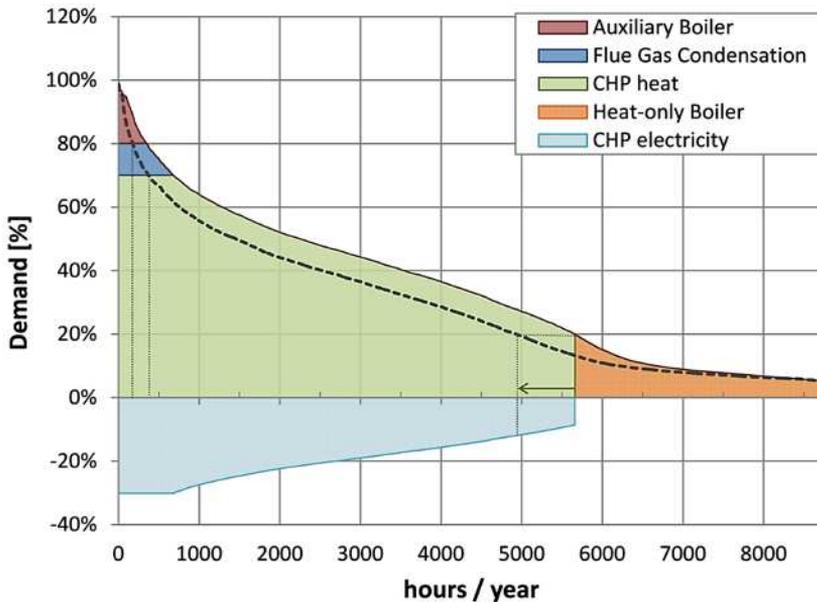


Figure 10-1. Load duration curve (LDC) of the CHP-based DH network scenario with heat production units

The LDC in the figure shows the DH network supplied mainly by the CHP plant, with additional heat recovery through flue gas condensation (FGC), supported by a heat only boiler in the summer, and an auxiliary boiler in the winter. The dotted line represents the shifted heat load profile due to the end use reduction of heat demand that would occur when all the network buildings would have sustained a moderate renovation to become more energy efficient.

For this evaluation, the input operating parameters in terms of the average values of each described period are described in **Table 10-1**. The total annual heat supplied is estimated at 82 GWh, from which 10.6 GWh are distribution losses (13%). The heat input to the DH network is driven by a bio-fueled CHP station such that the heat demand drives the electricity production.

Considering that a moderate building renovation for higher energy efficiency is necessary for the use of LTDH in the buildings in this network, it is assumed that the space heating (SH) load after renovation is 20% lower, and DHW demand remains nearly unchanged. The renovation would result in a 15% reduction in total annual heat demand (SH + DHW) when all buildings in the network would have been refurbished. The reduction on the heat demand due to energy efficient building renovation modifies the operating hours of each heat production unit (see **Table 10-1** and **Figure 10-1** *dotted line*).

The change in operating hours of the heat production units (caused by the future reduction in heat demand) presents both advantages and drawbacks: on the one hand, it reduces the operating hours of the auxiliary (peak only) fossil-fueled boiler and thus the amount of heat produced, considering its higher marginal cost and CO₂ emissions, it is beneficial; yet, the operating hours of the heat-only boiler for low load operation increase; on the other hand, the operating hours of both the FGC and the CHP are reduced, the FGC would produce less heat at a very low marginal cost, while for the CHP less electricity is generated during the year (refer to **Table 10-1**). Nevertheless, in a long term perspective it also means that additional customers can be connected to the network without causing bottlenecks or increasing peak demands, and thus additional investments to increase heat generation capacity could be deferred or avoided.

10.2. Estimation of savings and additional revenues for the CHP-based DH network

The estimation of savings and additional revenues is performed by assessing the annual DH operation considering the reduction in the aggregated return temperature that the LTDH subnets would bring. The savings are related to: (1) the reduction in distribution heat losses in the return pipe; and (2) lower

pumping power demand. Likewise, additional revenues are assessed from: (3) improved Power-to-Heat ratio for electricity production; and (4) enhanced heat recovery through Flue Gas Condensation (FGC).

Lower return temperatures have a positive effect on CHP plants connected to DH networks, and increase the available heat recovery from exhaust gases (FGC) at the plant. Regarding electricity generation, the return temperature has an important effect on 2-stage CHP plants where electricity generation is driven by the heat production. The Power-to-Heat ratio, also referred as *alpha value*, expresses how many MW of electricity are produced per every MW of heat, shown in Eq. (38). Only heat recovered in the CHP condensers is considered (heat recovery from FGC is not accounted at this point), and is influenced by the return temperature among other parameters. As the return temperature decreases, the alpha value increases making it possible to generate more electricity for every MW of total heat produced.

$$\alpha = \frac{P_{el}}{P_{th}} \quad \text{Eq. (38)}$$

Although the *alpha value* varies slightly throughout the year, in this study a constant average value of 0.43 is selected as baseline and the increase of electricity production is assumed to be 5 kW_{el}/MW_{th} for every 10°C reduction of the return temperature [28]. This amount may not seem significant enough from the energy perspective, but from the economic point of view it is valuable due to the electricity sales on a yearly basis.

Flue gas condensers (FGC) recover latent heat of the water in gaseous phase of the exhaust gases resulting from the combustion process. The recovered heat is then used to preheat the DH water before entering the main plant HEx, resulting in an efficiency improvement. A lower return temperature increases the cooling capacity of the FGC, so more moisture is condensed, and thus more latent heat is recovered. The economic advantage of the FGC lies in the fact that fuels are priced according to their dry energy content –Low Heating Value (LHV). Therefore, the heat recovered using this technology is not priced. For this reason, the marginal cost of heat production of a FGC is very low, around 5-10 EUR/MWh [28].

FGC increases the total heat recovery in a range from 10% to 35% depending on the technology and the fuel characteristics. In this analysis, a maximum value of 14% is used, typical for gaseous fuels. Also, in terms of the return temperature, the heat recovery at the FGC unit is assumed to increase 1% over the total heat production per every 5 °C reduction of the return temperature [28].

In this scenario, to estimate savings and revenues, two economic inputs are required: the electricity tariff paid for the pumping work, and the electricity market spot price at which the CHP electricity is sold. All prices vary throughout the year, so average values were used for these periods. **Table 10-2** shows the corresponding costs and prices of the heat production units and electricity. When several heat production units are operating simultaneously, the unit with the highest cost establishes the marginal cost of heat generation, corresponding to the last produced MWh (the most expensive).

The outputs from the thermodynamic assessment are used to estimate the economic variables (the total mass flow, the temperature profile of the return pipe of the branch, and the return temperature at the heat plant). The savings and additional revenue are calculated based on the reference scenario without LTDH. The savings are defined and estimated in terms of heat losses and pumping energy, while the earnings are the additional electricity generation from the CHP and additional heat recovery from the FGC. The total is calculated using the prices from **Table 10-2** and Eq. (39):

$$S = Q_{loss_{sav}} \cdot C_{mc} + W_{pump_{sav}} \cdot C_{el_{tariff}} - 0.75 \cdot W_{pump_{sav}} \cdot C_{mc} + P_{CHP} \cdot C_{el_{spot}} + Q_{FGC} \cdot C_{mc} \quad \text{Eq. (39)}$$

Where Q represents heat saved or produced, W_{pump} the energy saved in the pumps, P_{CHP} the additional electrical energy produced by the CHP; C_{mc} is the marginal cost of heat production; $C_{el_{tariff}}$, the electricity tariff and $C_{el_{spot}}$, the electricity market spot price. Note that it is assumed that, on average, 75% of the pumping work is converted into heat, thus the equivalent saved pumping energy has to be produced as heat at the corresponding marginal cost.

Table 10-1. Heat production units and operating conditions for the CHP based network scenario

	Operating hours (baseline)	Operating hours (reduced)	t_{amb} (avg)	t_s (avg)	t_r (avg)	LTr (avg)	LTr (avg)	Relative Losses
	<i>hr/yr</i>	<i>hr/yr</i>	°C	°C	°C	°C	°C	%
Heat-only boiler	3100	3830	14.9	74.2	49.7	54.8	32.8	34.22
CHP (partial load)	4980	4560	2.2	83.9	44.7	55.7	29.0	11.39
CHP (full load) + FGC	330	195	-7.5	92.6	44.5	56.5	27.4	7.62
CHP + FGC + Aux. Boiler	350	175	-11.3	96.5	46.9	56.3	27.0	6.56
Network (annual)	8760	8760	5.3	81.7	46.3	55.2	30.1	13.05

Table 10-2. Heat production units capacity and costs for the CHP based network scenario

	Maximum Capacity	Marginal Cost of Heat (average) Ref. [114]	Electricity Market Spot Price (CHP) Ref. [115]	Electricity Tariff (avg.) Pumping Ref. [116]	Annual Heat Production (baseline scenario)
	MW_{th}	EUR/MWh_{th}	EUR/MWh_{el}	EUR/MWh_{el}	GWh_{th}/yr
Heat-only boiler	5	<u>69</u>	-	59	9.1
CHP (partial load)	17.5	<u>62</u>	22	55	56.8
CHP (full load) + FGC	17.5 + 2.5	<u>62</u> , 10	30	51	7.2 + 0.3
CHP + FGC + Aux. Boiler	17.5 + 2.5 + 5	62, 10, <u>84</u>	30	51	7.1 + 0.9 + 0.8
Network Total	25				82.1

10.3. Performance analysis: LTDH subnets impact on the CHP-based network operation

For this performance assessment, the simulation model used the LT substations based on the ‘mixer’ type (A) described in section 9.1.1 and the conventional substations according to the reference substation. Moreover, the network branch model from the previous subsection 9.3.1 was also used for the simplified model of the network, as depicted in **Figure 8-0**. In this analysis, the synthetic load and temperature curves are not directly used, but instead the operating points described in Table 10-1 to account for the average yearly performance in a simplified manner.

The results presented deal with the effect on the network distribution costs: heat losses and pumping energy. As a comparison, it is estimated that if the demand reduction due to improved building energy efficiency (end energy use savings) would occur at the conventional DH temperature levels, the relative heat losses would increase from 13% to 15.3%. **Figure 10-2** compares the relative heat losses as a function of the share of LTDH load. It is found that, despite the reduced heat demand, the lower return temperature keeps the relative heat losses at a similar level instead of increasing, and so the cost per MWh of heat delivered is also maintained. The shape of the curve will depend on where in the network the subnets are being replaced with LTDH. Their location might be difficult to influence, yet depending on their location the benefits might vary slightly.

This result is similar to that of a previous study [39] where the authors compare the relative heat losses, assuming a 20% annual heat demand reduction, in a conventional DH network compared to a LTDH network. In that study, the authors estimated that the relative losses in conventional DH would increase from 10.9% to 13.1%. Conversely, with the LTDH operation they found that it is possible to maintain the annual relative heat losses at 11.2% in their study.

With respect to the pumping effort, we analyse the ratio of energy required for pumping to the total heat delivered throughout the year: relative pumping energy use. The results show that the ratio decreases in spite of the reduction in annual heat demand (see **Figure 10-3**); and this is due to the increase in the network operating ΔT caused by the lower aggregated return

temperature, as well as the decrease in distribution losses. If this demand reduction would occur holding the conventional DH temperature levels, the relative pumping power would instead increase from 1.22% to 1.31%.

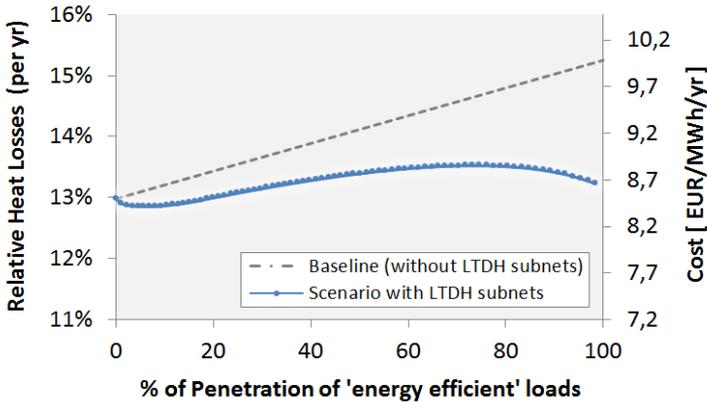


Figure 10-2. Relative losses as a function of 'energy efficient' load share

In the figure (both curves refer to both left and right axes), the relative losses axis on the left, and the equivalent annual cost on the right. Due to LTDH operation, relative heat losses are kept in a similar level (solid line), in spite of the 15% demand reduction due to energy efficiency savings. The dotted line represents the increase in relative heat losses assuming the demand reduction would occur with conventional DH temperature levels.

In absolute terms of savings in distribution heat losses and pumping energy, it is estimated that for a 10°C drop in the return temperature, there is a reduction of 6.7% in total distribution heat losses and 23% in total pumping energy. This occurs when LTDH penetration would reach 75%. According to previous studies [28], for a 10°C drop in the return temperature the heat loss reduction expected would be around 6%, and the pumping energy would be reduced by 40% approximately. The difference in the latter figure is partly attributed to the fact that in this work for the estimation of the pumping energy the variations in pumping efficiency are calculated using performance curves of existing equipment: the pump operating efficiency decreases at low pumping duties. Previous research has found that the overestimation of variable speed pump efficiencies is common when operating at speeds outside than the nominal range [117]. Moreover, the reduction in the pumping energy is similar to the figure already discussed in section 9.2.2 where the estimation is done based on measured data.

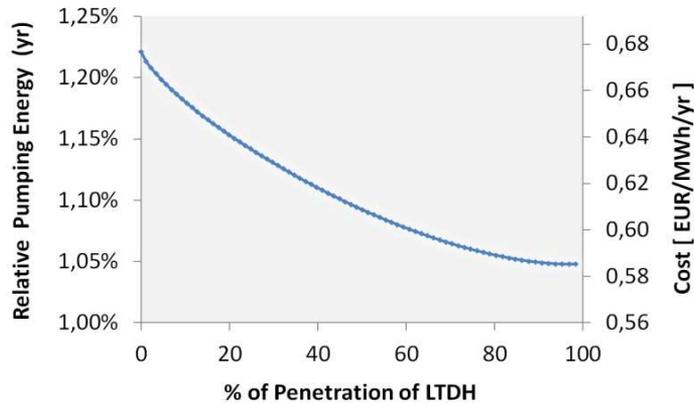


Figure 10-3. Pumping energy relative to the annual heat demand as a function of LTDH load share

The relative pumping energy demand of the primary network (left axis) and the corresponding related costs (right axis) decrease due to the LTDH subnets return temperature levels; if the demand reduction due to renovation would occur with the conventional DH temperature levels, relative pumping energy would increase; instead with LTDH, it decreases from 1.22% to 1.05%.

The total savings and additional revenues are calculated using the previous outcome, and taking into consideration the total annual heat delivered. As seen from **Figure 10-4a**, the combined potential revenues and savings increase together with the percentage of LTDH. It is possible to conclude that although the annual heat demand decreases due to building renovation, the costs for supplying each MWh of heat also decrease. Then, as seen from **Figure 10-4b**, most of the savings are driven by the heat losses, which have a larger share at low percentage of LTDH, which slowly decreases and then increases again.

Considering different points of the curve shown in **Figure 10-4a**, for instance, (a) at 10% penetration of LTDH the total cost reduction would be 19.5 k€/yr distributed as: 68% heat losses, 14% pumping costs, 8% CHP electricity, and 10% FGC heat. This represents 2.8% of the total costs of heat losses of the baseline scenario, achieving a reduction of $\sim 1.5^{\circ}\text{C}$ in the return temperature at the heating plant.

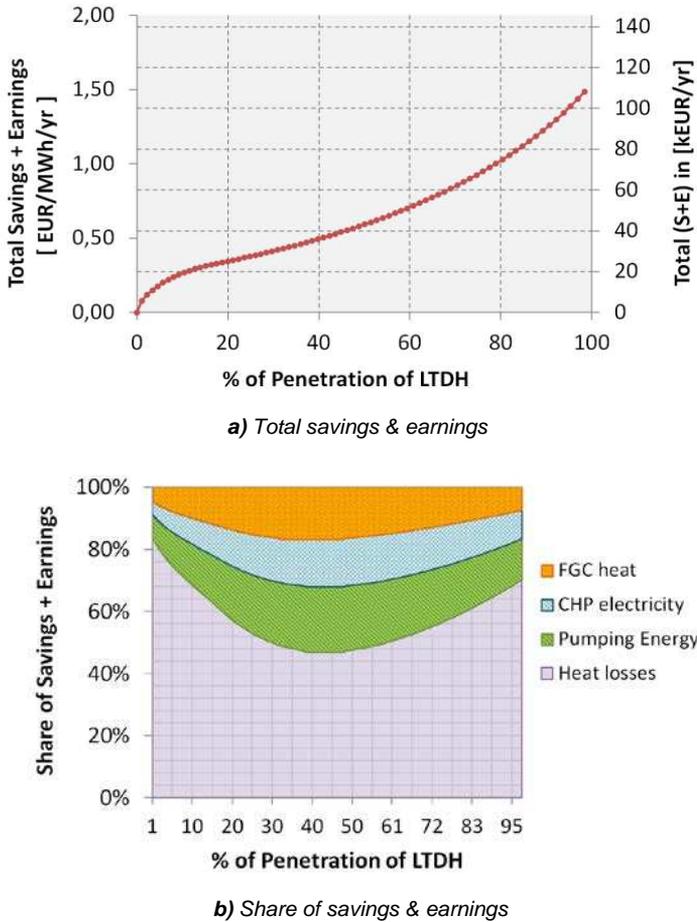


Figure 10-4. Total savings plus revenues as a function of LTDH load share

Figure (a) shows a positive relation between savings and the increase of LTDH subnets. On (b), the share of the contribution to the savings and earnings varies depending on the LTDH load percentage. It is also noted that more than half of the total amount is given by the combined effect of savings in heat losses.

Moreover in Sweden, with the green certificate system in place, additional earnings are generated, due to the extra 54.7 MWh_{el}/yr which can be produced by the CHP plant (not shown in the figures). In a second example: (b) a return temperature drop by 10°C (occurring at 75% penetration of LTDH) leads to a total cost reduction of 65.6 k€/yr distributed as: 57% heat

losses, 18% pumping costs, 12% CHP electricity, and 13% FGC heat. This represents a 9.7% reduction in the costs of heat losses of the baseline scenario. In this case, the CHP plant would produce extra 297 MWh_{el}/yr that would become additional earnings from the green certificate system.

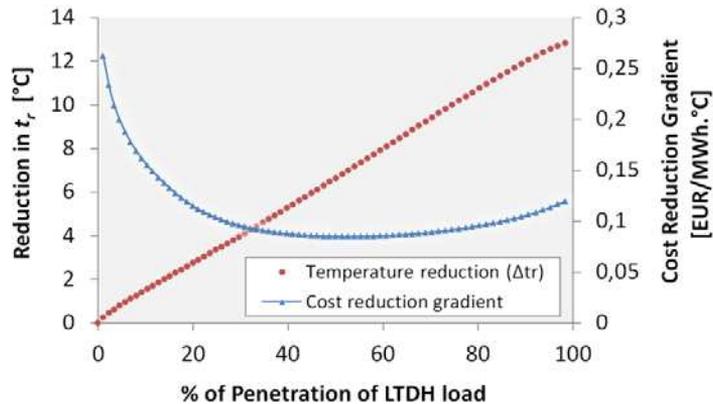


Figure 10-5. Cost reduction gradient and temperature reduction in the return flow

Figure 10-5 depicts the cost reduction gradient (in blue) as a concave curve with a steep downwards slope at the left. The cost reduction gradient is the amount (in EUR) that the utility saves, per MWh produced, and per each °C reduced in the primary return flow. Even though the return temperature at the heating plant decreases continuously (in red) with the increase in penetration of LTDH subnets, the cost reduction gradient value is higher at low penetration of LTDH, and as the penetration increases, the gradient shows a decline and then slowly climbs again.

Already, Figure 10-4 shows the savings per MWh as a function of the percentage of penetration of LTDH subnets. In order to supplement this information, **Figure 10-5** shows the cost reduction gradient also as a function of LTDH penetration. This value represents the amount, in EUR, that the utility saves, per MWh_{th} produced, and per each °C reduction in the return flow, which is a meaningful parameter to evaluate DH systems refurbishment projects [12].

In this case, the reduction in the return temperature is given because of the substitution of conventional DH with LTDH subnets feeding energy efficient loads. As seen from the figure, the savings don't present a linear behaviour such as the reduction in return temperature; the gradient becomes smaller as LTDH share increases. This means that, although all LTDH loads

contribute to a similar reduction of the return temperature, the first loads that are replaced or refurbished contribute to more savings per °C reduced. As the penetration percentage increases, the additional LTHD loads don't contribute as much in savings per °C, as the initial ones. The change in the slope of the gradient is due to the fact that the savings in EUR/MWh continually increase (see **Figure 10-4a**) at a higher rate from 60% penetration rate onwards, while the temperature reduction behaviour is still rather linear as seen from **Figure 10-5**.

11. The thermal micro-grid as prosumer: solar-assisted active substation¹³

This chapter presents the findings regarding the performance of the solar-assisted, grid-connected, active substation. At the beginning, more details are given concerning the model and the layouts to be examined. Then, the performance analysis results are presented focused on the thermodynamic assessment, and a clean-cut analysis of operating costs/savings is also laid out.

11.1. Solar-assisted active substation, temperature cascading and connection layouts

The active thermal micro-grid is complemented by a local thermal energy source to become a *prosumer*. By means of a customised substation, several heat sources can be managed to supply heat to the low-temperature subnet and load. A study on an active solar-assisted low-temperature substation is here presented. The substation uses a mix of heat streams: the solar heat, the return flow from the primary DH network (temperature cascading), and the primary DH network's supply flow. Additionally, it considers the use of the primary network as short-term storage buffer for the solar heat plant, so that no thermal energy storage is required and the plant can be sized according to the available area for the solar collectors.

The performance of the solar-assisted LTDH substation is evaluated through modelling and simulation. The objective is to investigate the share of the energy demand that can be covered by the low-temperature sources in different layouts during a typical year. It functions as the coordinating interface among three different systems: the DH network, the low-temperature substation, and a solar collector. The purpose of the integrated system is to supply heat to the building low-temperature

¹³ This chapter is based on excerpts from **Paper [C]**, referred in the 'Publication List' of this dissertation, and to be submitted for publication.

network coupled at the substation secondary side. A high-level schematic of the subsystems involved is depicted in **Figure 11-1**.

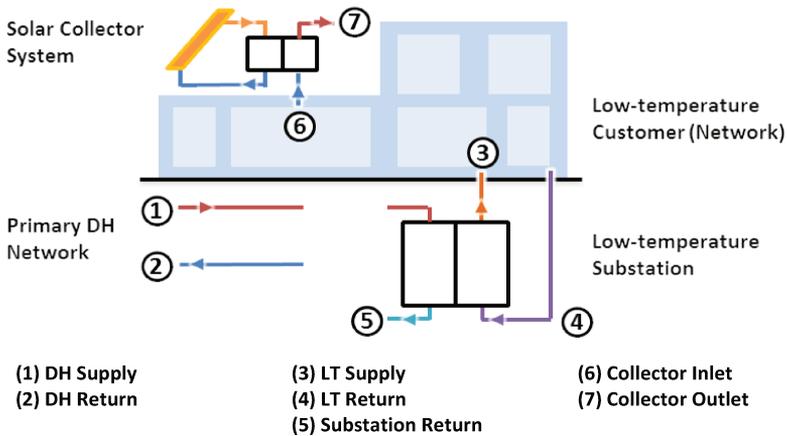


Figure 11-1. High-level depiction of the integrated solar collector-substation system

The figure shows a high-level schematic of the grid-connected solar assisted active substation. The subsystems interacting include: the primary network, the solar collector and the active substation feeding a LT subnet. It is assumed that an energy-efficient building is the load to be fed in this scenario.

As an alternative to the existing coupling layouts of solar collectors to DH networks, an integrated substation with three different solar collector hydraulic layouts is proposed, analysed and compared (see **Figure 11-2**). The first layout *R-S assisted*, shown in **Figure 11-2a**, and the second one *R-R assisted*, **Figure 11-2b**, are detailed and discussed already in section 6.3.2. The performance analysis is based on thermal efficiency and total heat recovered, and for comparison, a substation without solar collector is used as baseline.

The third hydraulic layout studied is a proposed *sR-R assisted* (substation return-to-return). This layout is expected to exploit the advantages of operating the solar collector using the low-temperature DH flows. In this configuration, the feed for the solar collector comes mainly from the LT substation return in the primary side (see **Figure 11-2c**). Then, the heated flow is pumped into the return pipe that goes to the substation, in a

feedback loop type. This third configuration has similar advantages regarding pumping power and lower average operating temperature as the R-R assisted layout. Additionally, with the lower inlet temperature at the collector, coming from the LT substation return, a lower T_m is expected and thus an increased efficiency in comparison.

In both R-R assisted and sR-R assisted layouts, the output of the solar collector is coupled at the level of the DH return pipe. In order to prevent the increase of the primary DH network return temperature that goes back to the heat plant, the direction of the flow of the solar collector is forced to the substation inlet with a check valve (non-return or retention valve), i.e. there is no flow going from the solar collector to the primary DH return. The motivation for this operating mode and layout is that the overall increase in the return temperature of the primary network has a negative impact on the efficiency of heat production plants, and heat distribution losses increase [93].

If the generation is greater than the load at the substation, then a secondary branch with a pump will direct this flow to the primary DH supply (see **Figure 11-2b** and **Figure 11-2c**). This secondary branch follows the same principle as the R-S assisted topology, yet it operates fewer hours and with a lower flow, which is slightly different than the R-R assisted of section 6.3.2. When the solar collector is supplying heat to the primary DH network (the generation being greater than load), the supply temperature set-point of the collector is set to approximately match that of the DH supply, with some tolerance. This temperature match is needed to prevent DH supply temperature drops, which may occur when the solar collector output temperature could be lower than the DH supply temperature that may affect nearby customers or customers located farther away in the network [69]. Thus, the operating temperature range of the solar collector output may vary (from 65°C up to 90°C) depending on the collector manufacturer.

The system operation was simulated following specific operating targets and organised in a heuristic approach, rather than performing a global optimization for simplicity. These targets are: (1) use the least possible flow from primary network supply; (2) aim for the lowest substation return temperature for higher operating efficiency; (3) boost solar heat recovery (with low T_m); (4) feed-in the most solar heat directly to the substation,

reducing the need for short-term network storage. These operating objectives may also be arranged in a different hierarchy, and can be modified, or additional objectives can be added according to the operator priorities. Therefore, the presented results are dependent on the operation scheme chosen, and consequently they might differ if these priorities are modified.

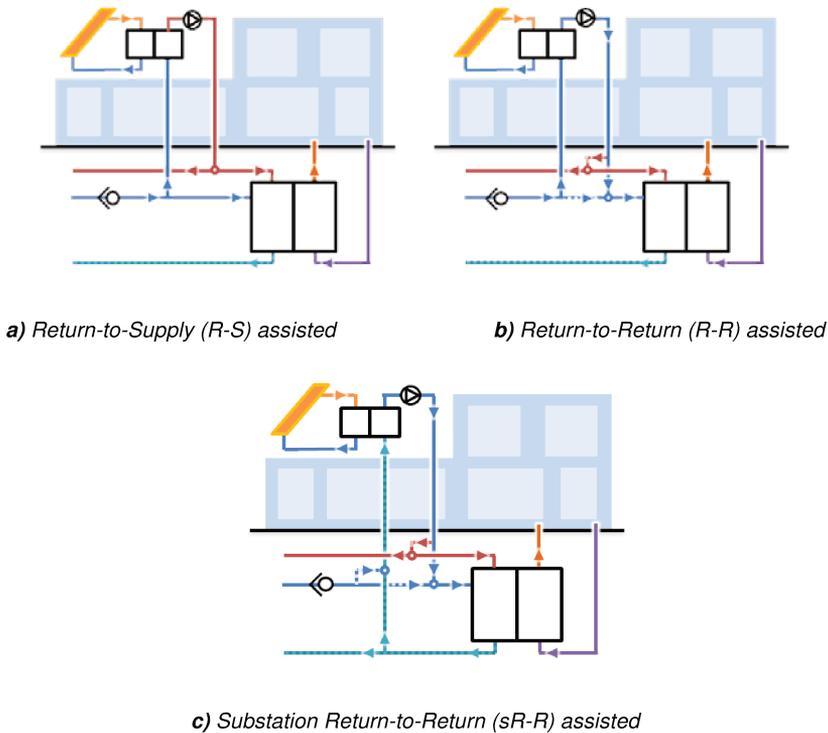


Figure 11-2. Solar-assisted substation layouts

Figure 11-2 shows the simplified process flow diagrams (PFD) of the proposed solar-assisted substations. The *R-S* assisted (a) represents a standard connection. The *R-R* assisted (b) has an additional valve and connection to prevent high temperature streams to flow back into the primary return. The *sR-R* assisted (c) has a similar layout but in this case the LT substation return is used as an input for the solar collector.

11.2. Solar-assisted active substation: thermodynamic performance analysis & potential savings

The outcomes from the thermodynamic simulation are here presented with focus on the share of energy and flows from each source for a one year period, and because of the relevance of the collector's performance in this system, the summer period is analysed in more detail. For this performance assessment, the simulation model used the LT substations based on the 'mixer' type (A) described in section 9.1.1. Moreover, the synthetic load and temperature curves from the previous subsection 8.3 were also used as input, as the information flow shows in **Figure 8-0**. For simplicity, in this substation system, the electricity needed for pumping power is considered negligible, since it only represents a marginal part of the total energy supplied and this part of the analysis is focused on the energy performance. Thus, constant differential pressure throughout the year was assumed.

A summary of the solar collector performance in terms of annual energy figures regarding heat and flows are shown in **Table 11-1**. As seen from the table, the total annual solar fraction is within the range of 4-6%. The energy generated by the collector in the layouts *R-R* assisted and *sR-S* assisted is larger than the 43 MWh/yr of the *R-S* assisted layout. It represents an increase in yield of 20% and 40% respectively, which is substantial. Another performance indicator is the substation return temperature, which in all cases is a yearly average between 35-36°C, without significant differences among the different topologies. This temperature is 5°C above the LT side return temperature average of 30°C, and 13°C below the primary DH return temperature average of 48°C. In general, the operating scheme allows for a low substation return temperature. It is noted that the *sR-R* layout circulates the least amount of flow: 4% less than the case without solar collector.

In the baseline system, without collector and only with temperature cascading, the heat demand is covered in 70% by the DH supply flow, and 30% by DH return flow. All throughout the year, part of the load is met by the DH return. A portion of DH supply flow is needed almost during all hours of the year except for some summer hours, when the solar heat takes its place. In the *R-S* assisted layout the solar heat replaces the DH supply when the collector is operating (see **Figure 11-3**). However, in the *R-R* assisted layout a larger amount of the DH return flow is heated with the

solar heat, because the collector output temperature can be lower than 65°C, as shown in **Table 11-1**. This allows for more operating hours in comparison with the *R-S* layout. When the generation is larger than the load, the surplus solar heat is fed to the network as short-term storage and so it is then used during evenings, nights or early morning hours.

Table 11-1. Solar collector assisted substation: summary annual performance indicators

a) Heat Demand (ref. 1000 MWh/yr)					
Layout	<i>DHs</i>	<i>DHr</i>	<i>Solar Fraction</i>	<i>Solar Generation</i>	<i>Network Storage Losses</i>
No Solar	70%	30%	-	(MWh/yr)	(MWh/yr)
R-S	66%	30%	4.1%	43.3	2.1
R-R	65%	30%	5.0%	52.2	2.1
sR-R	67%	27%	6.1%	60.8	0.2

b) Flows				
Layout	<i>Total (m³/yr)*</i>	<i>DHs</i>	<i>DHr</i>	<i>Solar Collector</i>
No Solar	35.6	42%	58%	-
R-S	35.4	40%	54%	5%
R-R	35.3	40%	47%	14%
sR-R	34.4	41%	45%	15%

In the *R-S* assisted and *R-R* assisted layouts, the solar heat replaces part of the *DH* supply share. However, in the *sR-R* layout, the solar heat displaces part of the low temperature *DH* return share also. Then, when comparing the *sR-R* assisted layout with the other two, in this case, the solar heat is used at the substation at the time it is recovered by the collector and only a small portion is fed to the primary *DH* network as seen from the estimated network storage losses. In the *R-S* layout and *R-R* layout, the solar heat takes the share from the *DH* supply, while in the *sR-R* layout it replaces also the *DH* return flow (as in **Table 11-1**). This difference is partially explained because of the hierarchy of the operating objectives of the substation.

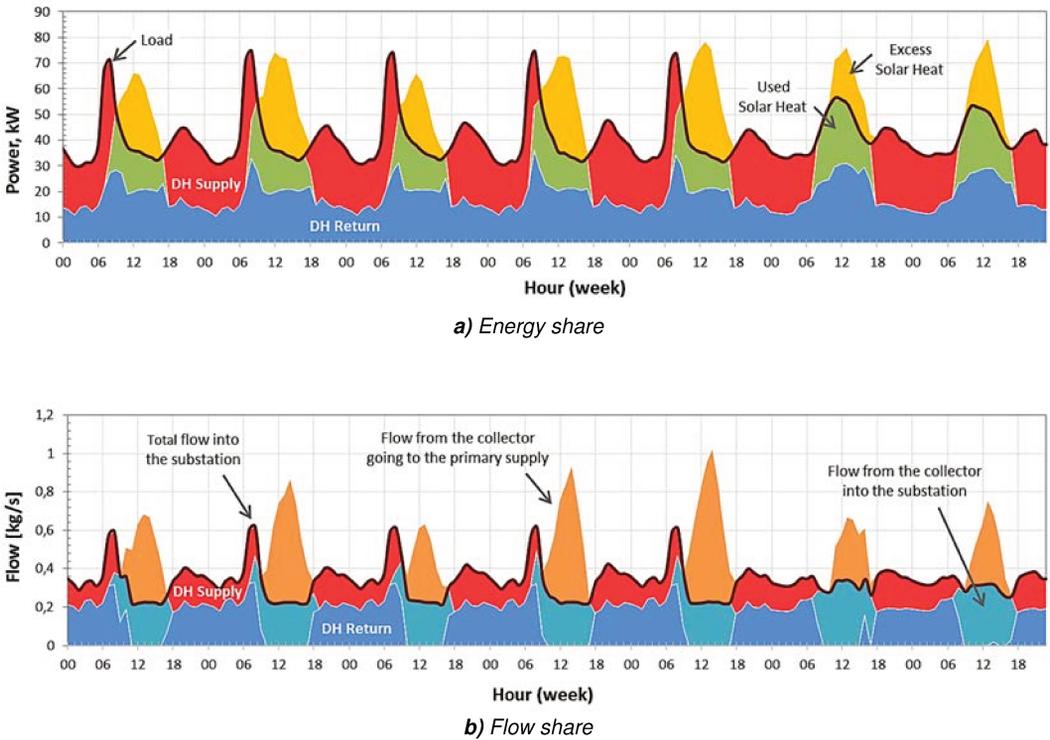


Figure 11-3. Energy and flows in an average summer week for the R-S assisted substation

Figure 11-3a illustrates an average summer week for the R-S assisted substation. In this figure, the average week heat load curve is plotted and the shaded areas show the heat supply source that covers the hourly demand: primary supply, primary return, and solar heat. The figure shows the demand peak at the morning and the solar heat generation peak in the afternoon. When the solar heat exceeds the demand, the surplus is fed into the primary network supply that acts as short-term storage.

As it is a priority to consume most of the energy produced by the collector locally, and to enhance solar collector yield, the output temperature from the solar collector is most of the time below 65°C, except when the generation is greater than the load, then the collector temperature is increased to meet the DH network supply temperature.

11.2.1. Solar collector performance

The analysis of the collector operation shows that it is active in the summer months, late spring and early autumn. From a total of 8760 hours in a year, there are 4340 hours in average with sunlight in Stockholm. Then, considering all conditions, it is possible to operate the collector mostly between the months of April and November: most of these hours during the summer. The rest of the year, either the solar radiation is not enough, or the outside ambient temperature is too low in order to recover sufficient solar heat. **Table 11-2** shows a comparison of the performance of the different layouts analysed.

Table 11-2. Solar collector layouts and performance indicators

	Operating Hours	T_m Avg [°C]	Annual Avg. Efficiency [η_c]	Specific Yield (kWh/m ² yr)
No Sol	0	-	-	
R-S	1468	59	22.1%	217
R-R	2071	56	26.6%	260
sR-R	2266	53	31.0%	305

The sR-R assisted layout has, in overall, better performance than the other two layouts: it operates more hours during the year, at a higher efficiency, and presents a higher collector specific yield. More operating hours result in more heat recovered, even though it may occur at lower operating collector efficiency. Performance improvements come from a lower T_m : in the R-R layout, by having a lower output temperature ($T_{out} < 65^\circ\text{C}$), and in the sR-R assisted by having also a lower T_{in} . The sR-R assisted takes the advantage of a lower T_{in} given by the LT network operation in the secondary side of the substation.

The \mathcal{R} - \mathcal{R} layout, besides having a higher yield and operating at higher efficiency, has as advantage that most of the solar heat is used at the substation at the time when it is recovered. Therefore, less solar heat is fed into the network for short-term storage, which reduces the pumping power required, as well as the network losses related to heat distribution and storage. In the \mathcal{R} - \mathcal{S} and the \mathcal{R} - \mathcal{R} layouts, these losses are estimated to be 5% and 4% of the total solar heat recovered, while in the proposed \mathcal{R} - \mathcal{R} layout they are reduced to less than 0.5%.

11.2.2. Prosumer operation: metering, energy and costs savings

In this section, the effect of the installed collector on the heating costs for the building owner are analysed assuming that the collector and substation belong to the same building. Following the Swedish model of a net-metering contract, the collector heat is bought from the prosumer at about 80% of the district heating tariff from the utility. The net debiting is done either in a monthly or annual basis [118]. In this case, the heat price for the customer is 0,09 EUR/kWh, which is an average price for Sweden.

For a building's consumption of 1002 MWh/yr the annual heating cost is then 90 200 EUR. **Table 11-3a** shows the potential annual savings in heating costs that the proposed system can provide for the building owner, assuming the collector heat is bought at 0,07 EUR/kWh by the utility. Metering is done to calculate the total heat recovered by the collector. It is independent of whether the heat is used at the moment it is recovered, or stored in the network.

However, considering the topologies presented in this paper, this metering and contract model fits well for the \mathcal{R} - \mathcal{S} assisted connection: with primary network feed-in at the forward pipe, and the collector is operated mainly as an independent system. However, for the other two layouts, a portion of the solar heat is fed directly at the substation without going into the network; therefore, the independent solar generation metering scheme may not be completely suitable. One option is to meter the net load at the substation separately, accounting for the heat that is used at the same time as it is recovered. Then, only the solar heat that is fed into the main DH forward pipe is bought at the agreed price. **Table 11-3b** shows the potential annual savings in heat costs with the different metering condition proposed.

Table 11-3. Heating cost savings with different load metering schemes

<i>Layout</i>	a) With solar generation metering		b) With net heat load metering	
	<i>Savings</i>	<i>(EUR/yr)</i>	<i>Savings</i>	<i>(EUR/yr)</i>
R-S	3.4%	3 000	3.4%	3 000
R-R	4.0%	3 600	4.7%	4 300
sR-R	4.7%	4 300	6.1%	5 500

The results show that the savings are sensitive to the metering scheme, and therefore it should be considered when making an economic analysis of the project in a period of several years. In this case, only operating costs are included, so the estimated savings do not account for the investment in the collector installation, which should be examined in the scenario when evaluating the economic project.

11.2.3. Thermal micro-grids, cascading, and solar collectors: discussion

The common practice regarding solar collector installations in buildings is to design the system for a maximum peak load, considering local storage. In this study, the coupling layout of the solar collector system uses the primary DH network as short-term buffer storage. This coupling principle has the following advantages: (1) the collector field can be sized without the limitations of sizing for the buildings load, considering the DH branch, and the available area; (2) overheating of the solar collector in summer is avoided by allowing network feed-in; (3) different stakeholders can participate in the ownership of the system and investment, for instance the housing facility owner, a third party specific plant owner, and/or the DH utility.

Moreover, solar thermal installations have the potential reduce the fuel cost and fuel tax cost of DH heat generation especially for the summer months by replacing the supplied heat from base load heat plants [31]. It is reasonable to expect that the coordinated operation of distributed generation in combination with distributed heat storage could displace conventional heat generation during a large share of the summer operating

hours. Thus, higher overall performance due to auxiliary or base load plants shut down can be expected. One particular challenge would be the coordinated control of the supply temperature and flows, for instance solar collectors and storage would have to supply heat at a network temperature that is high enough for DHW preparation.

In this study, when considering the effects of the solar collector on the primary network, it has been assumed that the heat generation is low in comparison to the network size. With higher penetration level of solar heat in the DH network, some issues may arise regarding the DH network stability, such as pressure cones, temperature fronts and changes in flow direction [69]. In addition, the residual LDC of the subnet should be examined when evaluating the network heat sources and their operating flexibility. For instance, during summer months the typical daily load curve will change according to the solar heat recovered. Therefore, the network should be able to react to changes by quickly ramping up or down the heat generation. In this case, the role of active substations in coordination with heat storage becomes more relevant to minimise the steepness of these ramps.

Part V. Concluding Section

This last part of the dissertation delivers a wrap-up discussion gathering the main conclusions, and lays out perspectives for further research. First, a brief summary of the performed work is given, followed by highlights of the main results and key findings. Then, these results are compared to the contributions that are associated to the research objectives set at the beginning of this work. The common conclusions that follow are assembled in the form of a brief meta-analysis that synthesizes the various outcomes of the incremental assessments. Next, some implications of the results of this research are discussed, and a few recommendations are given. Finally yet importantly, this section portrays a description of the outlook and outlines newly opened research paths.

12. Concluding remarks

This chapter begins with a synthesis of the outcomes from the hereby presented cumulative assessments. It focuses on highlighting key findings and contributions, and associates them to the research objectives set at the beginning of this work. Finally, overall implications are discussed together with general recommendations; and lastly, future work pathways are drawn.

12.1. Summary of the conducted work

This dissertation has developed and discussed the background, methodology, and results that support the premise that multi-source, low-temperature based, active thermal micro-grids will likely become a subsequent step in the technological development of the conventional DH distribution networks. By means of a collection of cumulative technical and/or economic performance assessments, the dissertation evaluated the set of technologies showing that it is a potentially effective and cost-efficient solution. In addition, it has aimed to facilitate the identification of synergies and challenges that arise by operating the subnet as an integrated system in coordination with the primary network.

In the first chapters, the dissertation introduced the overall work, motivation and objectives. Then, it described the fundamentals of DH and a literature review that led to the identification of knowledge gaps, missing links, and challenges concerning the interaction among the system components load/subnet/substation/sources. It has been followed by the discussion of the proposed concept that is object of study. The subsequent chapters described the developed methodology, and modelling and simulation approach. The results of applying the methodology in the form of a series of incremental studies then follow. These studies have covered: the pattern identification on aggregated LTDH load and temperature signatures; the high-level design and modelling of an active substation as aggregator and some possible operating strategies; and the quantification of the impact of LTDH subnets on a conventional DH grid. Moreover, this

research addressed the integration of locally available low-grade thermal energy sources, through the analysis of a hybrid concept of a solar assisted LTDH substation, and –including the Appendix– a basic discussion of the implications of active latent heat storage applications and LTDH compatibility.

12.2. Main outcomes & key findings

The research herewith developed yielded valuable results according to the objectives previously established, following the identification of the relevant research paths. Some of these results were somehow expected, while others added or revised previous research, or cleared some knowledge gaps.

From the micro-grid operation perspective, the analysis of the demonstration project data showed that the operating return temperature of the LT subnet follows a slightly different pattern than that of conventional DH networks (*refer to sections 8.1.3 and 8.1.4*). The aggregated return temperature is the result of the combination of the customer base substations individual patterns and the primary supply temperature. In the LTDH demonstration project, the data analysis results showed that the aggregated return temperature of the subnet has a different behaviour than conventional DH networks near lower outdoor temperatures. After considering other factors, such as the lack of individual heat storage units and a fixed supply temperature, it can be concluded that the aggregated return temperature is strongly dependant on the aggregated heat load of the subnet. In conventional DH networks, the ΔT ($t_s - t_r$) and so the return temperature depend on the primary supply temperature defined by the heat plant operator. In the LT subnet, given a constant supply temperature and no individual heat storage at the customers' substations, the aggregated subnet return temperature showed a strong correlation with the aggregated subnet load. This points to the feasibility to definite a specific *return temperature signature* as a particular characteristic of the LT subnet with constant supply temperature and without individual heat storage units at the customers' installations.

Also from the subnet performance perspective, the thermodynamic analysis conducted on the measurement data set from the LTDH demonstration project (*refer to section 9.2.1*) was useful to expand the results presented in

[9],[43],[10], where it is stated that the primary return covers about 80% of the total supply. This statement is at most misleading, as the data analysis performed in this research uncovered that although more than 75% of the flow comes from the primary return, in reality in terms of energy, only 35% of the annual demand is covered by the primary return flow. Indeed, the mayor share of the annual energy demand is still covered by the primary supply. Although this result may appear counterintuitive, thermodynamic principles explain the situation as follows: because the supply flow has a higher temperature, for a given ΔT , the heat carried per unit mass is two times more, in average, than in the primary return flow, and thus a larger share of heat is transferred from the primary supply flow to the subnet. Only during the summer period, it is possible to maintain that 75% of the total energy supply comes from the primary return, but this period corresponds to less than 10% of the total annual energy demand, and a little more than 25% of the operating hours in a year.

This detailed data analysis also provided a benchmark to compare the results from the simulation model of the LT substation and subnet presented in section 9.1.1. The results from both the measurement data set analysis and the simulation output support each other. The yearly performance results are reliable because of the aggregated parameters, such that uncertainties regarding hourly variation and individual human behaviour are reduced. The findings from this section show that roughly from one quarter to one third of the total annual heat demand of the proposed LT subnet can be covered by the primary DH return flow. This share can be potentially larger in networks with higher return temperatures, which is usually the norm in conventional DH systems in many countries. With such temperature cascading layout, the yearly average substation return temperature in the primary side is reduced 2 to 3 degrees compared with the conventional type. This is the result of the combination of this layout and a larger thermal length of the LT heat exchanger. Additionally, the sensitivity analysis presented in section 9.2.2 to the measurement data set in section gives further insights on how the subnet would perform with changes in the subnet return temperature.

Moreover, the large-scale effect of temperature cascading and LT substations was analysed in order to investigate how the aggregated behaviour of LT subnets with energy efficient loads will affect the operation

of existing networks, and to identify differences with respect to the conventional systems. Based on the scenario where several LT subnets/substations are located in series one after the other within a branch or section in a conventional network, because of the incremental reduction in the primary return temperature caused by each individual substation return, not all substations would be able to recover the same amount of heat (*refer to section 9.3.2*). Under the given conditions ($T_r = 43^\circ\text{C}$), it was shown that at nominal operation a maximum in energy recovered from the primary return occurs when the percentage of LTDH load reaches nearly 58% in terms of load penetration rate, assuming all conventional DH loads are located towards the end of the network. Besides, the energy recovered from the primary return flow approaches a maximum of $\sim 5\%$ of the nominal heat load, and if the primary return temperature of the network would be 10 degrees higher ($T_r = 53^\circ\text{C}$) it would be possible to recover $\sim 10.5\%$. Although these results correspond to the subnet nominal operating point, from the previous assessment on yearly operation, it is fair to assume that similar results would hold for the annual operation.

Then, the results present the quantification of the impact of low-temperature subnets as they increase their share in the heat demand (*refer to Ch.10*). In this chapter, the methodology discussed in [29] was applied in a mixed scenario with LT and conventional DH. It was concluded that although the annual heat demand decreases due to the end use savings via LT renovation, the costs for supplying each MWh of heat also decrease. The lower aggregated primary return temperature keeps the relative heat losses at a similar level, and so the cost per MWh supplied remains relatively constant, (*refer to section 10.3*). When considering the savings and additional earnings, the cost reduction gradient (savings per MWh produced, and per each $^\circ\text{C}$ reduction in the primary return flow temperature) curve shows that, the first loads or subnets that are replaced or refurbished contribute to more savings per $^\circ\text{C}$ reduced, than the loads that are replaced after the penetration rate reaches 20% approximately. Although this analysis was made for a simplified network and not for a network as a whole, it is applicable for each individual network branch/section in a network. Thus, assuming that the DH network is a linear system consisting on the sum of its sections, if the conditions are replicated in each branch, the results would hold for the entire network.

Following the thread of results, it was observed that for a 10°C drop in the primary return temperature, there is a reduction of 6.7% in total distribution heat losses and 23% in total pumping energy input. According to a previous study [28], for a 10°C drop in the return temperature the heat loss reduction expected would be around 6%, and the pumping energy would be reduced by 40% approximately. The difference in the pumping effort figure is partly attributed to the fact that in this work, the pumping energy duty is estimated using curves of existing equipment, and so pumps that are sized for nominal operation at full load, present a sharp decrease in operating efficiency at low duties. This finding is again supported by the sensitivity analysis performed on the measurement data set from the LTDH demonstration project (*refer to section 9.2.2*). There, the estimation reveals that for a 10°C decrease in the average subnet return temperature, there is a 36% reduction in the required flow. This would lead to a 27% decrease in pumping energy input, despite the variable speed pump in place [10], similar to the previously estimated figure.

In the case of the solar-assisted active DH substation (*refer to section 11.2*), it was found that using different layouts and operating strategies can increase the solar collector efficiency and yield. By modifying the temperature levels of the input and output flows of the collector within the extended ranges that alternative layouts make possible, the system performance can be improved. For instance, by directly feeding-in the collector output into the substation, the output temperature can be lower than 65°C; thus increasing the yearly operating hours as well. Besides, the collector can take the advantage of a lower T_{in} given by the LT subnet in the substation primary return. Here, it was pointed out that heat metering and contracts should take into consideration differences in the layouts in order to fairly assign costs and tariffs. These conclusions can hold for other local heat sources, assuming that similar connection layouts and control is possible.

12.3. Revision of research objectives & contributions

In this dissertation, the research objectives have been developed such that the prospective results would yield valuable contributions. The main objective of technically and economically evaluating the performance improvement is attained by the development of a systematic methodology, which has also been presented and discussed, and is supported by

peer-reviewed publications. This has been elaborated by a careful introduction and discussion of the hybrid, low-temperature based, active thermal micro-grid concept, and a discussion on how and why it will likely become a subsequent step in the technological development of the conventional DH distribution networks. Following the same rationale, the secondary objectives were formulated to make concrete and specific contributions, within the scope and focus of the performance assessment.

From the scientific and methodology perspectives, Part I of this dissertation contributes by discussing and delimiting the concept of low-temperature based active thermal micro-grid at the network distribution level. This is supported by the identification of research paths from the state-of-the-art analysis described in Part II, which also adds to narrowing the concept definition. It covers a combination of concepts regarding hybrid heat supply, multiple heat sources, alternate connection layouts, and operating strategies, which had not been previously studied in detail. In Part III, the systematic methodology developed for the performance analysis of the low-temperature based thermal micro-grids is detailed, and it is valuable due to its novelty and its attributes as a generic approach to be replicated for the analysis of other case studies involving active distribution thermal networks. In particular, an improved/updated model of aggregated heat loads is presented and then validated with measured data. The value of this improved model is that it can be applied to any DH system independent of its location, and thus it represents a general contribution.

In Part IV, the analysis of the measurement data reveals that the aggregated load signature of this subnet aligns with the conventional DH knowledge, but it also adds that the aggregated return temperature signature has a slightly different pattern, and is strongly dependant on the aggregated subnet load. This case-specific conclusion may also be extended to other LT subnets with constant supply temperature and no individual heat storage units. In parallel, this work also contributes with the identification of key aspects regarding the compatibility in operation between active latent heat thermal energy storage (LH-TES) and LTDH, which is further discussed in Annex A.

From the engineering perspective, this research offers several other contributions. Throughout parts III and IV, it presents the high-level design and modelling of the LTDH substation subsystem, and it compares possible layouts based on the temperature cascading concept. It presents a feasibility assessment of the LT substation, and tests an operating strategy assuming single-objective optimization control, which is complemented with detailed energy and exergy analysis. Although this simulation is case-specific and used fixed design conditions for the substation and the synthetic load and temperature data, such general conclusions would hold for other subnets using temperature cascading. Then, using the available measurement data set from the existing LTDH demonstration project, its comparison validates the feasibility analysis from the simulation model, in particular the range of share of total annual energy demand that could be covered by the primary return flow in the LT subnet. Thus, given that both the measurement data set analysis and the simulation output support each other, it can be said that these conclusions are robust.

Moreover, the performance sensitivity assessment contributes to showing how the aggregated behaviour of low-temperature subnets, would affect the existing DH networks on a large scale, as they increase their share in the total network heat demand. In the case of temperature cascading, it was revealed that a maximum energy recovered from the primary return is reached under the given conditions, as well as the corresponding maximum share of LTDH load that allows it. This contribution can be considered general for any branch of any network, and likewise assuming that a DH network can be described as the sum of its sections/branches as a linear system, it can also hold for an entire network. The results also add a rectification regarding pumping energy, which decreases given the drop in primary return temperature: the reduction seems to be lower than previously estimated due to the low pumping efficiency when operating at low duties. As the conclusion regarding pumping energy comes independently from both the simulation model and the measurement data set, it seems to be applicable for several types of networks, although it should be further studied to assume it as a generic conclusion.

Lastly, this work yields more case-specific contributions with the modelling and analysis of a multi-source, grid-connected, solar-assisted, active substation concept, and the quantification of the impact of the active

(prosumer) system on the subnet operation and costs. These contributions altogether help to expand the current knowledge in the field of district heating. They show how an integrated operation of the subsystems can also benefit the overall network, and assist to meet the thermal energy demands of energy efficient building stock in an effective and cost-efficient manner.

12.4. Concluding discussion

The set of presented results have shown that the strategic operation of an active thermal micro-grid as a unit can potentially increase the performance of the subnet, and make a positive impact on the primary network. By designing and operating the subnet system using an integrated approach, rather than in an individual manner, it may be possible to benefit both the consumers and the suppliers on a large scale.

The LT subnet operating parameters such as the aggregated load and temperatures might have slightly different operating characteristics that should be taken into consideration for the design and planning of these systems, such as the strong subnet return temperature dependency on the aggregated load. In addition, the cascade usage of the DH primary network return flow is feasible, although limited, and can be coordinated by the active subnet/substation. However, there would be a maximum share of subnets that could take advantage of the temperature cascading layout, and it depends on the network operating temperatures. Likewise, an increasing number of LTDH micro-grids in a conventional network reduces the primary return temperature, and thus leads to lower generation & operating costs for the overall network.

The impact of modifying the network operating temperatures can involve conflicting objectives for the overall cost reduction. Investing in lowering operating temperatures increases some expenses while lowering others. For instance, as the penetration rate of LTDH increases, in a long-term perspective it might be possible to lower the primary supply temperature a few degrees. Consequently, distribution losses would substantially decrease, and since the losses on the supply pipe represent more than two thirds of the total losses, larger savings would be then achieved. Nonetheless, this reduction may come at the expense of increased mass flow rate, and so increased pumping energy input and its related costs. Still, in most cases,

lowering the network operating temperatures leads to reduced operating costs, and if the investment necessary is balanced, an improvement in economic performance is also achieved.

Additionally, having local heat sources or storage on the primary side of the substation, such as the primary return flow, improves the efficiency of the subnet and increases the degree of supply/demand match in time, quantity & quality. For instance, the yield, efficiency, and operating hours of solar collectors can be potentially increased. In addition, the operating strategy followed by the active subnet can be useful to coordinate the flows, and so to achieve the desired operation objectives such as the minimization of a cost function, higher system efficiency, and/or a higher share of renewable distributed heat. These advantages are transferrable from solar collector systems, to other type of low-grade heat resources, locally available, and connected to the DH systems as distributed heat sources. In this case, special attention has to be paid to the heat-metering in place, in order to fully economically exploit these sources for the benefit of all actors.

This work has revealed that the low-temperature active thermal micro-grid concept enhances the potential of the DH system to integrate low-grade heat sources and loads to the existing network by effectively coupling several agents despite differences in energy quality and quantity. A successful integration of these elements into active thermal subnets will require further investigation, to clearly assess all benefits and drawbacks, and to be able to contribute to the goal of achieving a low-carbon, energy efficient and renewable energy supply.

12.5. Recommendations & further work

The rates of new building construction and building refurbishment in Europe range from 1% to 2% per year with respect to the existing infrastructure. This figure, although minor, presents an opportunity to expand the DH networks and to introduce innovative technologies, such as 4GDH. Therefore, a transition will gradually occur spanning several decades, and it presents a challenge for utilities that will have to adapt to the different conditions and plan their investments carefully, especially in those countries with an already large share of DH networks. The potential savings offered by the new technologies and combined measures should be then

compared with the respective investment and/or depreciation, so as to select the most cost-efficient alternative.

It is also recommended to further introduce and study new models of aggregated load and return temperature, if necessary, as a unique characteristic of LT subnets with constant supply temperature and without individual heat storage units. This is particularly important to ensure that the LT network equipment is correctly sized and will perform as expected during full load conditions.

Furthermore regarding the sizing of equipment, it was found from both simulations and the measurement data analysis that pumping energy might not be efficiently used, particularly during summer when the heating load is minimum, and consequently also the flow throughout the network. As pumps are sized for nominal operation at full load, their operating efficiency presents a sharp decrease, for instance from 70% to 30%, when operating at low duties. Already, many DH systems have pumps in parallel to ensure the robustness of the system, and the designs address the changes in flow with variable speed pumps; yet the operating flow during summer is so low that even the variable speed pumps may run at very low efficiencies. This issue may be approached in a few ways. For example, sizing 3 pumps each at 50% of the peak duty would yield higher efficiency than 2 pumps both sized for 100% of peak duty [18]. Another option is to use one, or more, smaller 'jockey' pumps to be operated during the summer period and sized for the average summer duty. This period comprises more than 25% of the total yearly operating hours and such measure could bring sufficient savings in pumping energy that could justify the required design and an additional but relatively small investment.

Moreover, when looking into more detail on the impact of LT subnets in a conventional DH network, some suggestions can be given based on the results of this research. It was also found that the first subnets that are replaced or refurbished contribute to more savings per °C reduced, than the ones that are replaced after the penetration rate reached ~20%. This could be a factor to motivate early adopters of 4GDH, and formulate economic incentives.

Although there might be little possibility to influence the location of the subnets to be refurbished, the results show that it is preferable to renovate the subnets closer to the heat plant if the main benefit is given by a lower return temperature. On the other hand, if heat losses are the priority, a subnet farther away towards the end of the line is preferred to be refurbished.

It is recommended to perform an integrated cost analysis involving different configurations and sizing. It is necessary to analyse the case for additional capital investment required by the new technologies. This applies to both the choices on investments and changes in the operation strategies to minimize costs or maximize earnings. The performance improvement given by the additional flexibility will probably yield additional operating profits that may pay the extra CAPEX/investment required. Then, it will be possible to evaluate the investments in a longer time horizon to determine whether the expected returns exceed or just balance the costs.

In order to continue and further develop this research work, the author recommends to expand the scope of the studies here presented. Regarding the substation model and layouts, it would be interesting to consider variable design conditions, looking towards a techno-economic optimization. This would require to expand the system boundaries and to verify that the operating points are within the minimum standards. In addition, local or distributed heat sources with different operating dynamics should be modelled, and their corresponding coordinated operation. In this regard, it would be interesting to analyse the applicability of multi-agent optimization strategies from other fields regarding resource allocation problems, such as electricity networks. Moreover, when considering the overall network, more accurate results could be obtained by estimating temperature and pressure drop, instead of assuming them negligible. In general, performing more sensitivity analyses on operating parameters with hourly resolution will result in deeper insights regarding the subsystems interaction, at the expense of intensive computing power/time that might be required. In addition, it is possible to extend the assessments to consider environmental indicators such as CO₂ emissions and LCA, in order to integrate a broader perspective and deliver more exhaustive results.

12.6. Outlook

There is still work to be done regarding the development of active thermal micro-grids and the assessment of its cost-efficiency. There are several challenges that require further investigation to identify and overcome the toughest barriers, and develop and improve the technology. The discussion of the concept itself opens several research paths. Particularly, it is necessary to clearly understand the value of flexibility and controllability given by active distribution thermal networks, which has become a matter of study already [119]. While the technical benefits such as security and reliability might follow a straightforward analysis, in order to test the economic benefits, it is necessary to look into the energy business, considering various possibilities for policy, models, and legal frameworks that will enhance the competitiveness of the 4GDH.

As 4GDH technologies become more integrated to the conventional DH system, it will be relevant to analyse the impact of these systems on the conventional network, as well as the benefits for suppliers and customers. It will be of particular interest for DH network operators to clearly understand the trade-offs that will arise with displaced central generation capacity, in terms of network investment, operating costs and maintenance. Their strategies regarding network control will require considering alternative network topologies, shifting operating parameters, and decentralised but coordinated heat generation.

The combined effects of an increasing share of low-temperature subnets on the existing DH networks remain an open question, thus alternative network topologies are also being studied. Within the 4GDH developments, different network layouts and innovative equipment become possible. The choice on whether choosing one layout over the other will depend on the trade-off between complexity and the potential benefits of efficiency and flexibility. Moreover, active thermal micro-grids also have the potential to become the first step towards nodal development of the DH system (bottom-up approach). That is, the development of small, independent, centralized energy networks that can be interconnected in the future to form one or more larger networks in a region.

With different options for connection layouts and ownership of the distributed generation systems, a wider variety of business models for distributed heat generation become possible. It also allows more flexibility for the participation of additional actors in the generation/use of heat. The range of possibilities opens the discussion regarding heating contracts, metering and billing. For instance, a business model in Germany for solar collectors considers individual feed-in from prosumers, while the network operator offers a storage service; there the surplus solar heat in the summer is 'stored' for an 8-month period and the prosumers have access to the heat later during the heating season [121].

Already, heat and electricity markets are linked through CHP as co-generation plants generating electricity and heat that are fed to these networks. Currently, additional synergies between heat production and electricity generation have been created, enhancing the integration of the two sectors. On the one hand, distributed heat generation and storage will likely become more integrated with the existing networks. This has the potential to reduce the marginal cost of heat supplied, by shifting loads and decreasing peak loads, and making the DH system more cost-competitive. On the other hand, the 4GDH could provide excellent aggregators to supply ancillary services to the electricity sector. Since electricity systems depend on an exact balance between demand and supply at any time, DH systems could provide the balancing of a large share of surplus renewable power.

For instance, the link between heat and electricity markets has already grown deeper in Denmark [120]. There, at times of high electricity prices, CHP plants feed electricity into the grid and store heat in large accumulators, distributed throughout the network. The balancing occurs when electricity prices are low –or approaching negative values–, due to high wind power generation, and so the surplus electricity is used in large-scale heat pumps or electric heaters to generate heat and feed it to the DH network. In parallel, co-generation plants are ramped down, and the stored heat feeds the DH network.

Furthermore, the coordinated operation of distributed generation in combination with distributed heat storage, and active substations becomes more relevant to reduce generation ramps at the central HPUs.

For example, with distributed solar collectors and storage, it will be useful to appropriate and adapt the knowledge from power systems to predict the day-ahead solar generation based on weather forecasts. In this way, the DH central supply and storage could use the flexibility of the distributed generation and adjust for ramping up/down its centralized units. This would also help increase the robustness and resiliency of energy system facing increasing variability caused by extreme weather events.

At present, there are several developments in the IT sector that may further the introduction of 4GDH technologies. For instance, wireless and smart metering may provide lots of information about the distribution network components performance. The internet of things (IoT) together with big data analytics are already permeating energy companies and utilities that are eager to exploit the potential of these technologies applied to their businesses. Data availability and better use of information offers opportunities to develop new businesses and business models that bring utilities, energy companies, consumers and new actors tighter together. This may imply that the operation and maintenance of the distribution network, including customer substations could be managed in an optimal manner to benefit the DH companies and their customers. For instance, there are already companies in Sweden dealing with big data applications for heating (energy) networks [122]. Their focus is to transform the data into valuable information in order to improve the total system operation and optimize its performance.

One technology in particular whose development should be followed closely is “Blockchain-Enabled Distributed Energy Trading”. Blockchain is the technology behind the well-known cryptocurrencies, still most energy related Blockchain applications are currently in the concept/prototype stage. In the medium-term, it is expected to allow for easy reconciliation of contracts between generators, distributors and customers through the execution of ‘smart contracts’. Moreover, other potential Blockchain DH applications include the ability to improve metering, introduce open billing systems, emission tracking, asset management and commissioning records. In the long-term, its ability to facilitate the integration of currently disjointed DH schemes around cities would be the most valuable outcome to watch for.

There are certain challenges regarding the economics of DH networks that the market has not been able to solve by itself, and thus the intervention of regulation authorities and measures has been required: the natural monopoly, bundled heating services, third party access, and effective competition. The introduction of 4GDH technologies adds to the uncertainty and to the opportunities, and thus further studies should focus on the market & policy mechanisms to ensure access to the network for consumers, prosumers and third parties. It is necessary to follow up the issues of ownership, contracts and tariffs, and how the distributed heat generation is properly metered. In order to enhance the security and certainty of the investments in the new technologies, the discussion should include new roles and responsibilities of supply/distribution companies and consumers/prosumers. This may include alternative ownership structures, energy service providers, and efficient allocation of the network costs and ancillary services for the new agents involved. Experience has shown that adequate regulation is needed to allow and encourage a smooth integration and deployment of such technologies.

This work presented a cumulative analysis of a possible path to improve the effectiveness and cost-efficiency of the DH system servicing new and refurbished building stock, to increase its flexibility and adaptability, and to become a successful element of the energy system infrastructure. In this manner, this work further expands the existing DH technology knowledge by enhancing the next DH generation ability to re-design, optimize and develop itself, in order to play a key role in the future smart and sustainable energy system.

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Appendix

This section consists of additional information and contributions of this research project that supplement the main text of this work. It helps the reader to better understand the context and some conclusions of the overall work. Appendix A discusses the performance characteristics of typical active latent heat thermal energy storage (LH-TES) systems. It focuses on possible issues that may arise regarding their compatibility with low-temperature thermal distribution networks based on the most recent developments.

A. Considerations on the integration of distributed active latent heat TES systems and LTDH¹⁴

This section presents a discussion of the integration of distributed thermal energy storage systems with LTDH with emphasis on active latent heat systems. A discussion on the performance characteristics of these systems is presented as well as their compatibility with LTDH according to the most recent literature. Several benefits are noted as well as barriers for their implementation; for the latter some recommendations and methods to address them are introduced. A more detailed techno-economic analysis of these systems with LTDH is conducted in [11].

The integration of distributed TES systems with the DH network has the potential to bring substantial benefits for the network, both from the economic and environmental points of view. The success of this integration and the extent of its benefits will vary depending on the design and configuration chosen for the TES, which will depend on factors, such as scale, regulations, incentives and space availability.

The typical active TES system consists of four main components: a heat storage medium that is heated and cooled; a containment vessel for this medium; a heat transfer fluid (HTF); and a heat exchanger (HEX) surface to transfer the heat between the HTF and the storage medium [56]. If the storage medium and heat transfer fluid are the same, such in the case of some water tanks, then the heat exchanger is not required.

Sensible heat (SH) TES systems represented by a water tank is the current benchmark. Some of the typical characteristics of SH based systems are the

¹⁴ Some segments of this section are based on excerpts from **Paper [E]**, referred in the 'Publication List' of this dissertation, and published in 2017 in *the International Journal of Sustainable Energy Planning and Management – IJSEPM*.

following: water is usually both storage medium and heat transfer fluid (HTF); they are easily scalable; require thorough insulation to minimize heat losses; might need pressurization to avoid evaporation; and stratification is desired in order to maximize the storage efficiency [63].

In the case of latent heat (LH) TES, the active system is represented by a tank filled with a PCM as storage medium. The internal layout or distribution of the PCM is still a subject of current research. In the charging process, the heat is stored by passing a heat transfer fluid (e.g. water) at high temperature through the storage until the PCM has fully melted. The discharge process occurs in the opposite way; the HTF at lower temperature is heated while passing through the storage and then supplied to the load/sink.

A.1. Active latent heat (LH) TES systems performance

Besides the PCM properties, the actual performance of the whole active LH-TES system will determine the suitability for specific applications, and will also be the basis to design strategies to improve this suitability. In the case of TES for DH applications, they are designed according to a heat load and storage capacity, but the most stringent limitations for their operation are the supply/return temperatures. Therefore, it is necessary to design for the performance of the active LH systems considering these parameters. There are some studies that report on the transient performance of LH systems [123], [124], [125] that may be suited for DH applications. Based on these performance analyses, **Figure A-1** illustrates the typical characteristic performance curves of active LH-TES in terms of HTF inlet/outlet temperatures as well as input/output power, assuming a constant flow rate.

During the charging process (see **Figure A-1a**), the HTF outlet temperature curve shows that the temperature of the HTF after passing the storage is equal or higher than the phase change temperature during most of the charging period, before full charge is achieved. It is the consequence of the PCM melting occurring within a narrow temperature range, and it means that the flow leaving at the storage outlet contains useful thermal energy with respect to the DH loads/sinks temperatures. So to maintain high

efficiency this outlet flow should not be channelled to the DH return pipe. On the other hand, during the discharge process (**Figure A-1b**), when approaching full discharge, the HTF outlet temperature is below the phase change temperature range. Thus, if this flow is to be used for DH supply, when the HTF temperature at the storage outlet drops below the minimum required level, a supporting strategy to boost the temperature of this flow will be required.

Figure A-1 also shows that thermal power output/input –the system property to release or store heat per unit time– is not constant: there is a maximum at the beginning of the charging/discharging process and then it decreases continuously until reaching zero. Therefore, a buffer or supporting heat source would be needed to match a specific load during the discharging process. An alternative scheme to control the HTF outlet temperature is to vary the flow rate passing through the storage. The flow rate would decrease during the discharging process to raise the output temperature, yet this action will further limit the power output, and would require more complex control. During the charging process increasing the HTF flow rate as a strategy to reduce the output temperature will be ineffective due to the relatively constant phase change temperature range and the high HTF temperature at the inlet.

Regarding thermal power, LH-TES systems exhibit a lower output compared to water-based SH systems. Therefore, a trade-off between energy and power densities arises. The lower thermal power of LH systems is due to the differences in the heat transfer processes with respect to SH systems [6],[126]. In water-based systems the heat exchange process is dominated by the convective heat transfer mechanism over conductive heat transfer. However, in LH systems, when phase change takes places, for instance during the discharge process as the PCM solidifies, it is deposited as solid layer over the heat transfer surfaces. Then conduction, instead of convection, becomes dominant. Since PCMs generally have low thermal conductivities, the heat exchange process is hindered, having a lower overall heat transfer coefficient and so heat transfer from the LH-TES is sluggish. Another consequence of this process is that melting (charging) occurs faster than discharging and a higher power input can be achieved.

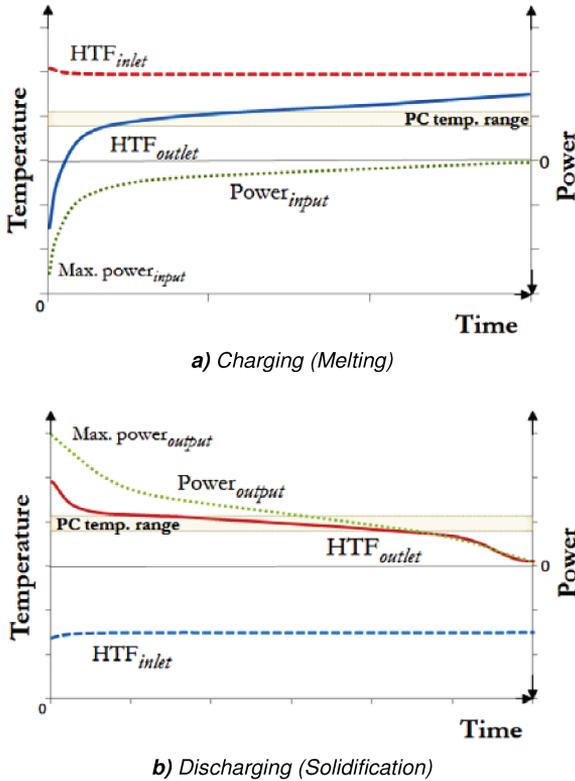


Figure A-1. Typical characteristic temperature curve (a) and power performance curve (b) of active LH-TES systems

The figure shows typical performance curves of active latent heat TES systems. On (a), the charging process is depicted with a constant input fluid temperature. On (b), the figure shows a typical discharge curve given a constant temperature fluid input. Note that the temperature of the outlet fluid varies outside the phase change temperature range, and that the system charge status can be defined at will according to the required specifications.

In order to improve the LH systems performance in this aspect, several solutions have been proposed, described, and studied in [127], [128]. When considering the full TES system, it is possible to influence the power density not only by enriching the storage medium, but also by the design of

the vessel and the HEX. These enhancing techniques include, among others: adding materials with higher conductivities into the PCM on a macro scale or composites on a micro scale (e.g. adding graphite to paraffins or salt hydrates), decreasing encapsulation size, or placing the PCM into metallic foams or a graphite matrix.

When choosing a suitable LH-TES system it is necessary to select a PCM whose phase change temperature is adequate to reach full melting/solidification within the operating temperature range of the application. In this regard, differences due to hysteresis should also be considered by comparing the heating and cooling cycles of the PCM. Moreover, in the case of full TES systems, the temperature range applicable to the storage material is further reduced by the temperature difference necessary for heat exchange [129], and should also be taken into account when selecting the appropriate storage medium.

A.2. Active LH-TES systems layouts and operation with LTDH subnets

TES systems can be located either at the heat production facility as a large centralized unit or at the DH substations in a decentralized manner, so that a building or group of buildings have their own TES. In this section we analyse the latter, since for small-scale TES, the use of LTDH and PCM could provide a cost-efficient competitive solution. Some configurations have already been explored comparing SH and LH TES coupled to DH, such as in [130] where the storage is placed as an interface between the primary and secondary sides, having the same function as the DH substation and providing hydraulic separation between the primary/secondary networks. However, this configuration would lead to high return temperatures on the primary side, and it requires a bypass system for the tank on the secondary side in order to control the supply temperature.

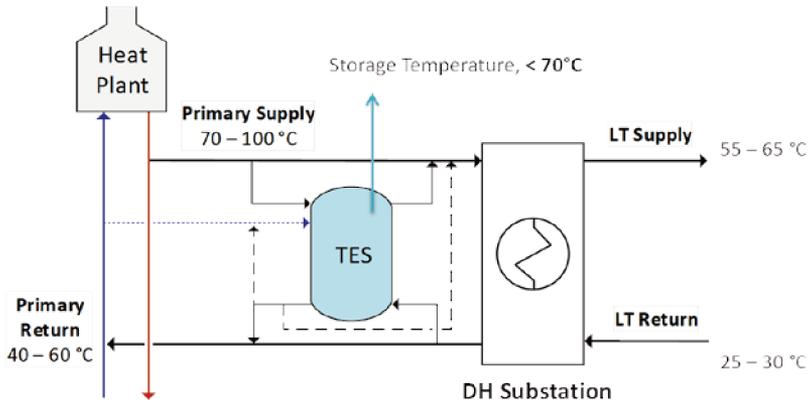


Figure A-2. LH-TES system application with LTDH substation

The figure shows a simplified process flow diagram of the latent heat TES system application with a LT substation. The storage temperature is expected to be just above the LT subnet supply temperature, and it can be reached by the primary supply, primary return, or a mix of both. The set of additional pipes and valves is to be used for particular charging/discharging conditions that are further explained in Figure A-3.

In a possible configuration shown in **Figure A-2**, the TES system is located in parallel on the substation primary side. The storage temperature is defined to be slightly above the LT supply, and so the required phase change temperature is around 70°C. An advantage of this configuration is that the primary network is used as support especially when the TES approaches full discharge. (Note that for ease of explanation, in both **Figure A-2** and **Figure A-3**, the HTF inlet to the tank and HEx, and the HTF outlet are represented with multiple lines, but they are in fact only two points: HTF inlet and outlet; plus additional pipes, valves and connections not shown for simplicity.)

The operation of this active LH-TES system evidently requires two main modes: charging and discharging. During the charging process (see **Figure A-3a**), the hot water from the DH primary supply, point (a) is used as HTF input. After exiting the storage, point (c), the cooled HTF is then directed to the primary return. Moreover, as an alternative heat source, when the primary return flow temperature is high enough ($>T_{pr}$), this flow

could be used to charge the storage, point (b), or either a mixture of both (a) and (b), and thus reuse some of this heat. A drawback of this approach is that the required charging time would be longer.

During the charging process of LH-TES systems, the temperature of the HTF leaving the storage at the outlet is very close and/or exceeds the PC temperature of the medium for a long period. This temperature could be significantly higher than the network return; therefore, it would not be desirable to channel this flow into the primary return due to the useful heat it contains with respect to the load/sinks and because of risking of penalties on high return temperatures. In this case, a variation of the charging process operating mode is necessary. This alternative is shown in **Figure A-3b**, where depending on the temperature level of the HTF at the storage outlet, the flow can be recirculated to the TES inlet, point (d), or to the DH substation inlet, point (e). At this point of connection, the flow temperature could be boosted by mixing it with the DH primary supply and so ensure a sufficiently high temperature at the DH substation inlet.

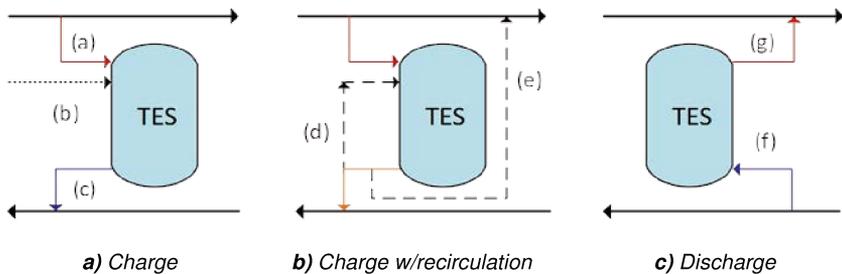


Figure A-3. LH-TES system operating modes of the proposed arrangement

This figure shows the possible modes to charge/discharge the LH-TES according to the network operating parameters and the storage performance curves previously shown in Figure A-1. These modes are required to improve the compatibility and operating efficiency of the storage to the network operating conditions.

During the discharging process (**Figure A-3c**), the flow at low temperature coming from the substation return is used as HTF input, point (f), to the TES. The heated flow leaving the storage, point (g), is then directed towards

the substation supply/inlet. When near the end of the discharge process the storage outlet cannot ensure a sufficiently high temperature (**Figure A-1b**), this flow could be mixed with the DH primary supply to boost the temperature.

In the future, as active LH-TES systems will be more integrated with the 4GDH technologies, it will be relevant to analyse the impact of these systems on the main network, as well as the benefits for suppliers and LTDH customers. The technology will have the potential to reduce the marginal costs of heat supplied to the LTDH subnets by shifting loads and decreasing peak loads, making it more cost-competitive.

Disclaimer



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About the author

José Fiacro Castro Flores, born in Mexico City, received his Bachelor's degree in 'Mechatronics Engineering' from *Monterrey Tech* (ITESM CEM) in Mexico State, Mexico, in 2008. He obtained a MSc. degree in 'Sustainable Energy Technology' from *Eindhoven University of Technology* (TU/e) in 2010, in The Netherlands, where he conducted his graduation project in the Electrical Energy Systems group (EES).

In 2011, he started his career as Development and Applications Engineer at *General Electric Co.* (GE Power) in Querétaro, México. There, he worked in R&D engineering of power generation projects and sustainable energy engineering, as part of GE's *Edison Engineering Development Program* (EEDP), GE's corporate entry-level technical leadership program.

In September 2013, he joined the Erasmus Mundus PhD programme *SELECT+* as an early-stage researcher/scientist, pursuant a double doctoral degree in Engineering Sciences at both *KTH – Royal Institute of Technology* in the Department of Energy Technology in Stockholm, Sweden, and *IMT Atlantique* (formerly *École des Mines de Nantes*) in the Department of Energy and Environmental Systems in Nantes, France. He has specialised in the modelling, simulation and analysis of the techno-economic aspects of energy networks and systems, and the assessment of complex systems and data. During his PhD tenure, he has also been associated with the *EIT InnoEnergy PhD School*, where in 2017, he completed and obtained the certification in 'Energy Innovation' for early-stage researchers.

He holds cross-disciplinary expertise in the fields of automation, power systems, combustion turbines, and energy networks, within multi-cultural settings. In a more personal level, he is interested in all things tech and science, is a supporter of sustainable development, and a volunteering enthusiast for projects in education and equality. His research and professional interests are focused on, but not limited to, energy networks, mobility and urban technologies.

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Thèse de Doctorat

Doctoral Thesis

José Fiacro CASTRO FLORES

Low-temperature based thermal micro-grids: operation and performance assessments

Micro-réseaux de chaleur urbains basse température : évaluation du fonctionnement et de la performance

Résumé

L'utilisation d'énergie en milieu urbain est essentielle pour le bon fonctionnement de notre société, en particulier pour les besoins de chauffage qui est un élément central de notre système énergétique souvent considéré comme allant de soi. Dans ce cadre, les systèmes énergétiques urbains et en particulier les réseaux de chaleur urbains ont besoin d'évoluer pour s'adapter à la transition à venir vers un système énergétique durable.

Ce travail de recherche a pour objectif de présenter, de discuter et d'évaluer, du point de vue technico-économique, le concept de micro-réseaux de chaleur urbains basse température comme réseaux secondaires de distribution de chaleur actifs. Dans cette thèse, une approche méthodologique mixte basée sur la simulation analytique pour l'évaluation des alternatives est développée et discutée pour étudier une combinaison de technologies associées aux sous-stations basse température.

Les principaux résultats de ce travail couvrent : le développement d'un modèle amélioré de charges thermiques agrégées ; la comparaison des performances des réseaux basse température ; l'analyse des avantages et des inconvénients des sous-stations actives couplées à des sources de chaleur ou du stockage distribuées ; et les effets d'une température de retour du réseau primaire plus basse.

Les conclusions révèlent que la conception et le fonctionnement intégrés du micro-réseau de chaleur urbain actif ont le potentiel d'améliorer les performances de l'ensemble du système, afin de relever ses défis d'une manière efficace et rentable. Ce travail fait progresser les connaissances actuelles sur le chauffage urbain en identifiant les synergies et les enjeux associés, en vue de que ces technologies jouent un rôle clé dans le futur système énergétique intelligent et durable.

Mots clés

chauffage urbain basse température ; micro-réseaux de chaleur urbains actifs ; évaluation de la performance ; sources de chaleur distribuées

Abstract

Energy use in the urban environment is vital for the proper functioning of our society, and in particular, comfort heating –and cooling– is a central element of our energy system that is often taken for granted. Within this context, district energy systems and especially, district heating (DH) systems must evolve to adapt to the upcoming decades-long transition towards a sustainable energy system.

This dissertation seeks to introduce, discuss, and assess from a techno-economic perspective, the concept of low-temperature based thermal micro-grids (subnets) as active distribution thermal networks. For this purpose, a mixed methodological approach based on analytical simulation for the assessment of alternatives is developed and discussed to evaluate a set of technologies.

Key findings of this research include: an updated and improved model of aggregated heat loads; the identification of differences in load and temperature patterns for certain LT subnets; the analysis of benefits and drawbacks of active substations with distributed heat sources and/or storage; and the impact of the reduction of the primary network return temperature, which leads to lower generation & operating costs.

These outcomes reveal that the integrated design and operation of the active thermal micro-grid have the potential to improve the performance of the entire system, to address the matter of providing comfort heating in an effective and cost-efficient manner. This work advances the current DH knowledge by identifying synergies and challenges that arise with these new developments, in order for DH to play a key role in the future smart and sustainable energy system.

Keywords

low-temperature district heating; active thermal micro-grid; performance assessment; distributed heat sources

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